MODELING WITHIN-TREE CHANGES IN LOBLOLLY PINE MICROFIBRIL ANGLE IN THE SOUTHEAST UNITED STATES

by

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(Under the Direction of Richard F. Daniels)

ABSTRACT

There has been an increased interest in wood properties within the last decade. Microfibril angle is one of the main determinants of the mechanical properties of wood. Microfibril angle significantly affects the dimensional stability and stiffness of sawn lumber and has been found to be highly correlated with the stretch, stiffness, and strength of paper properties. Sixty loblolly pine (*Pinus taeda* L.) trees from four distinct physiographic regions in the Southeastern United States were sampled for microfibril angle analysis. Prediction equations were developed from mathematical models to explain the change of microfibril angle at any height, distance from pith, and rings from pith. Consistent radial and longitudinal patterns in microfibril angle are predictable and suggest potential patterns of wood utilization of loblolly pine bole wood. The models developed here represent the first attempt to describe microfibril angle in 3-dimensional space and can be used in conjunction with height equations to predict microfibril angle at any position within loblolly pine trees grown in the Southeastern United States.

INDEX WORDS: Loblolly pine, Microfibril angle, Linear models, Nonlinear models

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DEDICATION

This thesis is dedicated to my mother and father, Mrs. Chris and Mr. Charlie Jordan. I cannot begin to express the amount of debt I owe you. You have always supported me in every facet of life. I am the most fortunate son to have loving parents like you.

Ralph Waldo Emerson pondering the measure of success said "…leaving the world a bit better, whether by a healthy child, a garden patch, a redeemed social condition, or a job well done. To know that even one other life has breathed easier because you have lived. This is to have succeeded." If Emerson is right, then I know that my parents are two of the most successful people I have ever, or will ever know. You have not only helped me to breathe easier, but you have helped to better the lives of all the children you have encountered in and out of the classroom, both on and off the football field. I love you so much.

> "Experience will teach you that, notwithstanding all appearances to the contrary, you will never receive such a love as is felt for you by your mother and father. That lives through your absence, difficulties and time. Your own feelings will teach you how much it should be returned and appreciated."
>
> -Robert E. Lee in a letter to his daughter Mildred Childe Lee,
> on December 21, 1866

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CHAPTER 1

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is the most important commercial species in the Southeastern U.S. This region produces 58 percent of the marketed timber in the United States and 16 percent of all timber marketed in the world (Wear and Greis 2002). Loblolly pine is the primary species of the U.S. pulp and paper industry and is also a desired resource for use in the manufacture of lumber and composite wood products. Among the many wood properties important to these manufacturing processes and uses, microfibril angle (MFA) is one of the most important measures due to its high correlation with paper and solid wood properties (Daniels *et al.* 2002).

Although widely used, the term 'timber quality', or 'wood quality' is not easily defined, and perceptions of what constitutes quality can vary between different sectors of the forestry and wood-using industries (Kliger et al, 1994). Wood quality could be defined as the physical and chemical characteristics that allow a tree, or its parts, to be used for different products. Briggs and Smith (1986) describe wood quality as "…the appropriateness of the wood for a particular end use'. Zhang (1997) defined wood quality as 'all the wood characteristics and properties that affect the value recovery chain and the serviceability of end products.' This definition takes into account the cost of operations throughout the wood chain process, such as the cost of harvesting, transporting and processing. All of these definitions imply that 'wood quality' is a subjective term that depends ultimately on the end-product to which the tree is converted (MacDonald and Hubert 2002).

Microfibril angle is known to be one of the main determinants of the mechanical properties of wood. MFA is defined by Lichtenegger *et al*. (1999) as the angle between the cellulose fibrils and the longitudinal cell axis. MFA is highly correlated with specific gravity, modulus of elasticity, modulus of rupture, the longitudinal and tangential shrinkage of wood and has a significant effect on both mechanical behavior and dimensional stability of wood, and as such is an important quality characteristic for sawn timber (MacDonald and Hubert 2002). In addition, MFA has been correlated with differences in paper properties such as stretch, stiffness, and strength (Watson and Dadswell 1964; Kellogg *et al.* 1975; Megraw 1985). Because of these relationships, MFA has become an important indicator of wood quality to the forest products industry.

In this project, individual tree models will be developed to describe how MFA changes within individual trees, from stump to tip and pith to bark for loblolly pine in the Southeast. These models allow measures of wood properties and quality to be added to current forest yield prediction systems. These models will also provide the basis for comparing properties from tree to tree, within a stand, and among stands in different regions in the Southeastern U.S., against which MFA from fast growing intensively managed plantations could be compared.

<u>OBJECTIVES</u>

A study was implemented in 1999 to assess the importance of wood properties of loblolly pine plantations in the Southeast. This is the first attempt to establish a baseline of loblolly pine plantation wood properties in relation to environmental conditions (Daniels 1999). The study was designed to address three objectives:

1) Review the existing literature on basic wood properties.

2) Determine wood properties for existing plantations.

3) Develop models that predict wood properties for loblolly pine, so that wood properties can be factored into growth and yield management models.

Currently, over 100 plantations have been characterized, measured, and sampled for basic wood properties including, specific gravity, moisture content, fiber length, and coarseness in the Southeastern United States. A subset of 20 plantations at or near rotation age, on various sites and growing conditions, and spanning 6 states (Florida, Georgia, South Carolina, North Carolina, Texas, and Virginia), were selected for MFA analysis. With the collection of these data, the first two objectives were fulfilled and allowed progression to the final objective, model development. This study focuses on, modeling microfibril angle.

SPECIFIC OBJECTIVES

The main objective of this study is to predict MFA from stump to tip and pith to bark for loblolly pine in the Southeastern United States. Specific study objectives include:

1) To identify the patterns of average MFA at various tree heights and diameters.

2) To develop models for prediction of earlywood and latewood MFA at any age and height.

3) To develop predictive 3-dimensional models describing MFA as a function of height, age, and distance from pith.

4) To develop whole disk models that will allow for prediction of average cross-sectional MFA at any age, height, and distance from pith.

CHAPTER 2

LITERATURE REVIEW

Increased growth rates and subsequent increases of juvenile wood in southern plantations have led to the need for more quantitative data to predict timber quality. Fast grown, short rotation southern pines may not have properties needed for products requiring structural strength and stiffness. Forest managers and silviculturalists are becoming aware that modern silviculture faces a two-sided problem: maintaining wood strength and dimensional stability while increasing stem diameter and growth. The race to produce maximum timber volume per acre cannot ignore consumers' needs for forest products best produced by slow growth (Harris 1981).

WOOD FORMATION AND DEVELOPMENT

Intensive management including: fertilization, herbaceous weed control, and genetic improvement alter the development and structure of wood. Fast-grown trees will have a greater proportion of juvenile wood, which results in inferior mechanical performance. Juvenile wood or corewood is produced by immature cambium within the active crown. Transition wood, is a zone where wood properties are changing rapidly from juvenile wood to mature wood, and is produced by all trees. Mature wood occurs as a stand grows older, crowns begin to close, lower branches begin to self-prune, and the vigorous crown moves up the stem. In the spring, radial growth begins at the apex of the bole in the vigorous crown accounting for the abundance of thin-walled earlywood cells and wider rings in the upper bole than in the lower bole. The transition to thick-walled latewood tracheids occurs first near the base of the bole and proceeds upward as moisture stress increases. Therefore, there is a more-or-less cylindrical core of crown-formed wood surrounded by a band of transition wood from the butt to the merchantable top of the tree (Clark and Saucier 1991).

The growth of southern pines is seasonal in nature. Growth proceeds rapidly in early spring and slows in late summer before ceasing in the fall. This kind of growth pattern results in different kinds of wood being formed in various seasons of the year. Alternating bands of wood formed early (earlywood) and late in a growing season (latewood) mark annual growth limits. Tracheids that compose earlywood are large in radial diameter, shorter in length, and relatively thin walled. The main function of earlywood cells is to transport water and nutrients from root to crown. In contrast, latewood cells are narrow in radial diameter, longer in length and have relatively thick walled cells. The cells of latewood provide strength to the new growth sheath and support for the expanding crown (Larson *et al.* 2001).

CONTRASTS IN JUVENILLE AND MATURE WOOD

From the onset of establishment, a young tree grows vigorously. The period of juvenility of Southeastern pines typically lasts from 6-15 years. Annual growth rings nearest the pith, regardless of tree height, contain a greater proportion of earlywood. Earlywood possesses lower than average strength and specific gravity; longitudinal shrinkage and MFA are higher than average; cell length is shorter than average. In trees from closely spaced stands where competition is established early, ring widths are reduced concomitant with the degree of competition. Thus, the radial extent of the juvenile core cannot be estimated on the basis of ring width patterns. Trees freed of competition by early and frequent thinnings or whose growth is enhanced by fertilization and cultivation can maintain wide growth rings well beyond the generally accepted juvenile period. On the contrary, trees subject to competition early in life might exhibit narrow growth ring patterns suggestive of mature wood (Larson *et al* 2001).

Juvenile wood is considered to be lower in quality than mature wood. The cells comprising juvenile wood are shorter than those of mature wood. Mature cells of pines may be three to four times the length of juvenile wood cells (Dadswell 1958). Tracheid length in the juvenile zone has been found to range from 2.92 mm to 3.79 mm for earlywood and latewood respectively. Similarly, the tracheid length of mature wood was found to range between 3.91 mm and 4.17 mm respectively (McMillan, 1968; Taylor and Moore 1981). Zobel and Jett (1995) reported that increased tracheid length was generally favorable for pulping, resulting in improved burst, tearing, and tensile strength of paper. Megraw (1985) states 'a direct connection between the strength properties of solid wood and tracheid length has never been established, and probably does not exist. The impact of shorter tracheids lengths are associated with larger microfibril angles which adversely affect both strength and longitudinal shrinkage'.

In addition to differences in cell length, cell structure differs as well. There are relatively few latewood cells in the juvenile zone, and a high proportion of cells have thin wall layers. The result is low density and a corresponding low strength in comparison to mature wood (Haygreen and Bowyer 1996). Zobel and Blair (1976) found that the proportion of juvenile wood in the mature bole of loblolly pine on a dry weight basis was 76, 50, and 15 percent for 15, 25, and 40-year-old stands respectively. Similarly, Clark and McAlister (1991) found juvenile wood in 36-year-old loblolly pine to have 76% the density, only 39% the stiffness, or modulus of elasticity (MOE), and 54% of the bending strength, or modulus of rupture (MOR) than mature wood from the same trees.

SILVICULTURAL EFFECTS

Any factor that changes the growth pattern or form of a tree may result in a change in wood quality and properties (Zobel and Jett 1995). Silvicultural practices, site factors, and geographic region can all affect tree growth, and subsequently wood quality. Brazier (1977) divided silvicultural operations into two broad categories:

1) Those that act directly on individual trees, or on groups of trees, such as initial spacing and rotation age.
2) Those that modify the site, and thus act on the crop as a whole such as cultivation and fertilizer application.

It has been suggested by Walker (1993) that the most significant feature of softwood plantation silviculture is the effect of the reduced age at which trees are harvested on wood properties. Increased growth rates brought about by advances in timber management techniques mean that plantation-grown trees are reaching merchantable sizes at younger ages. Consequently, trees harvested at a younger age will contain a greater proportion of juvenile wood, resulting in inferior mechanical performance (Zobel and Blair 1976; Clark and McCalister 1991).

Initial spacing in plantations affects the competition between trees for nutrients and moisture, which influences tree growth and wood formation. The major effects of wider spacing, which have long been recognized, are increased rates of early diameter growth and longer retention of a deep living crown as a suppression of branches is delayed (MacDonald and Hubert 2002). Trees planted at a wider initial spacing tend to have increased ring widths during the period of juvenile wood formation resulting in a larger juvenile core, and reduced average wood density. Clark and Saucier (1991) found that differing planting densities do not alter the period of juvenile growth of loblolly pine, but can be used to influence the size of the juvenile core. Recent work has shown that there is a strong correlation between wider spacing and larger grain angle for Sitka spruce, with implications for strength and stability of sawn timber (MacDonald and Hubert 2002).

Cultivation is the process of breaking up soil for planting or the removal of herbaceous weeds, grasses, and woody undergrowth. Planting on cultivated ground tends to result in faster initial growth due to improved drainage, soil aeration, and nutrient mineralization. This increased growth will likely affect the wood quality in the juvenile core, but the practical effects of this growth on wood utilization will depend largely on spacing or the amount of time that the tree grows free from competition. Schmidtling (1973) found that cultivation of a loblolly pine plantation during the first 3 years of growth resulted in a 6-foot growth advantage by the 9^{th} year compared with uncultivated controls. Despite the increase in growth rate, wood density values were not appreciably less than that of uncultivated controls. In a similar study, Clark *et al.* (1991) found that slash pine in the coastal plain of Georgia growing on moderately well and poorly drained sites that received no cultivation had a length of juvenility of 8 years. It was also found that the wood density on the moderately well drained sites was 6% higher than that of control trees on poorly drained cultivated sites.

Fertilization may be applied to relieve nutrient deficiencies or increase growth. Elliot (1970) stated that ‘generalisations on the role of a particular nutrient or combination of nutrients are so confounded by site and species effects as to be at best empirical if not dangerous’. The most obvious effect of fertilizer application is an increase in growth rates. This has been demonstrated for different southern pines by numerous authors (Clark and Saucier 1991;

Broerman 1967; Jokela and Morris 1998; Haywood and Burton 1990). Tree age at the time of fertilization has a significant effect on the nature of the response. Fertilization either at the time of planting or during the first few years of growth, especially if combined with cultivation, increases both height growth and crown development. Decreases in latewood percentage and wood density usually accompany the growth responses. In older trees, particularly beyond the juvenile stage, the response is less dramatic. Although a modest decrease in the percentage of latewood often occurs during the first few years after fertilization, it is usually short-lived and is probably due to an increase in earlywood rather than a reduction in latewood (Larson *et al.* 2001).

In a study by Williams and Hamilton (1961) the percentage of latewood was reduced by 2.8% on those plots receiving fertilizer. Similarly, wood density was lowered by 6.7%. Mitchell and Wheeler (1959) reported that a 0.01 unit change of wood density reflects a 50-pound change in the dry weight of an average cord of southern pine pulpwood. MacPeak *et al*. (1990) found that the average wood density, modulus of rupture, and modulus of elasticity were significantly lower in 20-year-old fertilized slash pine, than 50-year-old control trees of similar diameter.

MICROFIBRIL ANGLE FORMATION

Microfibril angle (MFA) refers to the mean helical angle between the cellulose fibrils and the longitudinal cell axis. A tree is sheathed by a thin cambial layer, which is composed of cells capable of repeated division. New cells produced on the inside of this sheath become new wood, while those moved to the outside become part of the phloem. In a process that may take several weeks to complete, the cell enlarges and the cell wall gradually thickens as biopolymers produced within the cells are progressively added to the inside of the wall. Eventually, the fluid filling the cell is lost and the cell has a thickened wall, consisting of primary and secondary wall layers and a hollow center (Haygreen and Bowyer 1996).

Megraw (1985) gives an excellent description of the structure of microfibrils. "Microfibrils are long strands of physically aggregated and more or less parallel polysaccharide chains. They contain a crystalline cellulose core surrounded by shorter chain hemicelluloses partly linked to this core, all encased into a rigid structure by the surrounding lignin. They are usually arranged in sheets or lamellae that lie parallel to the cell surface. In the primary wall they are loosely and more or less randomly interwoven. The secondary cell wall is comprised of three distinct layers: the S_1, S_2, and S_3 walls (Figure 2.1). The S_1 layer contains alternating lamellae of Z and S helical orientation at 50 to 70 degrees to the fiber axis. In the thick S_2 layer, they are usually oriented in a Z helix around the cell, but in some cases also occur in an S helix. In the S_2 layer microfibrils are highly parallel and steeply aligned to the fiber axis. In the S_3 layer they again occur in a very flat helical orientation, with angles 60 to 90 degrees to the cell axis. Because the S_2 layer is many times thicker than the other layers, its properties normally dominate, and the term fibril angle refers to the microfibular angle in the S_2 layer."

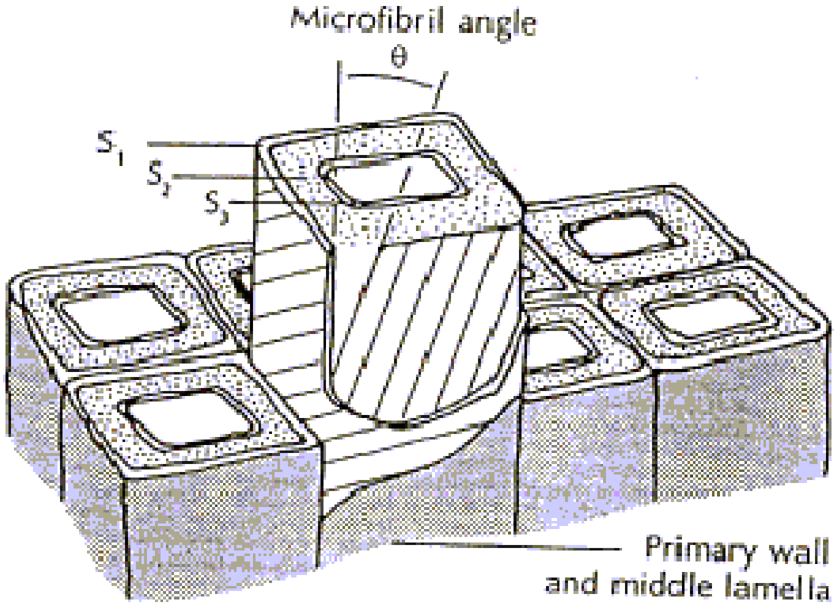

Figure 2.1. Orientation of microfibrils in the S2 layer of the tracheid cell wall (after Dickson and Walker 1997).

FACTORS INFLUENCING MICROFIBRIL FORMATION

A strong relationship between tracheid length and MFA exists. In mature wood, short tracheids tend to have large MFA's; with MFA tending to decrease as tracheid length increases. This relationship is also true in juvenile wood, but the correlation is not as strong, and it is for this reason that MFA's often continue to decline from pith to bark in the stem long after tracheid length values have stabilized (Larson *et al.* 2001). Strong correlations between wall thickness and MFA have also been reported, with thicker walls having corresponding lower MFA's. Hiller (1964) found that wall thickness accounted for 64%-81% of the variation in MFA. Thicker walls are generally associated with latewood cells, and thus smaller mean diameters and smaller lumens as well. 'It seems reasonable that not just the cell length, but overall cavity geometry may be the determining factor of MFA; long narrow cavities favoring deposition at low angles, short wide cavities favoring deposition at high angles' (Megraw 1985).

MICROFIBRIL ANGLE AND SHRINKAGE

The shrinkage of wood is governed to a large extent by its anatomical structure and by the orientation of the microfibrils in the cell walls (Harris and Meylan 1965). When water enters the cell wall it occupies spaces between the microfibrils. If the MFA is large, there is more swelling along the grain as water is added. The reverse applies as water is removed from woody cells. In agreement with this, Ying et al. (1994) reported that specific gravity and MFA are the best predictors of longitudinal shrinkage in wood. Numerous authors have found that longitudinal shrinkage increased with MFA, but in a non-linear fashion in radiata pine (*Pinus radiata*), (Walker and Butterfield 1996; Harris and Meylan 1965). Longitudinal shrinkage tends to be large when the MFA's are large, and negligible when the MFA is less than about 28^{o}. Meylan (1968) found that longitudinal shrinkage was minimal when the MFA was less than 30^{o}, but as MFA increased above this there was a very rapid increase in longitudinal shrinkage and a corresponding decrease in tangential shrinkage. Meylan also found that high longitudinal shrinkage was often associated with short fibered wood of low density and strength. The large S_2 MFA causes a high degree of longitudinal shrinkage and a corresponding decrease in transverse shrinkage. The longitudinal shrinkage of juvenile wood has been reported to average up to three times that of mature wood (McAlister and Clark 1992).

MICROFIBRIL ANGLE AND STIFFNESS

The stiffness of wood arises from its cellulose content and the way that this cellulose is distributed within the cell wall. Cave and Walker (1994) reported that the only known physical characteristic of wood capable of effecting large changes in the stiffness of wood, is the cellulose MFA in the S2 layer of the tracheid cell wall. There are also significant differences in MFA between earlywood and latewood. In an experiment carried out by Cowdrey and Preston (1966), a six-fold increase in stiffness in the earlywood of sitka spruce was observed as the MFA decreased from 40^{o} to 10^{o}. In close agreement with this, Walker and Butterfield (1996) observed that the stiffness of early wood in radiata pine increased five-fold as the MFA decrease from 40^{o} to 10^{o}. Tamalong *et al.* (1967), in a study of 17 species of tropical hardwood, found MFA to be the major determinant of fiber stiffness, and breaking load was found to be largely determined by cell wall area but, per unit of cell wall area, the major factor governing breaking load was MFA.

WITHIN TREE VARIATION OF MICROFIBRIL ANGLE

Variations in wood quality of any species can be attributed to variation within a tree, between trees in a particular stand, between different growing sites, and between different siliviculutural regimes (Addis *et al.* 1995). MFA varies within each growth ring, from pith to bark, with height in the stem and among trees. Cave and Walker (1994) reported that the MFA decreases from the first earlywood cell to the last latewood cell. MFA in loblolly pine is large near the pith and decreases rapidly out to 10 or more rings from the pith, and then continues dropping, regardless of height, but at a much slower rate until such time as it essentially stabilizes. MFA also tends to increase as tracheid length decreases after sudden increases in growth (Waldrop 1951). Just as for tracheid length, the decrease in angle with age takes place at a slower rate near the base of the tree than it does at upper heights. This results in higher MFA's for a given number of rings from the pith at the butt and breast height regions than at several meters in height and above (Megraw 1985).

MFA varies considerably within the three zones of tree wood (juvenile, transition, and mature), thus affecting the mechanical properties of the wood. Within tree cells, the MFA in the S_2 part of the secondary wall is characteristically greater in juvenile wood. Pillow *et al.* (1953) found that MFA in the juvenile wood of open-grown loblolly pines averaged 20^o larger than those in a closely spaced natural stand.

In mature loblolly pine, MFA is small, averaging about 5^o to 10^o, while in juvenile wood the MFA is large, averaging 25^o to 35^o and often up to 50^o in rings next to the pith, then decreasing outward in the juvenile core (Larson et al. 2001). MFA has been found to decrease from 33^o at age 1 to 23^o at age 10, and to 17^o at age 22, in fast-grown loblolly pines (Ying et al. 1994). Bendtsen and Senft (1986) found that MFA within loblolly pine had stabilized at age 30. The number of microfibrils is directly related to the size of the cell wall, and is reflected in the strong relationship between specific gravity and strength properties.

CHAPTER 3

METHODS AND MATERIALS

University of Georgia and U.S.D.A. Forest Service field crews collected stand data and wood samples from 20 stands during the summers of 1999 through 2001. Loblolly pine stands, 20-27 years old, were sampled across the Southeastern U.S. for MFA analysis and other wood properties. Plantations were sampled in each physiographic region, (Figure 3.1): Atlantic Coastal Plain (8), Piedmont (6), Gulf Coastal Plain (3), and Hilly Coastal Plain (3).

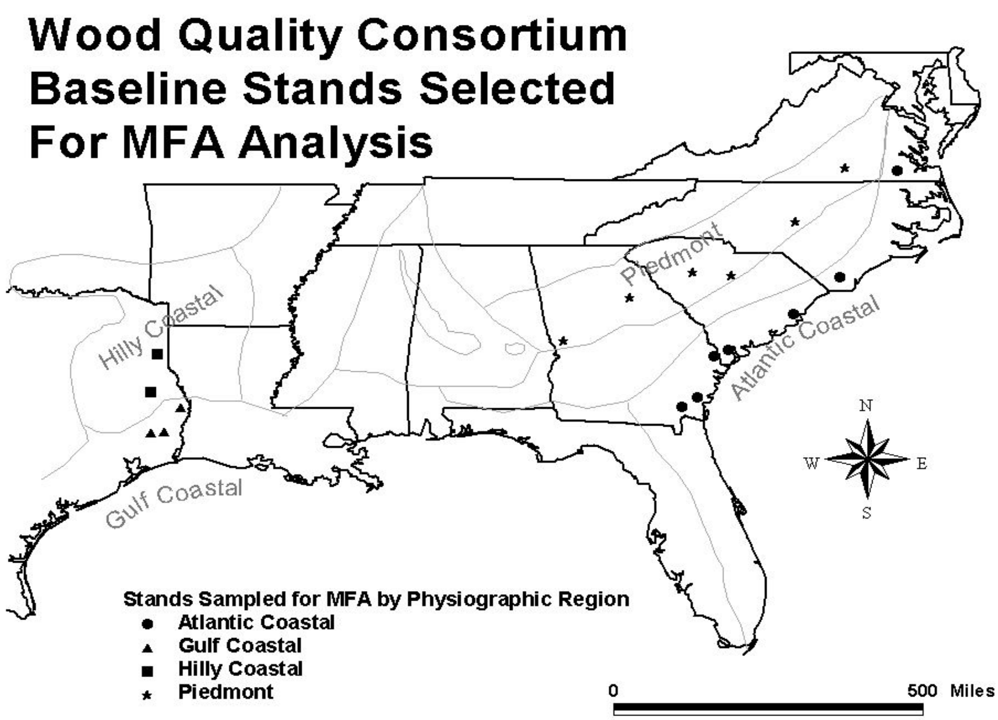

Figure 3.1. Map of the 20 stand locations sampled between 1999 and 2001 for microfibril angle analysis.

The stands selected for sampling were located on land owned by forest products companies, and included only stands with similar silvicultural history: 1) site preparation with no herbaceous weed control; 2) no fertilization at planting except phosphorus on phosphorus-deficient sites; 3) stand density of at least 250 trees per acre at the time of sampling. Trees larger than five inches in diameter were inventoried on 3 1/10-acre plots to determine stand density and diameter distribution. A sample of 3 trees was chosen for MFA analysis proportional to the diameter distribution of each stand to represent a range of tree sizes in the stand. A total of 60 trees were sampled for MFA in this study.

FELLED TREE ANALYSIS

One-inch thick cross-sectional disks were cut at the stump, 4.5 feet, 10 feet, and then at 5-foot intervals to a 2-inch top for all trees. A subsample of disks was then selected from each tree for MFA analysis. For the Hilly Coastal and Gulf Coastal regions disk heights selected for MFA analysis were taken at 4.5 feet, 10 feet, and then at 5-foot intervals to a disk height of 50 feet. Cross sectional disks subsampled for MFA analysis in the Piedmont and Atlantic Coastal regions were taken at 4.5 feet, 15 feet, and then at 10-foot intervals to a disk height of 45 feet. Radial strips were cut from each disk, dried, glued to core holders and sawn into two strips. One 0.063 inch wide strip was used for x-ray densitometry for measurement of earlywood and latewood as well as radial growth and specific gravity at 0.0024 inch intervals. One strip, 0.5 inch square, was cut for MFA and fiber length analysis from each disk, dried at 122^{o} Celsius, and shipped to Australia and analyzed by Silviscan® using x-ray diffraction at 0.04 inch intervals on the tangential surface.

MFA and specific gravity of earlywood and latewood of each annual ring for the trees selected for analysis from the Hilly Coastal Plain and Gulf Coastal Plain were determined at 0.04 and 0.0024 inch intervals respectively at heights of 4.5 feet and then at 10-foot intervals to a height of 45 feet. A specific gravity value of 0.530 was used to separate earlywood and latewood. The densitometer was calibrated to express specific gravity on an air dried basis. Separation of earlywood rings from latewood rings was accomplished using Silviscan's Analyse2001 program. Whole ring MFA was determined by weighting each ring with respect to the proportion of latewood and earlywood.

DATA PREPARATION

Whole ring MFA was generated for all trees not analyzed on a ring basis by using ring width characteristics from the disk strip that was measured for specific gravity using x-ray densitometry. Given that the strips used were from the same tree disk, but opposite one another, it was assumed that one side could possibly be longer/smaller than the other due to sample preparation error or a non-perfect circular tree. Even though the strips may not be of the same length, the individual ring properties from both strips should be similar. To resolve this problem ring width was calculated as:

$$GSRING_i = RWSG_i \frac{LMFA}{LSG}$$

where,

$GSRING_i$ = Generated ring width of MFA strip

$RWSG_i$ = Width of *ith* specific gravity ring

$LMFA$ = Total length of MFA strip

LSG = Total length of specific gravity strip

For example, let $LMFA$ = 4.17”, LSG = 3.91”, $RWSG_1$ = 0.45”. Thus $GPSRING_1$ = 0.480”. The program to make these calculations was done in SAS V8 and can be found in Appendix A.

CROSS-SECTIONAL MFA

Whole disk cross-sectional MFA was calculated for every age, by weighting the ring MFA to the proportion of its basal area. This calculation was done for every tree at every height level. For example, at age 1, the cross-sectional MFA would simply be the MFA of ring 1. The cross-sectional MFA of a tree at age 5 would be found by weighting rings 1-5 with respect to the proportion of the basal area of the total that each ring made up. The program to make these calculations was done in SAS V8 and can be found in Appendix B.

Whole disk cross-sectional MFA was also calculated by distance from pith by weighting the MFA at any distance to the proportion of its basal area. This calculation was done for every tree at every height level. For example, the 2-inch cross-sectional MFA value was calculated by weighting the sum of all 0.040 inch interval measurements to a diameter inside bark of 2 inches with respect to the proportion of the basal area of the total. The program to make these calculations was done in SAS V8 and can be found in Appendix C.

CHAPTER 4

MODELING EARLYWOOD AND LATEWOOD MICROFIBRIL ANGLE IN SOUTHEAST TEXAS LOBLOLLY PINE

ABSTRACT

Loblolly pine (*Pinus taeda* L.) is the primary species of the U.S. pulp and paper industry and is also a desired resource for use in the manufacture of lumber and composite wood products. Among the many wood properties important to these manufacturing processes and uses, microfibril angle (MFA) is one of the most significant measures due to its high correlation with paper and solid wood properties (Daniels *et al.* 2002). MFA was sampled from disks cut at 10 foot intervals from 18 trees in Southeast Texas. Prediction equations were derived from mathematical models to explain the 3-dimensional change of MFA from stump to tip and pith to bark.

Keywords: microfibril angle, loblolly pine, modeling, latewood, earlywood

INTRODUCTION

Microfibril angle is known to be one of the main determinants of the mechanical properties of wood. MFA is defined by Lichtenegger *et al*. (1999) as the angle between the cellulose fibrils and the longitudinal cell axis. MFA is highly correlated with specific gravity, modulus of elasticity, modulus of rupture, and the longitudinal and tangential shrinkage of wood. MFA has a significant effect on both mechanical behavior and dimensional stability of wood, and as such is an important quality characteristic for sawn timber (MacDonald and Hubert 2002). In addition, MFA has been correlated with differences in paper properties such as stretch, stiffness, and strength (Watson and Dadswell 1964; Kellogg *et al.* 1975; Megraw 1985). Because of these relationships, MFA has become an important indicator of wood quality to the forest products industry.

Variations in wood quality of any species can be attributed to variation within a tree, between trees in a particular stand, between different growing sites, and between different silvicultural regimes (Addis *et al.* 1995). MFA varies within each growth ring, from pith to bark, with height in the stem and among trees. Cave and Walker (1994) reported that the MFA decreases from the first earlywood cell to the last latewood cell. MFA in loblolly pine is large near the pith and decreases rapidly out to 10 or more rings from the pith, and then continues dropping, regardless of height, but at a much slower rate until such time as it essentially stabilizes. The decrease in MFA with age takes place at a slower rate near the base of the tree than it does at upper heights. This results in higher MFA's for a given number of rings from the pith at the butt and breast height regions than at several meters in height and above (Megraw 1985).

The objective of this paper is to develop models for predicting earlywood and latewood microfibril angle as a function of height and rings from pith.

METHODS AND MATERIALS

Eighteen trees representing six stands were selected from Southeast Texas for MFA analysis (Figure 4.1). The stands were located on land owned by forest products companies, and included only stands with similar silvicultural history: 1) site preparation with no herbaceous weed control; 2) no fertilization at planting except phosphorus on phosphorus-deficient sites; 3) stand density of at least 250 trees per acre at the time of sampling. Trees larger than five inches in diameter were inventoried on 3 1/10-acre plots to determine stand density and diameter distribution. A sample of 3 trees was chosen for MFA analysis proportional to the diameter distribution of each stand to represent a range of tree sizes in the stand. Stand attributes are summarized in Table 4.1.

One inch thick cross-sectional disks were cut at 4.5 feet, 15 feet, and then at 10-foot intervals to a height of 45 feet. Radial strips 0.5 inch square were cut from each disk, dried at 122^{o} Fahrenheit, and shipped to Australia and analyzed by Silviscan® using x-ray diffraction at 0.04 inch intervals on the tangential surface. A densitometer was used to determine specific gravity. The densitometer was calibrated to express specific gravity on an air dried basis and a specific gravity value of 0.530 was used to separate earlywood and latewood. Separation of earlywood rings from latewood rings was accomplished using Silviscan's Analyse2001 program.

The nonlinear models in this paper were fitted using the statistical package S-PLUS. S-PLUS allows for modeling of grouped and repeated measure data by associating random effects to observations sharing the same classification factor. This allows for an appropriate and flexible variance/covariance structure accounting for auto and spatial correlation. Within the data, the ring-by-ring MFA measurements led to autocorrelation. In such a situation, one may expect there to be a serial dependence structure to the errors, where observations close together in time are correlated with the strength of the correlation decreasing with the time lag. To account for this, an ARMA (1, 1) variance/covariance structure was used.

<u>MODEL DEVELOPMENT</u>

The data were plotted by wood type (earlywood/latewood) to identify patterns by ring and height. There is a noticeable difference between MFA at 4.5 feet and the other height levels for both early and late wood (Figures 4.2-4.5). The average MFA value for ring 1 at 4.5 feet was found to be 30.3^o and 27.5^o for earlywood and latewood respectively. The value of MFA at ring 1 for the other height levels was found to range from 27.7^o-26.5^o and 22.5^o-21.7^o respectively for early and late wood. Latewood was found to have lower initial values of MFA starting at ring 1 at all height levels. It can be seen from the graphs that both early and late wood approach some lower asymptotic bound of ~10.0^o, and that all height levels appear to converge and level off by age 13, although earlywood MFA at 4.5 feet retains some separation from the other height levels.

MODEL DEVELOPMENT: EARLYWOOD MFA

Several candidate model forms were selected to describe the change of earlywood MFA from stump to tip and pith to bark. A linear model was considered first with the form:

$$MFA_{ij} = \beta_0 + \beta_1 \ln(Ring_i) + \beta_2 \ln(Height_j) + \beta_3 DBH + \varepsilon_{ij} \quad (1)$$

where,

MFA_{ij} = earlywood MFA for *Ring i* at *Height* level *j,*

DBH = Diameter Breast Height,

ε_{ij} = random error for *Ring i* at *Height* level *j*

MFA appears to be decreasing in a non-linear fashion (Figure 4.2), so a non-linear function was found with the form:

$$MFA_{ij} = \frac{1}{(\beta_1 + \beta_2 Ring_i)} + \varepsilon_{ij} \quad (2)$$

where,

MFA_{ij} = earlywood MFA for *Ring i* at *Height* level *j*

ε_{ij} = random error associated with *Ring i* at *Height* level *j*

Model (2) is known as the reciprocal model and has been used extensively in yield-density studies with agricultural applications. The form of model (2) is a generalized linear model with a linear predictor $\beta_1 + \beta_2 Ring_i$ and a reciprocal link (Ratkowsky 1990). For model (2) to describe MFA in 3-dimensions, height must be added. This can be accomplished by letting the parameters B_1 and B_2 vary with height. Daniels *et al.* (2002) noted that the asymptote of specific gravity tended to decrease with increasing height. By making the parameters quadratic functions of height, they were able to successfully model specific gravity as a function of rings from pith and height. This was a reasonable assumption to make for model (2), thus the parameters become:

$$\hat{\beta}_1 = \phi_{01} + \phi_{11}\ln(Height_j) + \phi_{21}[\ln(Height_j)]^2$$

$$\hat{\beta}_2 = \phi_{02} + \phi_{12}\ln(Height_j) + \phi_{22}[\ln(Height_j)]^2$$

where,

$Height_j$ = height above ground at disk $_j$

$\phi_{01},\ldots,\phi_{22}$ = parameters to be estimated

The natural log of disk height was chosen to represent the independent height variable used in making model (2) a 3-dimensional predictor of earlywood MFA due to a stronger correlation than disk height with the dependent MFA variable.

<u>MODEL DEVELOPMENT: LATEWOOD MFA</u>

A linear model was first proposed to explain the change of latewood MFA in 3-dimensional space. The linear latewood model takes the form:

$$MFA_{ij} = \beta_0 + \beta_1 Ring_i + \beta_2 Ring_i^{1/2} + \beta_3 \ln(Height) + \beta_4(\ln(Height))Ring_i + \beta_5 DBH + \varepsilon_{ij} \quad (3)$$

where,

MFA_{ij} = latewood MFA for *Ring i* at *Height* level *j*

ε_{ij} = random error for *Ring i* at *Height* level *j*

A nonlinear model was developed to assess the nonlinear trend of latewood MFA as a function of rings from pith and height (Figure 4.4).

The nonlinear model proposed is:

$$MFA_{ij} = \beta_1 \exp[\beta_2 /(Ring_i + \beta_3)] + \varepsilon_{ij} \quad (4)$$

where,

MFA_{ij} = latewood MFA for *Ring i* at *Height* level *j*

ε_{ij} = random error associated with *Ring i* at *Height* level *j*

As for the nonlinear earlywood model, model (4) must include a dependent height variable to predict MFA in 3-dimensional space. Again, Daniels *et al.* (2002) method was used. Thus the parameters in model (4) become linear parameters of height and take the form:

$$\hat{\beta}_1 = \phi_{01} + \phi_{11} \ln(Height_j) + \phi_{21}[\ln(Height_j)]^2$$

$$\hat{\beta}_2 = \phi_{02} + \phi_{12} \ln(Height_j) + \phi_{22}[\ln(Height_j)]^2$$

$$\hat{\beta}_3 = \phi_{03} + \phi_{13} \ln(Height_j) + \phi_{23}[\ln(Height_j)]^2$$

where,

$Height_j$ = height above ground at disk $_j$

$\phi_{01},\ldots,\phi_{23}$ = parameters to be estimated

RESULTS

LINEAR EARLYWOOD MODEL

Parameter values and fit statistics for model (1) can be found in Table 4.2. All parameters in the model were significant at the 0.0001 level. Model (1) was found to have a residual standard error of 3.169^o and a fit index value of 0.74, where fit index equals one minus the residual sums of squares errors divided by the sums of squares total. The plot of residuals versus predicted values (Figure 4.6) indicates that the linear model is over predicting. This was confirmed by a median value of -0.27 for all residuals and from the graph, it is apparent that the majority of the residual lie below the 0 marker. This however, also indicates that the model is not biased and the majority of the residuals are centered on zero. The maximum and minimum residuals were found to be 13.3 and -8.4 respectively. Examination of the residuals plots (Figure 4.6) against the independent variables; the natural logarithm of ring, the natural logarithm of height, and DBH, shows some departure from the linear assumption, suggesting the need for a curvilinear regression function. Figure 4.6, shows the plot of fitted values vs. actual values. The model appears to be predicting well up to a MFA value of 20^o. One explanation for this may be that MFA decreases sharply up to ~ 13 rings then levels out, at which the model ceases to be linear in fashion. Figure 4.7 contains plots of the mean actual MFA values versus the fitted MFA values by disk height. It can be seen that the linear model, on average, is under predicting earlywood MFA at 4.5 feet up to ring 10. Above 4.5 feet, the model performs reasonably well, with the exception of it under predicting beyond ring 11 at disk heights of 25 and 35 feet. The final linear model is of the form:

$$\hat{MFA}_{ij} = 35.0089 - 6.5088 \ln(Ring) - 3.7120 \ln(Height) + 0.5122 \, DBH$$

NONLINEAR EARLYWOOD MODEL

Table 4.3 contains the fit statistics and parameter values for the nonlinear earlywood model (2). Many parameters were found to be insignificant and thus were dropped from the prediction equation. The final nonlinear earlywood model is:

$$\hat{MFA}_{ij} = \frac{1}{[\phi_{01} + \phi_{21}(\ln(Height_j))^2] + [\phi_{12}(\ln(Height_j))Ring_i]}$$

$$\hat{MFA}_{ij} = \frac{1}{[0.029 + 0.00028(\ln(Height_j))^2] + [0.00167 \ (\ln(Height_j))Ring_i]}$$

The remaining parameters in the model were significant at the 0.002 level. The median value of the residuals was found to be centered on zero with a value of -0.105, indicating little or no bias. The maximum and minimum residuals were found to be 3.9° and -2.7° respectively. Examination of the residuals plots (Figure 4.8) against the dependent variables ring and the natural logarithm of height show no apparent trends. Figure 4.8, shows the plot of actual values vs. fitted values. The nonlinear earlywood model appears to be predicting MFA well. The distribution of the fitted versus actual values appears to be more uniform in shape than the linear model (1). It can be seen that the nonlinear model is also under predicting earlywood MFA at 4.5 feet up to ring 10 (Figure 4.9). However, the rate at which earlywood MFA decreases at 4.5 feet is not as great as the linear earlywood model. Above 4.5 feet, the model is under predicting beyond ring 11 at disk heights of 25 and 35 feet.

