AGE DEPENDENCE OF SPIRAL GRAIN IN WHITE OAKS (*QUERCUS ALBA*) IN SOUTHCENTRAL ILLINOIS

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's Thesis of

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ABSTRACT

Spiral grain, the alignment of wood fibers (tracheids) to the longitudinal axis of trees, is thought to be an indicator of old age and is a phenomenon that has been only studied with destructive sampling methods (cutting down trees). In this study, the usefulness of non-fatal sampling methods and existing methods to quantify spiral grain patterns in living and dead deciduous trees are examined, particularly in white oaks (*Quercus alba*). The overall goal is to determine if spiral grain growth is a reasonable indicator of tree age. Methods that were tested included the use of a 12 mm increment borer (non-fatal sampling method) and Brazier's method (1965) of analyzing grain angles along just one diagonal to get a representative grain angle for the whole circumference at a certain height on a tree.

The 12 mm increment borer did not produce consistent results in this study; therefore, destructive sampling is necessary to study spiral grain in white oaks. Brazier's method (1965) should not be used in white oaks and should not be applied universally to all tree species. Samples from living and dead trees vary in severity and direction of spiral grain. The climatic factors that are most limiting to tree growth do not influence spiral grain growth in white oaks in this stand. Severe spiral grain does in general seem to be an indicator of age in white oaks, although most trees have severe left spiral grain and not right spiral grain. However, a tree without severe spiral grain is not necessarily young. To judge the severity of spiral grain, grain angles have to be examined in the outermost layer of the wood and not in the bark.

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Chapter 1

INTRODUCTION

Spiral grain, the alignment of wood fibers (tracheids) to the longitudinal axis of trees, has fascinated scientists for over 150 years. Being visible in trees and poles, causes of spiral grain growth are an interest of foresters, botanists, and geographers. Articles concerning spiral grain have been published in diverse journals such as New Zealand Journal of Forestry Science, Canadian Journal of Botany, Trees: Structure and Function, Holz als Roh- und Werkstoff (Wood as material), Forest Products Journal, and Mitteilungen der Deutschen Dendrologischen Gesellschaft (Information by the German Dendrological Association). In part, a need to understand spiral grain growth is motivated by demands of the timber industry to understand causes and processes that lead to spiral grain (Knigge and Schulz 1959, Kliger 2001). The timber industry loses millions of dollars when trees are harvested only to realize that those logs are not usable due to severe spiraling of the wood (McBride 1967, Banks 1969, Bechtel *et al.* 1990, Koch and Schlieter 1991). Therefore, causality of spiral grain in trees has received much attention (*e.g.* Baumert 1925, Cown and McConchie 1981, 1982, Burdon and Low 1992).

Causes of spiral grain are thought to include exogenous factors such as wind and gravity and endogenous factors such as longitudinal cell division and genetics. Although this phenomenon has been studied for many years, spiral grain growth is still not fully understood. Few aspects of spiral grain growth are agreed upon among spiral grain researchers (see reviews by Harris 1989, Kubler 1991, and Danborg 1994). However, most research suggests that spiral grain is a normal aspect of tree growth.

A lot of research has been done on the affects of age of the trees on the grain angles (Champion 1925, 1927a, 1927b, and 1929, Burger 1941, Northcott 1957, Kremple 1970, Whyte *et al.* 1980, Bues 1992, Cameron *et al.* 1995, Gjerdrum *et al.* 2002). The large body of literature on the relationship between tree age and grain angle could be due to the methodologies used: age related to a spiral grain angle is almost a "by-product" of known methods. In order to study spiral grain in trees, individual growth layers along a radius have to be removed and spiral grain angles are measured at each exposed growth layer (Noskowiak 1959, Gerischer and Kromhout 1964, Brazier 1965, Wobst *et al.* 1994).

Usually, researchers studying grain angles between growth layers cut down trees and take cross-sections (Harris 1989, Koch and Schlieter 1991, Danborg 1994). From these studies we know that spirality for the whole life of the tree cannot be identified within a stem just by looking at or under the bark. Examinations of the cambium were the focus of early spiral grain studies in the first half of the 20th century (Butler 1931, Herrick and Moore 1932, Sears 1950).