LINEAR LATEWOOD MODEL

All parameters in model (3) were found to be significant at the 0.0001 level (Table 4.4). As with the earlywood linear model, model (3) seems to be over predicting latewood MFA (Figure 4.10). Plots of residuals versus ring and ring$^{1/2}$ show no general pattern suggesting a strong linear correlation (Figure 4.10). However, the residual plots for the natural logarithm of height suggest some deviation from the linear assumption (Figure 4.10). From Figure 4.10, it can be seen that some additional function of height may be required to describe these data. The residual standard error for the linear latewood model was found to be 2.7$^{\mathbf{o}}$, with a fit index of 0.75. Plots of mean actual MFA values versus mean fitted values for the linear latewood model can be seen in Figure 4.11. The linear model is not capable of reproducing the sigmoid shaped curve at 4.5 feet. On average, the model is over predicting latewood MFA at 15 feet from ring 1 to ring 11. Also, at 45 feet, the model is grossly under predicting MFA, although the shapes of both the actual and fitted values are similar. The final linear latewood model form is:

$$\hat{MFA}_{ij} = 46.121 + 0.801\,Ring - 11.871\,Ring^{1/2} - 5.040\ln(Height) +$$
$$0.235(\ln(Height))Ring + 0.312DBH$$

NONLINEAR LATEWOOD MODEL

Initial examination of the fit statistics and residual plots of the nonlinear latewood model indicated a need for additional data to describe the change of latewood MFA by rings from pith. Upon further investigation it was decided to include ring$^{1/2}$ in the model. Attempts were made to include this variable inside the exponential function; however the model repeatedly failed to converge. It was then decided to let ring$^{1/2}$ enter linearly in the model. Thus the improved model becomes:

$$MFA_{ij} = \beta_1 \exp[\beta_2 / (Ring + \beta_3)] + \beta_4 (Ring^{1/2})^{-1} + \varepsilon_{ij}$$

where, all parameters are defined previously and

$$\hat{\beta}_4 = \phi_{04} + \phi_{14} \ln(Height_j) + \phi_{24} [\ln(Height_j)]^2$$

Table 4.5 contains the fit statistics and parameter values for the nonlinear latewood model (4). The coefficients ϕ_{21} and ϕ_{04} were dropped from the final model because their estimates were not significantly different from zero at the 0.05 level. It can be seen from Figure 4.12 and the median residual value of -0.099 that the residuals are distributed around zero. The deviation of the fitted versus actual values of MFA was greatly improved by fitting the nonlinear model. Upon comparison of the standardized residual plots of the linear and nonlinear models, it can be seen that the majority of the nonlinear residuals lie within $\pm$ 2°. The normalized residual plots of ring, ring$^{1/2}$, and the natural logarithm of height variables (Figure 4.12) indicate no trends, a significant improvement over the linear latewood model. The nonlinear model also produced a much tighter fit with the fitted values uniformly distributed around the regression line (Figure 4.12). The nonlinear latewood model was found to mimic the curves of latewood MFA extremely well at all heights (Figure 4.13). The model was able to take on the sigmoid shaped curve at 4.5 feet and the transform to a decreasing exponential function. The nonlinear model also reaches a lower asymptotic bound, an attribute that the linear model does not possess. The final nonlinear latewood model is:

$$MFA_{ij} = \beta_1 \exp[\beta_2 / (Ring + \beta_3)] + \beta_4 (Ring^{1/2})^{-1} + \varepsilon_{ij}$$

where,

$$\hat{\beta}_1 = [6.143 + 3.836 \ln(Height)]$$

$$\hat{\beta}_2 = [32.544 - 14.691\ln(Height) + 1.984\{\ln(Height)\}^2]$$

$$\hat{\beta}_3 = [Ring + 17.319 - 8.099\ln(Height) + 1.113\{\ln(Height)\}^2]$$

$$\hat{\beta}_4 = \left[\ \left\{\{-32.314\ln(Height) + 4.337\{\ln(Height)\}^2\right\}\ (Ring^{1/2})^{-1}\right]$$

DISCUSSION

Earlywood and latewood models were developed to represent the change of MFA from stump to tip and pith to bark for 18 loblolly pine trees sampled in Southeastern Texas. Both linear and nonlinear model forms were developed to explain the trends of MFA in 3-dimensional space. Nonlinear models tended to explain the change of MFA better than the linear models. Fit index values were found to be 0.74 for both models. The residual standard error of the models was found to be 2.76$^{\mathbf{o}}$ and 3.17$^{\mathbf{o}}$ respectively for the nonlinear and linear models. From examination of the residual and fitted versus actual plots, the nonlinear model would be preferred. Upon examination of the fit statistics, residual plots and fitted versus actual plots, the nonlinear latewood model is preferred over the linear model. The nonlinear model is more flexible and will more accurately model the rate of change of MFA in 3-dimensional space. Fit index and residual standard error values were found to be 0.75 and 0.81, 2.7$^{\mathbf{o}}$ and 2.15$^{\mathbf{o}}$ respectively for the linear and nonlinear models.

Why though is the nonlinear model a better choice overall? Interpretation of the data is one reason to prefer the nonlinear model over the linear model. It is obvious from Figures 4.2 and 4.3, that over the range of ring and height values, MFA decreases in a nonlinear fashion. The linear function may adequately predict MFA, but not over the entire range of data. There does appear to be a linear trend occurring from rings 1 to 13. However, at this point the data ceases to be linear. Thus the linear model may not accurately represent what is occurring.

There has been an increased interest in wood properties data within the last decade. Forest products firms' desire improved wood and better quality in addition to maximizing growth rates. With the use of intensive silvicultural management including fertilization, herbaceous weed control, and site preparation, forest companies are producing loblolly pine at rates faster than ever before. However, more emphasis is beginning to be placed on the quality of timber produced rather than the quantity. This is one of the first attempts to model MFA as a function of height and ring from pith. These models can be used to evaluate not only MFA, but solid wood strength and stiffness along with pulp and paper properties.

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TABLES AND FIGURES FOR CHAPTER 4

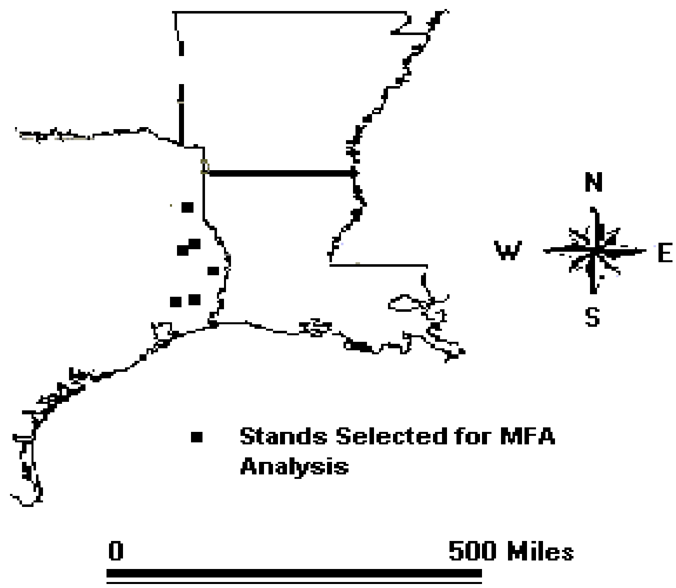

Figure 4.1. Location of loblolly pine stands sampled for microfibril angle analysis in Southeast Texas.

Table 4.1. Range and average tree size (in parenthesis) characteristics for 18 loblolly pine trees sampled for MFA analysis.

DBH (inches)	TOTAL HEIGHT (feet)	AGE (years)	MFA (degrees)
5.5 – 11.5 (7.9)	37.4 – 71.2 (56.5)	20-27 (22)	8.1 - 39.8 (16.5)

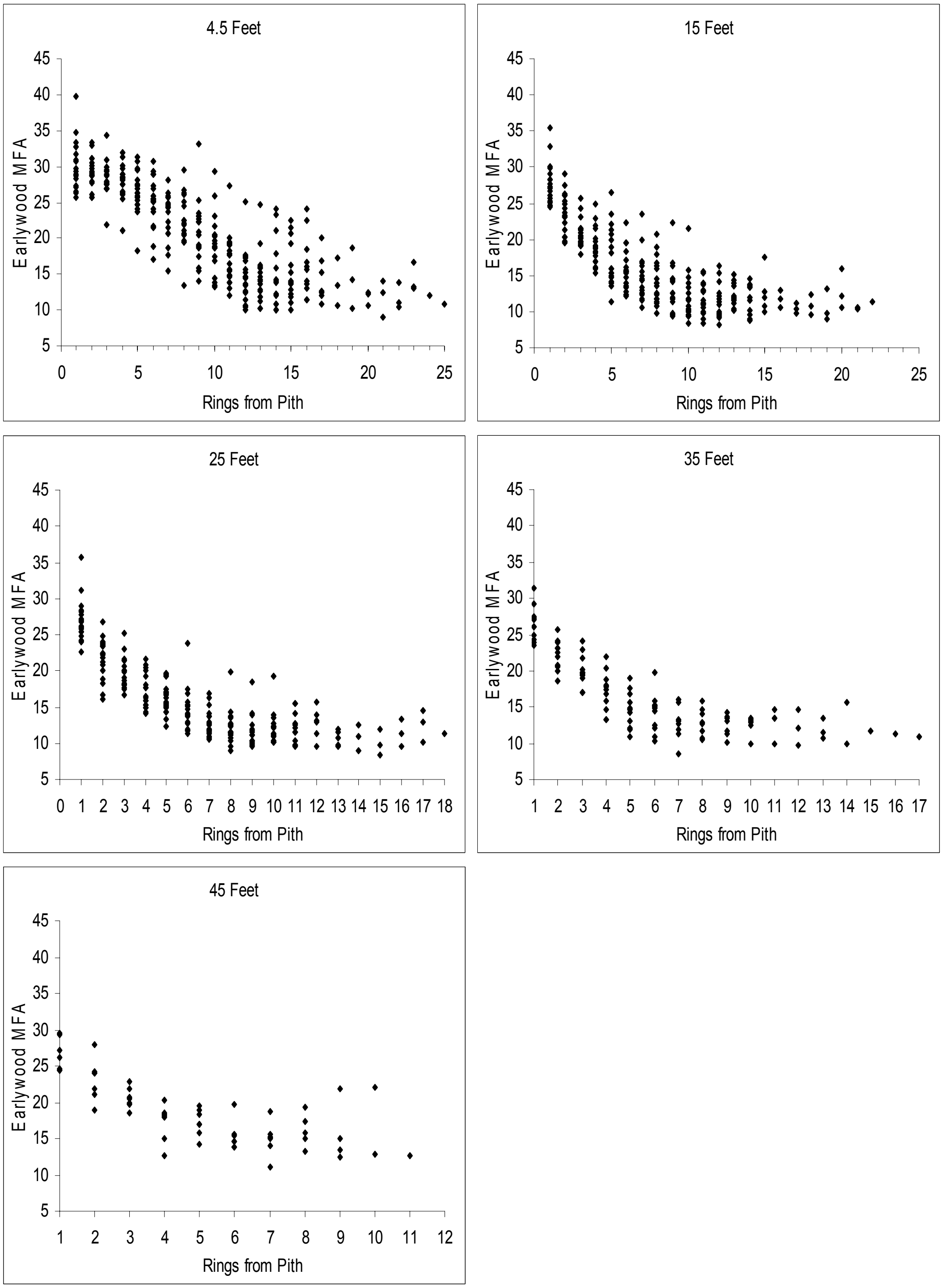

Figure 4.2. Plot of earlywood microfibril angle versus rings from pith at different height levels.

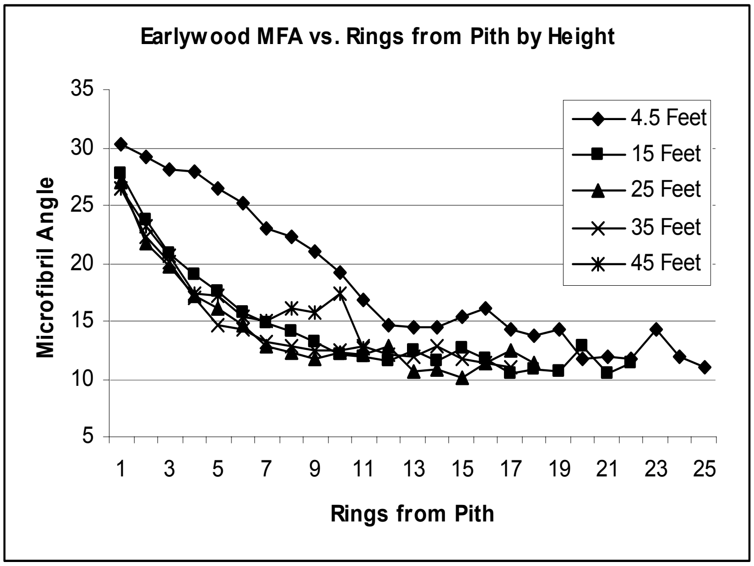

Figure 4.3. Plot of average ring earlywood microfibril angle versus rings from pith by disk height.

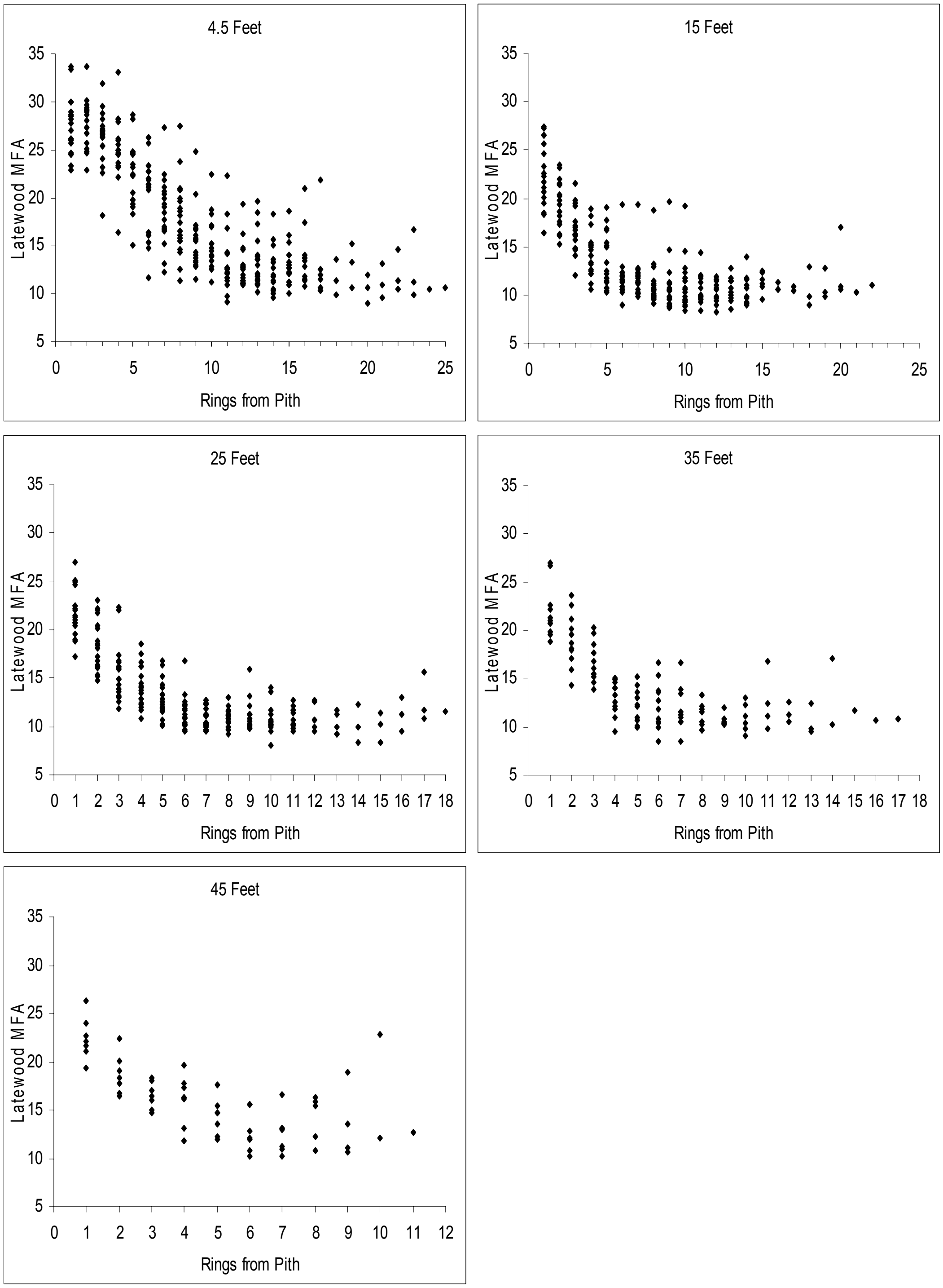

Figure 4.4. Plot of latewood microfibril angle versus rings from pith at different height levels.

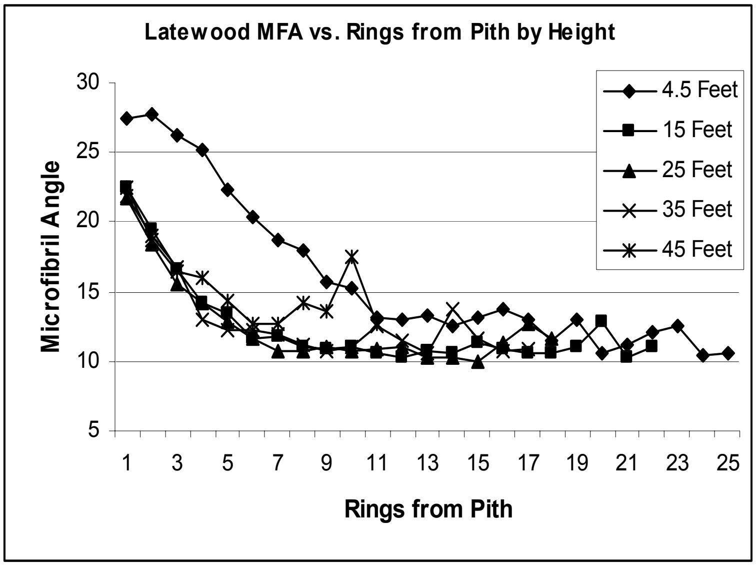

Figure 4.5. Plot of average ring latewood microfibril angle versus rings from pith by disk height.

Table 4.2. Parameter estimates and fit statistics for the linear earlywood model (1).

Coefficient	**Value**	**Std. Error**	**t value**	**p value**
β_0	35.0889	0.6223	56.3891	0.0000
β_1	-6.5088	0.1345	-48.4044	0.0000
β_2	-3.7120	0.1294	-28.6888	0.0000
β_3	0.5122	0.0597	8.5770	0.0000

Fit index: 0.740

Residual standard error: 3.169

Residuals:

Min	**Median**	**Max**
-8.394	-0.2674	13.31

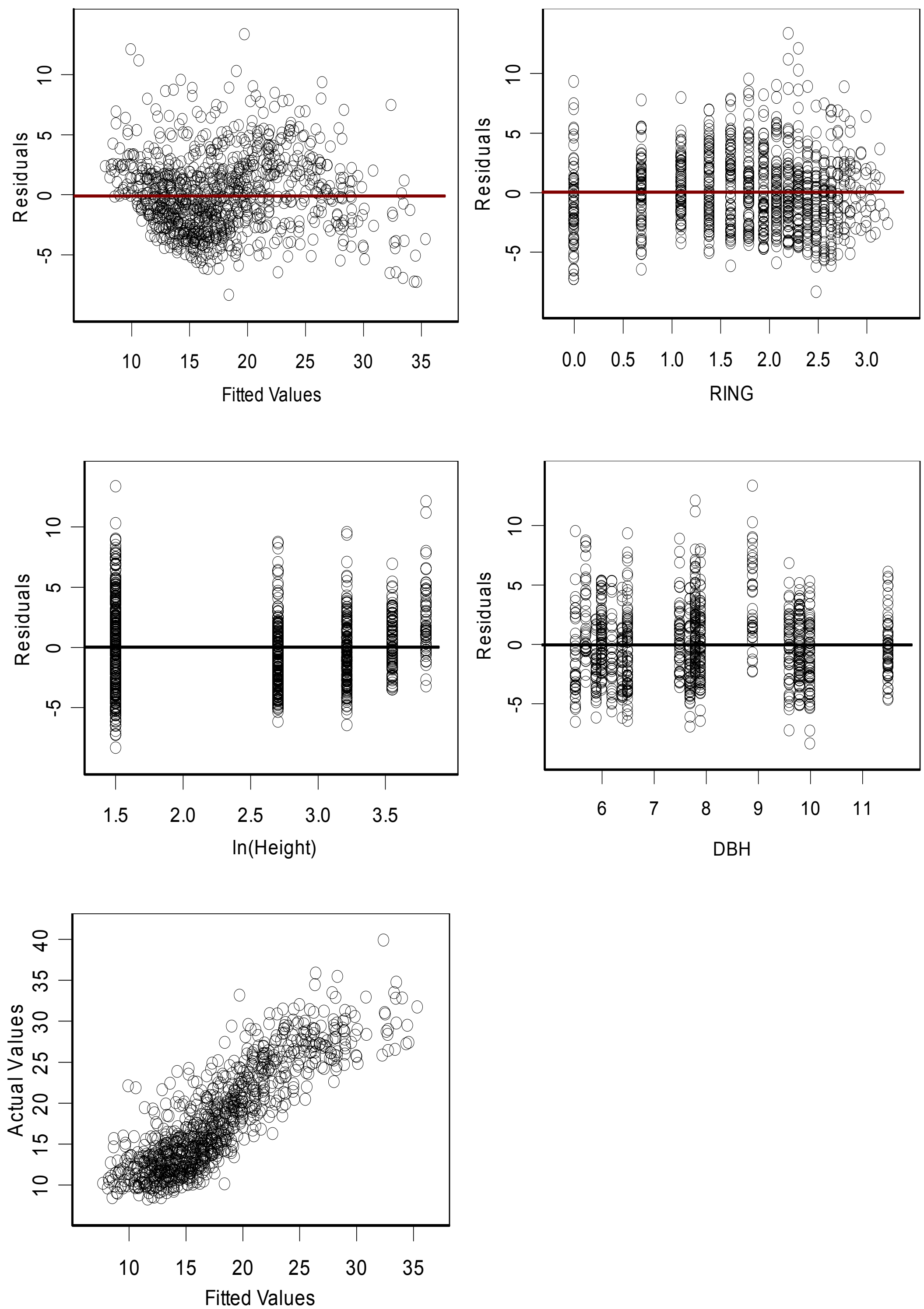

Figure 4.6. Residual plots versus the independent variables and actual MFA values versus fitted MFA values for the linear earlywood model (1).

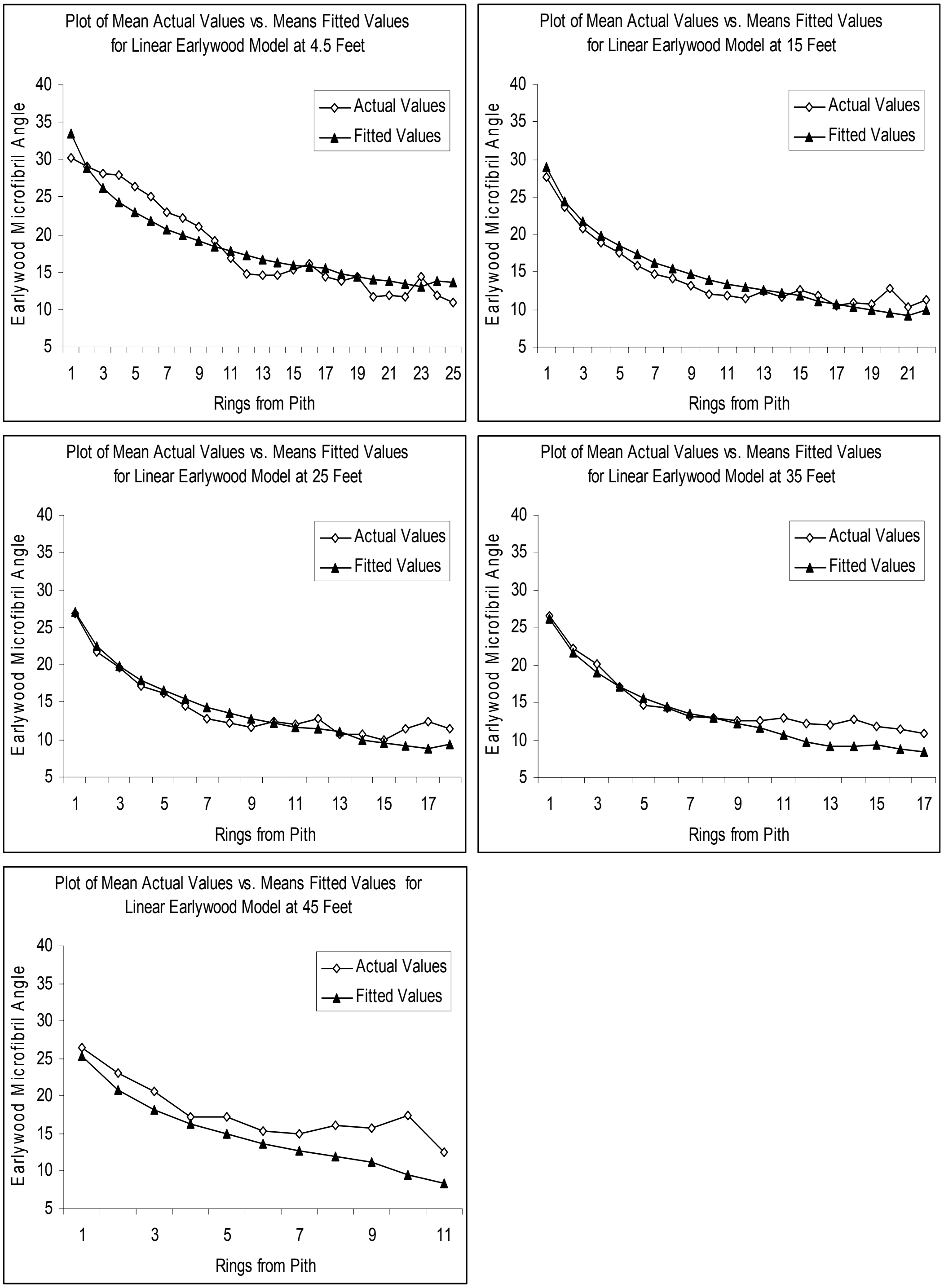

Figure 4.7. Plot of mean actual values versus mean fitted values for the linear earlywood model (1) by disk height.

Table 4.3. Parameter estimates and fit statistics for the nonlinear earlywood model (2).

Coefficient	**Value**	**Std. Error**	**t value**	**p value**
ϕ_{01}	0.029427	0.001045158	28.15631	<0.0001
ϕ_{21}	0.000277	0.000089229	3.10549	0.002
ϕ_{12}	0.001674	0.000091816	18.23246	<.0001

Overall Fit Statistics:

AIC	**BIC**	**logLik**
4079.26	4118.01	-2031.63

Fit index: 0.740

Residual standard error: 2.763049

Residuals:

Min	**Med**	**Max**
-2.703964	-0.105041	3.934785

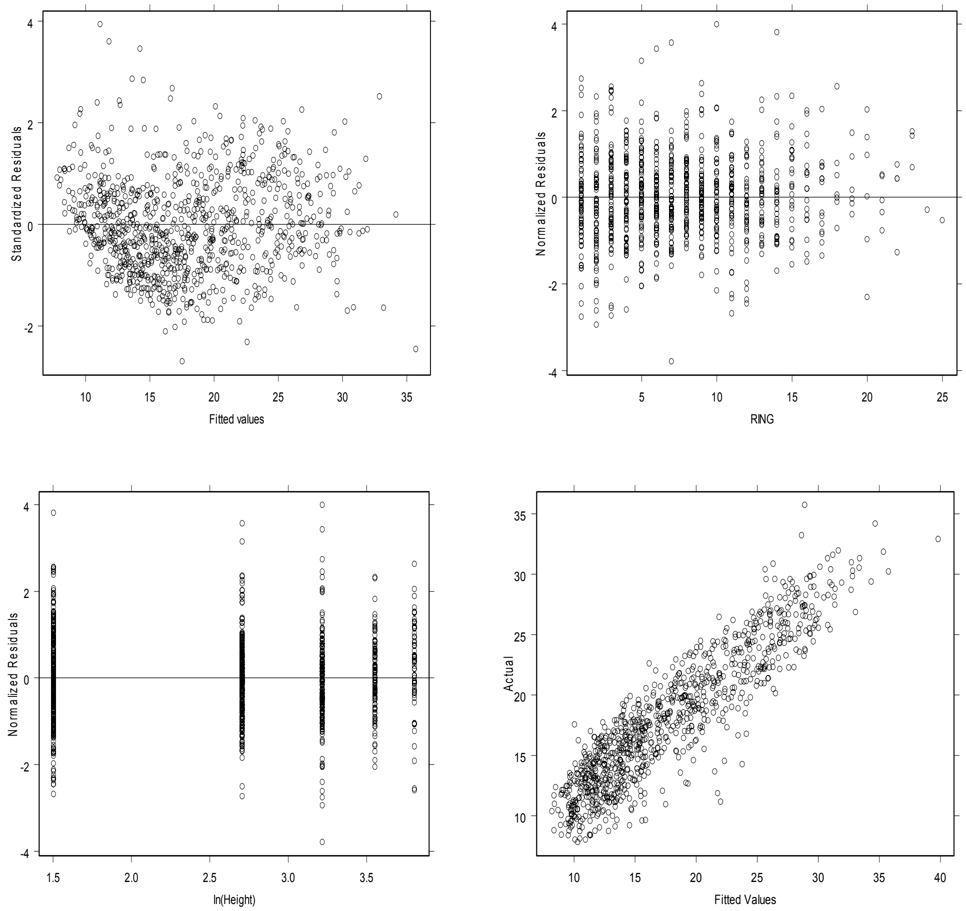

Figure 4.8. Residual plots versus the independent variables and actual MFA values versus fitted MFA values for the nonlinear earlywood model (2).

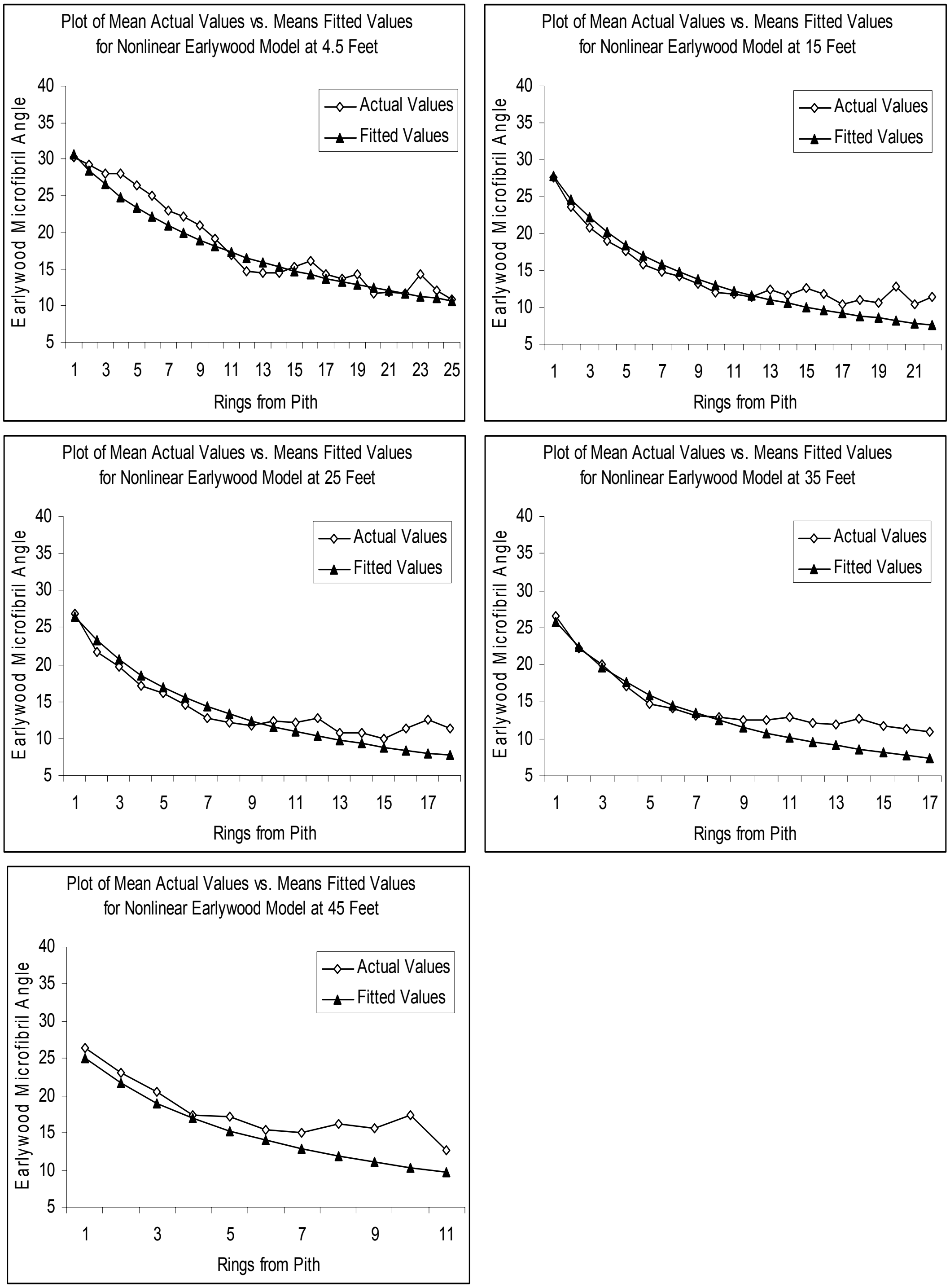

Figure 4.9. Plot of mean actual values versus mean fitted values for the nonlinear earlywood model (2) by disk height.

Table 4.4. Parameter estimates and fit statistics for the linear latewood model (3).

Coefficient	**Value**	**Std. Error**	**t value**	**p value**
β_0	46.1212	1.0359	44.5228	0.0000
β_1	0.8007	0.1043	7.6767	0.0000
β_2	-11.8712	0.5512	-21.5365	0.0000
β_3	-5.0401	0.2140	-23.5514	0.0000
β_4	0.2352	0.0254	9.2515	0.0000
β_5	0.3125	0.0519	6.0244	0.0000

Fit index: 0.753

Residual standard error: 2.714

Residuals:

Min	**Median**	**Max**
-7.669	-0.2578	10.41

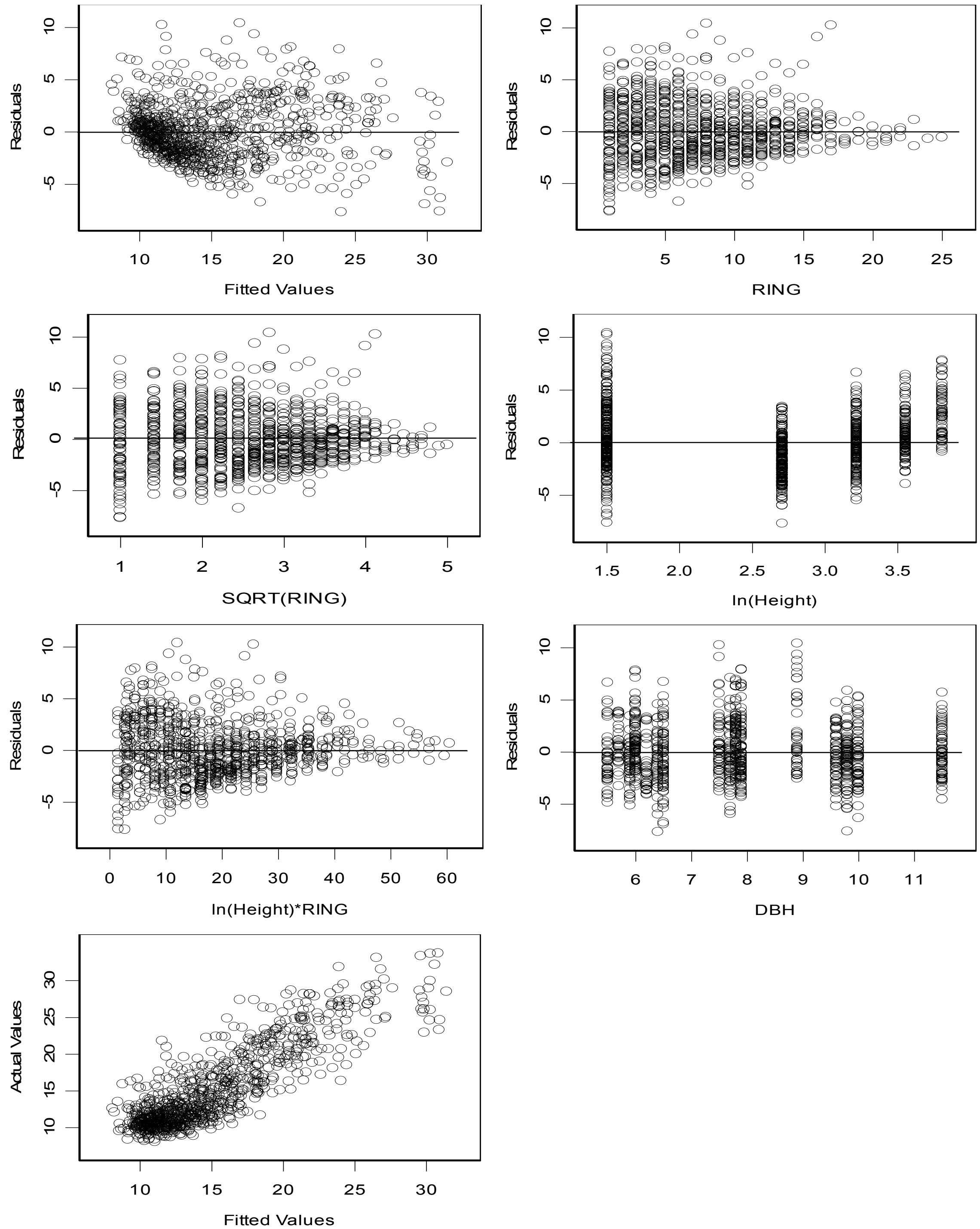

Figure 4.10. Residual plots versus the independent variables and actual MFA values versus fitted MFA values for the linear latewood model (3).

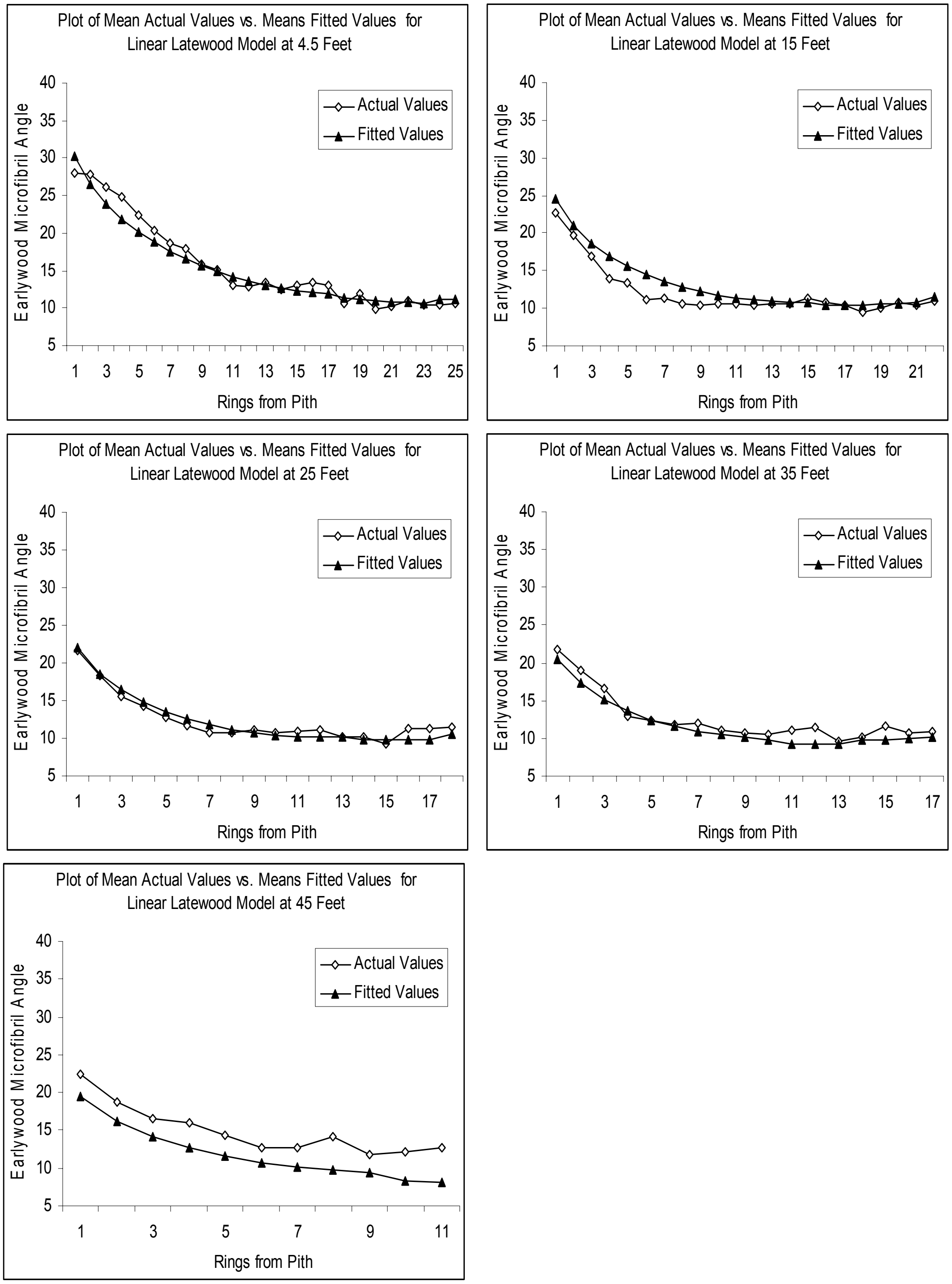

Figure 4.11. Plot of mean actual values versus mean fitted values for the linear latewood model (3) by disk height.

Table 4.5. Parameter estimates and fit statistics for the nonlinear latewood model (4).

Coefficient	Value	Std. Error	t value	p value
ϕ_{01}	6.14373	1.724062	3.56	0.0004
ϕ_{11}	3.83642	0.856088	4.48	0.0001
ϕ_{02}	32.54439	4.734458	6.87	0.0001
ϕ_{12}	-14.69113	2.970155	-4.94	0.0001
ϕ_{22}	1.98485	0.475620	4.17	0.0001
ϕ_{03}	17.31994	2.197035	7.88	0.0001
ϕ_{13}	-8.09903	1.387472	-5.83	0.0001
ϕ_{23}	1.13047	0.223947	5.04	0.0001
ϕ_{14}	-32.31373	5.335321	-6.05	0.0001
ϕ_{24}	4.33751	1.607745	2.69	0.0071

Overall Fit Statistics:

AIC	BIC	logLik
3586.012	3662.939	-1777.006

Fit index: 0.812

Residual standard error: 2.154227

Residuals:

Min	Med	Max
-3.181732	-0.09921649	4.220346

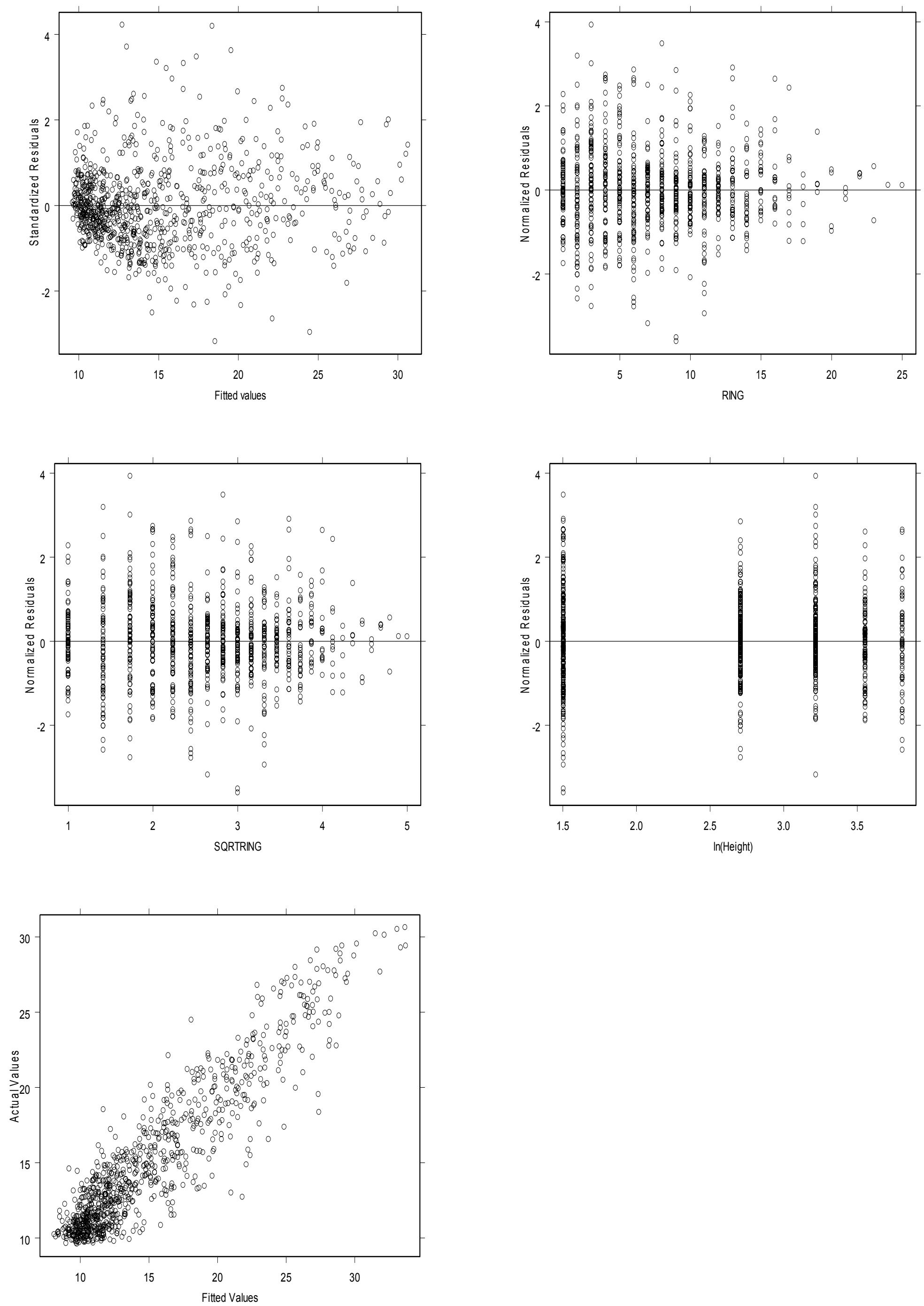

Figure 4.12. Residual plots versus the independent variables and actual MFA values versus fitted MFA values for the nonlinear latewood model (4).

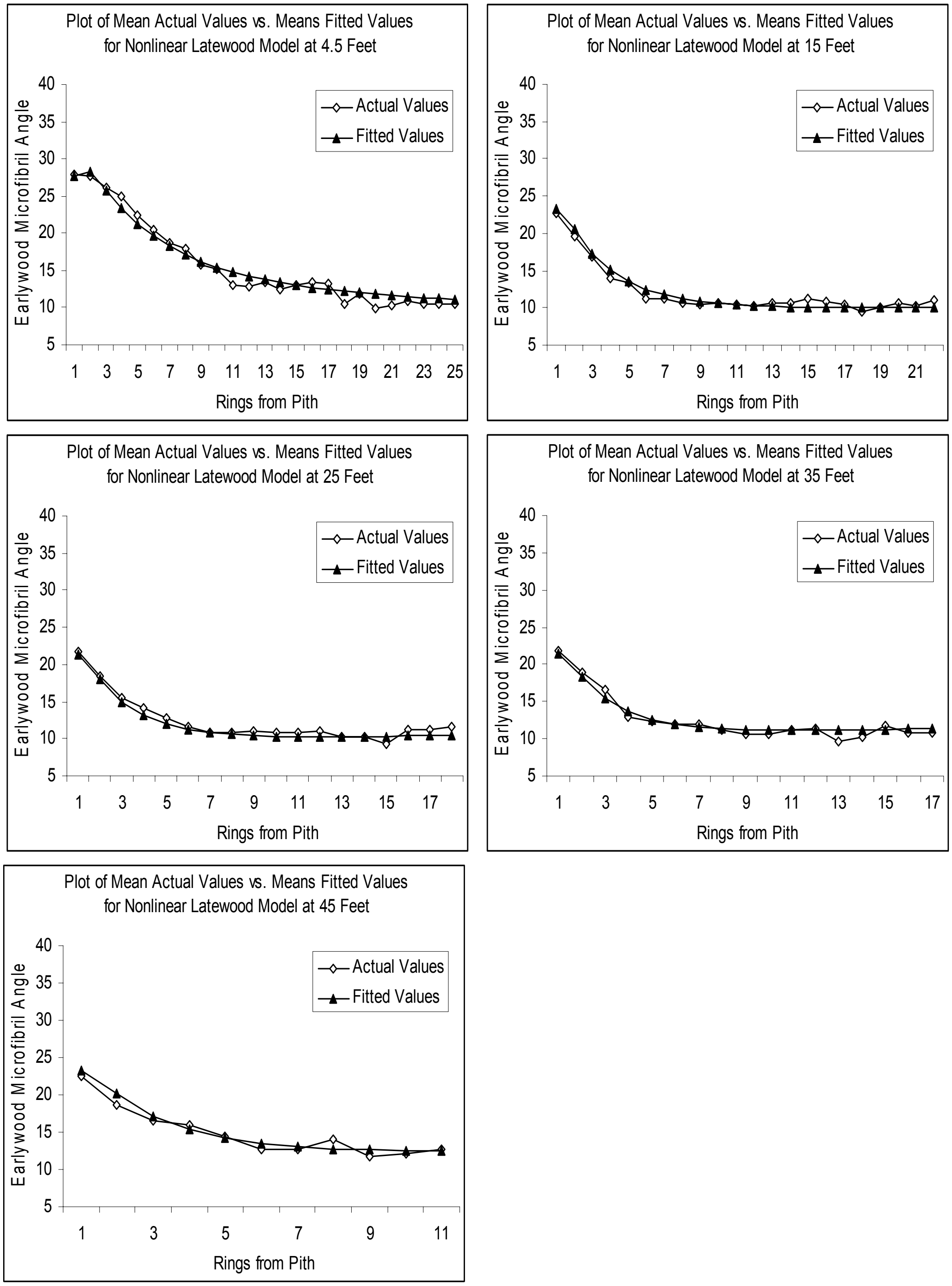

Figure 4.13. Plot of mean actual values versus mean fitted values for the nonlinear latewood model (4) by disk height.

CHAPTER 5

MODELING MICROFIBRIL ANGLE FROM STUMP TO TIP AND PITH TO BARK IN LOBLOLLY PINE GROWN IN THE SOUTHEASTERN UNITED STATES

ABSTRACT

Microfibril angle (MFA) was determined using x-ray diffraction at 0.04 inch intervals from sixty loblolly pine (*Pinus taeda* L.) trees representing four physiographic regions in the Southeastern United States. Linear and nonlinear models were developed to predict MFA at any ring from pith, distance from pith, and height. The relationship of physiographic region, total tree height, disk height, diameter breast height, and average MFA values were examined.

Keywords: microfibril angle, loblolly pine, modeling

INTRODUCTION

Microfibril angle is known to be one of the main determinants of the mechanical properties of wood. MFA is defined by Lichtenegger *et al*. (1999) as the angle between the cellulose fibrils and the longitudinal cell axis. MFA is highly correlated with specific gravity, modulus of elasticity, modulus of rupture, and the longitudinal and tangential shrinkage of wood. MFA has a significant effect on both mechanical behavior and dimensional stability of wood, and as such is an important quality characteristic for sawn timber (MacDonald and Hubert 2002). In addition, MFA has been correlated with differences in paper properties such as stretch, stiffness, and strength (Watson and Dadswell 1964; Kellogg *et al.* 1975; Megraw 1985).

Because of these relationships, MFA has become an important indicator of wood quality to the forest products industry.

Microfibrils are polysaccharide chains with a cellulose core within a hardened shell. In the primary cell wall, microfibrils are randomly interspersed (Megraw 1985). The secondary cell wall is comprised of three distinct layers: the S_1, S_2, and S_3 walls (Figure 5.1). The S_1 layer contains alternating flat sheets of microfibrils with an orientation of 50^o to 70^o to the fiber axis. In the S_2 layer microfibrils are highly parallel and steeply aligned to the fiber axis. In the S_3 layer they again occur in a very flat orientation, with angles 60^o to 90^o degrees to the cell axis. Because the S_2 layer is many times thicker than the other layers, its properties normally dominate, and the term fibril angle refers to the microfibular angle in the S_2 layer.

Variations in wood quality of any species can be attributed to variation within a tree, between trees in a particular stand, between different growing sites, and between different silvicultural regimes (Addis *et al.* 1995). MFA varies within each growth ring, from pith to bark, with height in the stem and among trees. Cave and Walker (1994) reported that the MFA decreases from the first earlywood cell to the last latewood cell. MFA in loblolly pine is large near the pith and decreases rapidly out to 10 or more rings from the pith, and then continues dropping, regardless of height, but at a much slower rate until such time as it essentially stabilizes (Megraw 1985). The decrease in MFA with age takes place at a slower rate near the base of the tree than it does at upper heights. This results in higher MFA's for a given number of rings from the pith at the butt and breast height regions than at several meters in height and above (Megraw 1985).

MFA varies considerably within each of the three zones of wood, juvenile, transitional, and mature wood, thus affecting the mechanical properties of the wood. Within tree cells, the

MFA in the S_2 part of the secondary wall is characteristically greater in juvenile wood. The large S_2 MFA causes a high degree of longitudinal shrinkage and a corresponding decrease in transverse shrinkage. The shrinkage of juvenile wood has been reported to average up to three times that of mature wood (McAlister and Clark 1992). Pillow *et al.* (1953) found that MFA in the juvenile wood of open-grown loblolly pines averaged 20^{o} greater than those in a closely spaced natural stand.

In mature loblolly pine, MFA is small, averaging about 5^{o} to 10^{o} as measured by deviation from the vertical. In juvenile wood, the MFA is large, averaging 25^{o} to 35^{o} and often up to 50^{o} in rings next to the pith, then decreasing outward in the juvenile core (Larson et al 2001). MFA has been found to decrease from 33^{o} at age 1 to 23^{o} at age 10, and to 17^{o} at age 22, in fast-grown loblolly pines (Ying et al. 1994). Bendtsen and Senft (1986) found that MFA within loblolly pine had stabilized at age 30.

The objective of this paper is to develop models for predicting MFA at any ring, distance from pith, and height. These models will allow measures of wood properties and quality to be added to current forest yield prediction systems. These models will also provide the basis for comparing properties from tree to tree, within a stand, and among stands in different regions in the Southeastern United States.

METHODS AND MATERIALS

Sixty loblolly pine trees from twenty loblolly pine stands, 20-27 years old, were sampled across the Southeastern United States for MFA analysis. Plantations were sampled by the USDA Forest Service and the University of Georgia's Wood Quality Consortium in each physiographic region, (Figure 5.2): Atlantic Coastal Plain, Piedmont, Gulf Coastal Plain, and Hilly Coastal Plain.

The stands were located on land owned by forest products companies, and included only stands with similar silvicultural history: 1) site preparation with no herbaceous weed control; 2) no fertilization at planting except phosphorus on phosphorus-deficient sites; 3) stand density of at least 250 trees per acre at the time of sampling. Trees larger than five inches in diameter were inventoried on 3 1/10-acre plots to determine stand density and diameter distribution. A sample of 3 trees was chosen for MFA analysis proportional to the diameter distribution of each stand to represent a range of tree sizes in the stand. Stand attributes are summarized in Table 5.1.

One-inch cross-sectional disks were cut at 4.5 feet, 10 feet, and then at 5-foot intervals to a height of 50 feet for the Hilly Coastal and Gulf Coastal regions. Cross sectional disks for the Piedmont and Atlantic Coastal regions were cut at 4.5 feet, 15 feet, and then at 10-foot intervals to a height of 45 feet. Two one-half inch square radial strips were cut from each disk. One strip was dried, glued to core holders and used for x-ray densitometry for measuring earlywood and latewood, radial growth, and specific gravity at 0.0024 inch intervals. The second strip, was used for MFA and analysis from each disk, dried at 122^{o} Celsius, and shipped to Australia for analysis by Silviscan® using x-ray diffraction at 0.04 inch intervals on the tangential surface.

Whole ring MFA was generated using ring width characteristics from the disk strip that was measured for specific gravity using x-ray densitometry. Given that the strips used were from the same tree disk, but opposite one another, it was assumed that one side could possibly be longer/shorter than the other due to sample preparation error or a non-perfect circular tree. Even though the strips may not be of the same length, the individual ring proportions from both strips were similar. To resolve this problem ring width was calculated as:

$$GSRING_i = RWSG_i \frac{LMFA}{LSG}$$

where,

$GSRING_i$ = Generated width of *ith* ring from MFA strip

$RWSG_i$ = Ring width of *ith* specific gravity ring

$LMFA$ = Total length of MFA strip

LSG = Total length of specific gravity strip

For example, let $LMFA$ = 4.17", LSG = 3.91", $RWSG_1$ = 0.45". Thus, $GSRING_1$ = 0.480".

Due to the variation of MFA over the small measurement interval of 0.04 inches from pith, a moving average was calculated for modeling purposes. An average of MFA was taken over five and ten measurements, making the interval lengths 0.20 and 0.40 inches respectively, which are the standard lengths used by forest products companies when evaluating MFA.

MODEL DEVELOPMENT

The data were plotted by region and height level to identify patterns and changes of ring MFA by rings and distance from pith and height (Figures 5.3-5.6). The minimum and maximum values for MFA by distance from pith at 4.5 feet was found to be 8.0^o and 63.45^o, 8.8^o and $59.8\,^o$, 9.04^o and 49.6^o, 9.2^o and 41.5^o for the Atlantic, Piedmont, Gulf Coastal, and Hilly Coastal regions respectively. Above 10 feet MFA is similar for all height levels. MFA by distance from pith was found to be on average higher in the Atlantic Coastal and Piedmont regions and display more variability in MFA versus the Gulf and Hilly Coastal regions at all height levels (Table 5.2 and Figure 5.8).

Examining MFA by rings from the pith, there is an apparent difference between whole ring MFA at 4.5 feet versus the other height levels for all regions (Figures 5.9 and 5.10). The minimum and maximum values for whole ring MFA at 4.5 feet by rings from pith was found to be 8.4^{o} and 47.0^{o}, 10.0^{o} and 50.7^{o}, 9.5^{o} and 38.3^{o}, 10.0^{o} and 33.7^{o} for the Atlantic, Piedmont, Gulf Coastal, and Hilly Coastal regions respectively. MFA by rings from pith dropped significantly by 10 feet for the Gulf and Hilly Coastal regions (Figure 5.9). Above 10 feet the effect of height on MFA appears to be negligible. MFA by rings from pith was found to be on average higher in the Atlantic Coastal and Piedmont regions versus the Gulf and Hilly Coastal regions at all height levels (Table 5.3 and Figure 5.10).

The same general trends of MFA can be observed using 0.20 and 0.40 inch intervals from pith. MFA was found to be on average higher at 4.5 feet than any other height level for all regions (Figures 5.11-5.14). For the Gulf and Hilly Coastal regions, MFA can be seen to be greatest at 4.5, above which MFA display the same general trends across all regions. Regional differences can still be observed at 0.20 and 0.40 inch intervals. On average, MFA values were found to be higher in the Atlantic Coastal and Piedmont regions versus the Gulf and Hilly Coastal regions (Figures 5.12, 5.14, Table 5.4, Table 5.5).

MODEL DEVELOPMENT: WHOLE RING MFA

Several candidate model forms were selected to describe the change of MFA by ring and height. The independent variables used in the linear model were selected based upon the linear correlation they exhibited with MFA. The variables chosen to be included in the model were the natural log of ring, $\frac{Total\ \ Height}{\ln(Disk\ \ Height)}$, ln (ring) ln (disk height) interaction, and form with correlation coefficients of -0.60333, 0.34146, -0.75064, and 0.42487 respectively. Thus, the linear model becomes:

$$
\begin{aligned}
MFA_{ij} = {} & (\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + \\
& (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P)\ln(Ring_i) + \\
& (\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P)\frac{Total\ \ Height}{\ln(Disk\ \ Height)} + \\
& (\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P)\left[\ln(Ring)\ln(DiskHeight_j)\right] + \\
& (\beta_4 + \beta_4 I_H + \beta_4 I_G + \beta_4 I_P) Form
\end{aligned} \tag{1}
$$

where, the base model represents the Atlantic Coastal region and I_H, I_G, and I_P, represent deviations from the base parameters for the Hilly Coastal, Gulf Coastal and Piedmont regions respectively, and

MFA_{ij} = MFA at *Ring i* and *Disk Height j*,

Ring = Ring from pith,

$Form = \dfrac{\ln(DBH)\ \ (in.)}{\ln(Disk\ \ Height)\ \ (ft.)}$,

Disk Height = Height above Ground (ft.),

DBH = Diameter Breast Height (in.),

$I_H =$ 1 if Hilly Coastal Region
0 otherwise

$I_G =$ 1 if Gulf Coastal Region
0 otherwise

$I_P =$ 1 if Piedmont Region
0 otherwise

Whole ring MFA appears to be decreasing in a non-linear fashion with ring, so a non-linear model was found with the form:

$$
MFA_{ij} = \phi_1 \exp\left[(\phi_2 + \phi_3 + \phi_4)\ln(Ring)\right] \tag{2}
$$

where,

$$\phi_1 = [(\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P) Form]$$

$$\phi_2 = (\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P)$$

$$\phi_3 = (\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P) Form$$

$$\phi_4 = (\beta_4 + \beta_4 I_H + \beta_4 I_G + \beta_4 I_P) \frac{Total\ \ Height\ \ (ft.)}{\ln(Disk\ \ Height)\ \ (ft.)}$$

and,

MFA_{ij} = MFA at *Ring i* and *Disk Height j*,

$I_H =$ 1 if Hilly Coastal Region
0 otherwise

$I_G =$ 1 if Gulf Coastal Region
0 otherwise

$I_P =$ 1 if Piedmont Region
0 otherwise

and all other parameters previously defined.

MODEL DEVELOPMENT: MFA AT 0.20 INCH INTERVALS

A linear model was selected to explain the change of MFA by 0.20 inch interval from pith and height. The linear model proposed is:

$$\begin{aligned} MFA_{ij} = {} & (\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + \\ & (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P) \ln(Interval_i) + \\ & (\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P) ILH + \\ & (\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P) Form \end{aligned} \quad (3)$$

where,

MFA_{ij} = MFA at *Interval i from pith* and *Disk Height j*,

Interval = 0.20 Inch Intervals

*Distance from Pith (Inches) = Interval** 0.20

$$ILH = \frac{\ln(Total\ \ Height)\ \ (ft.)}{\ln(Disk\ \ Height)\ \ (ft.)}$$

I_{H} = 1 if Hilly Coastal Region
0 otherwise

I_{G} = 1 if Gulf Coastal Region
0 otherwise

I_{P} = 1 if Piedmont Region
0 otherwise

and all other parameters previously defined.

MFA appears to be decreasing in a nonlinear fashion (Figures 5.4, 5.10, and 5.11) with distance from pith. Thus, a nonlinear model was developed to represent the change of MFA at 0.20 inch intervals and height. The model takes the form:

$$MFA_{ij} = \phi_1 \exp\left(\phi_2\right) + \phi_3 \exp\left(\phi_4\right) \tag{4}$$

where,

$$\phi_1 = \left[\left(\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P\right) + \left(\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P\right) Form\right]$$

$$\phi_2 = \left(\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P\right) \ln\left(Disk\ \ Height\right)$$

$$\phi_3 = \left(\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P\right)$$

$$\phi_4 = \left(\beta_4 + \beta_4 I_H + \beta_4 I_G + \beta_4 I_P\right) Interval$$

and,

MFA_{ij} = MFA at *Interval i from pith* and *Disk Height j*,

Interval = 0.20 Inch Intervals

*Distance from Pith (Inches) = Interval** 0.20

$I_H =$ 1 if Hilly Coastal Region
0 otherwise

$I_G =$ 1 if Gulf Coastal Region
0 otherwise

$I_P =$ 1 if Piedmont Region
0 otherwise

and all other parameters previously defined.

MODEL DEVELOPMENT: MFA AT 0.40 INCH INTERVALS

A linear model was first selected to represent the change of MFA by 0.40 inch interval from pith. The linear model takes the form:

$$\begin{aligned} MFA_{ij} = {} & (\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + \\ & (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P)\ln(Interval_i) + \\ & (\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P) ILH + \\ & (\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P) Form \end{aligned} \qquad (5)$$

where,

MFA_{ij} = MFA at *Interval i from pith* and *Disk Height j*,

Interval = 0.40 Inch Intervals

*Distance from Pith (Inches) = Interval** 0.20

$I_H =$ 1 if Hilly Coastal Region
0 otherwise

$I_G =$ 1 if Gulf Coastal Region
0 otherwise

$I_P =$ 1 if Piedmont Region
0 otherwise

and all other parameters previously defined.

MFA appears to be decreasing in a nonlinear fashion (Figures 5.4, 5.10, and 5.11) at 0.40 inch intervals from pith. Thus, a nonlinear model was developed to represent the change of MFA at 0.40 inch intervals and height. The model takes the form:

$$MFA_{ij} = \phi_1 \exp\left(\phi_2\right) + \phi_3 \exp\left(\phi_4\right) \tag{6}$$

where,

$$\phi_1 = \left(\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P\right) Form$$

$$\phi_2 = \left(\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P\right) \ln\left(Disk\ \ Height\right)$$

$$\phi_3 = \left(\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P\right)$$

$$\phi_4 = \left[\left(\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P\right) + \left(\beta_4 + \beta_4 I_H + \beta_4 I_G + \beta_4 I_P\right) Form\right] Interval$$

and,

MFA_{ij} = MFA at *Interval i from pith* and *Disk Height j*,

Interval = 0.40 Inch Intervals

*Distance from Pith (Inches) = Interval** 0.40

$I_H =$ 1 if Hilly Coastal Region
0 otherwise

$I_G =$ 1 if Gulf Coastal Region
0 otherwise

$I_P =$ 1 if Piedmont Region
0 otherwise

RESULTS

Parameter estimates and fit statistics for the linear whole ring MFA model (1), for are found in Table 5.6. The linear model was found to account for 75% of the variation in MFA with a mean square error of 11.35°. The plot of residuals versus the natural log of ring indicates a deviation from the linear assumption and appears to be quadratic in form (Figure 5.15). Plots of the residuals versus $\frac{Total\ Height\ \ (ft.)}{\ln(Disk\ Height)\ \ (ft.)}$ and Form (Figure 5.15) show no trends, and are all centered on zero. The plot of residuals versus the ln (ring) ln (disk height) interaction indicates non-constant variance over the interaction term. Parameter estimates were found to differ by region. Intercept estimates were found to be 16.98° for the Atlantic and Gulf, 17.98° for the Hilly, and 12.43° for the Piedmont regions respectively. From Figure 5.10, it can be seen that the Gulf Coastal region, on average, had higher values of whole ring MFA above 15 feet, however the Atlantic region was found to have the highest MFA values at height levels of 4.5 and 15 feet. Whole ring MFA was found to decrease -7.90° in the Atlantic and Hilly regions, -9.03° in the Gulf, and -8.97° in the Piedmont regions given a one unit change in rings from pith. MFA was found to decrease -0.56° and -0.031° in the Atlantic and Hilly regions, and increase 0.255° and 0.133° in the Gulf and Piedmont regions with the $\frac{Total\ Height\ \ (ft.)}{\ln(Disk\ Height)\ \ (ft.)}$ term. Parameter estimates for the Form term were found to be 31.05° in the Atlantic, 11.97° in the Hilly, 6.13° in the Gulf, and 14.18° in the Piedmont regions. This means that if DBH is held constant, MFA will decrease with increasing disk height. Figure 5.16 shows the plots of the mean actual versus mean predicted values by disk height. It can be seen at 4.5 feet, that the linear model is incapable of reproducing the observed sigmoidal shaped curve of MFA. The model produces higher initial values of MFA at ring 1, and then decreases exponentially, under estimating the true value of MFA. At height levels above 4.5 feet, the model tracks MFA well. However, instead of reaching some lower asymptote, the linear model continues decrease, over estimating MFA at larger ring values.

All parameters for the nonlinear whole ring MFA model (2) were found to be significant at the 0.05 level (Table 5.7). With Form held constant, initial values of MFA were found to be 31.57°, 30.58°, 30.85°, and 30.79° in the Atlantic, Hilly, Gulf, and Piedmont regions respectively. The general rate of change of MFA for this model can be evaluated by examining the ϕ_2 parameter. ϕ_2 was found to be -0.42 in the Atlantic, Hilly, and Gulf regions, and -0.34 in the Piedmont region, signifying that MFA decreases more rapidly in the Atlantic, Hilly, and Gulf regions than in the Piedmont region. Parameter estimates for the Form term were found to be 0.62 in the Atlantic, 0.098 in the Hilly, -0.02 in the Gulf, and 0.099 in the Piedmont regions. This means that if DBH is held constant, MFA will decrease with increasing disk height in the Atlantic, Gulf, and Piedmont regions, and increase in the Hilly region. Examination of the residual versus predicted plot (Figure 5.17) indicates no trends and all residuals are centered on zero. The model does seem to be over predicting at higher ring values. The plot of residuals versus the natural log of ring indicates a slight deviation from the linear assumption and appears to be quadratic in form (Figure 5.17). Plots of the residuals versus $\frac{Total\ Height\ \ (ft.)}{\ln(Disk\ Height)\ \ (ft.)}$ and Form (Figure 5.17) show no trends, and are all centered on zero. Figure 5.18 shows the plots of the mean actual MFA versus mean predicted MFA values by disk height. It can be seen at 4.5 feet, that the model is incapable of reproducing the observed sigmoidal shaped curve of MFA. The model produces higher initial values of MFA at ring 1, and then decreases exponentially, under estimating the true value of MFA. At height levels above 4.5 feet, the model predicts

MFA better than the linear model. However, at height levels of 45 and 50 feet, the model tends to be under predicting the true values of MFA.

Parameter estimates and fit statistics for the linear 0.20 inch interval model (3) were found to be significant at the 0.0001 level (Table 5.8). The linear model was found to account for 67% of the variation of MFA with a means square error of 16.63°. Plots of the residuals versus the independent variables can be found in Figure 5.19. The plot of the residuals versus predicted values shows that the majority of the residuals are centered on zero, and the model is unbiased. The model was found to be over predicting at higher values of MFA. MFA values this high were found near intervals 1-3 at 4.5 feet, indicating estimation problems in this area of the tree. The plot of residuals versus the natural log of interval are all centered on zero, but may indicate a slight quadratic trend. Plots of the residuals versus the independent variables ILH and Form show no general patterns. Intercept estimates for the linear 0.20 inch interval model were found to be 22.08° in the Atlantic, Hilly, and Gulf regions, and 19.51° in the Piedmont region. MFA was found to decrease at a rate of -6.55 ° in the Atlantic, Hilly, and Gulf regions, and -5.67° in the Piedmont region given a one unit change in interval. ILH parameter estimates were found to be -4.79 in the Atlantic and Hilly regions, 0.40 in the Gulf, and -0.15 in the Piedmont region respectively. The high parameter values in the Atlantic and Hilly region suggest that the effect of disk height on MFA changes rapidly as disk height increases, and MFA changes little as disk height increases in the Gulf and Piedmont regions. The Form parameter estimates were found to be 20.99, 19.43, 9.25, and 13.31 for the Atlantic, Hilly, Gulf, and Piedmont regions respectively. This indicates that if DBH is held constant; MFA will decrease with increasing disk height. Figure 5.20 shows the plots of the mean actual MFA versus mean predicted MFA values by disk height. It can be seen at 4.5 feet, that the model is incapable of reproducing the observed sigmoidal shaped curve of MFA. The model produces higher initial values of MFA at ring 1, and then decreases exponentially, severely under estimating the true value of MFA from intervals 3 to 12. At height levels above 4.5 feet, the model predicts MFA well. However, the model is incapable of reaching the lower asymptotic value of MFA, and consequently under estimates the true value of MFA at 0.20 inch intervals from pith.

All parameters for the nonlinear MFA model (4) at 0.20 inch intervals were found to be significant at the 0.05 level (Table 5.9). The nonlinear model was found to account for 69% of the variation of MFA with a mean square error of 16.1^{o}. Examination of the residual plots (Figure 5.21) indicates no general trends and the majority of the residuals are centered on zero. Overall, the nonlinear model may slightly over predict MFA. This was confirmed by a median residual value of -0.335^{o}. If all other independent variables are held constant, increasing disk height will result in shifting the model to reach a lower asymptotic value, while increasing DBH, will shift the asymptotic bound to a higher value. The functionality of the height and form variables in the model can be described as a linear adjuster. These values will be a constant fixed value and will shift the value of MFA interval up or down, depending on height level. It can be seen from the parameter estimates, that the Atlantic and Hilly regions have significantly higher asymptotic bounds than the Gulf and Piedmont regions. The second term in the model defines the rate of change of MFA from pith to bark. Initial values of MFA at the first interval were found to be 25.2^{o} in the Atlantic, 21.6^{o} in the Hilly, 21.6^{o} in the Gulf, and 22.3^{o} in the Piedmont regions. The rate of change of MFA at 0.20 inch intervals was found to be -0.09^{o}, -.14^{o}, -0.17^{o}, and -0.08^{o} in the Atlantic, Hilly, Gulf, and Piedmont regions respectively given a one unit change in the interval from pith.

Plots of the average predicted and actual values for the nonlinear 0.20 inch interval model are found in Figure 5.22. Since this model is essentially a decreasing exponential function with a constant shifter, it can be seen how the model would poorly represent the change of MFA at 0.20 inch intervals at 4.5 feet. The model at 4.5 feet over predicts MFA at the first 2 intervals from pith, and then significantly under-estimates the true value of MFA from the fourth to the eleventh interval. It can be seen that the model is incapable of reproducing the observed sigmoid trend at 4.5 feet. At height levels greater than 4.5 feet, it was found that the model performed reasonably well. The model does have a tendency to under predict MFA from the 13^{th} interval out to the bark. This may be attributed to the fact that the models developed, do not truly reach a lower asymptotic.

Parameter estimates and fit statistics for the linear 0.40 inch interval model (5) were found to be significant at the 0.0006 level (Table 5.10). The linear model was found to account for $70^{\%}$ of the variation of MFA with a means square error of 14.83^{o}. Plots of the residuals versus the independent variables can be found in Figure 5.23. The plot of the residuals versus predicted values shows that the majority of the residuals are centered on zero, and the model is unbiased. The plot of residuals versus the natural log of interval are all centered on zero, but may indicate a slight quadratic trend. Plots of the residuals versus the independent variables ILH and Form show no general patterns. Intercept estimates for the linear 0.40 inch interval model were found to be 19.65^{o} in the Atlantic, Hilly, and Gulf regions, and 17.38^{o} in the Piedmont region. MFA was found to decrease at a rate of -7.63^{o} in the Atlantic, Hilly, and Gulf regions, and -6.54^{o} in the Piedmont region given a one unit change in interval. ILH parameter estimates were found to be -5.29 in the Atlantic and Hilly regions, -0.10 in the Gulf, and -0.79 in the Piedmont region respectively. The high parameter values in the Atlantic and Hilly region suggest that the effect of disk height on MFA changes rapidly as disk height increases, and MFA changes little as disk height increases in the Gulf and Piedmont regions. Form parameter estimates were found to be 21.89, 20.35, 10.15, and 14.38 for the Atlantic, Hilly, Gulf, and Piedmont regions respectively. This indicates that if DBH is held constant; MFA will decrease with increasing disk height. Figure 5.24 shows the plots of the mean actual MFA versus mean predicted MFA values by disk height. It can be seen at 4.5 feet, that the model is incapable of reproducing the observed sigmoidal shaped curve of MFA. The model produces higher initial values of MFA at interval 1, and then decreases exponentially, severely under estimating the true value of MFA from intervals 3 to 12. At height levels above 4.5 feet, the model predicts MFA well. However, the model is incapable of plateauing at the lower asymptotic value of MFA, and consequently under estimates the true value of MFA at 0.40 inch intervals from pith.

All parameters for the nonlinear MFA model (6) at 0.40 inch intervals were found to be significant at the 0.008 level (Table 5.11). The nonlinear model was found to account for 71% of the variation of MFA with a mean square error of 14.3^{o}. Examination of the residual plots (Figure 5.25) indicates no general trends and the majority of the residuals are centered on zero, with a median residual value of -0.34^{o}. If all other independent variables are held constant, increasing disk height is going to result in shifting the model to reach a lower asymptotic value, while increasing DBH, will shift the asymptotic bound to a higher value. The functionality of the height and form variables in the model can be described as a linear adjuster. These values will be a constant fixed value and will shift the value of MFA at any 0.40 inches up or down, depending on height level. It can be seen from the parameter estimates, that the Atlantic and Hilly regions have significantly higher asymptotic bounds than the Gulf and Piedmont regions. The second term in the model defines the rate of change of MFA from pith to bark.

Plots of the average predicted and actual values for the nonlinear 0.40 inch interval model are found in Figure 5.25. Since this model is essentially a decreasing exponential function with a constant shifter, it can be seen how the model would poorly represent the change of MFA at 0.40 inch intervals at 4.5 feet. The model at 4.5 feet is over predicting MFA at the first interval and then significantly under-estimates the true value of MFA from the second to the sixth interval. It can be seen that the model is incapable of reproducing the observed sigmoid trend at 4.5 feet. At height levels greater than 4.5 feet, it was found that the model performed reasonably well. The model does have a tendency to under predict MFA from the 7^{h} interval out to the bark. This may be attributed to the fact that the models developed, do not truly reach a lower asymptotic.

DISCUSSION

MFA was found to be significantly higher at 4.5 feet and to decrease with increasing height. Regional differences in MFA were also found with higher values of MFA found in the Atlantic Coastal and Piedmont regions than the Gulf and Hilly Coastal regions. The finding of higher MFA values in the Piedmont region than the Atlantic Coastal Plain is consistent with higher specific gravity findings by Clark (2002). Clark (2002) found that specific gravity values, which are highly inversely correlated with MFA, were on average higher in the Lower Coastal Plain of Georgia and South Carolina than in the Piedmont. With the Atlantic Coastal region receiving more summer rainfall and an extended growing season, it would be expected that trees in this area would have a greater percentage of latewood and conversely lower MFA values. Regional weather patterns are not the sole factor influencing MFA. Initial stocking density, the number of trees per acre at the time of sampling, or genetics could influence MFA.

MFA models were developed to represent the change of MFA from stump to tip and pith to bark for 60 loblolly pine trees sampled in the Southeastern United States. Both linear and nonlinear model forms were developed to explain the trends of MFA in 3-dimensional space. Identifying the patterns and change of MFA by rings from pith, distance from pith, and height allowed candidate model forms to be developed.

The linear models developed for predicting MFA at any ring are quadratic in form, and may truly estimate the correct values of MFA at rings close to the pith at 4.5 feet, and rings close to the bark at all height levels. All models developed to predict MFA at any ring from pith and height were found to be over predicting. MFA appears to be linear or sigmoid in shape at 4.5 feet, above which MFA decreases rapidly in nonlinear fashion. However, these patterns were found to vary from tree to tree, with some trees exhibiting an almost perfect linear relationship at all height levels and others representing nonlinear trends.

The models developed for predicting MFA by interval from pith were found to be less useful. Taking the average of MFA over any specified distance points out the variability between trees. Dominant trees in the stand would be expected to have larger rings, not necessarily larger MFA values. However, when averaging across a specific distance in the dominant trees, it may be that the MFA value includes only earlywood, while suppressed trees may be averaged over both earlywood and latewood MFA. Average MFA values over wider intervals may provide a more stable dependent variable. In fact, higher fit index values were found when averaging over 0.40 inch intervals, which indicates a reduction in variability at wider intervals.

The models developed here represent the first attempt to describe MFA in 3-dimensional space and can be used in conjunction with localized site index and height equations to predict

MFA at any ring, interval from pith, and height for loblolly pine grown in the Southeastern United States.

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TABLES AND FIGURES FOR CHAPTER 5

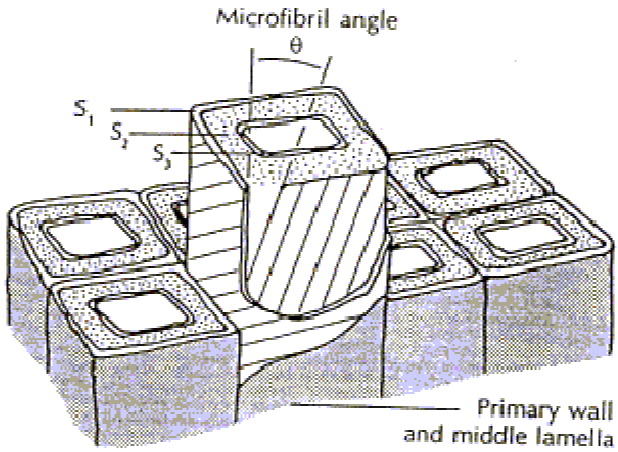

Figure 5.1. Orientation of microfibrils in the S2 layer of the cell wall (after Dickson and Walker 1997).

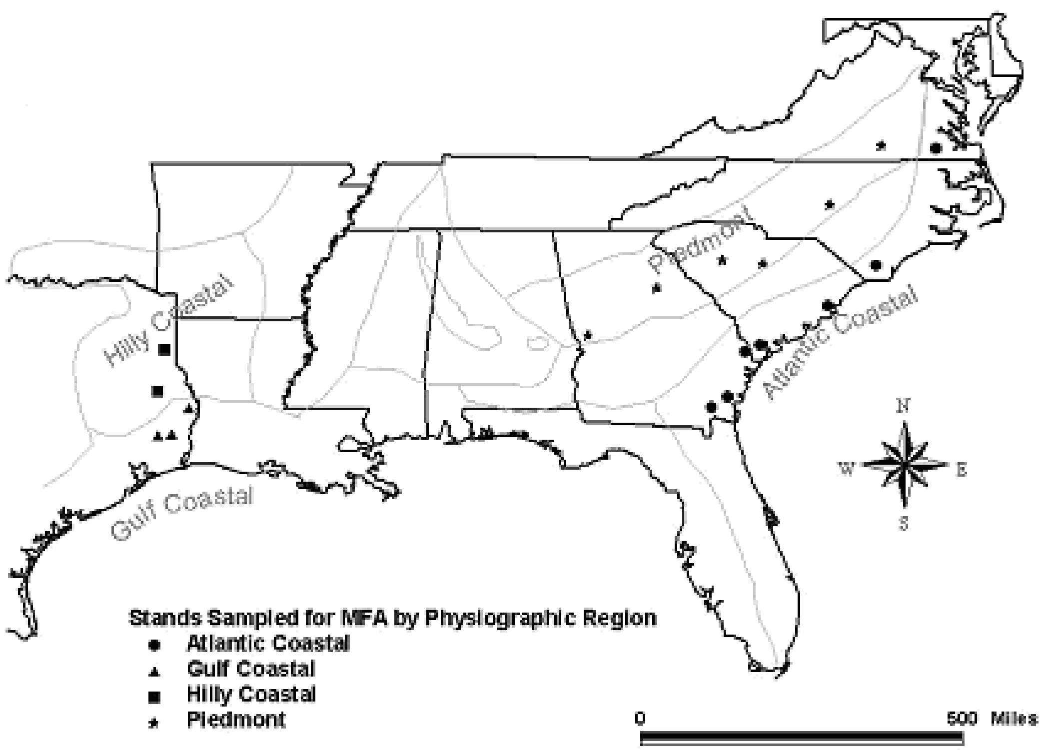

Figure 5.2. Map of the 20 stand locations sampled between 1999 and 2001 for microfibril analysis.

Table 5.1. Range and average tree size characteristics (in parenthesis) for 60 loblolly pine trees sampled for MFA analysis by physiographic region.