In this study, age dependency of spiral grain growth was examined. Although extensive research has been conducted on spiral grain growth (Figure 1.1), existing research does not cross disciplinary boundaries. Spiral grain is one of the characteristics for old tree selection in dendrochronology (Fritts 2001), but causes of spiral grain are not well understood. One goal of the current study is to bring literature on spiral grain formation to the dendroecological community.

This study also examined methodologies for assessing spiral grain in living trees (*i.e.*, use of a sampling method that does not kill the tree). This research project is one of the first to use a 12 mm diameter increment borer on living trees to assess spiral grain in white oak (*Quercus alba*). A previous study (Noskowiak 1959) that tried to use a 4.5 mm diameter increment borer, failed because of deformation of the core after removal from the tree and the size (diameter) of the core. However, Noskowiak (1968) successfully used a 10 mm increment borer to analyze spiral grain growth although his method of measuring grain angles was rather complex. Harris (1984) suggested a simplified method that was not tested prior to this thesis (will be described later).

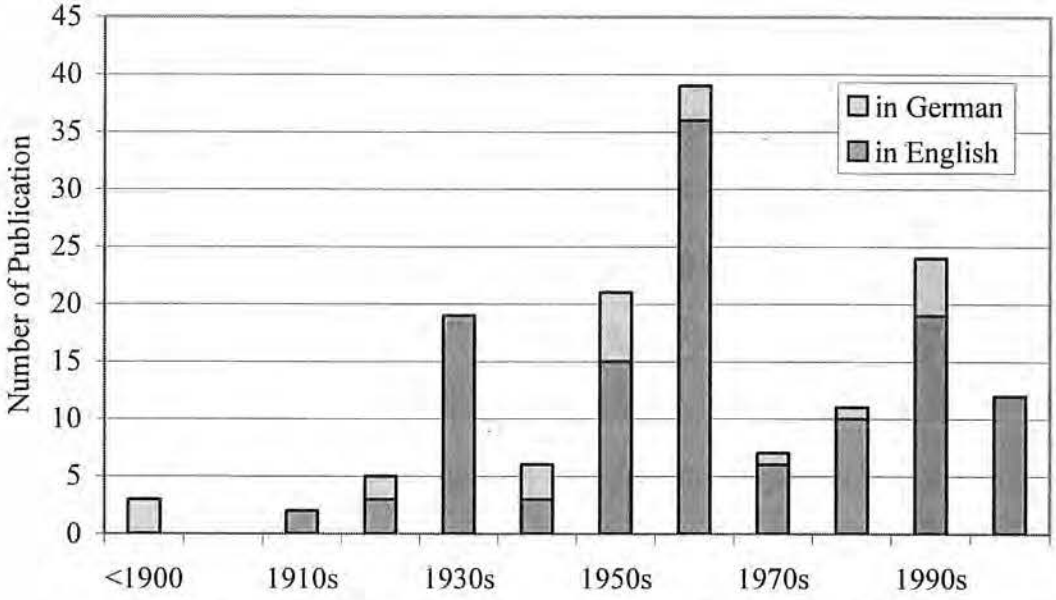

Figure 1.1. Number of publications on spiral grain after searching databases such as OCLC, EBSCOhost, and ProQuest, and looking at references in articles and books. Includes German as well as English papers.

As another component of this study, I tested if grain angles become more pronounced after the tree has died. When in the field, spiral grain is observed in debarked trees or snags while in living trees spiral grain is not as apparent. Studies focusing on changes in spirality after trees are harvested indicate that spiral grain changes with loss of moisture (Lowery and Erickson 1967, Koch and Schlieter 1991).