REGION	TREES SAMPLED (NO.)	DBH (inches)	TOTAL HEIGHT (feet)	AGE (years)	MFA (degrees)
Atlantic Coastal	24	6.1 – 12.7 (9.3)	51 – 83 (69.2)	21 – 24 (22)	10.2 - 47.0 (21.3)
Piedmont	18	6.2 – 14.2 (10.1)	49.6 – 65.4 (60.0)	21 – 25 (23)	12.0 – 50.7 (22.2)
Gulf Coastal	9	5.7 – 9.8 (7.5)	41.3 – 61.3 (55)	20 – 27 (24)	12.7 – 38.3 (19.3)
Hilly Coastal	9	5.5 – 11.5 (8.3)	37.4 – 71.2 (58.0)	20	12.4 – 34.7 (19.4)

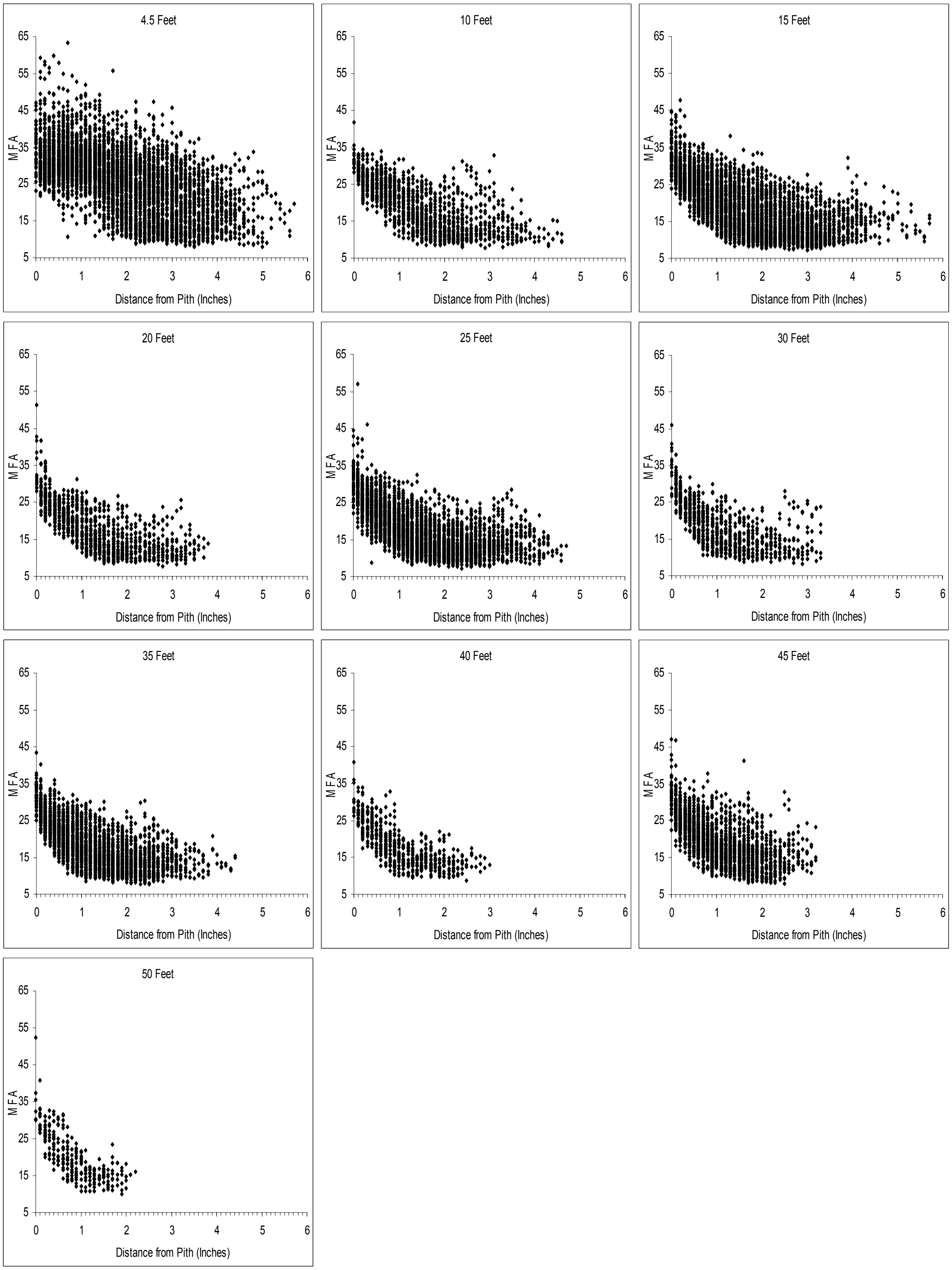

Figure 5.3. Plot of microfibril angle versus distance from pith at different height levels.

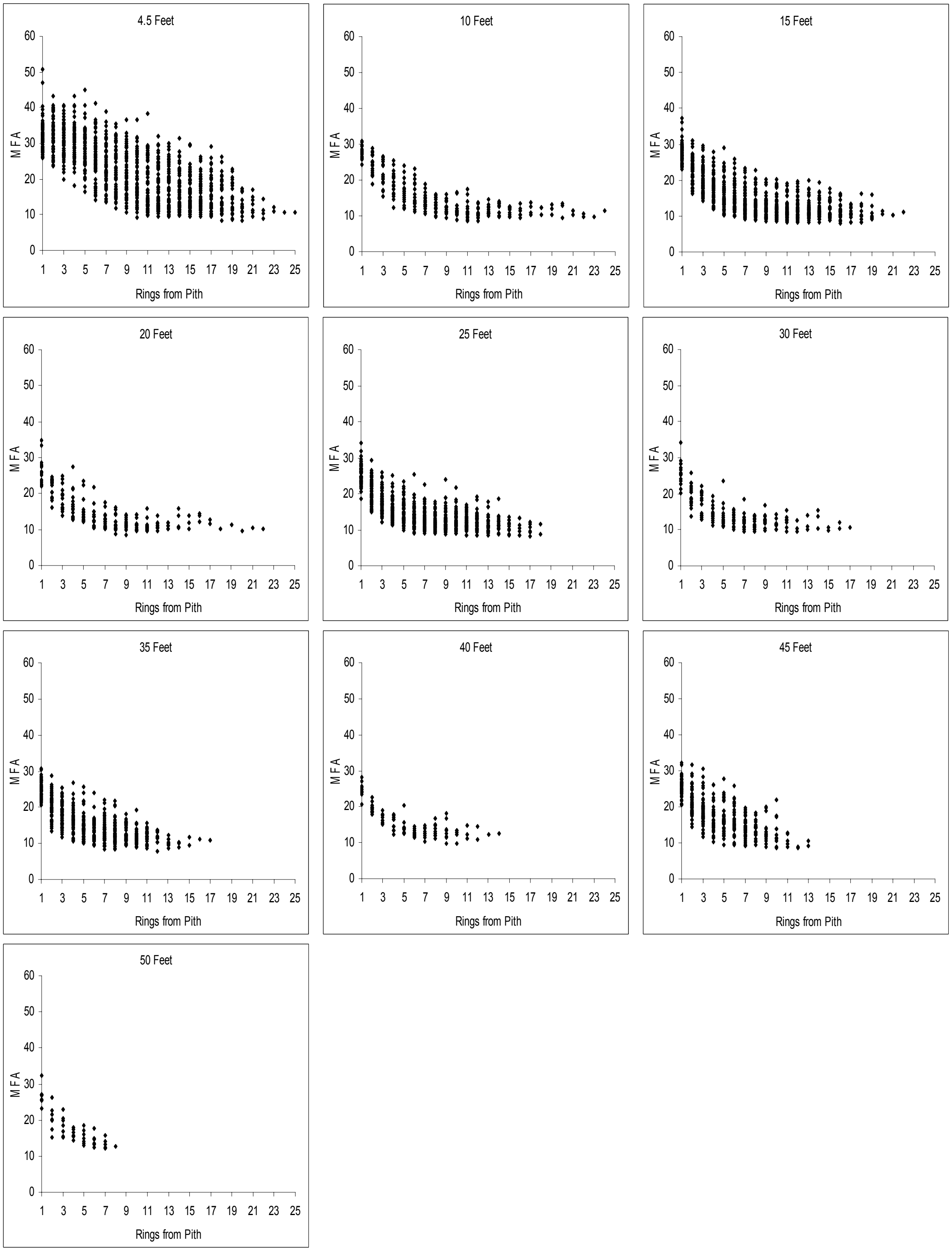

Figure 5.4. Plot of whole ring microfibril angle versus rings from pith at different height levels.

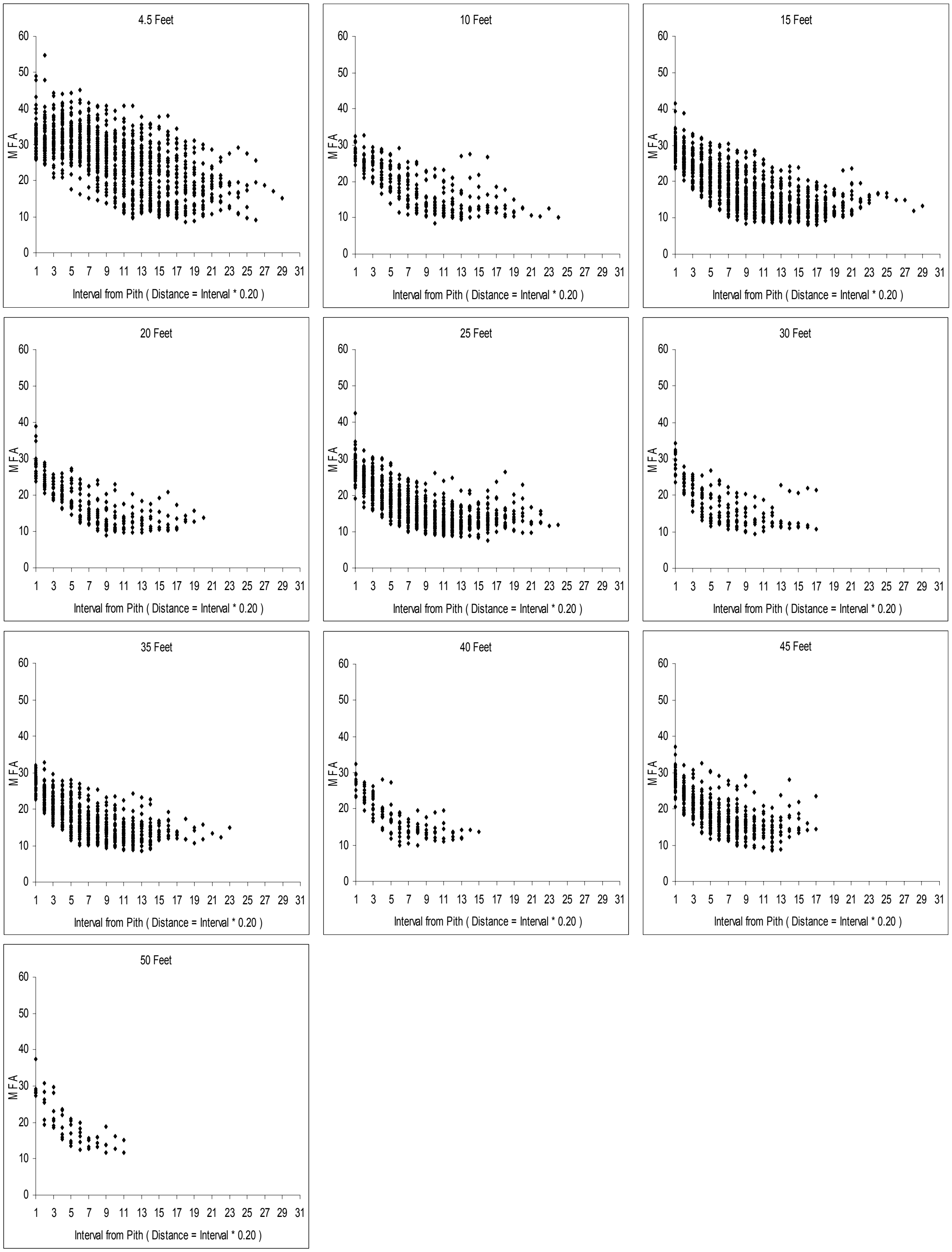

Figure 5.5. Plot of microfibril angle versus distance from pith at 0.20 inch intervals at different height levels

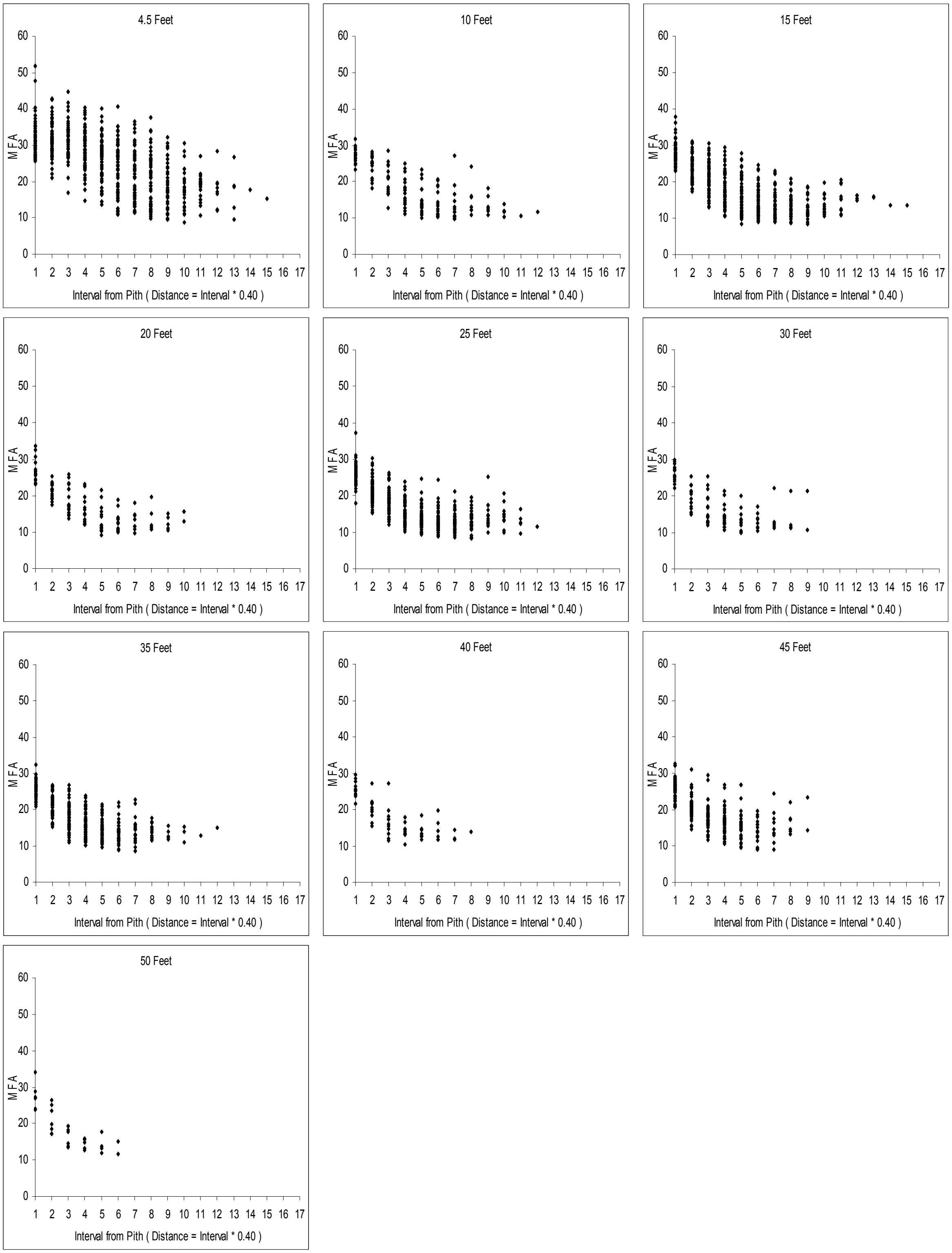

Figure 5.6. Plot of microfibril angle versus distance from pith at 0.40 inch intervals at different height levels

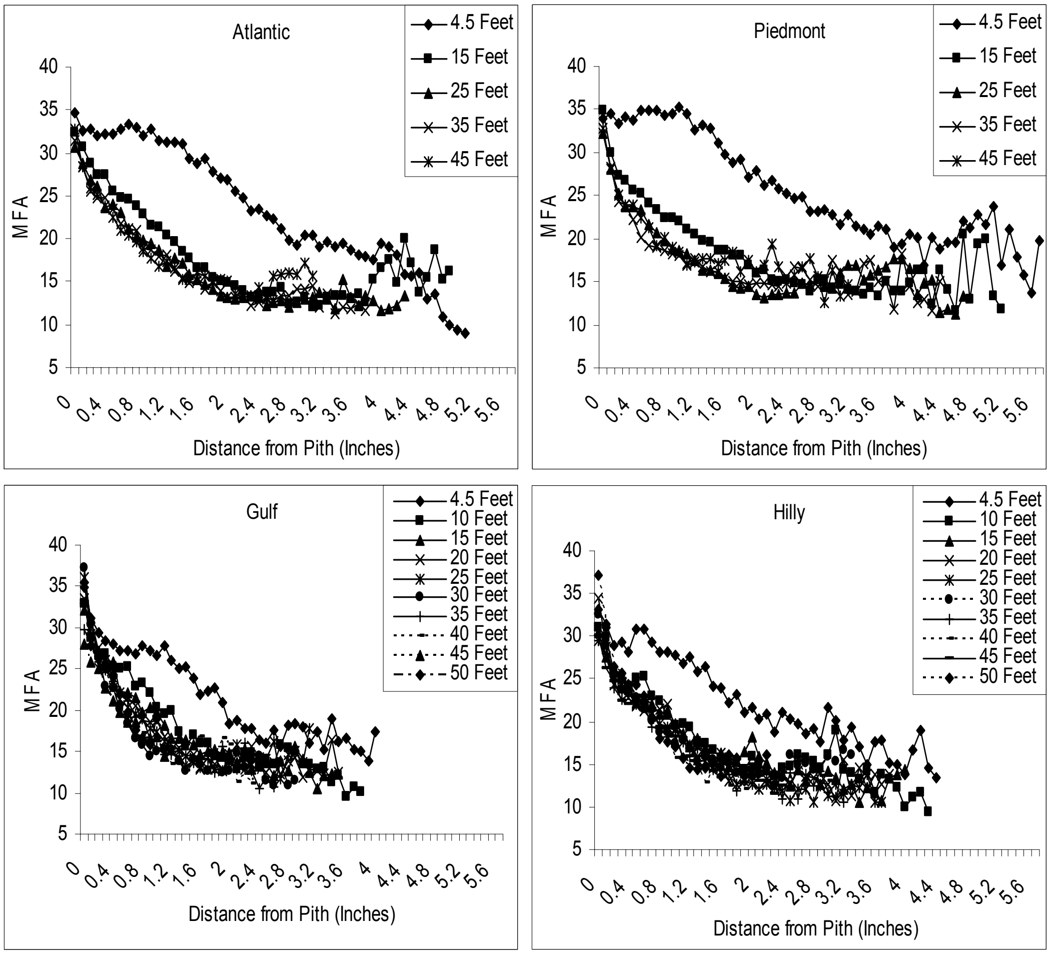

Figure 5.7. Average microfibril angle versus distance from pith in inches (rounded to the nearest one-tenth inch) at different height levels for the Atlantic, Piedmont, Gulf Coastal, and Hilly Coastal regions.

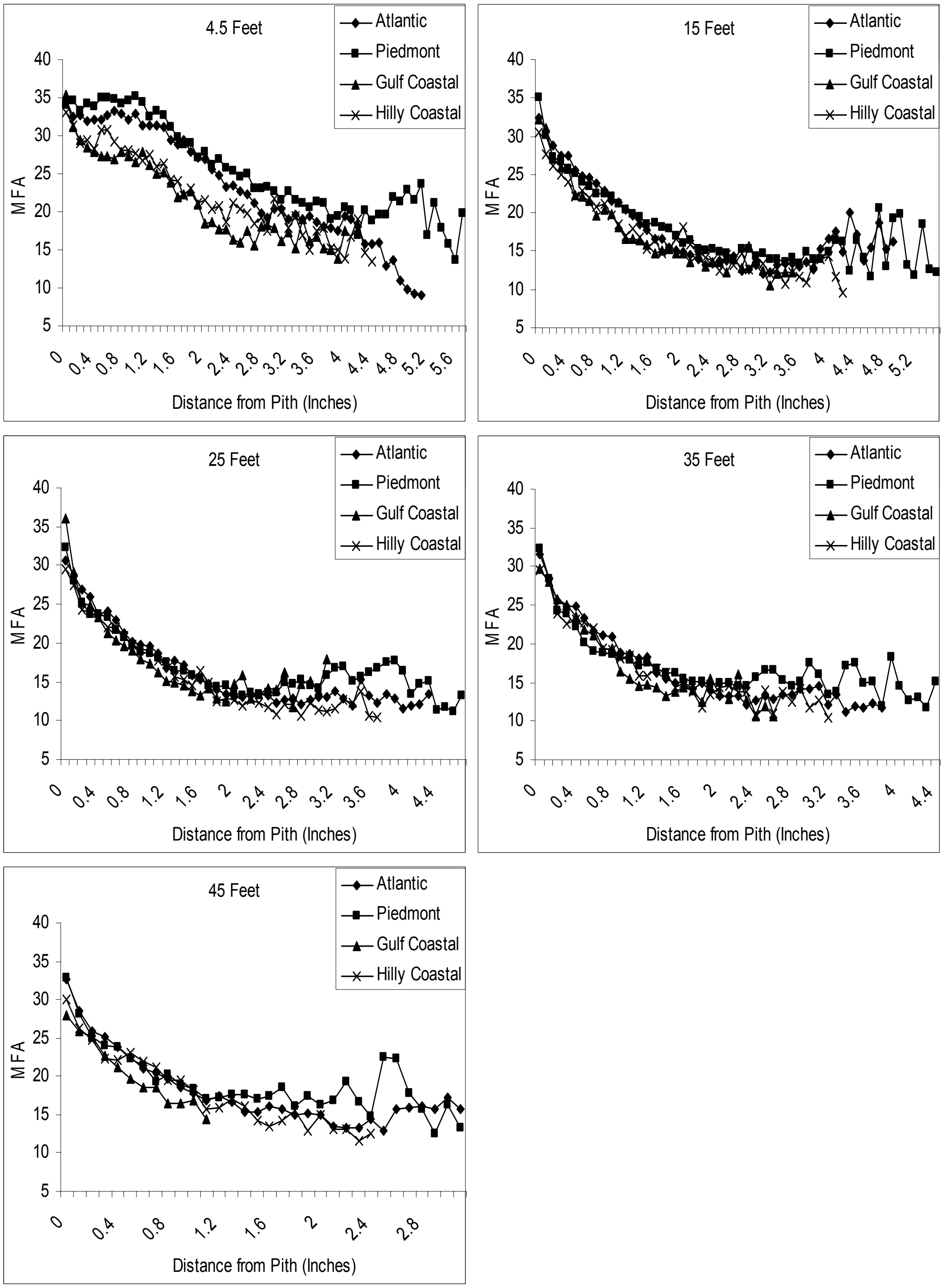

Figure 5.8. Average microfibril angle versus distance from pith in inches (rounded to the nearest one-tenth inch) by physiographic region and height level.

Table 5.2. Mean, minimum, and maximum, distance from pith MFA values, by physiographic region and height level.

DISK HEIGHT	REGION	MEAN MFA	MINIMUM MFA	MAXIMUM MFA
4.5	Atlantic	26.8	8.04	63.45
4.5	Piedmont	27.8	8.76	59.76
4.5	Gulf	22.8	9.04	49.57
4.5	Hilly	23.8	9.19	41.46
15	Atlantic	18.8	7.19	47.71
15	Piedmont	19.0	7.47	44.8
15	Gulf	18.2	7.81	42.18
15	Hilly	18.1	8.08	33.63
25	Atlantic	17.7	7.21	57.11
25	Piedmont	17.6	8.21	44.52
25	Gulf	18.0	8.38	42.77
25	Hilly	17.3	7.65	35.25
35	Atlantic	18.1	7.54	43.38
35	Piedmont	18.0	8.32	40.11
35	Gulf	18.0	9.27	33.61
35	Hilly	17.6	8.51	37.15
45	Atlantic	19.0	7.96	42.81
45	Piedmont	20.2	9.84	46.93
45	Gulf	20.2	12.09	31.85
45	Hilly	18.3118	9.38	36.64

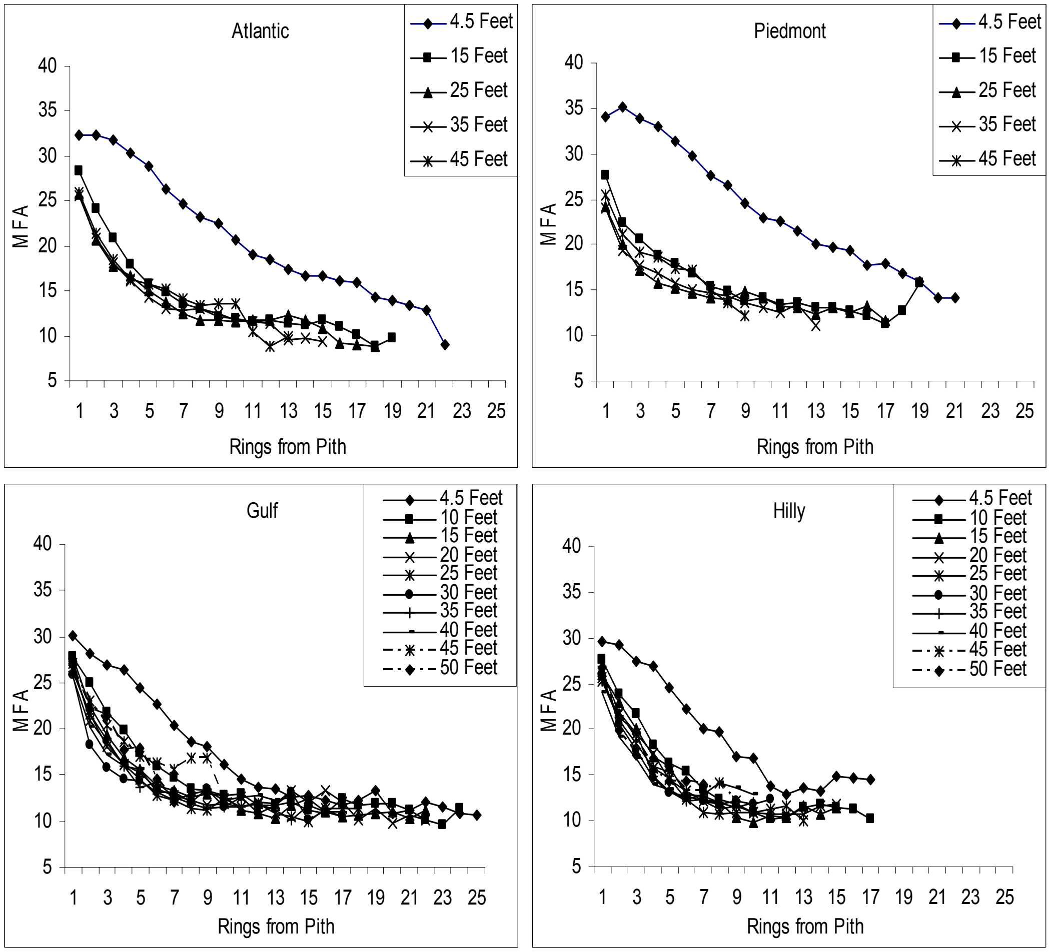

Figure 5.9. Average microfibril angle versus rings from pith at different height levels for the Atlantic, Piedmont, Gulf Coastal, and Hilly Coastal regions.

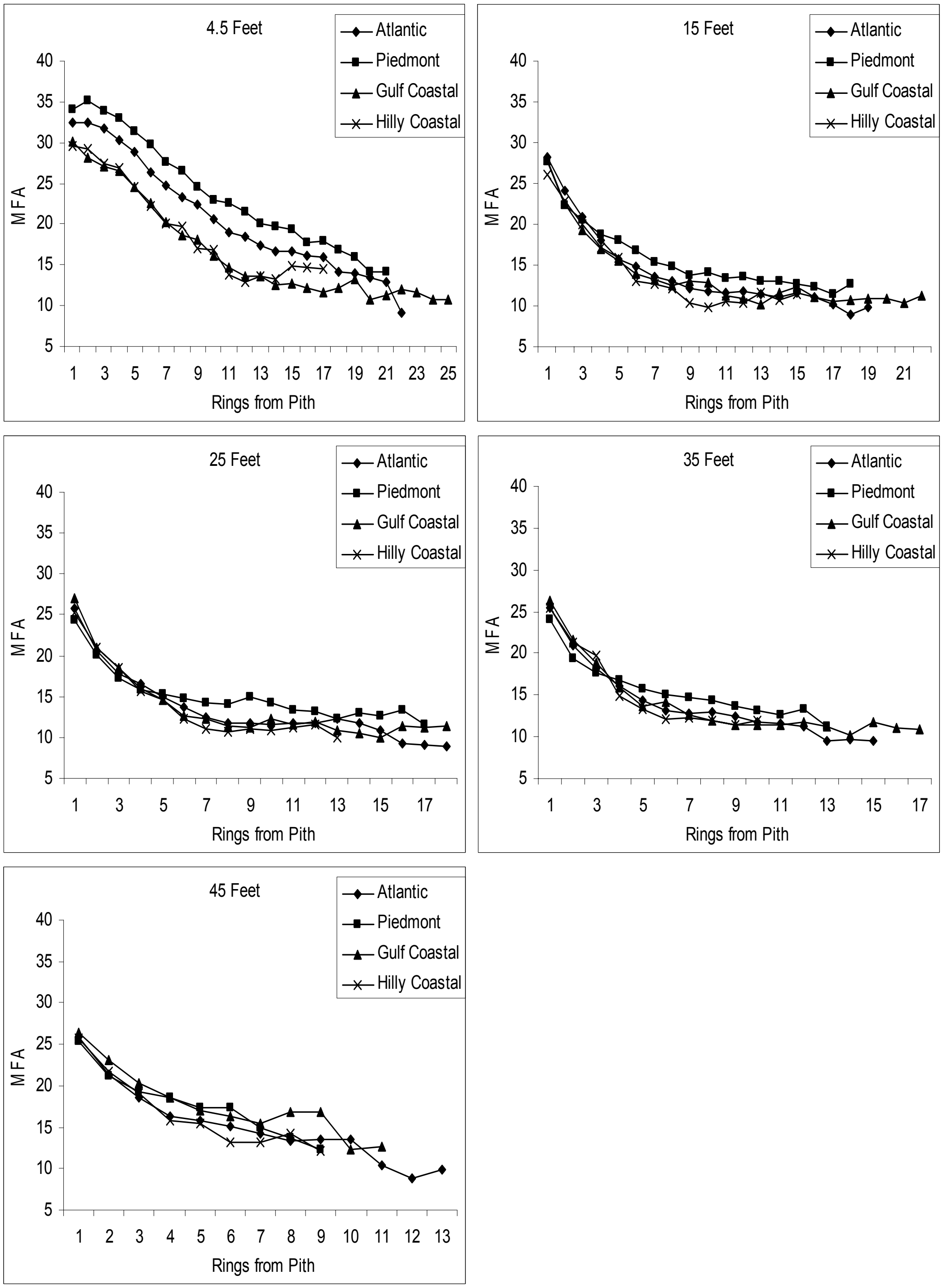

Figure 5.10. Average microfibril angle versus rings from pith by physiographic region and height level.

Table 5.3. Mean, minimum, and maximum whole ring MFA values by physiographic region and height level.

DISK HEIGHT	REGION	MEAN MFA	MINIMUM MFA	MAXIMUM MFA
4.5	Atlantic	22.8	8.4	47.0
4.5	Piedmont	24.9	10.0	50.7
4.5	Gulf	18.8	9.5	38.3
4.5	Hilly	19.8	10.0	33.7
15	Atlantic	15.2	7.9	37.2
15	Piedmont	16.3	8.7	31.0
15	Gulf	15.1	9.1	34.1
15	Hilly	14.5	8.2	29.9
25	Atlantic	14.8	8.1	31.9
25	Piedmont	15.7	9.4	29.1
25	Gulf	15.1	8.4	34.0
25	Hilly	14.6	9.1	30.5
35	Atlantic	15.5	7.8	28.5
35	Piedmont	16.5	9.3	30.5
35	Gulf	15.3	9.8	29.0
35	Hilly	15.8	8.5	30.7
45	Atlantic	17.1	8.7	31.7
45	Piedmont	19.1	11.5	32.1
45	Gulf	18.4	12.3	28.8
45	Hilly	17.2	10.4	28.6

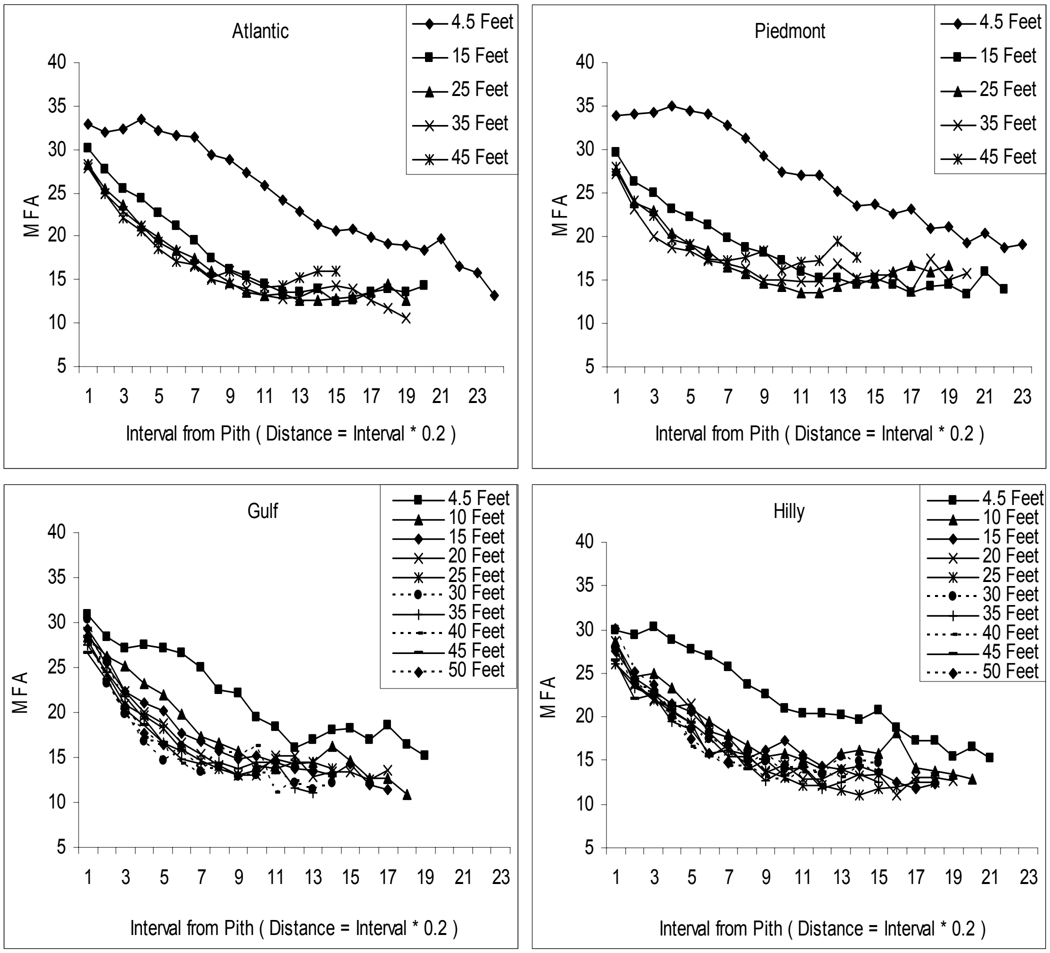

Figure 5.11. Average microfibril angle versus distance from pith at 0.20 inch intervals at different height levels for the Atlantic, Piedmont, Gulf Coastal, and Hilly Coastal regions.

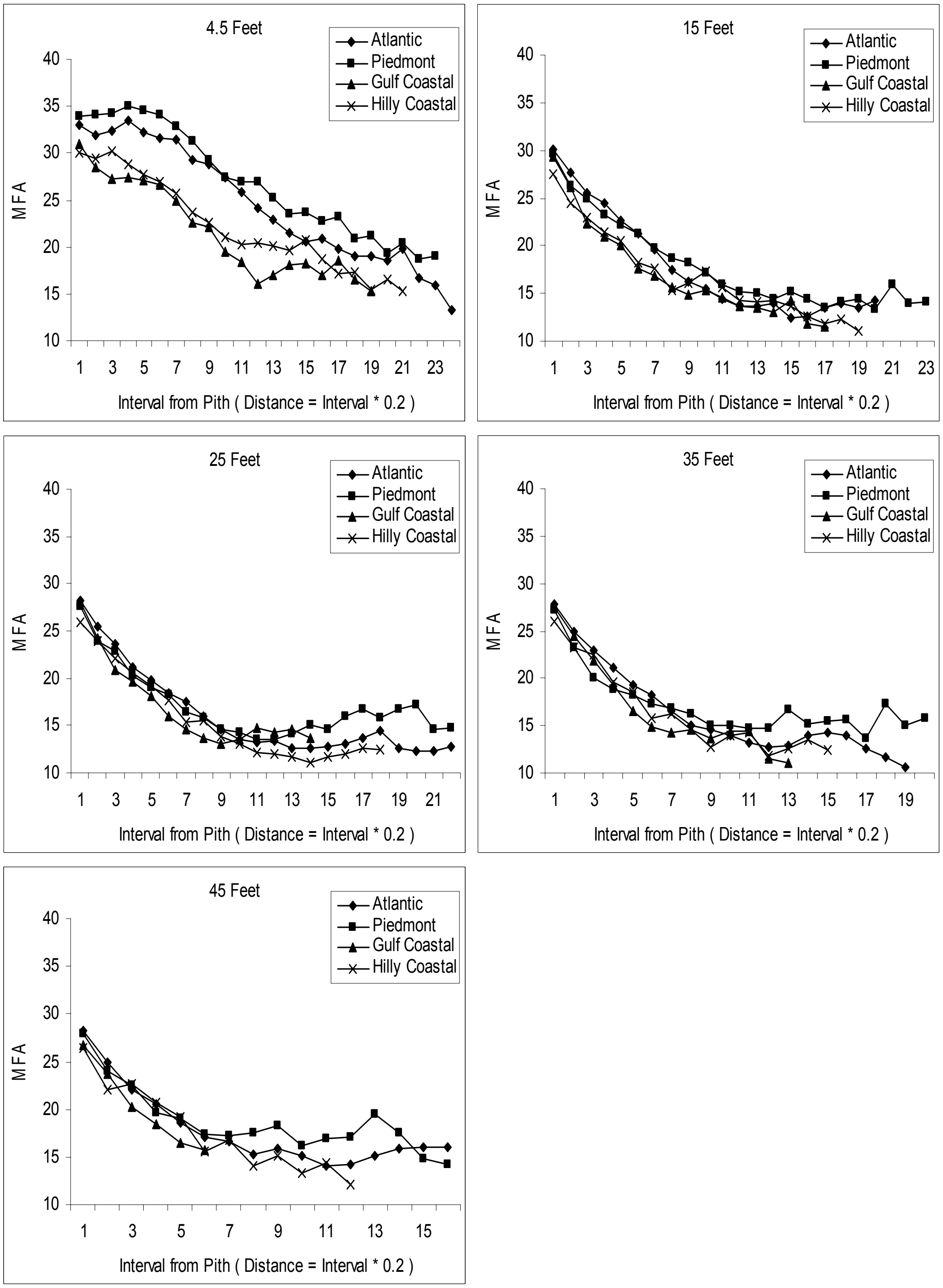

Figure 5.12. Average microfibril angle versus distance from pith at 0.20 inch intervals by physiographic region and height level.

Table 5.4. Mean, minimum, and maximum MFA values at 0.20 inch intervals by physiographic region and height level.

DISK HEIGHT	REGION	MEAN MFA	MINIMUM MFA	MAXIMUM MFA
4.5	Atlantic	26.5	8.6	47.9
4.5	Piedmont	27.6	10.6	54.7
4.5	Gulf	22.7	10.7	40.0
4.5	Hilly	23.6	10.0	35.5
15	Atlantic	18.6	8.2	41.5
15	Piedmont	18.8	9.3	34.8
15	Gulf	18.1	9.4	32.3
15	Hilly	17.9	8.3	32.0
25	Atlantic	17.5	7.6	42.5
25	Piedmont	17.5	9.6	34.6
25	Gulf	17.8	9.6	32.9
25	Hilly	17.0	9.2	32.6
35	Atlantic	17.8	8.4	31.2
35	Piedmont	18.0	9.9	32.8
35	Gulf	17.8	10.1	28.9
35	Hilly	17.5	10.2	31.6
45	Atlantic	18.9	8.5	35.0
45	Piedmont	20.1	11.6	37.0
45	Gulf	20.2	13.9	28.9
45	Hilly	18.2	10.8	32.3

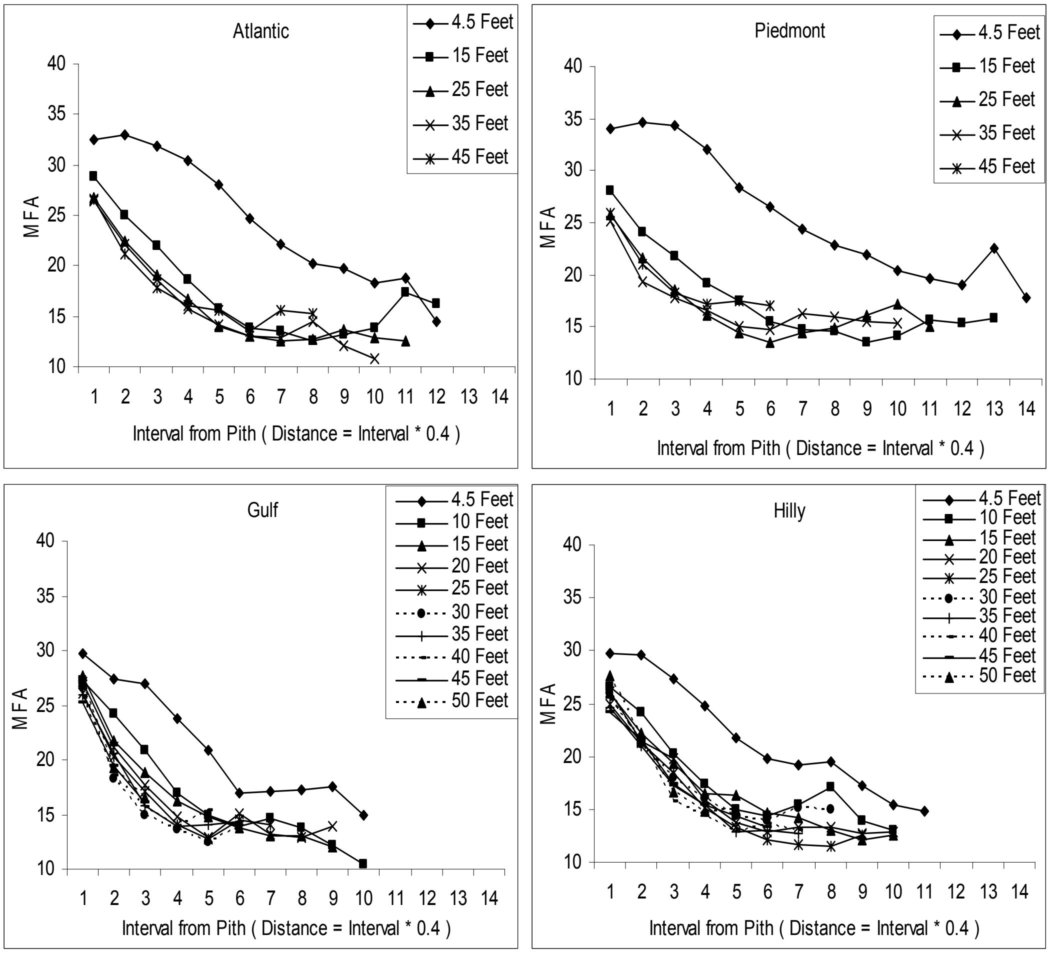

Figure 5.13. Average microfibril angle versus distance from pith at 0.40 inch intervals at different height levels for the Atlantic, Piedmont, Gulf Coastal and Hilly Coastal regions.

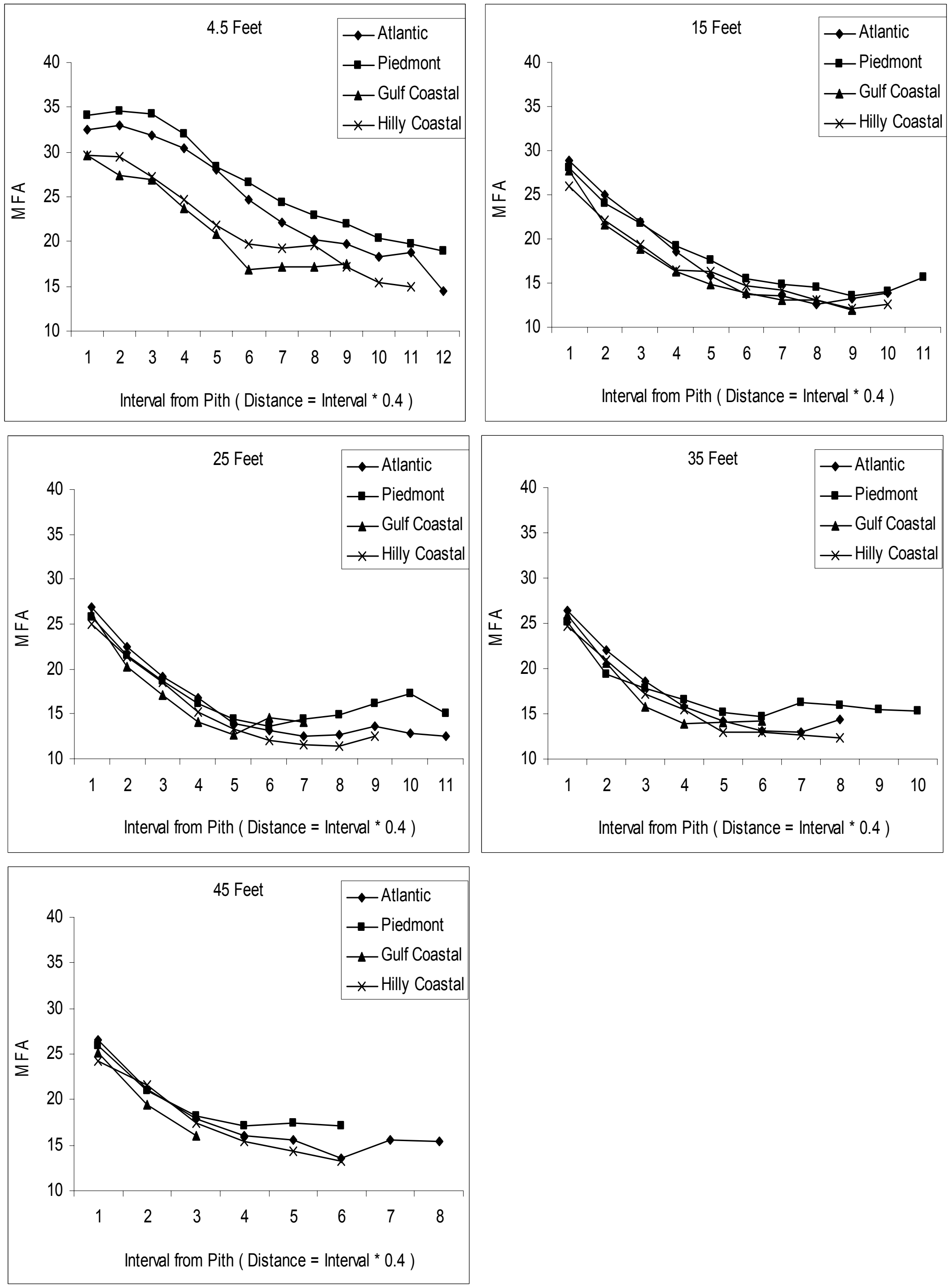

Figure 5.14. Average microfibril angle versus distance from pith at 0.40 inch intervals by physiographic region and height level.

Table 5.5. Mean, minimum, and maximum MFA values at 0.40 inch intervals by physiographic region and height level.

DISK HEIGHT	REGION	MEAN MFA	MINIMUM MFA	MAXIMUM MFA
4.5	Atlantic	26.1	8.7	47.8
4.5	Piedmont	27.3	11.2	51.8
4.5	Gulf	22.4	10.9	35.3
4.5	Hilly	23.6	11.2	34.5
15	Atlantic	18.4	8.3	37.9
15	Piedmont	18.7	9.7	33.4
15	Gulf	17.9	9.4	30.8
15	Hilly	17.5	8.3	29.3
25	Atlantic	17.3	8.4	37.4
25	Piedmont	17.4	9.9	30.4
25	Gulf	17.6	9.8	28.3
25	Hilly	16.8	9.2	31.0
35	Atlantic	17.7	8.5	28.6
35	Piedmont	17.9	10.3	32.4
35	Gulf	17.7	10.3	27.2
35	Hilly	17.5	10.4	28.8
45	Atlantic	18.7	8.9	32.1
45	Piedmont	19.9	11.9	32.7
45	Gulf	20.2	13.9	26.4
45	Hilly	18.1	10.8	29.1

Table 5.6. Parameter estimates and fit statistics for the linear whole ring MFA model (1).

Parameter	Estimate	Std. Error	P-Value
β_0	16.98542	0.3703	<0.0001
$\beta_0 I_H$	1.00130	0.4116	0.0150
$\beta_0 I_P$	-4.55486	0.7368	<0.0001
β_1	-7.90223	0.2522	<0.0001
$\beta_1 I_G$	-1.12871	0.3953	0.0043
$\beta_1 I_P$	-1.06440	0.4689	0.02330
β_2	-0.56274	0.0263	<0.0001
$\beta_2 I_H$	0.53181	0.0333	<0.0001
$\beta_2 I_G$	0.81825	0.0467	<0.0001
$\beta_2 I_P$	0.69609	0.0514	<0.0001
β_3	0.50459	0.0854	<0.0001
$\beta_3 I_G$	0.50449	0.1090	<0.0001
$\beta_3 I_P$	0.70330	0.1684	<0.0001
β_4	31.04751	0.8841	<0.0001
$\beta_4 I_H$	-19.0748	1.0540	<0.0001
$\beta_4 I_G$	-24.9087	1.3280	<0.0001
$\beta_4 I_P$	-16.8601	1.4138	<0.0001

Fit index: 0.7533

Mean Square Error: 11.3465

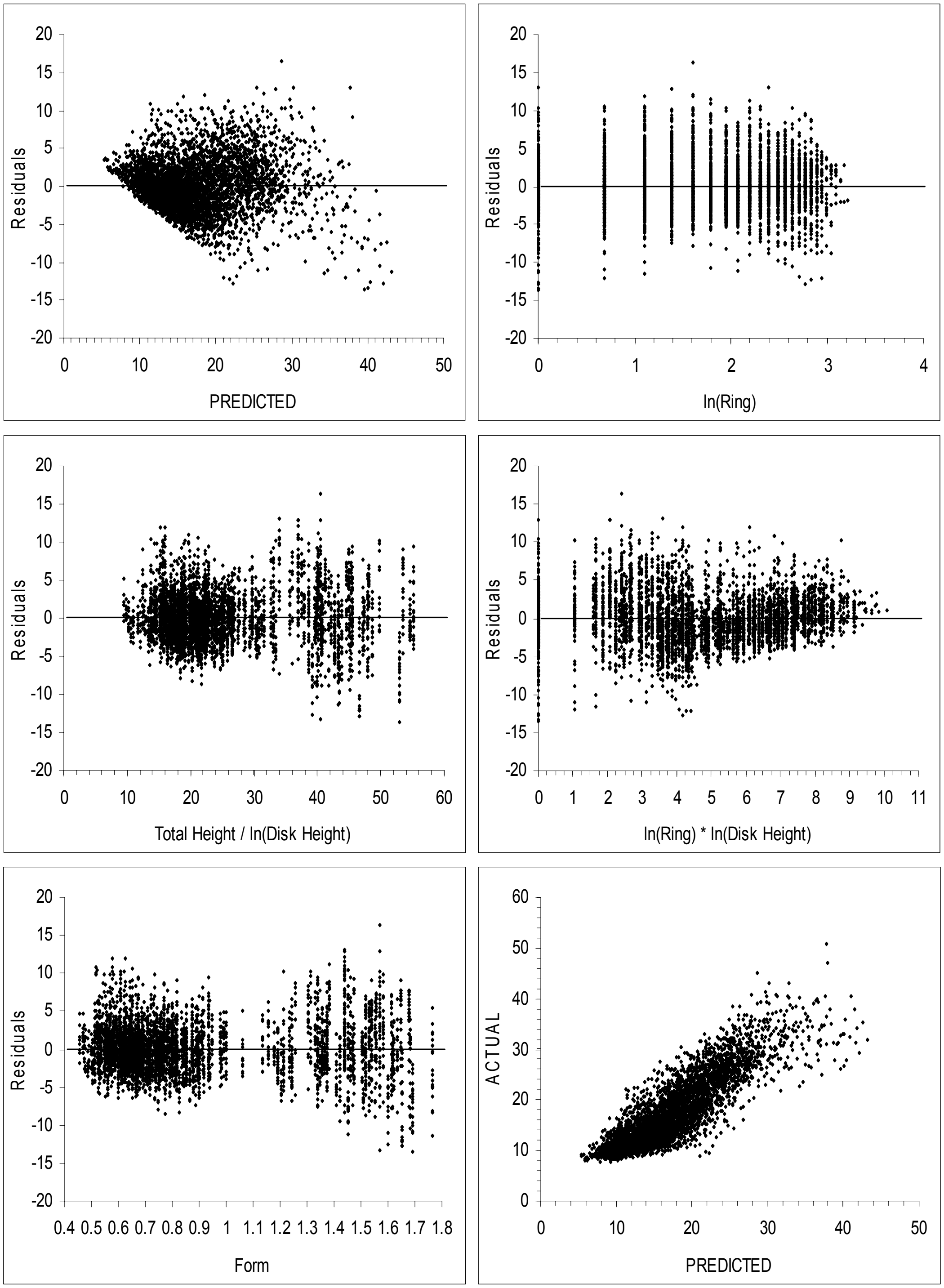

Figure 5.15. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the linear whole ring MFA model (1).

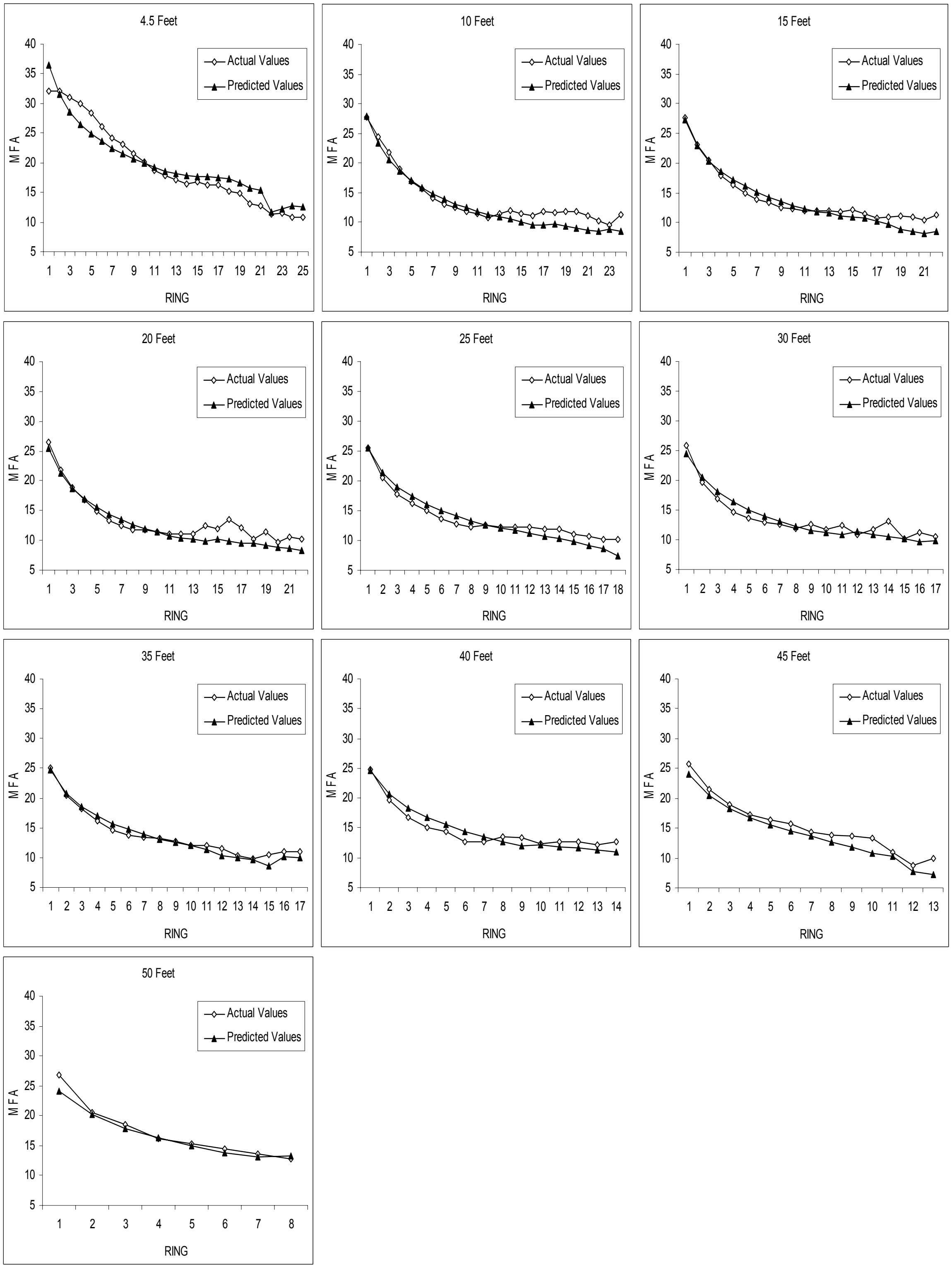

Figure 5.16. Plot of mean actual values versus mean predicted values for the linear whole ring MFA model (1) by disk height.

Table 5.7. Parameter estimates and fit statistics for the nonlinear whole ring model (2).

Parameter	Estimate	Std. Error	P-Value
β_0	18.16769	0.5190	<0.0001
$\beta_0 I_G$	2.78029	0.7353	0.0002
$\beta_0 I_P$	-3.58567	0.9308	0.0001
β_1	13.40483	0.5980	<0.0001
$\beta_1 I_H$	-0.99328	0.4862	0.0411
$\beta_1 I_G$	-3.49886	1.0763	0.0012
$\beta_1 I_P$	2.81024	0.9967	0.0048
β_2	-0.41598	0.0107	<0.0001
$\beta_2 I_P$	0.07719	0.0199	<0.0001
β_3	0.62724	0.0247	<0.0001
$\beta_3 I_H$	-0.52893	0.0303	<0.0001
$\beta_3 I_G$	-0.64856	0.0445	<0.0001
$\beta_3 I_P$	-0.52823	0.0378	<0.0001
β_4	-0.01718	0.0007	<0.0001
$\beta_4 I_H$	0.01612	0.0010	<0.0001
$\beta_4 I_G$	0.02104	0.0015	<0.0001
$\beta_4 I_P$	0.01599	0.0013	<0.0001

Fit index: 0.7398

Mean Square Error: 11.9673

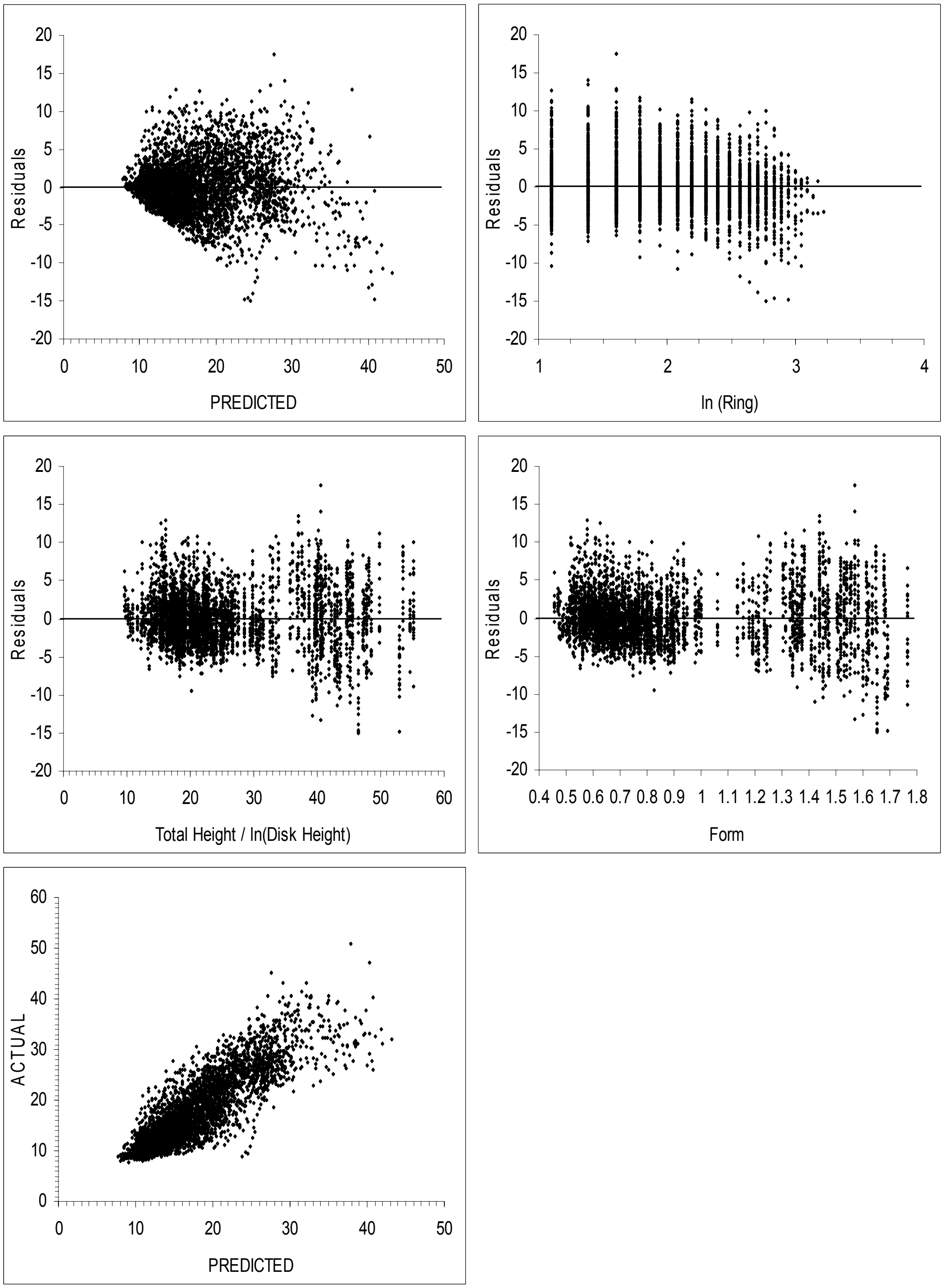

Figure 5.17. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the nonlinear whole ring MFA model (2).

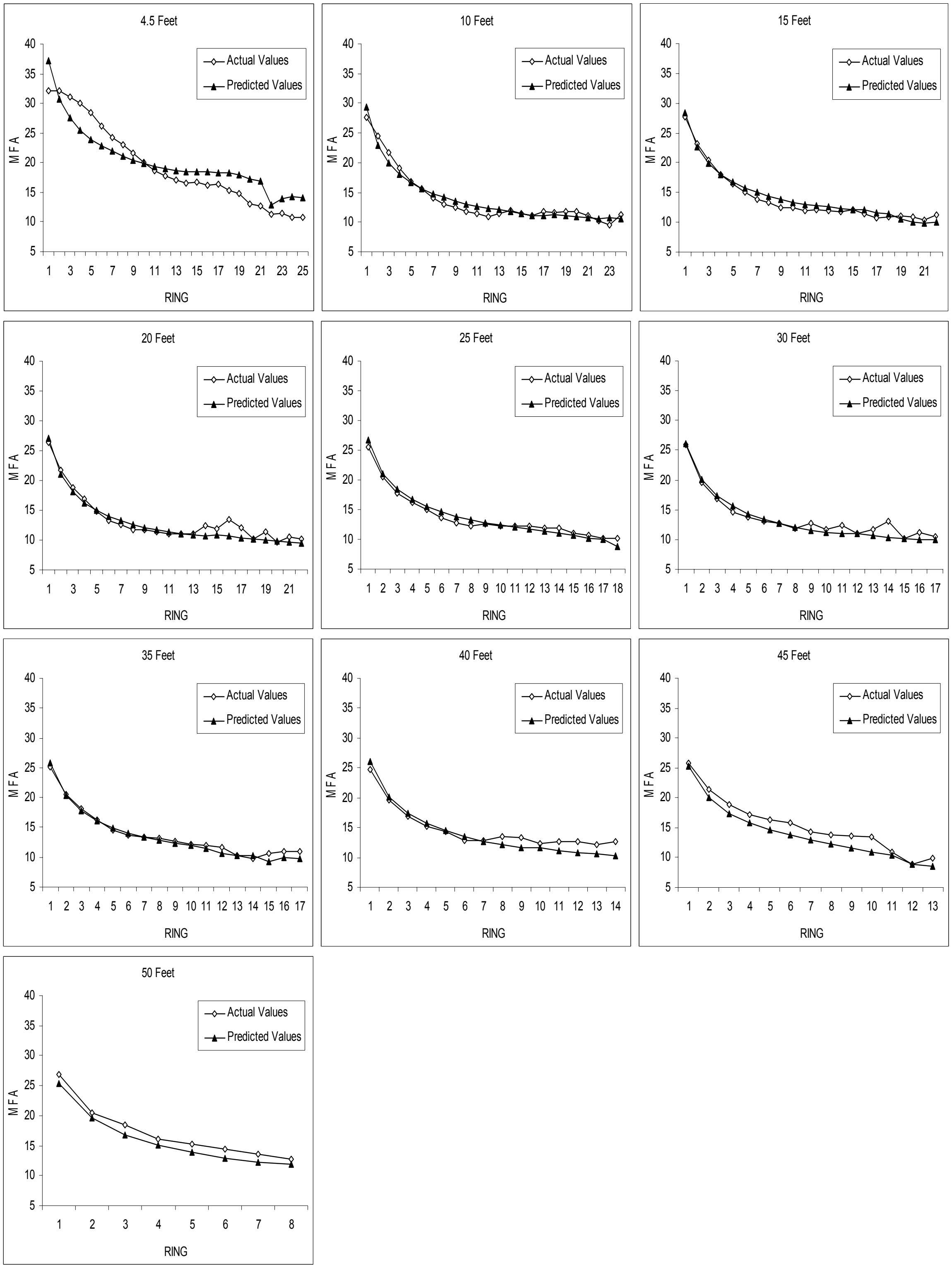

Figure 5.18. Plot of mean actual values versus mean predicted values for the nonlinear whole ring MFA model (2) by disk height.

Table 5.8. Parameter estimates and fit statistics for the linear 0.20 inch interval model (3).

Parameter	Estimate	Std. Error	P-Value
β_0	22.0776	0.2400	<0.0001
$\beta_0 I_P$	-2.5681	0.4432	<0.0001
β_1	-6.5526	0.0891	<0.0001
$\beta_1 I_P$	0.8861	0.1657	<0.0001
β_2	-4.7930	0.4773	<0.0001
$\beta_2 I_G$	5.1941	1.1155	<0.0001
$\beta_2 I_P$	4.6403	0.9330	<0.0001
β_3	20.9938	0.9042	<0.0001
$\beta_3 I_H$	-1.5589	0.1849	<0.0001
$\beta_3 I_G$	-11.7456	2.1924	<0.0001
$\beta_3 I_P$	-7.6780	1.6573	<0.0001

Fit index: 0.6740

Mean Square Error: 16.6331

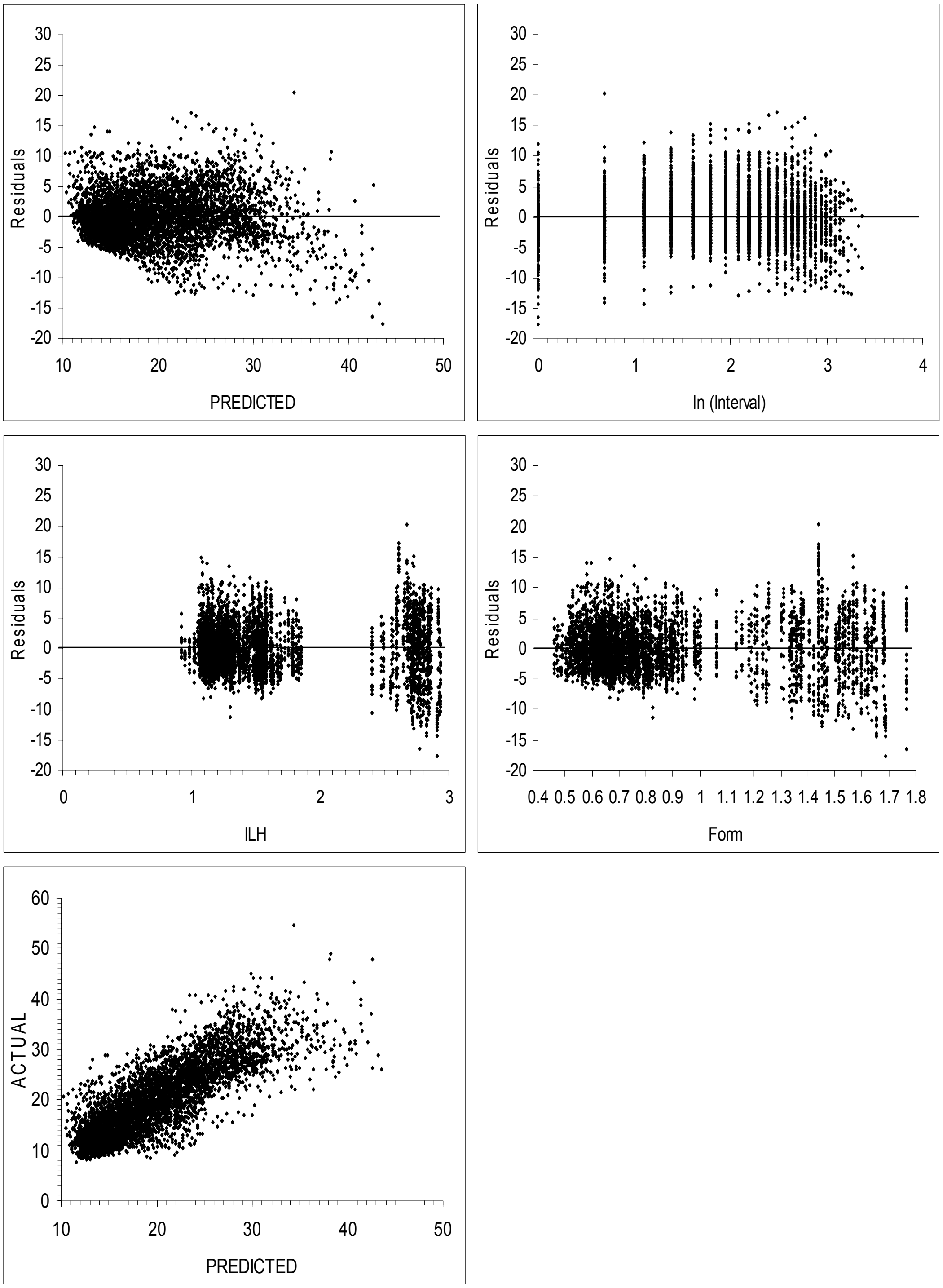

Figure 5.19. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the linear 0.20 inch interval model (3).

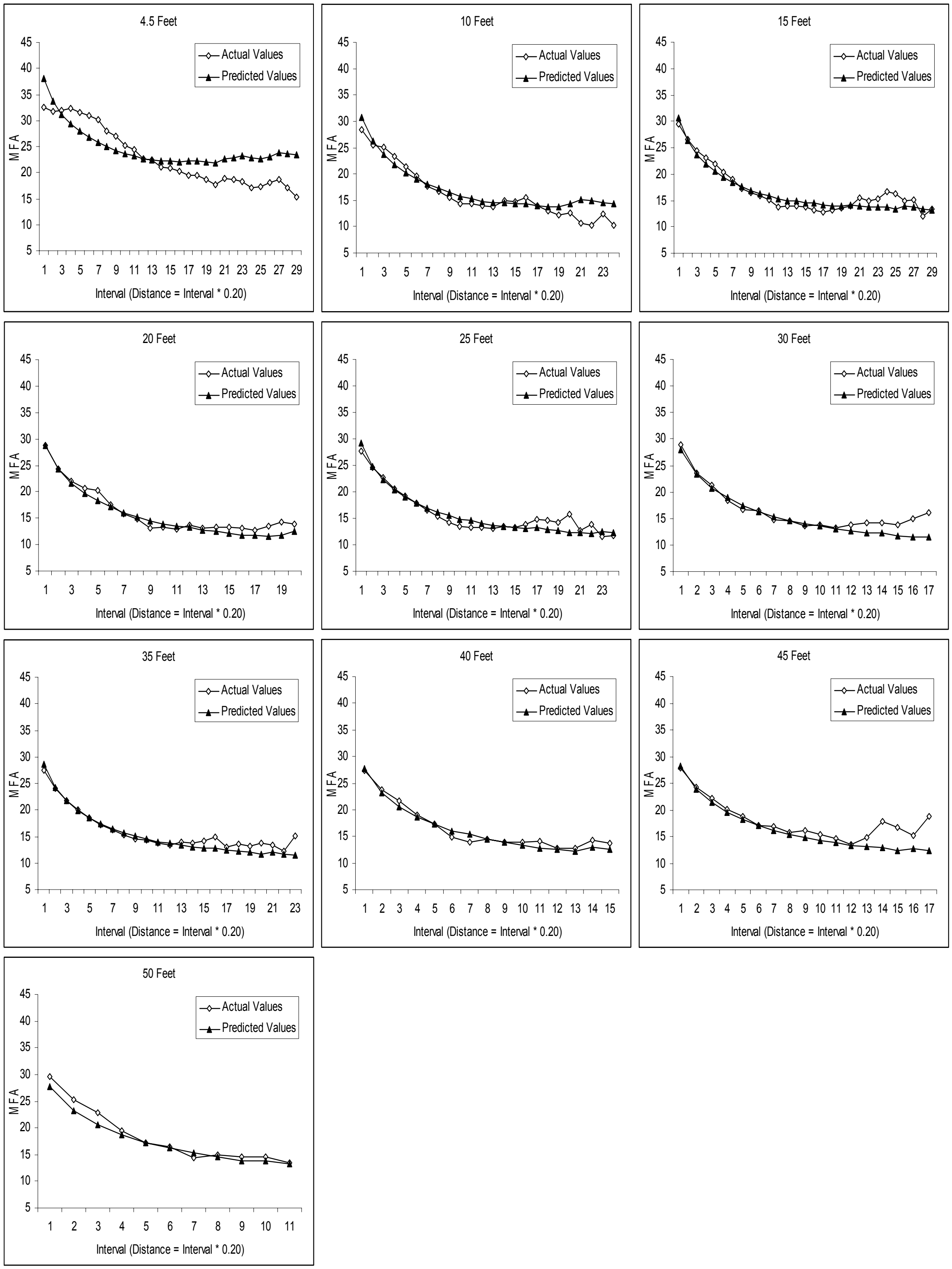

Figure 5.20. Plot of mean actual values versus mean predicted values for the linear 0.20 inch interval model (3).

Table 5.9. Parameter estimates and fit statistics for the nonlinear 0.20 inch interval model (4).

Parameter	Estimate	Std. Error	P-Value
β_0	-4.6489	0.2233	<0.0001
$\beta_0 I_H$	1.8324	0.4075	<0.0001
$\beta_0 I_G$	5.5889	1.6300	0.0006
β_1	9.7365	0.2915	<0.0001
$\beta_1 I_P$	3.2016	0.6283	<0.0001
β_2	0.2598	0.0219	<0.0001
$\beta_2 I_G$	-0.1732	0.0643	0.0070
$\beta_2 I_P$	-0.1965	0.0484	<0.0001
β_3	25.2108	0.5774	<0.0001
$\beta_3 I_H$	-3.6322	0.7926	<0.0001
$\beta_3 I_G$	-3.6471	0.8844	<0.0001
$\beta_3 I_P$	-2.9476	0.6038	<0.0001
β_4	-0.0886	0.0047	<0.0001
$\beta_4 I_H$	-0.0518	0.0108	<0.0001
$\beta_4 I_G$	-0.0853	0.0176	<0.0001
$\beta_4 I_P$	0.0114	0.0055	0.0374

Fit index: 0.6849

Mean Square Error: 16.0944

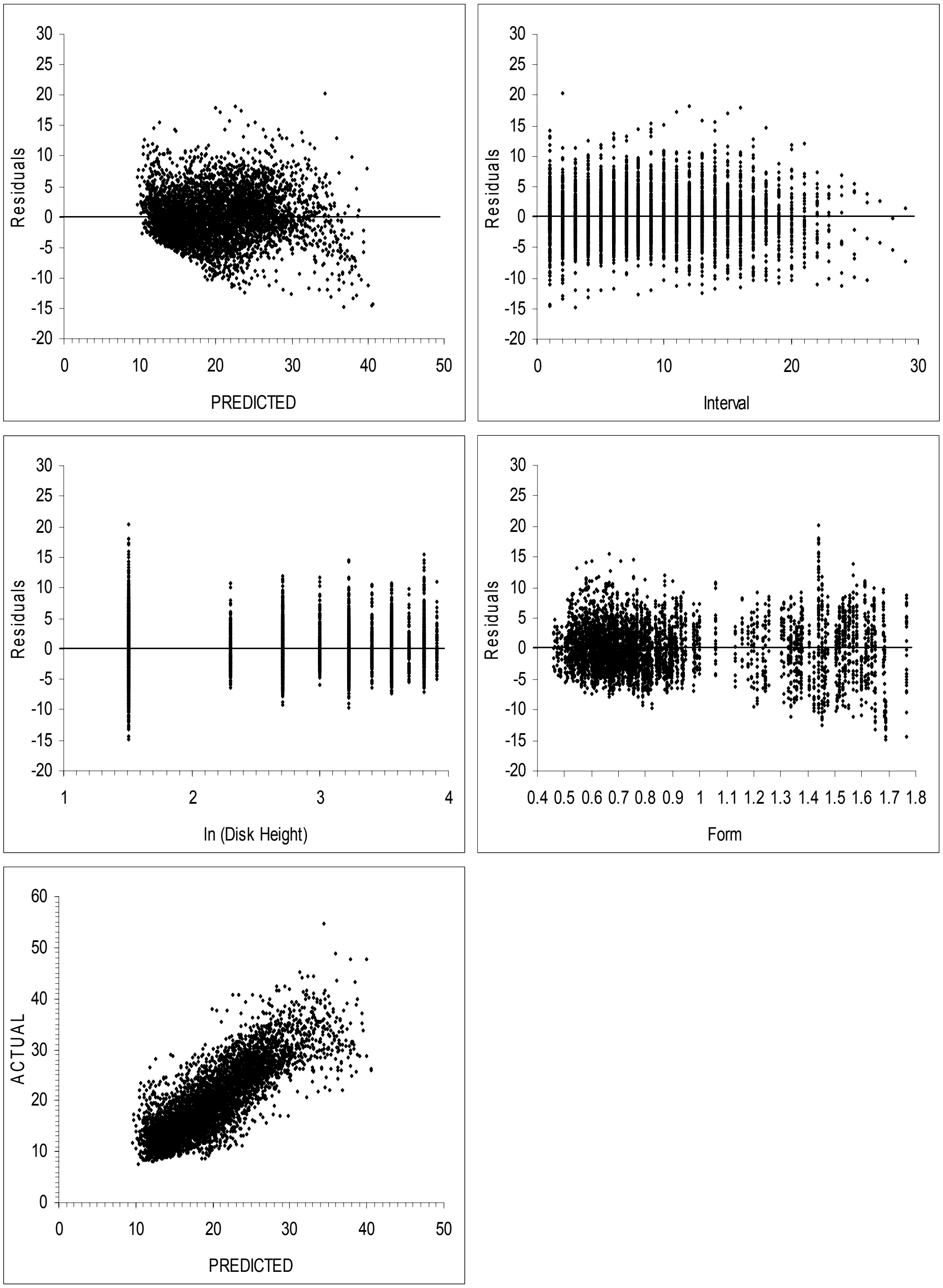

Figure 5.21. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the nonlinear 0.20 inch interval model (4).

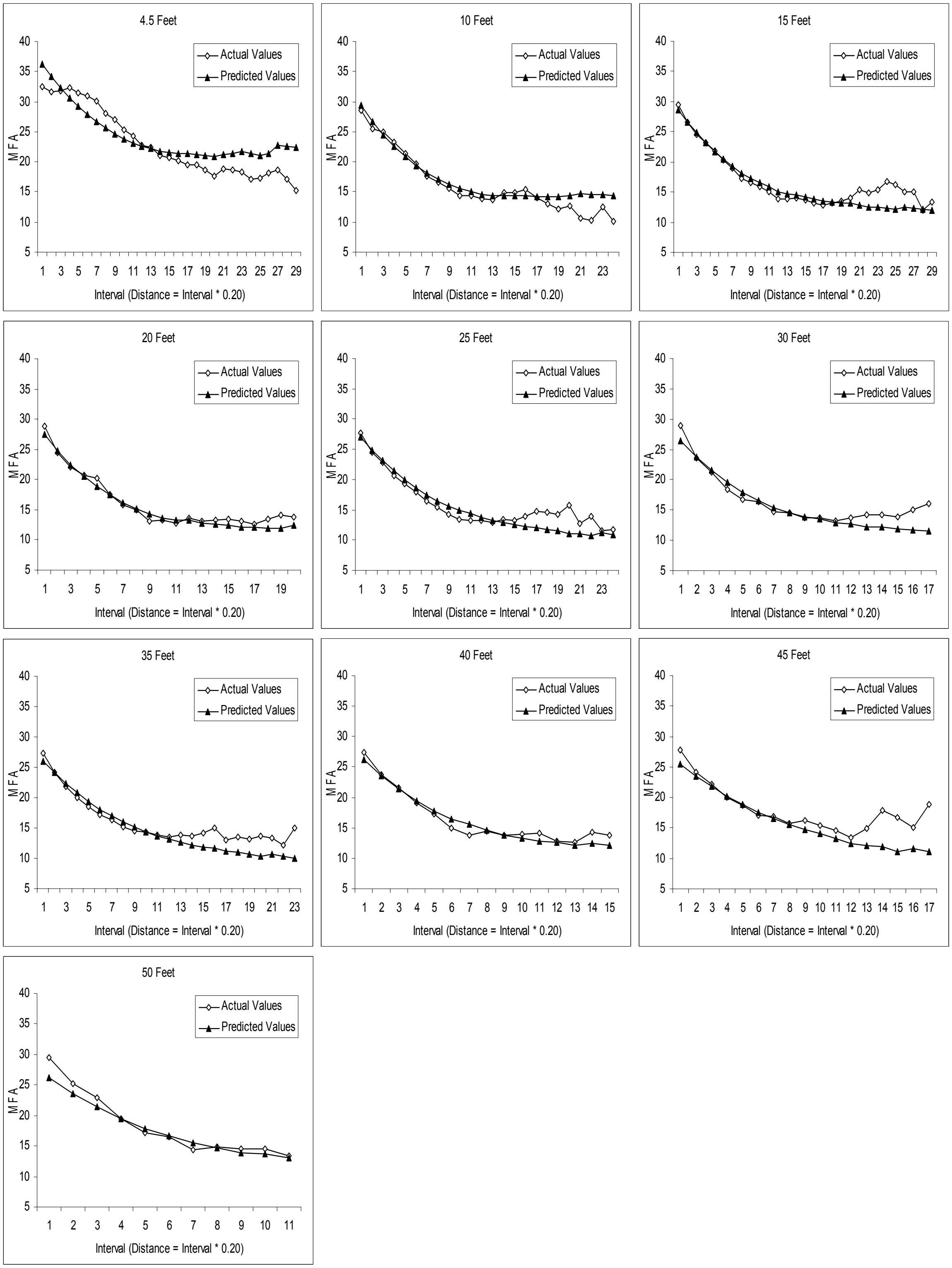

Figure 5.22. Plot of mean actual values versus mean predicted values for the nonlinear 0.20 inch interval model (4).

Table 5.10. Parameter estimates and fit statistics for the linear 0.40 inch interval model (5).

Parameter	Estimate	Std. Error	P-Value
β_0	19.6463	0.2941	<0.0001
$\beta_0 I_P$	-2.2669	0.5401	<0.0001
β_1	-7.6313	0.1352	<0.0001
$\beta_1 I_P$	1.0925	0.2505	<0.0001
β_2	-5.2866	0.6290	<0.0001
$\beta_2 I_G$	5.1811	1.4635	0.0004
$\beta_2 I_P$	4.4971	1.2275	0.0003
β_3	21.8924	1.1925	<0.0001
$\beta_3 I_H$	-1.53785	0.2437	<0.0001
$\beta_3 I_G$	-11.7453	2.8777	<0.0001
$\beta_3 I_P$	-7.5053	2.1823	0.0006

Fit index: 0.6992

Mean Square Error: 14.8335

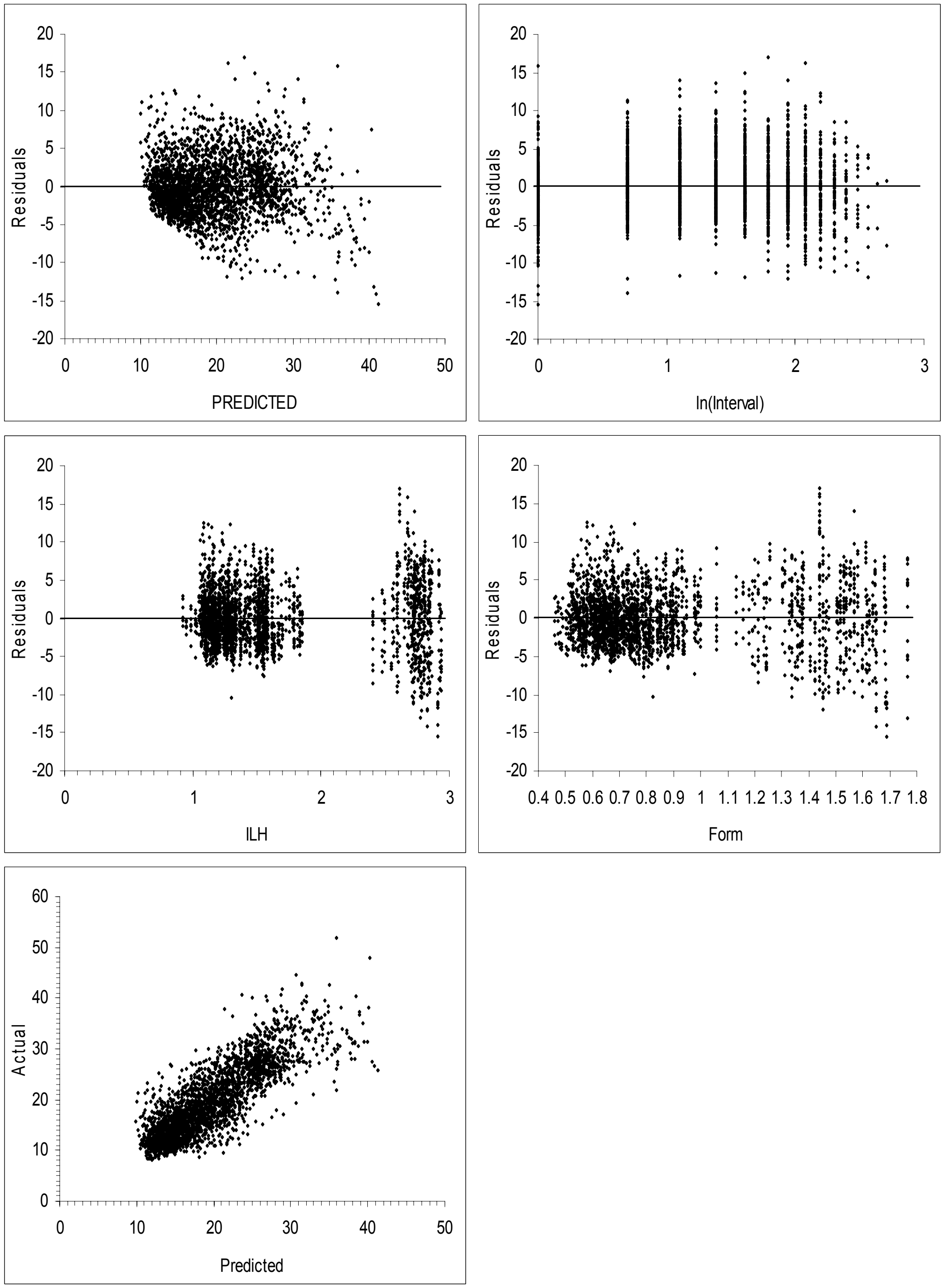

Figure 5.23. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the linear 0.40 inch interval model (5).

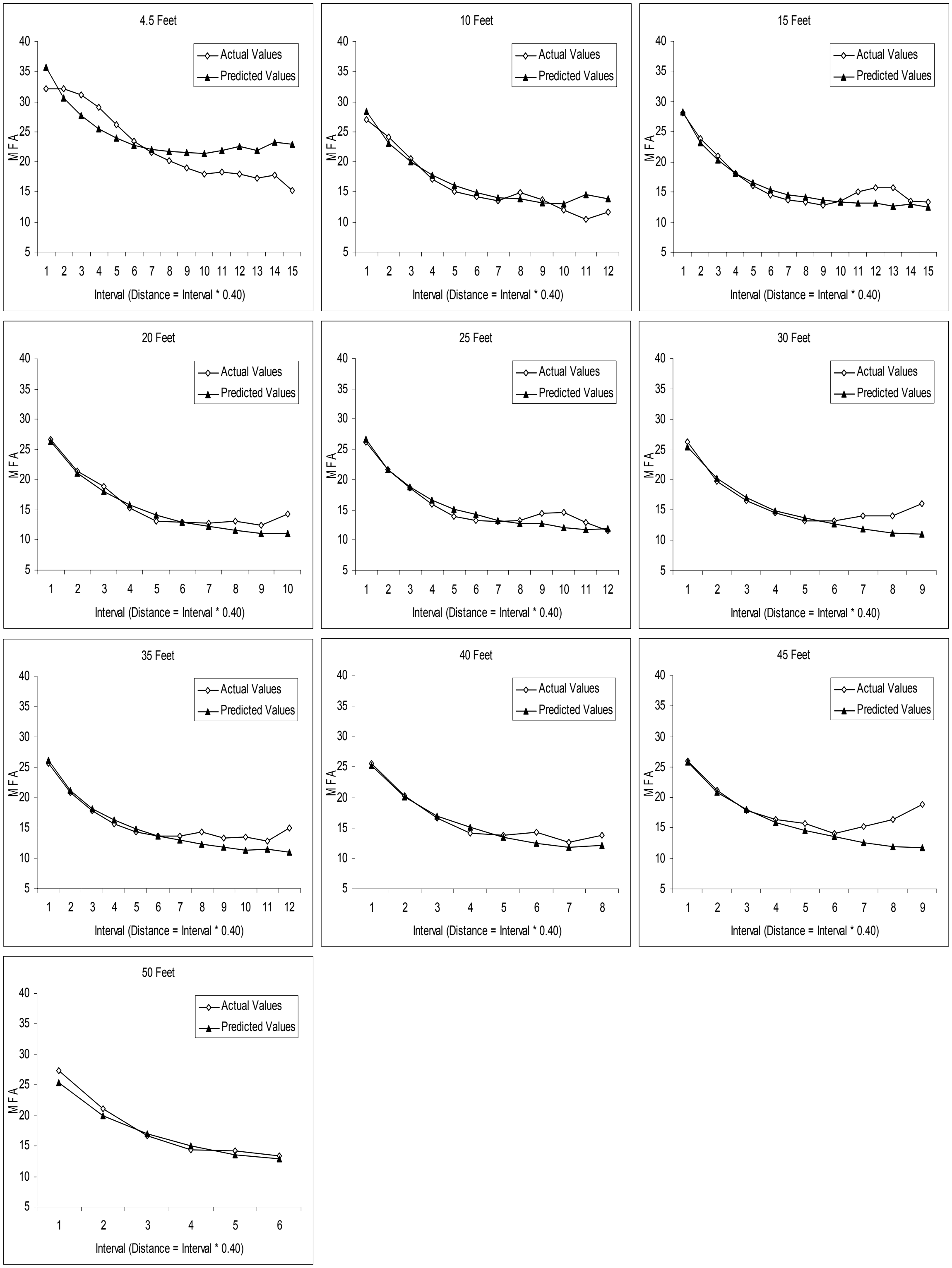

Figure 5.24. Plot of mean actual values versus mean predicted values for the linear 0.40 inch interval model (5).

Table 5.11. Parameter estimates and fit statistics for the nonlinear 0.40 inch interval model (6).

Parameter	Estimate	Std. Error	P-Value
β_0	6.6496	0.4026	<0.0001
$\beta_0 I_P$	1.5543	0.3606	<0.0001
β_1	0.2298	0.0190	<0.0001
$\beta_1 I_P$	-0.0417	0.0159	0.0088
β_2	24.7956	0.4317	<0.0001
$\beta_2 I_H$	-2.1701	0.4709	<0.0001
$\beta_2 I_P$	-3.0727	0.7721	<0.0001
β_3	-0.4333	0.0215	<0.0001
$\beta_3 I_G$	-0.0328	0.0086	0.0001
β_4	0.18741	0.0143	<0.0001

Fit index: 0.7106

Mean Square Error: 14.2640

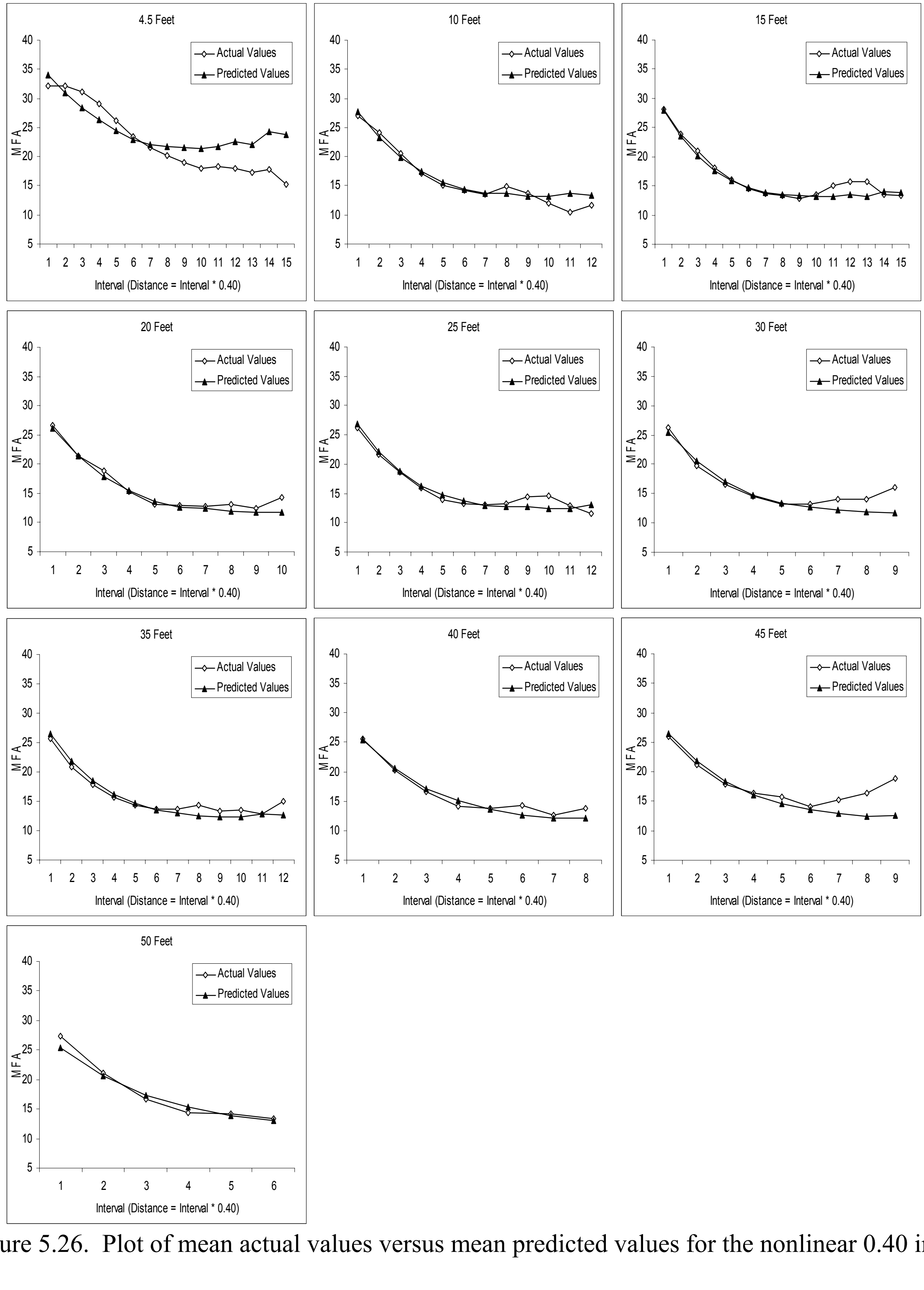

Figure 5.26. Plot of mean actual values versus mean predicted values for the nonlinear 0.40 inch interval model (6).

CHAPTER 6

MODELS FOR PREDICTING AVERAGE CROSS-SECTIONAL MICROFIBRIL ANGLE OF PLANTED LOBLOLLY PINE IN THE SOUTHEASTERN UNITED STATES

ABSTRACT

Microfibril angle (MFA) was determined using x-ray diffraction at 0.04 inch intervals from sixty loblolly pine (*Pinus taeda* L.) trees representing four physiographic regions in the Southeastern United States. Linear and nonlinear prediction equations were developed to model the average cross-sectional MFA value at any age, distance from pith, and height. The relationship of physiographic region, total tree height, disk height, diameter breast height, and average cross-sectional MFA values were examined. All equations developed were found to account for at least 70 percent of the variation in average cross-sectional MFA.

Keywords: microfibril angle, loblolly pine, modeling

INTRODUCTION

Microfibril angle (MFA) is known to be one of the main determinants of the mechanical properties of wood. MFA is defined by Lichtenegger *et al*. (1999) as the angle between the cellulose fibrils and the longitudinal cell axis. MFA is highly correlated with specific gravity, modulus of elasticity, modulus of rupture, and the longitudinal and tangential shrinkage of wood. MFA has a significant effect on both mechanical behavior and dimensional stability of wood, and as such is an important quality characteristic for sawn timber (MacDonald and Hubert 2002).

In addition, MFA is correlated with stretch, stiffness, and strength properties of paper (Watson and Dadswell 1964; Kellogg *et al.* 1975; Megraw 1985). Because of these relationships, MFA has become an important indicator of wood quality to the forest products industry.

Microfibrils are polysaccharide chains with a cellulose core within a hardened shell. In the primary cell wall, microfibrils are randomly interspersed (Megraw 1985). The secondary cell wall is comprised of three distinct layers: the S_1, S_2, and S_3 walls (Figure 6.1). The S_1 layer contains alternating flat sheets of microfibrils with an orientation of 50^o to 70^o to the fiber axis. In the S_2 layer microfibrils are highly parallel and steeply aligned to the fiber axis. In the S_3 layer they again occur in a very flat orientation, with angles 60^o to 90^o degrees to the cell axis. Because the S_2 layer is many times thicker than the other layers, its properties normally dominate, and the term microfibril angle generally refers to the microfibril angle in the S_2 layer.

MFA in loblolly pine is large near the pith and decreases rapidly out to 10 or more rings from the pith, then continues dropping, but at a much slower rate until such time as it essentially stabilize. The decrease in MFA with age takes place at a slower rate near the base of the tree than it does at upper heights. This results in higher MFA's for a given number of rings from the pith at the butt and breast height regions than at several feet in height and above (Megraw 1985).

MFA varies considerably within juvenile and mature zones of tree wood, thus affecting the mechanical properties of the wood. MFA is characteristically greater in juvenile wood than mature wood. The large MFA causes a high degree of longitudinal shrinkage and a corresponding reduction in tangential shrinkage. Longitudinal shrinkage of juvenile wood has been reported to average up to three times that of mature wood (McAlister and Clark 1992). Pillow *et al.* (1953) found that MFA in the juvenile wood of open-grown loblolly pines averaged 20^o larger than that in a closely spaced natural stand.

In mature loblolly pine, MFA is small, averaging about 5^o to 10^o as measured by deviation from the vertical. In juvenile wood, the MFA is large, averaging 25^o to 35^o and often up to 50^o in rings next to the pith, then decreasing outward in the juvenile core (Larson et al. 2001). MFA has been found to decrease from 33^o at age 1 to 23^o at age 10, and to 17^o at age 22, in fast-grown loblolly pines (Ying et al. 1994). Bendtsen and Senft (1986) found that MFA within loblolly pine had stabilized at age 30.

The objective of this research was to develop models for predicting average cross-sectional MFA (ACMFA) at any age, distance from pith, and height. These models will allow measures of wood properties and quality to be added to current forest yield prediction systems. These models will also provide the basis for comparing properties from tree to tree, within a stand, and among stands in different regions in the Southeastern U.S.

METHODS AND MATERIALS

Sixty loblolly pine trees from twenty stands, 20-27 years old, were sampled across the Southeastern United States for MFA analysis. Plantations were sampled in the Atlantic Coastal Plain, Piedmont, Gulf Coastal Plain, and Hilly Coastal Plain physiographic regions (Figure 6.2).

The stands were located on land owned by forest products companies, and included only stands with similar silvicultural history: 1) site preparation with no herbaceous weed control; 2) no fertilization at planting except phosphorus on phosphorus-deficient sites; 3) stand density of at least 250 trees per acre at the time of sampling. Trees larger than five inches in diameter were inventoried on 3 1/10-acre plots to determine stand density and diameter distribution. A sample of 3 trees was chosen for MFA analysis proportional to the diameter distribution of each stand to represent a range of tree sizes in the stand. Stand attributes are summarized in Table 6.1.

One-inch thick cross-sectional disks were cut at the stump, 4.5 feet, 10 feet, and then at 5-foot intervals to a 2-inch top for all trees. A sub-sample of disks was then selected from each tree for MFA analysis. For the Hilly Coastal and Gulf Coastal regions disk heights selected for MFA analysis were taken at 4.5 feet, 10 feet, and then at 5-foot intervals to a disk height of 50 feet. Cross sectional disks sub sampled for MFA analysis in the Piedmont and Atlantic Coastal regions were taken at 4.5 feet, 15 feet, and then at 10-foot intervals to a disk height of 45 feet. Radial strips 0.5 inches square were cut from each disk, dried, glued to core holders and sawn into two strips. One strip was used for x-ray densitometry for measurement of earlywood and latewood as well as radial growth and specific gravity at 0.0024 inch intervals. One strip was cut for MFA analysis from each disk, dried at 122^{o} Celsius, and shipped to Australia and analyzed by Silviscan® using x-ray diffraction at 0.04 inch intervals on the tangential surface.

Whole ring MFA was generated for all trees not analyzed on a ring basis by using ring width characteristics from the disk strip that was measured for specific gravity using x-ray densitometry. Given that the strips used were from the same tree disk, but opposite one another, it was assumed that one side could possibly be longer/smaller than the other due to sample preparation error or a non-perfect circular tree. Even though the strips may not be of the same length, the individual ring properties from both strips should be the same. To resolve this problem ring width was calculated as:

$$GSRING_i = RWSG_i \frac{LMFA}{LSG}$$

where,

$GSRING_i$ = Generated ring width of MFA strip

$RWSG_i$ = Ring width of *ith* specific gravity ring

$LMFA$ = Total length of MFA strip

LSG = Total length of specific gravity strip

For example, let *LMFA* = 4.17", *LSG* = 3.91", $RWSG_1$ = 0.45". Thus, $GPSRING_1$ = 0.480".

Whole disk cross-sectional MFA was calculated for every age, by weighting the ring MFA to the proportion of its basal area. This calculation was done for every tree at every height level. For example, at age 1, the cross-sectional MFA would simply be the MFA of ring 1. The cross-sectional MFA of a tree at age 5 would be found by weighting rings 1-5 with respect to the proportion of the basal area of the total that each ring made up.

Whole disk cross-sectional MFA was also calculated by distance from pith by weighting the MFA at any distance to the proportion of its basal area. This calculation was done for every tree at every height level. For example, the 2-inch cross-sectional MFA value was calculated by weighting the sum of all 0.040 inch interval measurements to a diameter inside bark of 2 inches with respect to the proportion of the basal area of the total.

MODEL DEVELOPMENT

The data were plotted by region and height level to identify patterns and changes of ACMFA by age. There is an apparent difference in patterns of ACMFA between 4.5 feet and the other height levels for all regions (Figures 6.5-6.8), whether weighted by age or distance from pith. The minimum and maximum values for ACMFA weighted by age at 4.5 feet was found to be 23.8^{o} and 37.4^{o} for the Atlantic, 24.1^{o} and 34.1^{o} for the Piedmont, 16.5^{o} and 30.1^{o} for the Gulf Coastal, 20.9^{o} and 29.65^{o} for the Hilly Coastal regions respectively. The minimum and maximum values for ACMFA weighted by distance from pith was found to be 15.0^{o} and 34.7^{o} for the Atlantic, 21.4^{o} and 34.0^{o} for the Piedmont, 20.4^{o} and 35.4^{o} for the Gulf Coastal, 20.1^{o} and 33.1^{o} for the Hilly Coastal regions respectively. Values of ACMFA weighted by distance and age were found to be lower at 10 and 15 feet (Figures 6.5 and 6.6) than at 4.5 feet, above which the effect of height on ACMFA appears to diminish. The change of ACMFA by height can be described by two different trends. At 4.5 feet, the change of ACMFA by ring or distance appears to be linear or sigmoid in shape. At 10 feet and above ACMFA appears to be decrease with ring or distance in a nonlinear fashion. Plots of ACMFA by rings and distance from pith and region are plotted by each height level (Figures 6.3, 6.4, 6.7, and 6.8). ACMFA values were found to be larger in the Atlantic and Piedmont regions at heights of 4.5 and 15 feet. Above 15 feet, the differences of ACMFA by region appear to be negligible.

MODEL DEVELOPMENT: AVERAGE CROSS-SECTIONAL MFA WEIGHTED BY AGE

Several candidate model forms were selected to describe the change of ACMFA by age and height. A linear model was considered first to explain how ACMFA changes in 3-dimensional space. The independent variables used in the linear model were selected based upon the linear correlation they exhibited with ACMFA. The variables chosen to be included in the model were the natural log of age, ILH, and form with correlation coefficients of -0.43017, 0.60166, and 0.62037 respectively. The linear model thus has the form:

$$\begin{aligned} MFA_{ij} = {} & (\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + \\ & (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P)\ln(Age_i) + \\ & (\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P)\, ILH + \\ & (\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P)\, Form \end{aligned} \qquad (1)$$

where, the base model represents the Atlantic Coastal region and I_H, I_G, and I_P, represent deviations from the base parameters for the Hilly Coastal, Gulf Coastal and Piedmont regions respectively, and

MFA_{ij} = ACMFA at *Age i* and *Disk Height j*,

Age = Age of interest,

$$ILH = \frac{\ln(Total\ \ Height)\ \ (ft.)}{\ln(Disk\ \ Height)\ \ (ft.)},$$

$$Form = \frac{\ln(DBH)}{\ln(Disk\ \ Height)\ \ (ft.)},$$

Disk Height = Height above Ground (ft.),

DBH = Diameter Breast Height (in.),

$I_H =$ 1 if Hilly Coastal Region
0 otherwise

$I_G =$ 1 if Gulf Coastal Region
0 otherwise

$I_P =$ 1 if Piedmont Region
0 otherwise

ACMFA appears to be decreasing with age in a non-linear fashion (Figures 6.3, 6.5, 6.7), so a non-linear model was found with the form:

$$\begin{aligned} MFA_{ij} &= (\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P)Age_i^{(\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P)} + \\ &\quad (\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P)\ln(Disk\ \ Height_j)^{(\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P)} \end{aligned} \tag{2}$$

where, the base model represents the Atlantic Coastal region and I_H, I_G, and I_P, represent deviations from the base parameters for the Hilly Coastal, Gulf Coastal and Piedmont regions respectively, and all other parameters previously defined.

MODEL DEVELOPMENT: AVERAGE CROSS-SECTIONAL MFA WEIGHTED BY DISTANCE FROM PITH

A linear model was developed to represent the change of ACMFA weighted by distance from pith in 3-dimensional space. The independent variables used in the linear model were selected based upon the linear correlation they exhibited with ACMFA. The variables chosen to be included in the model were the natural log of distance from pith (Inches), inverse log of relative height (ILH), distance by ILH interaction, and form with correlation coefficients of -0.52095, 0.51277, -0.67184, 0.51604 and significance levels of 0.0001, respectively. The linear model becomes:

$$\begin{aligned} MFA_{ij} = {} & (\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + \\ & (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P) \ln(Dist) + \\ & (\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P) ILH + \\ & (\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P)\left(\frac{Dist}{ILH}\right) + \\ & (\beta_4 + \beta_4 I_H + \beta_4 I_G + \beta_4 I_P) Form \end{aligned} \qquad (3)$$

where, the base model represents the Atlantic Coastal region and I_H, I_G, and I_P, represent deviations from the base parameters for the Hilly Coastal, Gulf Coastal and Piedmont regions respectively, and

MFA_{ij} = ACMFA at *Distance i* and *Disk Height j*,

Dist = Distance from pith (in.),

$I_H =$ 1 if Hilly Coastal Region
0 otherwise

$I_G =$ 1 if Gulf Coastal Region
0 otherwise

$I_P =$ 1 if Piedmont Region
0 otherwise

and all other parameters previously defined.

ACMFA appears to be decreasing with distance from pith in a non-linear fashion (Figures 6.4, 6.6, 6.8), so a non-linear model was found with the form:

$$MFA_{ij} = (\phi_1)(\phi_2) + (\phi_3)(\phi_4) \quad (4)$$

where,

$$\phi_1 = [(\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P) ILH]$$

$$\phi_2 = \left[\exp\ [(\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P) Dist]\right]$$

$$\phi_3 = [(\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P) + (\beta_4 + \beta_4 I_H + \beta_4 I_G + \beta_4 I_P) ILH]$$

$$\phi_4 = \left[\exp\ [(\beta_5 + \beta_5 I_H + \beta_5 I_G + \beta_5 I_P +) + (\beta_6 + \beta_6 I_H + \beta_6 I_G + \beta_6 I_P) DBH] Dist\right]$$

where, the Atlantic Coastal region represents the base model and I_H, I_G, and I_P, represent deviations from the base parameters for the Hilly Coastal, Gulf Coastal and Piedmont regions respectively, and all other parameters previously defined.

RESULTS

Parameter estimates and fit statistics for the linear ACMFA model (1) weighted by age are found in Table 6.2. The linear model was found to account for 76% of the variation in ACMFA with a mean square error of 8.27°. Residual values were found to range from -13.1° to 13.4° with a median value of -0.139°. The plot of residuals versus the natural log of age show some indication of non-constant variance (Figure 6.9). Because the ACMFA at any age is an average over all ages, indicates that ACMFA becomes more stable as age increases. Plots of the residuals versus ILH and FORM (Figure 6.9) show no patterns, indicating no bias. Parameters were found to differ by region. Intercept estimates were found to be 17.87°, 18.93°, 19.27°, and

14.59^o for the Atlantic, Hilly, Gulf, and Piedmont regions respectively. The rate of change of ACMFA over age was found to decrease with an estimated -4.65^o change in ACMFA for a one unit increase in age for the Atlantic, Hilly and Gulf regions. ACMFA was found to decrease at a slower rate in the Piedmont region with a parameter estimate of -4.01^o. ACMFA was found to increase 0.77^o for the Atlantic, -0.55^o for the Hilly, 5.64^o for the Gulf, and 5.98^o for the Piedmont regions with a one unit change of ILH, indicating ACMFA decreases with increasing height. Estimates of FORM parameters were found to be 11.27^o for the Atlantic and Hilly regions, -0.82^o Gulf, and 4.68^o for the Piedmont regions. Given DBH is held constant, this indicates that ACMFA decreases with increasing disk height for the Atlantic, Hilly, and Piedmont regions and increases with increasing disk height in the Gulf Coastal region. Plots of the mean actual values versus the mean predicted values for model (1) can be found in Figure 6.10. It can be seen that the model was unable to represent the sigmoid shaped function of ACMFA at 4.5 feet. At disk heights between 10 and 40 feet, the model on average, is accurately predicting ACMFA. Above 40 feet, the linear model tends to be under predicting ACMFA.

All parameters for the nonlinear ACMFA model (2) were found to be significant at the 0.05 level (Table 6.3). The nonlinear model was found to account for 75$^{\%}$ of the variation of ACMFA with a root mean square error of 8.51^o. The median residual value of the nonlinear model was found to be of -0.189^o. Residual plots versus the independent variables of age and the natural log of disk height (Figure 6.8) show no general trends and are centered on zero, indicating no bias. Upper values of ACMFA were found to be 24.93^o for the Atlantic and Hilly regions, 25.68^o for the Gulf, and 23.65^o for the Piedmont region. ACMFA was found to decrease with increasing age for all regions. A one unit change of age was found to decrease ACMFA by -0.23^o, -0.25^o, -0.26^o, and -0.22^o, in the Atlantic, Hilly, Gulf, and Piedmont regions respectively.

The height function of model (2) acts as constant value, shifting ACMFA up and down the y-axis depending on disk height. The β_2 parameter acts as an initial value, while the β_3 parameter indicates how ACMFA changes with disk height. β_2 parameter values were found to be 34.06° for the Atlantic, 25.33° for the Hilly, 24.63° for the Gulf, and 41.77° for the Piedmont region, indicating higher ACMFA values at all ages in the Piedmont and Atlantic regions versus the Hilly and Gulf regions (Figure 6.7). ACMFA was found to decrease at a rate of -2.62° for a one unit change in disk height for all regions. Plots of the mean actual values versus the mean predicted values for the nonlinear ACMFA model (2) weighted by age can be found in Figure 6.12. As in the linear ACMFA model (1), the nonlinear model was unable to represent the sigmoid shaped function of ACMFA at 4.5 feet. At disk heights between 10 and 40 feet, the model on average, is accurately predicting ACMFA. Above 40 feet, the nonlinear model also tends to be under predicting ACMFA, but less severely than the linear model.

All parameters for the linear ACMFA model (3) weighted by distance from pith were found to be significant at the 0.01 level (Table 6.4). The model accounted for 72% of the variation in ACMFA with a mean square error of 12.13°. Intercept estimates were found to be 17.74°, 16.92°, 14.95°, and 12.69° for the Atlantic, Hilly, Gulf, and Piedmont regions respectively. The rate of change of ACMFA over distance from pith was found to decrease with an estimate -2.33° in the Atlantic, -2.91 in the Hilly, -4.08 in the Gulf, and -2.91 in the Piedmont regions respectively, with a one unit increase in distance from pith. ACMFA was found to increase -5.78° in the Atlantic and Hilly regions, 1.92° in the Gulf, and 2.66° in the Piedmont region with a one unit change of ILH, indicating ACMFA increases in the Atlantic and Hilly regions, while decreasing in the Gulf and Piedmont regions with increasing height. A significant distance by ILH interaction was found in all regions. Parameter estimates were found to be -

4.01^{o}, -2.95^{o}, -1.70^{o}, and -1.98^{o} for the Atlantic, Hilly, Gulf, and Piedmont regions respectively. Estimates of FORM parameters were found to be 20.65^{o} for the Atlantic, 19.06^{o} for the Hilly regions, 4.72^{o} for the Gulf, and 8.419^{o} for the Piedmont regions. Given DBH is held constant; this indicates that ACMFA decreases with increasing disk height for the Atlantic, Hilly, and Piedmont regions. Residual values were found to range from -19.2^{o} to 23.3^{o} with a median value of -0.113^{o}. The plot of the residuals versus the predicted values (Figure 6.13) shows that the majority of the residual values are centered on zero. The model was also found to have a median residual value of -0.113^{o}. Plots of the residuals versus the natural log of distance, ILH, the distance by ILH interaction, and FORM (Figure 6.13) show no patterns, indicating no bias. The plot of residuals versus the natural log of distance does indicate that model predictions at distance values less than 0.20 inches are highly variable. From the plot of actual values versus predicted values (Figure 6.13), it can be seen that the model is not precisely estimating higher values of ACMFA. Given that higher values of ACMFA are found close to the pith and at 4.5 feet, indicates that the model is not representing the change of ACMFA at a height level of 4.5 feet. Plots of the mean actual values versus the mean predicted values for model (3) can be found in Figure 6.14. It can be seen that the model is unable to represent the sigmoid shaped function of ACMFA at 4.5 feet. The mean predicted values at 4.5 feet appears to be exponential in shape and is under estimating ACMFA up to a distance of 2.5 inches, and over estimating beyond 2.5 inches. Plots of mean actual values versus mean predicted values at other height levels show that the model is capable of reproducing the shape of ACMFA. However, the predicted ACMFA values continue to decrease as distance from pith increases at a faster rate than the actual values.

Parameter estimates and fit statistics for the nonlinear sum of exponentials ACMFA model (4) weighted by distance from pith are found in Table 6.5. All parameters were found to be significant at the 0.05 level. The model accounted for 75% of the variation of ACMFA weighted by distance from pith with a mean square error of 10.68°. Residual plots (Figure 6.15) indicate no bias and an overall good fit. The functionality of model (4) may be decomposed to evaluate the performance of the parameter values at differing height levels, distances from pith and DBH values.

Let,

$$\phi_1 = \left[(\beta_0 + \beta_0 I_H + \beta_0 I_G + \beta_0 I_P) + (\beta_1 + \beta_1 I_H + \beta_1 I_G + \beta_1 I_P) ILH\right]$$

$$\phi_2 = \left[\exp\ \left[(\beta_2 + \beta_2 I_H + \beta_2 I_G + \beta_2 I_P) Dist\right]\right]$$

$$\phi_3 = \left[(\beta_3 + \beta_3 I_H + \beta_3 I_G + \beta_3 I_P) + (\beta_4 + \beta_4 I_H + \beta_4 I_G + \beta_4 I_P) ILH\right]$$

$$\lambda_4 = \left[\exp\ \left[(\beta_5 + \beta_5 I_H + \beta_5 I_G + \beta_5 I_P +) + (\beta_6 + \beta_6 I_H + \beta_6 I_G + \beta_6 I_P) DBH\right] Dist\right]$$

α is a fixed value and increases with increasing disk height given total height is held constant. χ is a constant decreasing exponential function. Given total height is held constant, ϕ will decrease with increasing disk height. λ is a constant decreasing exponential function, and as DBH increases the rate of change of λ decreases shifting the ACMFA curve up the y-axis, indicating that larger diameter trees have a higher asymptotic bound than smaller diameter trees (Figure 6.17). As a result, the model becomes very flexible and is capable of producing sigmoid, linear, and exponentially shaped curves (Figure 6.18). Plots of the mean actual values versus the mean predicted values at all height levels can be found in Figure 6.16. At 4.5 feet, it can be seen that the model is capable of reproducing the sigmoid shaped response of ACMFA at 4.5 feet.

Above 4.5 feet, the shape of the model appears to be a decreasing exponential function, which resembles the shape of the true data (Figures 6.4, 6.6, 6.8). The model does however have problems in accurately predicting ACMFA at extreme values of distance from pith.

DISCUSSION

ACMFA was found to be significantly higher at 4.5 feet and to decrease with increasing height. ACMFA was found to decrease with increasing age and distance from pith (Figures 6.3-6.8). The plots show that the rate of change of ACMFA decreases sharply in the juvenile core then slows in the transition zone from age 1 to 10, and eventually stabilizes in the zone of mature wood by age 11.

Regional differences in ACMFA were also found with higher values of ACMFA found in the Atlantic Coastal and Piedmont regions than in the Gulf and Hilly Coastal regions. The finding of higher ACMFA values in the Piedmont region than the Atlantic Coastal Plain is consistent with cross-sectional specific gravity findings by Clark (2002). Clark (2002) found that cross-sectional specific gravity values, which are highly inversely correlated with MFA, were on average higher in the Lower Coastal Plain of Georgia and South Carolina than in the Piedmont. With the Atlantic Coastal region receiving more summer rainfall and an extended growing season, it would be expected that trees in this area would have a greater percentage of latewood and conversely lower MFA values. Regional weather patterns are not the sole factor influencing MFA. The number of trees per acre at the time of sampling or genetics could influence MFA.

Cross-sectional MFA models were developed to represent the change of ACMFA from stump to tip and pith to bark for 60 loblolly pine trees sampled in the Southeastern United States.

Both linear and nonlinear model forms were developed to explain the trends of ACMFA in 3-dimensional space. Identifying the patterns and change of ACMFA by age, distance from pith, and height allowed candidate model forms to be developed.

The nonlinear model developed for predicting ACMFA at any age and height for is preferred. The nonlinear model accounted for the same amount of variation in ACMFA as the linear model,75$^{\%}$, but requires less information. The nonlinear ACMFA model weighted by rings from pith is a constant decreasing exponential function, whose values are then shifted accordingly up or down by the natural log of disk height term. Upon evaluating the linear ACMFA model with changing independent variables, it was found that instead of decreasing smoothly, the model made a rapid change in the predicted ACMFA value from age 1 to 2, a value on the order of $\pm$ 10^{o}. Also, the linear ACMFA ring model predicted lower ACMFA values than were observed in the true data. By age 17, the linear model is predicting ACMFA values of less than 5^{o}, which are unrealistic.

The nonlinear ACMFA weighted by distance from pith should be preferred over the linear ACMFA. The nonlinear model is extremely flexible and is capable of reproducing the sigmoid shaped curve of ACMFA at 4.5 feet, and then shifting to a decreasing exponentially shaped curve. The nonlinear model accounted for more variation in ACMFA and had a lower mean square error. The linear ACMFA weighted by distance from pith was found to be exponentially shaped at all disk height values, but is capable of predicting ACMFA at disk levels above 10 feet in height.

All models developed to predict ACMFA at any age and height were found to be over predicting. Even though the linear models act in a nonlinear fashion, they are still not capable of reproducing the true change of ACMFA at differing height levels. The nonlinear models developed to describe the change of ACMFA in 3-dimensional space by distance from pith were found to be extremely flexible. These models allowed for changes in the curves representing ACMFA at differing height levels. Given the variation of ACMFA by distance from pith, (Figures 6.4, 6.6, 6.8) these models adequately describe the ACMFA at any distance from pith and height.

The models developed here represent the first attempt to describe ACMFA in 3-dimensional space and can be used in conjunction with height prediction equations to predict ACMFA at any age and height for loblolly pine grown in the Southeastern United States. This is one of the first attempts to model MFA as a function of height, distance, and rings from pith. These models can be used to predict MFA for manufacturing and provide a baseline for comparison of intensively managed stands to gain insight into how silvicultural treatments affect not only MFA, but solid wood strength, stiffness, and paper properties.

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TABLES AND FIGURES FOR CHAPTER 6

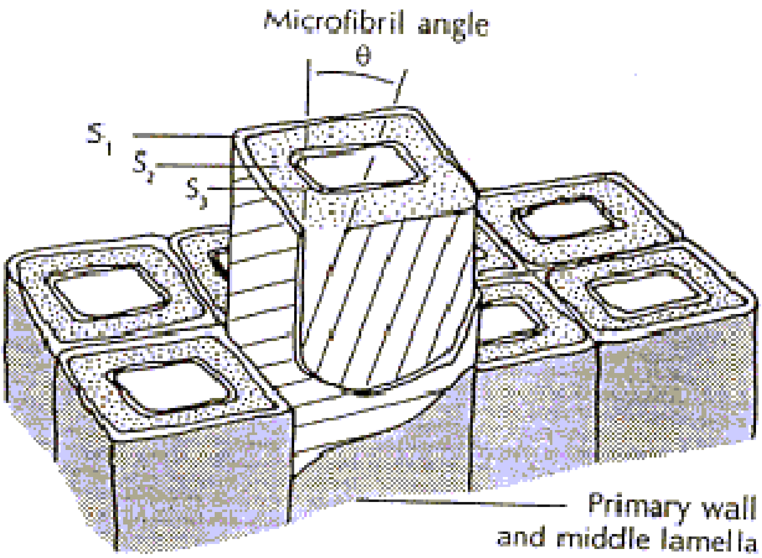

Figure 6.1. Orientation of microfibrils in the S2 layer of the cell wall (after Dickson and Walker 1997).

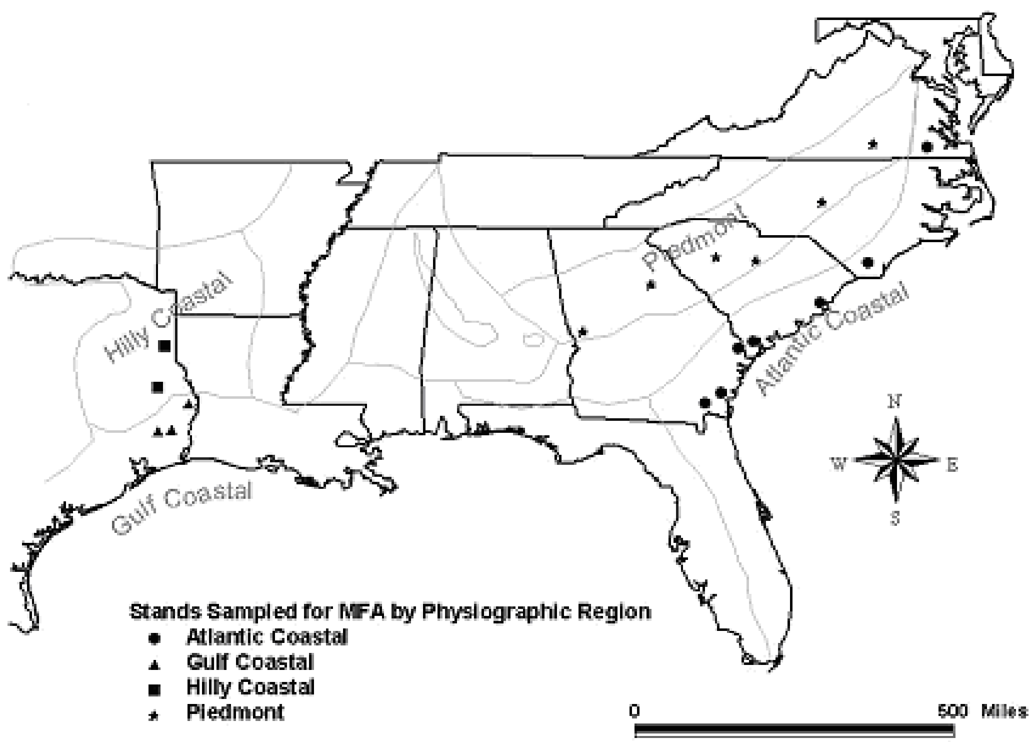

Figure 6.2. Map of the 20 stand locations sampled between 1999 and 2001 for microfibril analysis.

Table 6.1. Range and average tree size characteristics (in parenthesis) for 60 loblolly pine trees sampled for MFA analysis by physiographic region.

REGION	TREES SAMPLED (NO.)	DBH (inches)	TOTAL HEIGHT (feet)	AGE (years)	MFA (degrees)
Atlantic Coastal	24	6.1 – 12.7 (9.3)	51 – 83 (69.2)	21 – 24 (22)	10.2 - 47.0 (21.3)
Piedmont	18	6.2 – 14.2 (10.1)	49.6 – 65.4 (60.0)	21 – 25 (23)	12.0 – 50.7 (22.2)
Gulf Coastal	9	5.7 – 9.8 (7.5)	41.3 – 61.3 (55)	20 – 27 (24)	12.7 – 38.3 (19.3)
Hilly Coastal	9	5.5 – 11.5 (8.3)	37.4 – 71.2 (58.0)	20	12.4 – 34.7 (19.4)

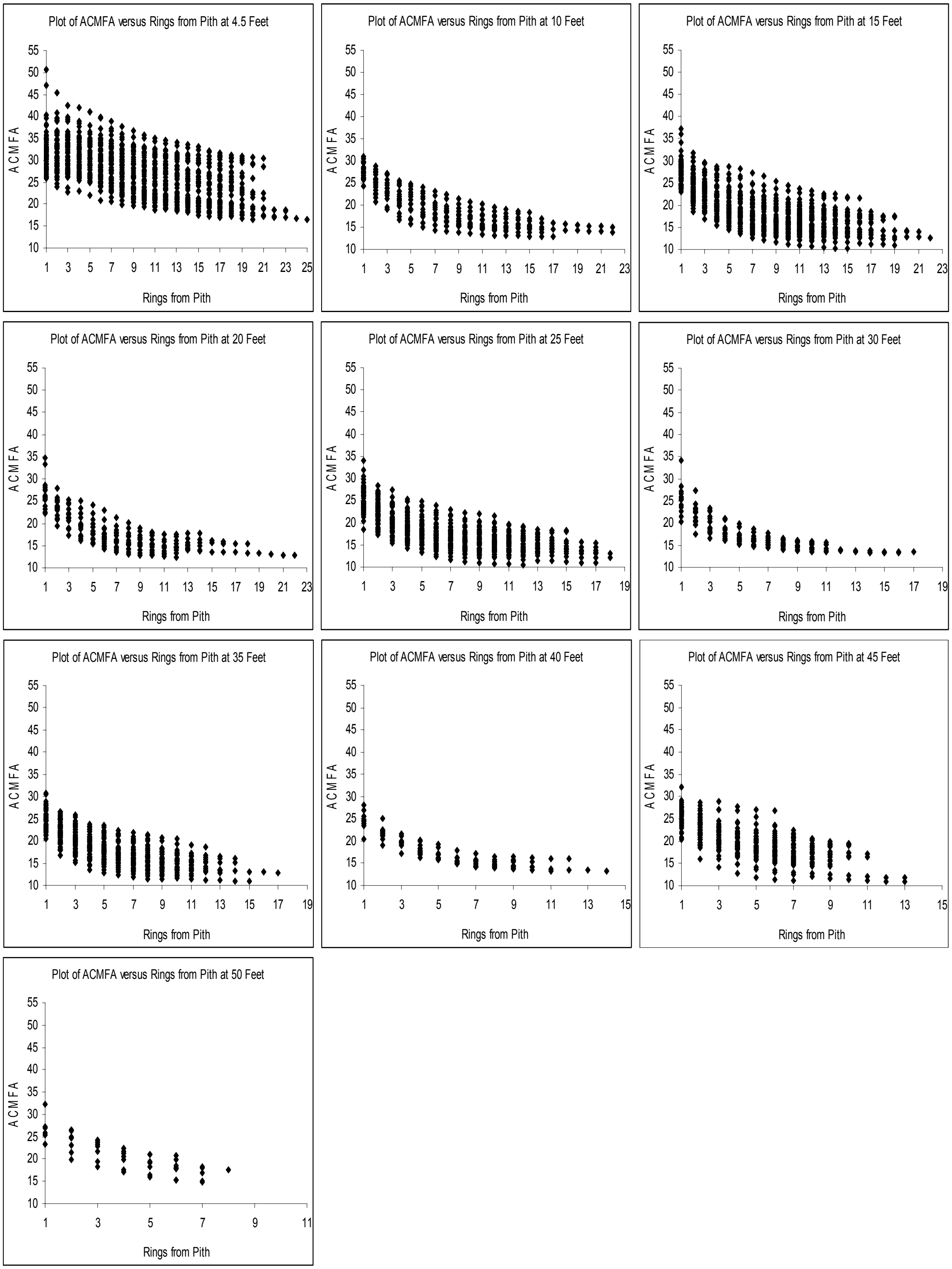

Figure 6.3. Plot of average cross-sectional microfibril angle versus rings from pith at different height levels.

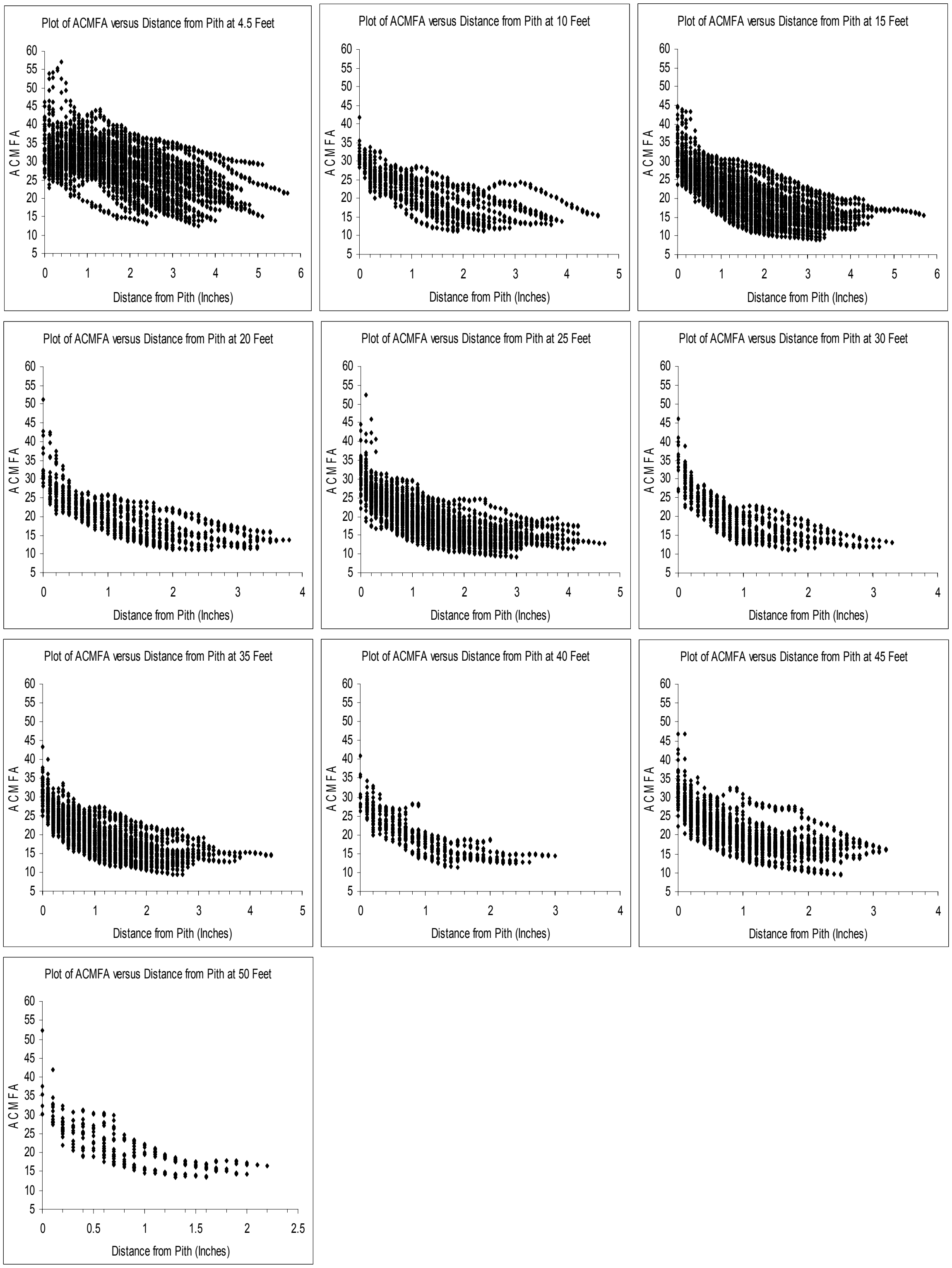

Figure 6.4. Plot of average cross-sectional microfibril angle versus distance from pith in inches (rounded to the nearest one-tenth inch) at different height levels.

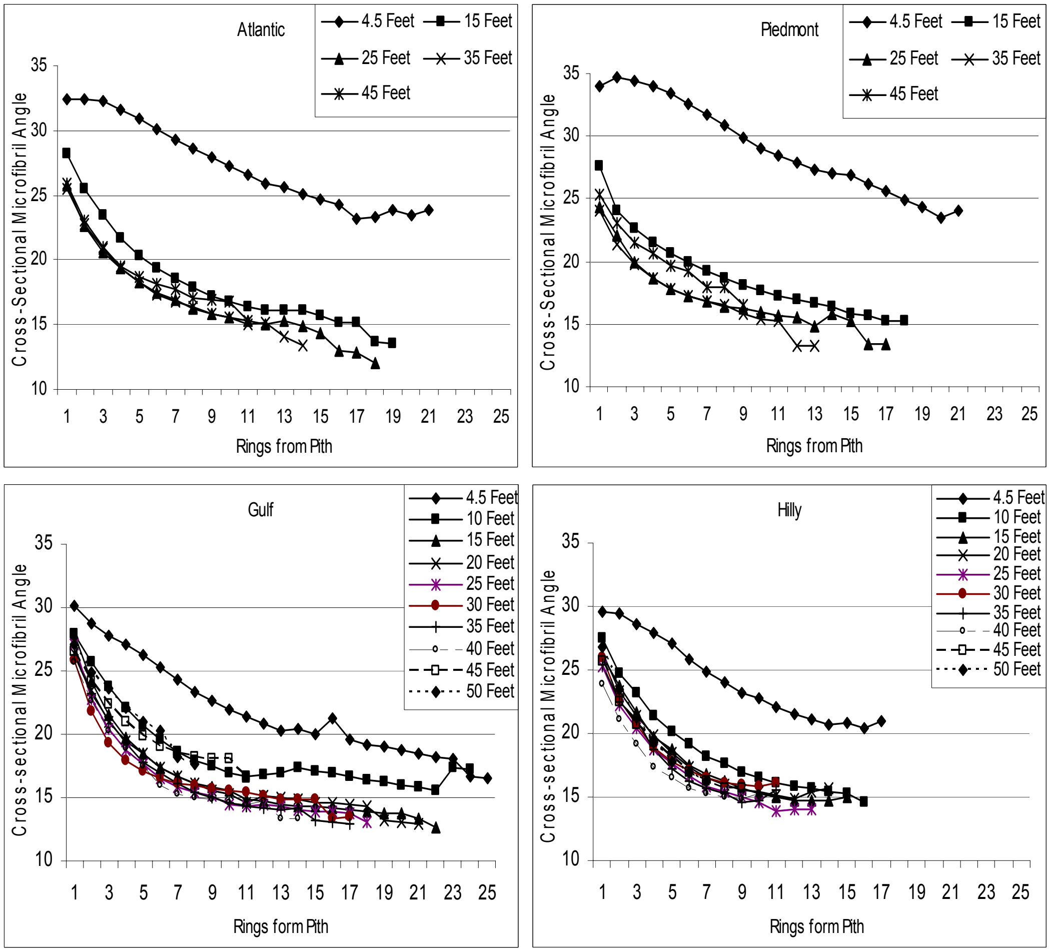

Figure 6.5. Average cross-sectional microfibril angle by rings from pith at different height levels for the Atlantic Coastal Plain, Piedmont region, Gulf Coastal Plain, and Hilly Coastal Plain.

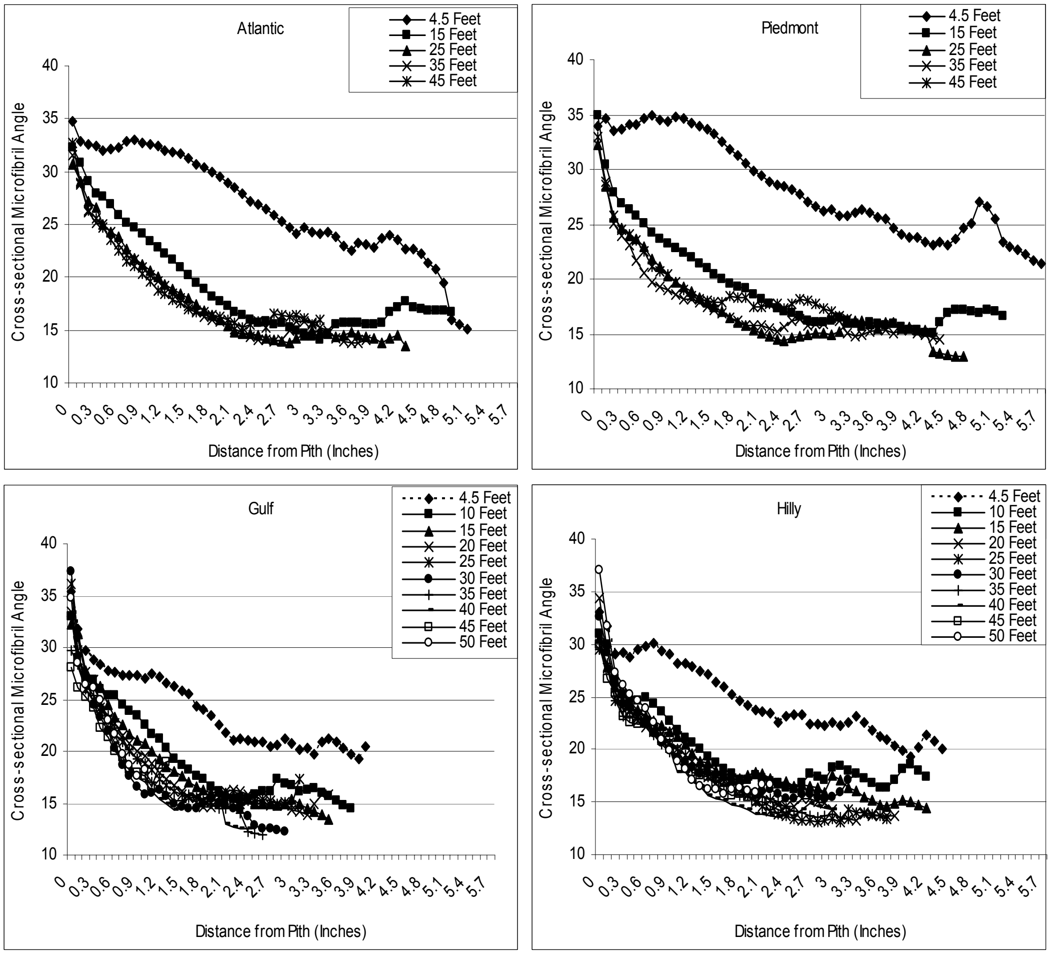

Figure 6.6. Average cross-sectional microfibril angle by distance from pith in inches (rounded to the nearest one-tenth inch) at different height levels for the Atlantic Coastal Plain, Piedmont region, Gulf Coastal Plain, and Hilly Coastal Plain .

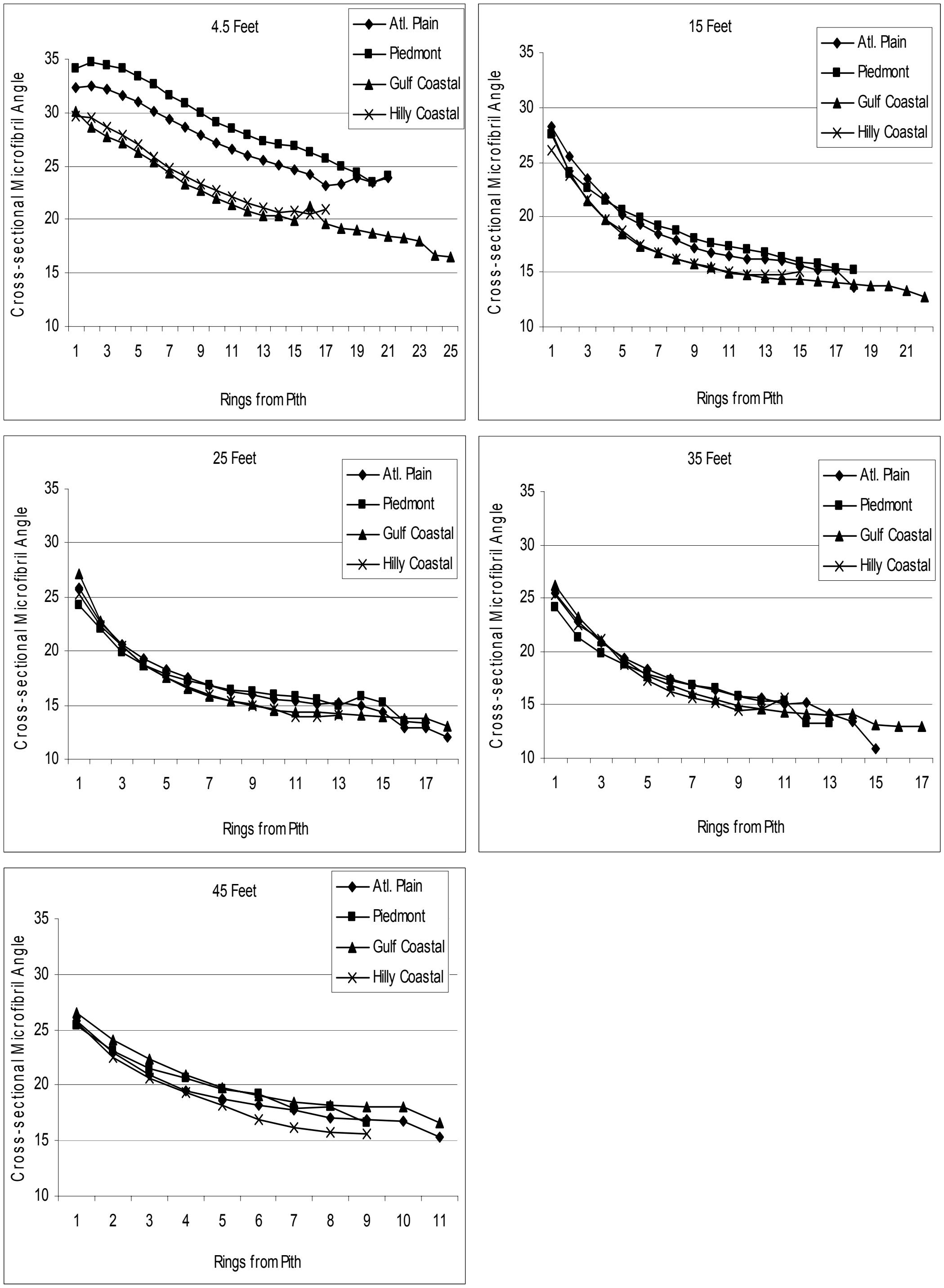

Figure 6.7. Average cross-sectional microfibril angle by rings from pith by physiographic region at 4.5 feet, 15 feet, 25 feet, 35 feet, and 45 feet.

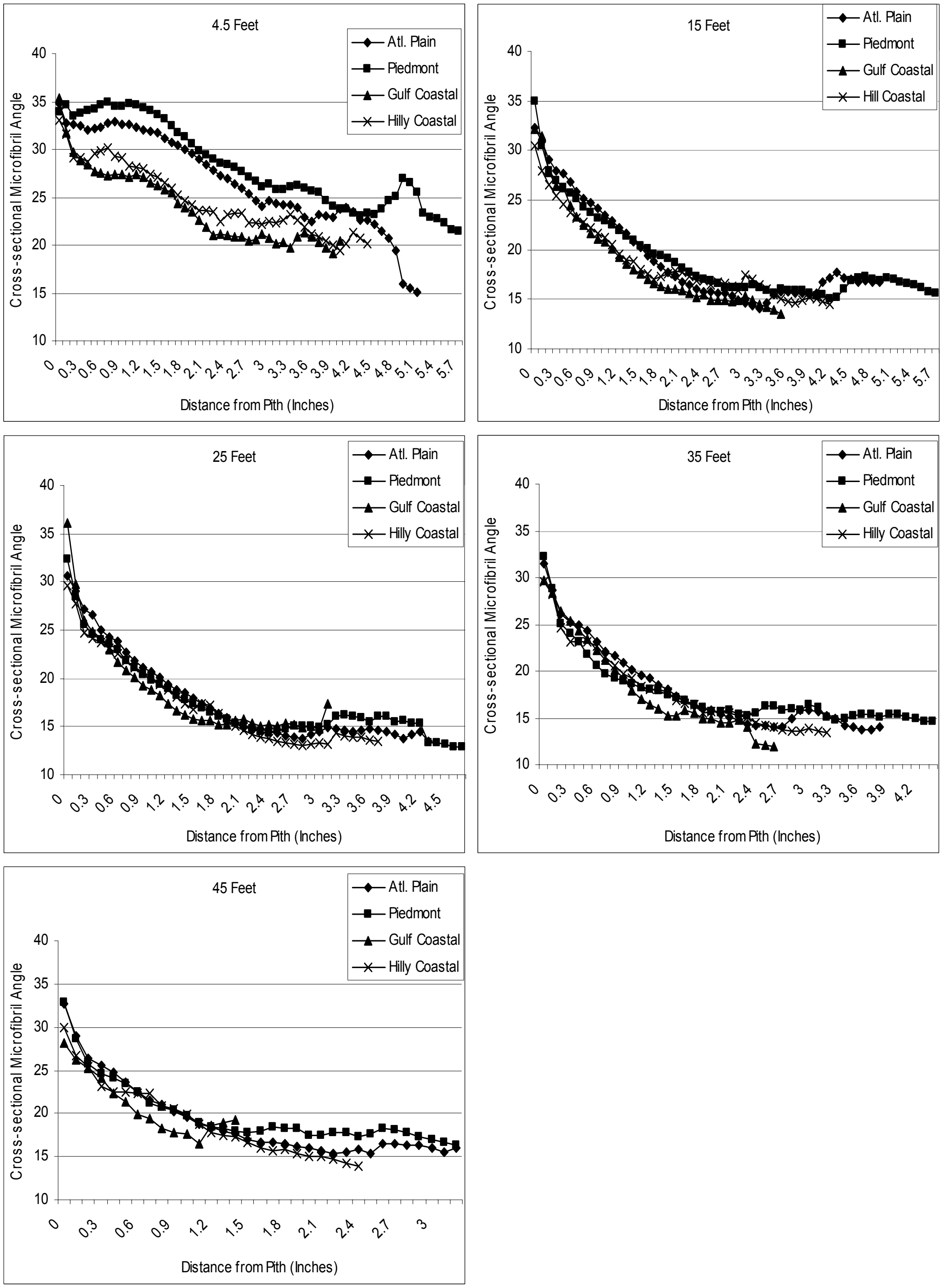

Figure 6.8. Average cross-sectional microfibril angle by distance from pith in inches (rounded to the nearest one-tenth inch) by physiographic region at 4.5 feet, 15 feet, 25 feet, 35 feet, and 45 feet.

Table 6.2. Parameter estimates and fit statistics for the linear ACMFA weighted by rings from pith, model (1).

Parameter	Estimate	Std. Error	P-Value
β_0	17.87136	0.2212	<0.0001
$\beta_0 I_H$	1.06289	0.3617	0.0033
$\beta_0 I_G$	1.39745	0.3737	0.0002
$\beta_0 I_P$	-3.28527	0.3571	<0.0001
β_1	-4.64862	0.0662	<0.0001
$\beta_1 I_P$	0.551637	0.1316	<0.0001
β_2	0.76493	0.3686	0.0380
$\beta_2 I_H$	-1.31435	0.2116	<0.0001
$\beta_2 I_G$	4.87512	0.7882	<0.0001
$\beta_2 I_P$	5.21745	0.6826	<0.0001
β_3	11.27284	0.6740	<0.0001
$\beta_3 I_G$	-12.0964	1.5067	<0.0001
$\beta_3 I_P$	-6.59098	1.2051	<0.0001

Fit index: 0.7604

Mean Square Error: 8.2691

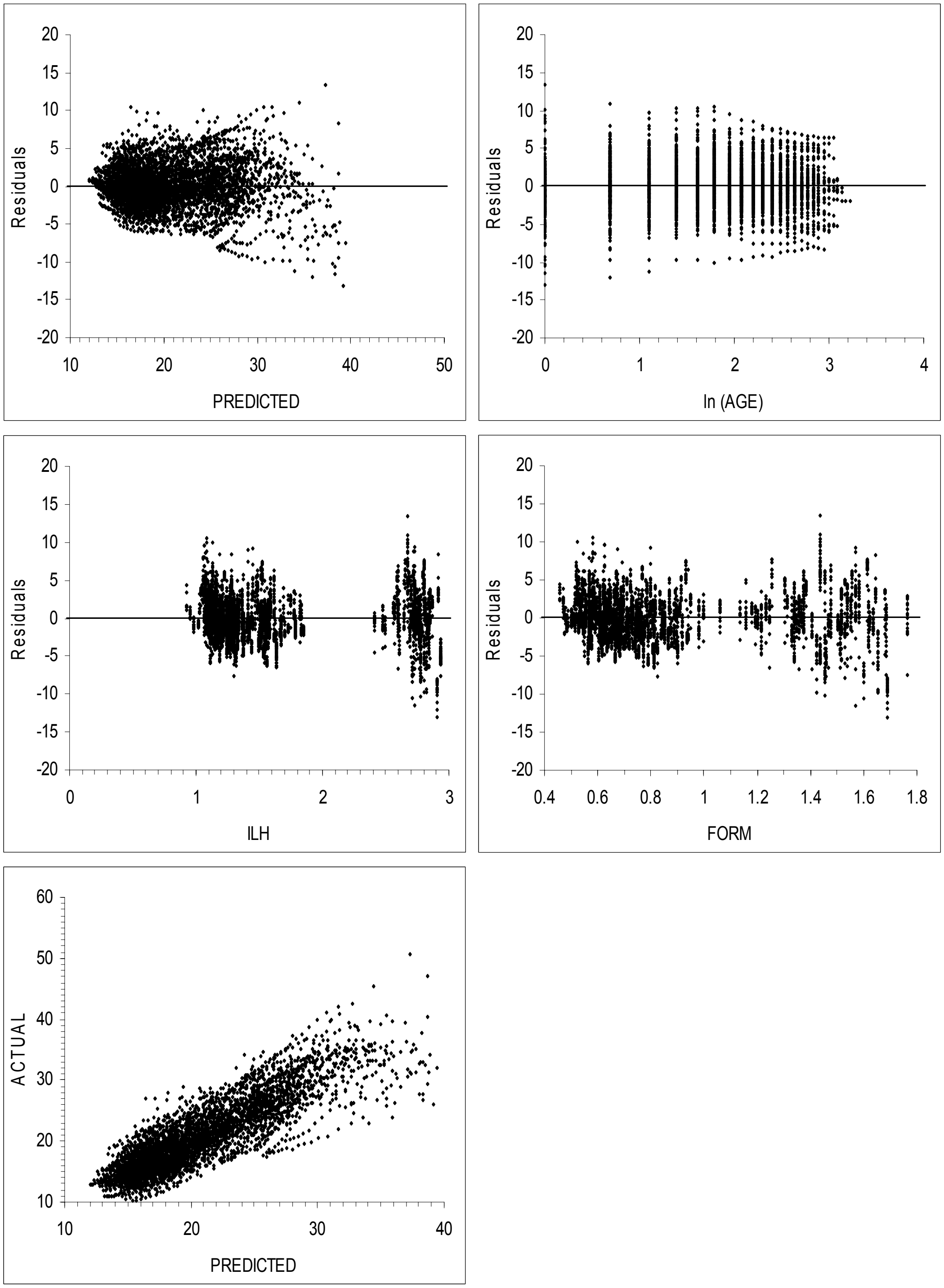

Figure 6.9. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the linear ACMFA weighted by rings from pith, model (1).

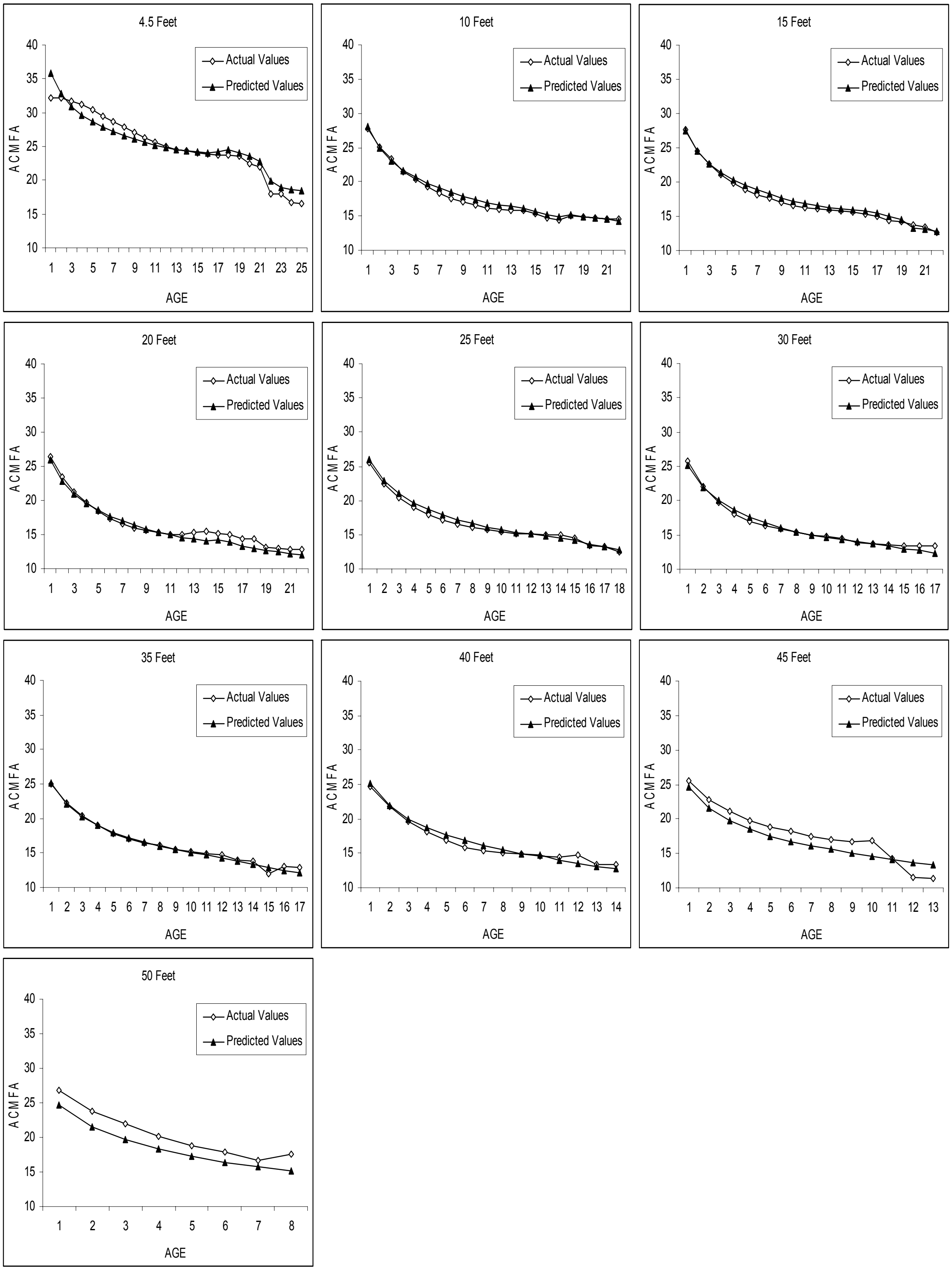

Figure 6.10. Plot of mean actual values versus mean predicted values for the linear ACMFA model (1) by disk height.

Table 6.3. Parameter estimates and fit statistics for the nonlinear ACMFA weighted by rings from pith, model (2)

Parameter	Estimate	Std. Error	P-Value
β_0	24.92894	0.2707	<0.0001
$\beta_0 I_G$	0.747387	0.3450	0.0303
$\beta_0 I_P$	-1.27621	0.3126	<0.0001
β_1	-0.23406	0.00619	<0.0001
$\beta_1 I_H$	-0.01624	0.00629	0.0098
$\beta_1 I_G$	-0.02669	0.00869	0.0021
$\beta_1 I_P$	0.018616	0.00807	0.0211
β_2	34.06431	1.9107	<0.0001
$\beta_2 I_H$	-8.73043	-7.46	<0.0001
$\beta_2 I_G$	-9.43081	1.2134	<0.0001
$\beta_2 I_P$	7.709588	0.9555	<0.0001
β_3	-2.6239	0.1818	<0.0001

Fit index: 0.7533

Mean Square Error: 8.5093

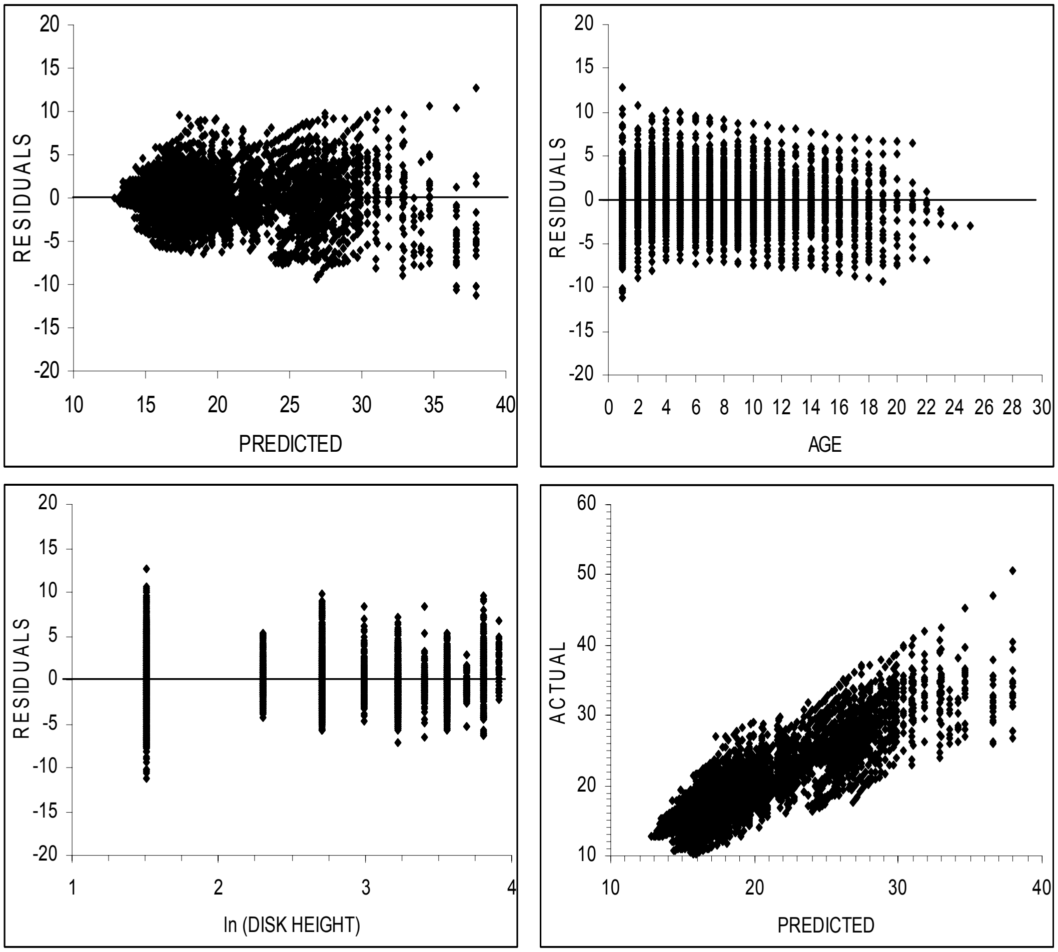

Figure 6.11. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the nonlinear ACMFA weighted by rings from pith, model (2).

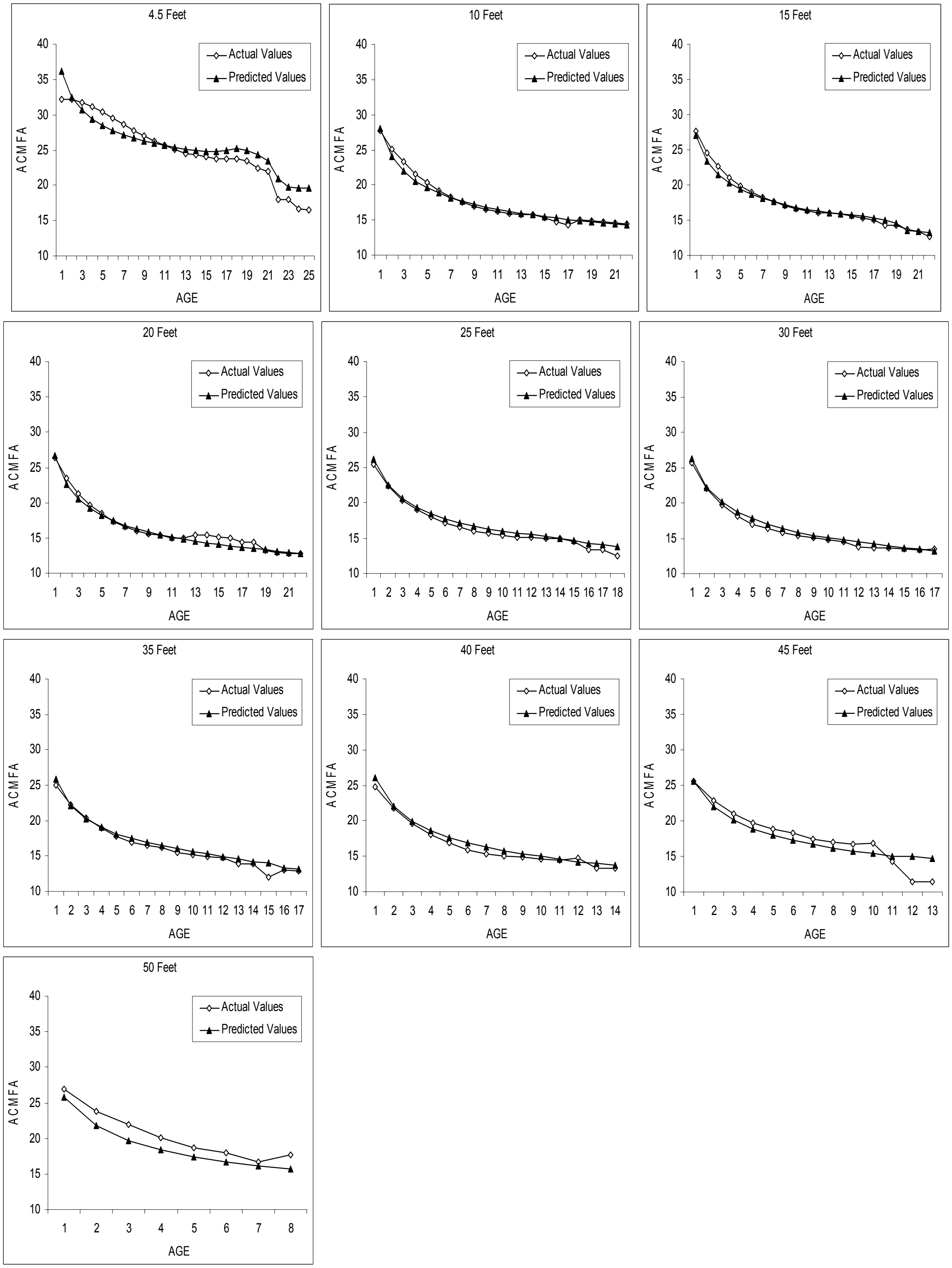

Figure 6.12. Plot of mean actual values versus mean predicted values for the nonlinear ACMFA model (2) by disk height.

Table 6.4. Parameter estimates and fit statistics for the linear ACMFA weighted by distance from pith, model (3).

Parameter	Estimate	Std. Error	P-Value
β_0	17.73548	0.2156	<0.0001
$\beta_0 I_H$	-0.81077	0.3419	0.0177
$\beta_0 I_G$	-2.78112	0.4447	<0.0001
$\beta_0 I_P$	-5.04442	0.3222	<0.0001
β_1	-2.32973	0.0824	<0.0001
$\beta_1 I_H$	-0.58324	0.1336	<0.0001
$\beta_1 I_G$	-1.75122	0.1621	<0.0001
$\beta_1 I_P$	-0.58772	0.1228	<0.0001
β_2	-5.77776	0.2103	<0.0001
$\beta_2 I_G$	7.69381	0.5059	<0.0001
$\beta_2 I_P$	8.44289	0.3977	<0.0001
β_3	-4.00787	0.1193	<0.0001
$\beta_3 I_H$	1.05993	0.1871	<0.0001
$\beta_3 I_G$	2.30627	0.2635	<0.0001
$\beta_3 I_P$	2.02774	0.1721	<0.0001
β_4	20.65439	0.4030	<0.0001
$\beta_4 I_H$	-1.59213	0.2530	<0.0001
$\beta_4 I_G$	-15.93350	0.9824	<0.0001
$\beta_4 I_P$	-12.2350	0.6859	<0.0001

Fit index: 0.7182

Mean Square Error: 12.1292

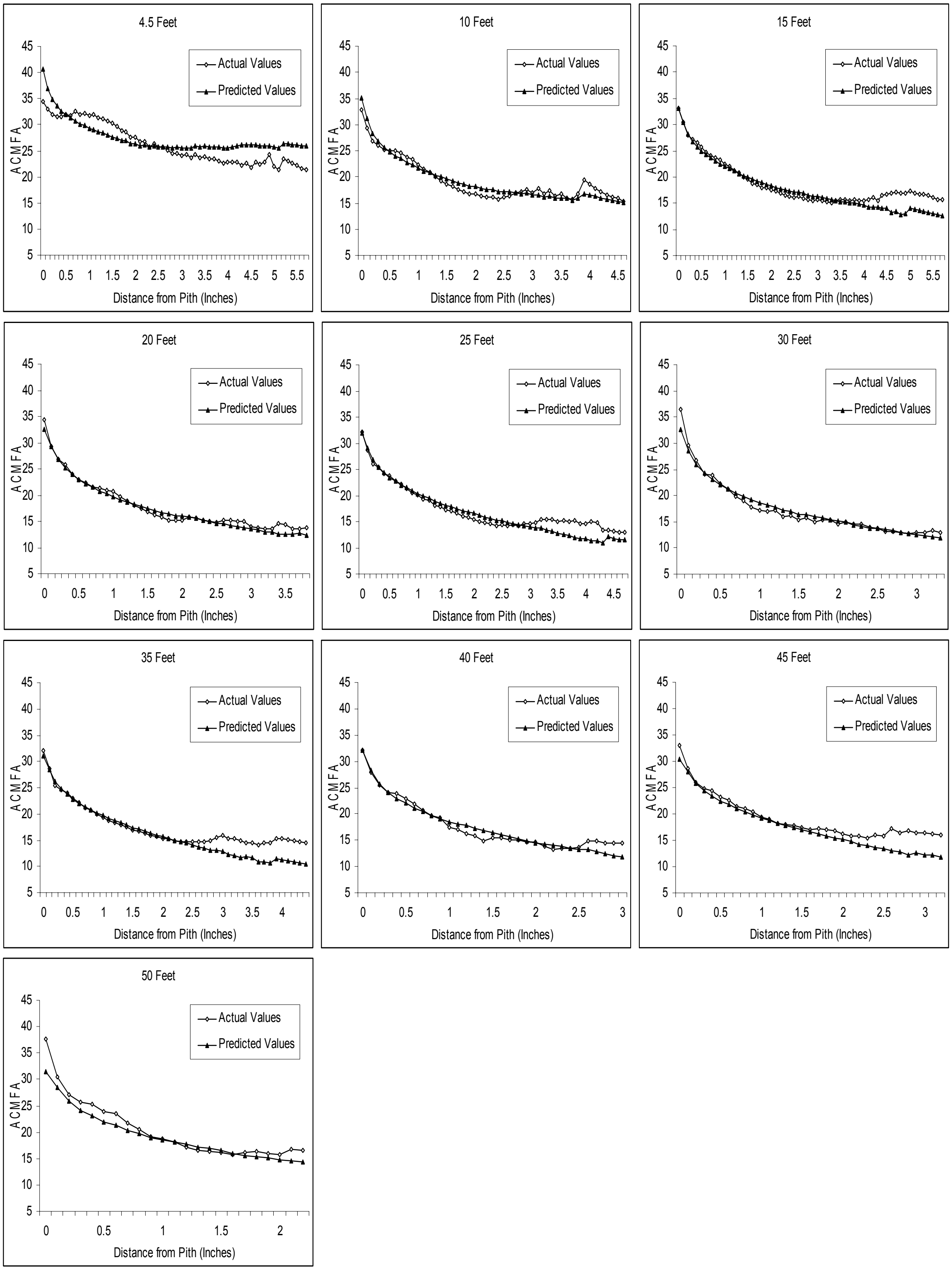

Figure 6.14. Plot of mean actual values versus mean fitted values for the linear ACMFA model (3) by disk height (rounded to the nearest one-tenth inch).

Table 6.5. Parameter estimates and fit statistics for the nonlinear ACMFA weighted by distance from pith, model (4).

Parameter	Estimate	Std. Error	P-Value
β_0	24.50328	0.3422	<0.0001
$\beta_0 I_H$	-2.94461	0.7860	0.0002
β_1	-14.18110	0.2934	<0.0001
$\beta_1 I_H$	1.30028	0.6162	0.0348
$\beta_1 I_G$	3.39996	0.3898	<0.0001
$\beta_1 I_P$	1.53276	0.2918	<0.0001
β_2	-1.40476	0.0399	<0.0001
$\beta_2 I_G$	-0.99743	0.1791	<0.0001
$\beta_2 I_P$	-0.87764	0.0668	<0.0001
β_3	5.75615	0.2054	<0.0001
$\beta_3 I_H$	2.53055	0.3743	<0.0001
$\beta_3 I_G$	4.26512	0.5655	<0.0001
β_4	14.28021	0.2112	<0.0001
$\beta_4 I_H$	-1.86568	0.3615	<0.0001
$\beta_4 I_G$	-5.02220	0.3091	<0.0001
$\beta_4 I_P$	-0.97231	0.1942	<0.0001
β_5	-0.46428	0.0081	<0.0001
$\beta_5 I_H$	-0.18934	0.0154	<0.0001
$\beta_5 I_G$	0.06339	0.0088	<0.0001
$\beta_5 I_P$	0.13726	0.0109	<0.0001
β_6	0.02579	0.0006	<0.0001
$\beta_6 I_H$	0.02066	0.0011	<0.0001
$\beta_6 I_P$	-0.00944	0.0008	<0.0001

Fit index: 0.7519

Mean Square Error: 10.6776

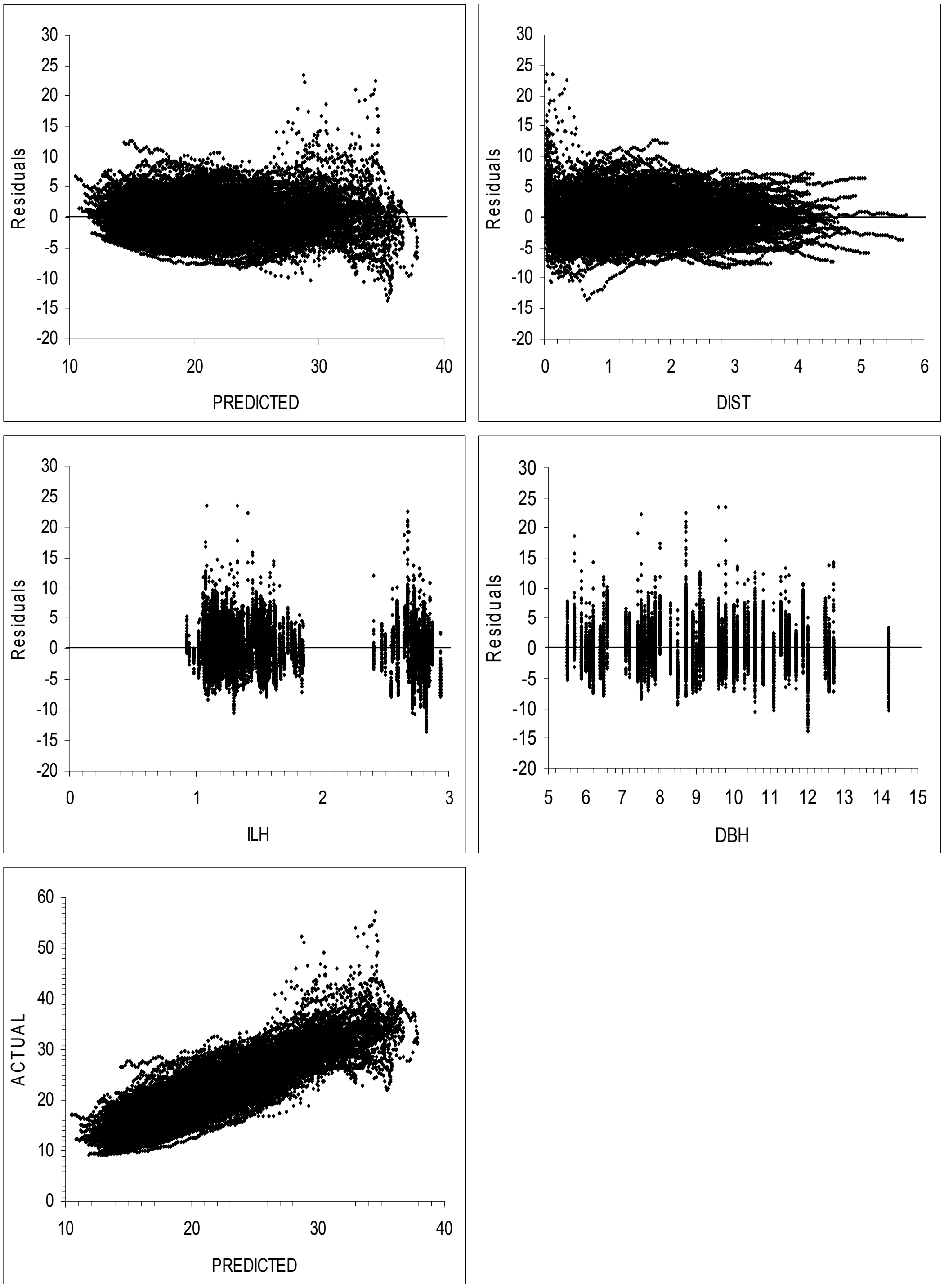

Figure 6.15. Residual plots versus the independent variables and actual MFA values versus predicted MFA values for the nonlinear ACMFA weighted by distance from pith, model (4).

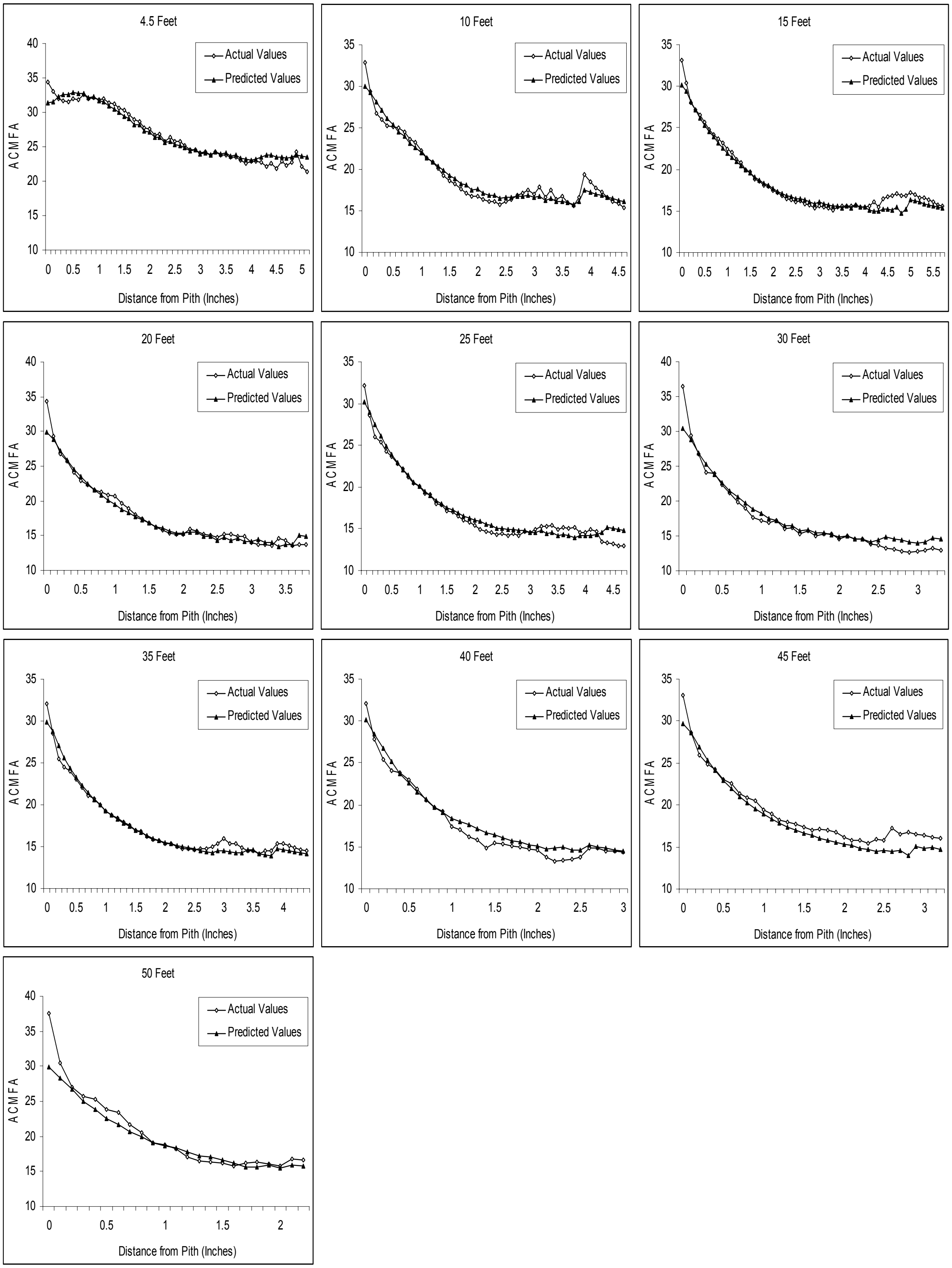

Figure 6.16. Plot of mean actual values versus mean fitted values for the nonlinear ACMFA model (4) by disk height (rounded to the nearest one-tenth inch).

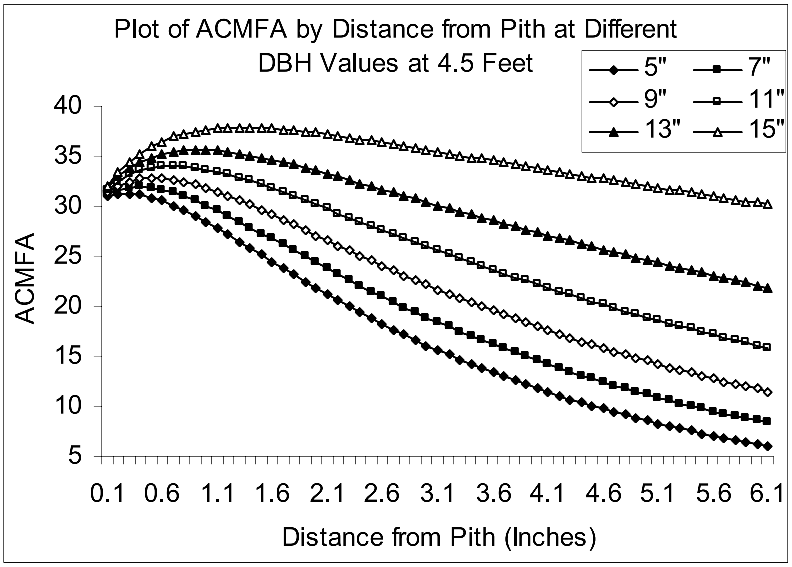

Figure 6.17. Plot of ACMFA by distance from pith at 4.5 feet with different DBH values.

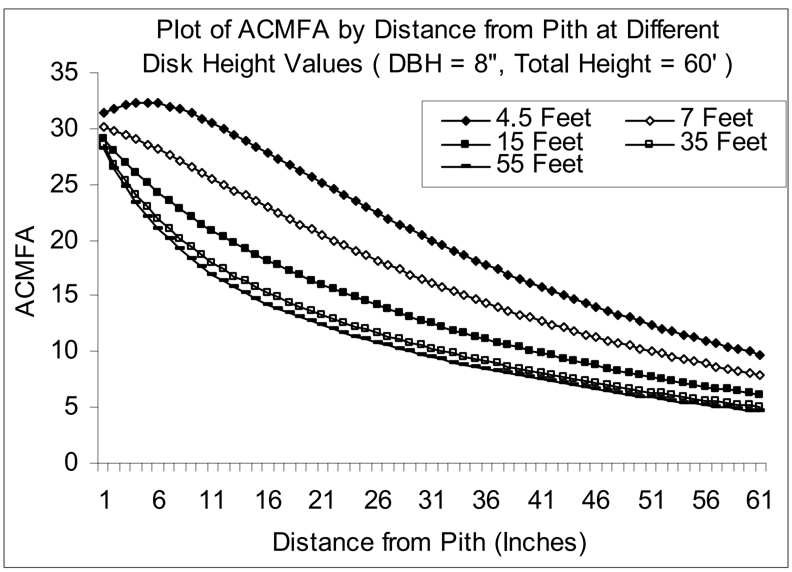

Figure 6.18. Plot of ACMFA by distance from pith at different disk height levels

(DBH = 8”, Total Tree Height = 60’).

CHAPTER 7

CONCLUSIONS

There has been an increased interest in wood properties within the last decade. Forest managers are growing loblolly pine at rates faster than ever before. Prediction of wood properties is becoming critical for forest managers and manufacturers. Wood strength and stiffness ultimately affect the end use of forest products. Microfibril angle is one of the main determinants of the mechanical properties of wood. Microfibril angle significantly affects the dimensional stability and structure of sawn lumber and has been found to be highly correlated with the stretch, stiffness, and strength of paper properties. Sixty loblolly pine (*Pinus taeda* L.) trees from four distinct physiographic regions in the Southeastern United States were sampled for microfibril angle analysis. Prediction equations were developed from mathematical models to explain the change of microfibril angle at any height, distance from pith, and rings from pith. Consistent radial and longitudinal patterns in microfibril angle are predictable and suggest potential patterns of wood utilization of loblolly pine bole wood. The models developed here represent the first attempt to describe microfibril angle in 3-dimensional space and can be used in conjunction with height equations to predict microfibril angle at any position within loblolly pine trees grown in the Southeastern United States.

Prediction models were developed for estimation of MFA given multiple levels of information. Linear and nonlinear models were developed to predict MFA of both earlywood and latewood. The nonlinear models were found to be superior to the linear models in terms of accurately predicting MFA at all height levels. The nonlinear models were capable of reproducing the sigmoidal shaped trend of MFA at 4.5 feet, a considerable advantage over the linear models.

The linear models developed for predicting MFA at any ring were found to be quadratic in form, decreasing rapidly from ring, reaching an inflection point, and then increasing, which is inconsistent with the patterns of MFA shown. All models developed to predict MFA at any ring from pith and height were found to be over predicting, with the models having negative median residual values. MFA by ring appears to be linear or sigmoid in shape at 4.5 feet, above which MFA decreases rapidly in nonlinear fashion. However, these patterns were found to vary from tree to tree, with some trees exhibiting an almost perfect linear relationship at all height levels and others representing nonlinear trends.

The models developed for predicting MFA by distance from pith were found to be inadequate. Taking the average of MFA over any specified distance, points out variability between trees. Dominant trees in the stand would be expected to have larger rings, not necessarily larger MFA values. However, when averaging across a distance, in the dominant trees, it may be that the MFA value includes only earlywood, while suppressed trees may be averaged over both earlywood and latewood. This leads to a substantial decrease in precision and accuracy when estimating MFA by interval from pith.

All models developed to predict average cross-sectional MFA (ACMFA) at any age and height were found to be over predicting. Even though the linear models act in a curvilinear fashion, they are still not capable of reproducing the true change of ACMFA at differing height levels. ACMFA appears to be linear or sigmoid in shape at 4.5 feet, above which ACMFA decreases rapidly in nonlinear fashion. However, these patterns were found to vary from tree to tree, with some trees exhibiting an almost perfect linear relationship at all height levels and others representing nonlinear trends.

The nonlinear models developed to describe the change of ACMFA in 3-dimensional space by distance from pith were found to be extremely flexible. These models allowed for changes in the curves representing ACMFA at differing height levels. Given the variation of ACMFA by distance from pith, these models adequately describe the ACMFA at any distance from pith and height.

The models developed here represent the first attempt to describe MFA in 3-dimensional space and can be used in conjunction with localized site index and height equations to predict MFA at any ring, interval from pith, and height for loblolly pine grown in the Southeastern United States. There has been an increased interest in wood properties data within the last decade. Forest products companies are realizing that faster growth may not be the right approach for producing high quality products. With the use of intensive silvicultural management including fertilization, herbaceous weed control, and site preparation, forest managers are growing loblolly pine at rates faster than ever before. However, emphasis is beginning to be placed on the quality of timber produced in addition to the quantity. This is one of the first attempts to model MFA as a function of height, distance, and rings from pith. These models can be used for comparison of intensively managed stands to gain insight into how silvicultural treatments affect MFA, affecting solid wood strength and stiffness and paper properties.

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APPENDICES

APPENDIX A

MICROFIBRIL ANGLE GENERATION OF PSEUDO-RINGS

Table 1. Example of specific gravity ring characteristics needed for microfibril angle pseudo-ring generation. Variables include: Observation, stand number, tree number, ring number, ring width (mm), and disk height.

Obs	STAND	TREENO	RINGNO	RINGWID	DISCHT
1	112	45	1	13.62	25
2	112	45	2	5.46	25
3	112	45	3	5.28	25
4	112	45	4	4.80	25
5	112	45	5	3.36	25
6	112	45	6	2.58	25
7	112	45	7	3.36	25
8	112	45	8	0.96	25

Table 2. Example of microfibril angle data used for pseudo-ring generation. Variables include: Observation, stand number, tree number, distance from pith (mm), and disk height.

Obs	STAND	TREENO	DIST	MFA	DISCHT
1	112	45	1.75	32.03	25
2	112	45	2.75	30.44	25
3	112	45	3.75	26.51	25
4	112	45	4.75	27.00	25
5	112	45	5.75	27.48	25
6	112	45	6.75	24.46	25
7	112	45	7.75	24.59	25
8	112	45	8.75	24.66	25
9	112	45	9.75	24.93	25
10	112	45	10.75	24.17	25
11	112	45	11.75	21.22	25
12	112	45	12.75	19.51	25
13	112	45	13.75	15.33	25
14	112	45	14.75	21.49	25
15	112	45	15.75	16.66	25
16	112	45	16.75	19.24	25
17	112	45	17.75	16.28	25
18	112	45	18.75	14.26	25
19	112	45	19.75	19.19	25
20	112	45	20.75	15.06	25
21	112	45	21.75	13.16	25
22	112	45	22.75	13.80	25
23	112	45	23.75	11.16	25
24	112	45	24.75	18.34	25
25	112	45	25.75	15.60	25
26	112	45	26.75	13.76	25
27	112	45	27.75	10.81	25
28	112	45	28.75	9.48	25

29	112	45	29.75	15.47	25
30	112	45	30.75	12.14	25
31	112	45	31.75	10.42	25
32	112	45	32.75	10.98	25
33	112	45	33.75	12.72	25
34	112	45	34.75	9.95	25
35	112	45	35.75	11.65	25
36	112	45	36.75	12.10	25

SAS code for pseudo-ring generation. In the following program, data SG represents the data from Table 1 and data MFA represents the data from Table 2.

*Note: This code will work for a data set that has any number of trees and any number of height levels. This is the reason for the statement "by stand treeno discht".

```
*************************************************************
     THIS PROGRAM GENERATES PSEUDO-RINGS FOR THE TREES
     ANALYZED FOR MFA AT 1 MM INTERVALS BY USING THE
     RING CHARACTERISTICS FROM THE SPECIFIC GRAVITY
     ANALYSIS USING X-RAYDENSITOMETRY
*************************************************************;

proc sort data=MFA;  by stand treeno discht dist;       run;
proc sort data=SG;   by stand treeno discht ringno;     run;

*BELOW ADDS THE INDIVIDUAL RING WIDTHS;
     data SG1; set SG ;by stand treeno discht ringno;
       retain sumwidth;
        if ringno=1 then do
     sumwidth=0;
         end;
       sumwidth+ringwidt;
     run;

*BELOW FINDS THE SUM OF THE OF THE RING WIDTHS.
THE NEW VARIABLE NAME IS "MSUMWIDTHS" AND
OUTPUTS THIS VALUE TO A DATA SET CALLED MAXSG;
     proc means noprint data=SG1;by stand treeno discht;
         var sumwidth;
        output out=maxsg max=msumwidth;
     run;

*DROPPING UNECCESSARY VARIABLES;
data maxsg; set maxsg;
   drop _type_ _freq_;
 run;
```

```
*BELOW FINDS THE MAXIMUM DISTANCE FROM PITH
FOR THE MFA DATA SET.  THE NEW VARIABLE IS CALLED
"MAXDIST"  AND OUTPUTS THIS VALUE TO
A DATA SET CALLED MAXDIST;
        proc sort data=MFA;     by stand treeno discht;     run;
                 proc means noprint data=MFA;     by stand treeno discht;
             var dist;
          output out=maxdist max=maxdist;
        run;

*DROPPING UNECCESSARY VARIABLES;
        data maxdist; set maxdist;
            drop _type_ _freq_;
         run;

*MERGING THE DATA SETS MAXSG MAXDIST TOGETHER;
        data dists;
            merge maxsg maxdist;
          by stand treeno discht;
        run;

*MERGING THE DATA SET DIST AND SG1 FOR CALCULATION
OF THE WEIGHTED RING WIDTH;
        data all;
            merge SG1 dists;
         by stand treeno discht;
        run;

*COMPUTING THE WEIGHTED RING WIDTH;
        data all1;   set all;
            wtring=ringwidt*(maxdist/msumwidth);
        run;

*MAKING A COPY OF DATA SET ALL1;
        data ringsum;   set all1;
        run;

        proc sort data=ringsum;
           by stand treeno discht ringno;
        run;
*USING A DO LOOP TO GET THE NUMBER OF 1 MM OBSERVATIONS
FOR EACH RING.  IF WTRING FOR RING 1 WAS FOUND TO BE 12.4 MM, THE DO
LOOP WOULD MAKE 12 OBSERVATIONS FOR RING 1;
        data one;   set ringsum;
          nrngwid=round(wtring);
             do i=1 to nrngwid;
```

```
        drop i;
      output;
    end;
  run;

*APPLYING A COUNT VARIABLE FOR EVERY OBSERVATION.
THIS WILL ALLOW THE USER TO MERGE THE MFA DISTANCE
DATA AND THE SPECIFIC GRAVITY RING DATA;
  data two;  set one;
        by stand treeno discht;
            retain ncount;
         if first.discht then do;
       ncount=0;
     end;
   ncount=ncount+1;
  run;

*APPLYING THE NCOUNT VARIABLE TO THE MFA DATA
FOR MERGING OF THE TWO DATA SETS BY A COMMON
VARIABLE;
  data mfa2;    set mfa;
         by stand treeno discht;
           retain ncount;
         if first.discht then do;
       ncount=0;end;
     ncount=ncount+1;
  run;

proc sort data=two;     by stand treeno discht ncount;    run;
proc sort data=mfa2;    by stand treeno discht ncount;    run;


*MERGING THE MFA DATA AND THE SPECIFIC GRAVITY
DATA BY STAND TREENO DISCHT AND NCOUNT;
  data merger;
       merge two mfa2;
     by stand treeno discht ncount;
  run;


*USING THE MEANS STATEMENT TO GET THE AVERAGE
RING MFA;
  proc sort data=merger2;
       by  stand treeno discht ringno ;
  run;
```

```
proc means data=merger2 noprint;
          by  stand treeno discht ringno;
       var mfa ;
     output out=finalmfa mean=;
run;

proc print data=finalmfa;   run;
```

Table 3. Final output of SAS "Pseudo-Ring" program. Variables include: Observation, stand number, tree number, disk height, and ring microfibril angle.

Obs	STAND	TREENO	discht	RINGNO	MFA
1	112	45	25	1	24.7946
2	112	45	25	2	17.5860
3	112	45	25	3	14.4740
4	112	45	25	4	14.6275
5	112	45	25	5	12.3633
6	112	45	25	6	10.7000
7	112	45	25	7	11.4400
8	112	45	25	8	12.1000

APPENDIX B

CALCULATION OF CROSS-SECTIONAL MFA FOR ANY AGE

Table 1. Example of ring characteristics needed for calculation of cross-sectional microfibril angle at any age. Variables include: Observation, stand number, tree number, ring number, disk height, ring number, ring MFA, and ring width (mm).

Obs	STAND	TREENO	discht	RINGNO	MFA	wtring
1	112	45	25	1	24.7946	12.6802
2	112	45	25	2	17.5860	5.0833
3	112	45	25	3	14.4740	4.9157
4	112	45	25	4	14.6275	4.4688
5	112	45	25	5	12.3633	3.1282
6	112	45	25	6	10.7000	2.4020
7	112	45	25	7	11.4400	3.1282
8	112	45	25	8	12.1000	0.8938

SAS code for weighted whole disk MFA at any age. In the following program, data wt_ring_mfa represents the data from Table 1.

*Note: This code will work for a data set that has any number of trees and any number of height levels. This is the reason for the statement “by stand treeno discht”.

```
*****************************************************************
        THIS SAS MACRO PROGRAM CALCULATES THE  WHOLE DISK
        WEIGHTED WITH RESPECT TO BASAL AREA CROSS-SECTIONAL
        MFA AT ANY AGE;
*****************************************************************;
* MAKING A COPY OF THE ORIGINAL DATA SET;
        data runmacro; set wt_ring_mfa;  run;

*CREATING A DUMMY DATA SET THAT WILL BE USED TO APPEND
THE DATA SETS THAT THE MACRO CREATES FOR EACH RING;
        data basemac;
              stand=99999;    treeno=99999;     discht=99999;  _type_=99999;
                 _freq_=99999;    bamfasum=99999;     widmfasm=99999;
            ringbas=99999; corebmfa=99999;
        run;

*THE PROC MEANS STATEMENT BELOW WILL TELL YOU THE
MAXIMUM NUMBER OF RINGS IN THE DATA SET
        proc means data=runmacro max;
           var ringno;
        run;

        options symbolgen mlogic mprint;
```

```
%macro ringmacro(START=);
     DATA ringmac1; SET runmacro;
          by stand treeno discht  ringno;
               if ringno le &START ;
            retain lastdib cumlba;
         if ringno=1 then do;
    lastdib=0;
  cumlba=0;
end;

*  MFA MEASURED IN MILLIMETERS CONVERTED TO INCHES
 AND CALCULATES BASAL AREA IN SQUARE FEET;
 lastdib=lastdib+(2*wtring/25.4);
           basalarea = .005454154 * lastdib**2-cumlba;
         earldib=lastdib;
       cumlba=cumlba+basalarea;
  ringba=basalarea;

* CAL WEIGHTED INCREMENT CORE MFA.;
  widtxmfa = wtring*mfa;

* CAL WEIGHTED BY RING BASAL AREA INCREMENT MFA;
  baxmfa = ringba*mfa;

  run;

  proc sort data=ringmac1; by stand treeno discht;   run;

  proc means noprint;
        by stand treeno discht;
             var baxmfa widtxmfa ringba;
        output out=core1 sum= bamfasum widmfasum ringmasum;
  run;

*RING VALUES WEIGHTED BY RING BASAL AREA TO ESTIMATE
CROSS-SECTIONAL DISK MFA;
  data core1;  set core1;
     corebmfa=bamfasum / ringbas;
  run;

  proc append base=basemac data=core1;  run;

  %mend ringmacro;


*******************************************************
```

```
THIS SAS MACRO %DOIT  BELOW CALLS IN THE MACRO
%RINGMACRO AND CALCULATES THE WEIGHTED BY
BASAL AREA CROSS-SECTIONAL MFA FOR EVERY RING;
*******************************************************;
          %macro doit;
                    %local start;
 *THE NUMBER 8 WAS THE LARGEST RING VALUE FOUND
FOR THIS TREE.;
                           %do i=1 %to 8 %by 1;
                       %let j=%eval(&i);
                   %let start=&j;
                 %ringmacro(START=&start);
              %end;
          %mend doit;

* THIS CALLS THE MACRO %DOIT AND RUNS THE PROGRAM;
          %doit;

*THE SORT STATEMENT DELETES DUPLICATE OBSERVATIONS.
FOR EXAMPLE IF THE DATA SET wt_ring_mfa HAD TWO TREES,
AND ONE HAD 8 RINGS AND THE OTHER 15, THE MACRO
WOULD MAKE 7 DUPLICATE OBSERVATIONS FOR THE
WEIGHTED CROSS-SECTIONAL MFA AT AGE 8.
THIS IS DUE TO THE STATEMENT IN THE %RINGMACRO
 if ringno le &START.  AFTER THE MACRO DOIT EVALUATES
8, IT WILL CONTINUE TO CALCULATE THE AGE 8 CROSS-
SECTIONAL MFA UNTIL IT REACHES THE 15TH RING;

          proc sort data=basemac nodup out=basemac2;
              by stand treeno discht _freq_;
          run;

          data basemac2;   set basemac2;
                 if stand=99999 then delete;
              age=_freq_;
            drop _type_ _freq_ widmfasm widsgsum ringage bamfasum;
          run;
```

Table 2. Final output of SAS "Weighted Cross-Sectional-ring MFA" program. Variables include: Observation, stand number, tree number, disk height, ring basal area, weighted cross-sectional microfibril angle, and age of corresponding corebmfa.

Obs	stand	treeno	discht	ringbas	corebmfa	age
1	112	45	25	0.005437	24.7946	1
2	112	45	25	0.010670	21.2592	2
3	112	45	25	0.017393	18.6366	3
4	112	45	25	0.024923	17.4254	4
5	112	45	25	0.030997	16.4334	5
6	112	45	25	0.036110	15.6215	6
7	112	45	25	0.043355	14.9228	7
8	112	45	25	0.045546	14.7870	8

APPENDIX C

CALCULATION OF CROSS-SECTIONAL MFA BY DISTANCE FROM PITH

Table 1. Example of microfibril angle data used to calculate weighted cross-sectional MFA by distance from pith. Variables include: Observation, stand number, tree number, distance from pith (mm), and disk height.

Obs	STAND	TREENO	DIST	MFA	DISCHT
1	112	45	1.75	32.03	25
2	112	45	2.75	30.44	25
3	112	45	3.75	26.51	25
4	112	45	4.75	27.00	25
5	112	45	5.75	27.48	25
6	112	45	6.75	24.46	25
7	112	45	7.75	24.59	25
8	112	45	8.75	24.66	25
9	112	45	9.75	24.93	25
10	112	45	10.75	24.17	25
11	112	45	11.75	21.22	25
12	112	45	12.75	19.51	25
13	112	45	13.75	15.33	25
14	112	45	14.75	21.49	25
15	112	45	15.75	16.66	25
16	112	45	16.75	19.24	25
17	112	45	17.75	16.28	25
18	112	45	18.75	14.26	25
19	112	45	19.75	19.19	25
20	112	45	20.75	15.06	25
21	112	45	21.75	13.16	25
22	112	45	22.75	13.80	25
23	112	45	23.75	11.16	25
24	112	45	24.75	18.34	25
25	112	45	25.75	15.60	25
26	112	45	26.75	13.76	25
27	112	45	27.75	10.81	25
28	112	45	28.75	9.48	25
29	112	45	29.75	15.47	25
30	112	45	30.75	12.14	25
31	112	45	31.75	10.42	25
32	112	45	32.75	10.98	25
33	112	45	33.75	12.72	25
34	112	45	34.75	9.95	25
35	112	45	35.75	11.65	25
36	112	45	36.75	12.10	25

SAS code for weighted whole disk MFA by distance from pith. In the following program, data wt_dist_mfa represents the data from Table 1.

*Note: This code will work for a data set that has any number of trees and any number of height levels. This is the reason for the statement “by stand treeno discht”.

```
*************************************************************
        THIS SAS MACRO PROGRAM CALCULATES THE  WHOLE DISK
        WEIGHTED WITH RESPECT TO BASAL AREA CROSS-SECTIONAL
        MFA AT ANY DISTANCE FROM PITH;
*************************************************************;


*MAKING A COPY OF THE DATA SET AND CONVERTING
DISTANCE FROM mm TO INCHES.;
        data one;  set   wt_dist_mfa ;
             distinch=dist/25.4;
        run;

*FINDING THE MAXIMUM  AND MINIMUM DISTANCE FROM PITH WHICH WILL BE
USED BELOW;
         proc means noprint data=one max min;
            var distinch;
          run;

*MAKING NEW VARIABLES TO BE COMPATIBLE
WITH THE "WEIGHTED MFA AT ANY AGE" MACRO;
        data stripdat  ;set one;
              ringno =distinch;
           earlwidt =distinch;
        run;

        data strpstar; set stripdat;
            proc sort;   by stand treeno discht;
        run;

* FIND STATING POINT FOR MEASUREING MFA ON CORE;
        proc means noprint data=strpstar;
                by stand treeno discht;
              var distinch ;
           output out= mfaminda min=distmin;
        run;

        proc sort data= mfaminda;    by stand treeno discht;    run;
        proc sort data=stripdat;         by stand treeno discht;    run;


*MERGING THE MINIMUM DISTANCE DATA TO
THE STRIPDAT DATA SET;
```

```
data stripdat;
     merge stripdat mfaminda;
   by stand treeno discht;
run;

data ringsum; set stripdat;
       drop _type_ _freq_;
   proc sort ;  by stand treeno discht distinch;
run;

*CREATING A DUMMY DATA SET THAT WILL BE USED TO APPEND
THE DATA SETS THAT THE MACRO CREATES FOR EACH RING;
data basemac;
         stand=99999;treeno=99999;discht=99999;
             _type_=99999;_freq_=99999;bamfasum=99999;
        ringbas=99999;coreBmfa=99999;
run;


options symbolgen mlogic mprint;
              %macro ringmacro(START=);
                   data ringmac1; set rinsum;
                        by stand treeno discht  ringno;
                    if ringno le &START ;
                 retain lastdib cumlba;
             if ringno=distmin then do;
        lastdib=0;
   cumlba=0;
 end;

lastdib=lastdib+(2*EARLWIDT);
       basalarea = .005454154 * lastdib**2-cumlba;
             earldib=lastdib;
         cumlba=cumlba+basalarea;
ringba=basalarea;

* CAL WEIGHTED BY RING BASAL AREA INCREMENT MFA.;
baxmfa = ringba*mfa;

run;


proc sort data=ringmac1;    by stand treeno discht;    run;

proc means noprint;
         by stand treeno discht;
```

```
            var baxmfa ringba;
          output out=core1 sum=  bamfasum   ringbasum ;
        run;

*DISTANCE VALUES WEIGHTED BY RING BASAL AREA TO ESTIMATE
CROSS-SECTIONAL DISK MFA;

        data core1; set core1;
            corebmfa = bamfasum   / ringbasum;
        run;

        proc append base=basemac data=core1;  run;

        %mend ringmacro;

************************************************************
        THIS SAS MACRO %DOIT  BELOW CALLS IN THE MACRO
        %RINGMACRO AND CALCULATES THE WEIGHTED BY
        BASAL AREA CROSS-SECTIONAL MFA BY DISTANCE;
************************************************************;
          %macro doit;
              %local start;
                  %do i=0 %to 145 %by 1;

*THE MAXIMUM DISTANCE IN INCHES WAS FOUND TO BE
  1.44 INCHES THE DO LOOP IN THIS MACRO WILL ONLY
  EVALUATE WHOLE NUMBERS.  SO BELOW WHEN
  EVALUATING THE MACRO, WE DIVIDE BY 100.  SO THE
  RANGE OF DISTANCES GOES FROM 0 TO 1.45 BY .01 INCHES;
                      %let j=%eval(&i);
                    %let start=&j/100;
                 %ringmacro(START=&start);
              %end;
        %mend doit;

* THIS CALLS THE MACRO %DOIT AND RUNS THE PROGRAM;
        %doit;

*THE SORT STATEMENT DELETES DUPLICATE OBSERVATIONS.
FOR EXAMPLE IF THE DATA SET wt_dist_mfa HAD TWO TREES,
AND ONE HAD A DISTANCE OF 4.5 INCHES AND THE OTHER
6.2 INCHES, THE MACRO WOULD MAKE 7 DUPLICATE
OBSERVATIONS FOR THE WEIGHTED CROSS-SECTIONAL MFA
AT DISTANCE 4.5 INCHES.THIS IS DUE TO THE STATEMENT IN
THE %RINGMACRO if ringno le &START.  AFTER THE MACRO
DOIT EVALUATES 4.5, IT WILL CONTINUE TO CALCULATE
```

```
THE 4.5 INCH CROSS-SECTIONAL MFA UNTIL IT REACHES
THE 6.2;
          proc sort data=basemac out=basemac2 nodup;
                by stand treeno discht _FREQ_;
          run;


*DELETING THE DUMMY VARIABLES;
          data basemac2;set basemac2;
                  if stand=99999 then delete;
               drop _type_;
          run;

*CREATING A VARIABLE TO MERGE BY;
          data two;  set one;
              _freq_=_n_;
          run;


*MERGING BASEMAC2 AND TWO FOR THE FINISHED
OUTPUT;
          data finish;
              merge basemac2 two;
                   by stand treeno discht _freq_;
              keep stand treeno discht dist distinch corebmfa mfa;
          run;

          proc print data=final;
```

Table 2. Final output of SAS “Weighted Cross-Sectional-Dist MFA” program. Variables include: Observation, stand number, tree number, disk height, distance weighted cross-sectional disk MFA, distance from pith (mm), MFA, distance from pith (inches).

Obs	stand	treeno	discht	coreBmfa	DIST	MFA	distinch
1	112	45	25	32.0300	1.75	32.03	0.06890
2	112	45	25	30.6805	2.75	30.44	0.10827
3	112	45	25	27.7508	3.75	26.51	0.14764
4	112	45	25	27.3024	4.75	27.00	0.18701
5	112	45	25	27.3946	5.75	27.48	0.22638
6	112	45	25	26.0466	6.75	24.46	0.26575
7	112	45	25	25.4467	7.75	24.59	0.30512
8	112	45	25	25.1531	8.75	24.66	0.34449
9	112	45	25	25.0769	9.75	24.93	0.38386
10	112	45	25	24.7918	10.75	24.17	0.42323
11	112	45	25	23.7508	11.75	21.22	0.46260
12	112	45	25	22.5989	12.75	19.51	0.50197
13	112	45	25	20.7502	13.75	15.33	0.54134
14	112	45	25	20.9271	14.75	21.49	0.58071
15	112	45	25	19.9644	15.75	16.66	0.62008
16	112	45	25	19.8097	16.75	19.24	0.65945
17	112	45	25	19.0942	17.75	16.28	0.69882
18	112	45	25	18.1616	18.75	14.26	0.73819
19	112	45	25	18.3509	19.75	19.19	0.77756
20	112	45	25	17.7719	20.75	15.06	0.81693
21	112	45	25	16.9947	21.75	13.16	0.85630
22	112	45	25	16.4781	22.75	13.80	0.89567
23	112	45	25	15.6515	23.75	11.16	0.93504
24	112	45	25	16.0537	24.75	18.34	0.97441
25	112	45	25	15.9883	25.75	15.60	1.01378
26	112	45	25	15.6782	26.75	13.76	1.05315
27	112	45	25	15.0234	27.75	10.81	1.09252
28	112	45	25	14.3020	28.75	9.48	1.13189
29	112	45	25	14.4492	29.75	15.47	1.17126
30	112	45	25	14.1671	30.75	12.14	1.21063
31	112	45	25	13.7229	31.75	10.42	1.25000
32	112	45	25	13.4071	32.75	10.98	1.28937
33	112	45	25	13.3302	33.75	12.72	1.32874
34	112	45	25	12.9622	34.75	9.95	1.36811
35	112	45	25	12.8231	35.75	11.65	1.40748
36	112	45	25	12.7485	36.70	12.10	1.44488