This study also examined Brazier's method of assessing spiral grain in cross-sections from dead trees (Brazier 1965). In order to save time, Brazier suggested that grain angles could be measured along two opposing radii in a cross-section and the averaged results of the two radii would represent the spiral grain angle for the whole circumference. He supported this hypothesis with a high correlation coefficient for Larch (*Larix* spp.). However, this method proved not to be applicable for all species (Wobst *et al.* 1994).

Climate and ring width analysis is a standard application in dendrochronology. Climate has a major affect on a tree and its growth rate, however, it is not clear how climate affects spiral grain formation. An analysis on the extent to which different climate variables, such as temperature, precipitation, and Palmer Drought Severity Index (PDSI), affect the growth of spiral grain was also examined in this study.

With the loss of millions of dollars a year for the timber industry, spiral grain research is still an important area of investigation. For several reasons, non-fatal methods for analyzing grain angles in tree are desirable. In addition, time-saving laboratory methods are also highly desirable. Assessing the usefulness of such non-fatal and time-saving methods is a crucial part for spiral grain research.

1.1. Objectives

The purpose of this study is to examine non-fatal sampling methods and to analyze spiral grain patterns in living and dead deciduous trees, particularly white oaks (*Quercus* *alba*). Another goal of this study is to summarize spiral grain research for the dendrochronological community. The ultimate goal is to determine if spiral grain growth is a good indicator of tree age. Methods that were tested include the use of a 12 mm increment borer (non-fatal sampling method) and Brazier's method (1965) of averaging spiral grain measurements from opposite sides of the tree taken from one diameter on a cross-section to determine grain angles within growth layers at a specific height.

1.2. Hypotheses

This research is designed to answer the following five research hypotheses:

1. Spiral grain growth is affected by climate as described by temperature, precipitation, or Palmer Drought Severity Index through time.
2. It is technically/physically possible to study spiral grain growth in deciduous trees, particularly white oaks, using a 12 mm increment borer.
3. Brazier's method is not an accurate technique to determine grain angles in white oak trees.
4. Spiral grain angles become more enhanced in white oaks after trees have died.
5. Spiral grain growth is a good indicator of tree age in white oaks.

To address these hypotheses I sampled living and dead white oak trees with a 12 mm increment borer and collected cross-sections from dead white oak trees. In the laboratory, these samples were processed and grain angles determined. Finally, statistical analyses have been used to test these hypotheses.

1.3. Significance

The stimulus for this study arose from the belief of dendrochronologists that spiral grain growth is related to age (personal communication with dendrochronologists). Despite this belief, they cannot explain this phenomenon. Digging deeper into the topic, it became apparent that much research has been done on spiral grain growth that has been published in biological and forestry literature. Thus, one goal of this study is to summarize spiral grain research for the dendrochronological community and to determine if grain angles are indeed a good indicator for the age of trees, particularly in deciduous trees.

More important, though, is the need to test non-fatal sampling methods for use in studying spiral grain. So far, only destructive sampling methods (*i.e.* cutting cross sections with a chainsaw) have successfully determined grain angle in research studies. Noskowiak (1959) tried to use a 4.5 mm increment borer to study spiral grain but was not successful. He mentioned, however, that a 10 mm increment borer might lead to more promising results and suggested further studies because a 10 mm increment borer was not available to him. In a study in 1968, Noskowiak successfully tested the use of a 10 mm increment borer and concluded on the usefulness of this method. The desire for non-fatal sampling methods becomes apparent when looking at the extensive studies that have been done to date. For a spatial analysis of spiral grain pattern, large areas and thus a lot of trees have to be cut down to take cross-sections. This does not only involve getting permission to harvest trees for research, but also logistic challenges. Cross-sections are heavy and have to be carried out of the field, and trees are dangerous to fell. Permission to core trees using increment borers may be easier to obtain, especially with recent publications about effects of coring trees (Grissino-Mayer 2003, Weber and Mattheck 2003). Weber and Mattheck concluded that coring does not introduce rot or fungi to trees, nor does it enhance already existing rot or fungi.

In relation to age dependency, it also seems to be important to realize that there might be a difference in spirality between living and dead trees. In the field, spirality is most obvious in dead trees while in living trees spiral grain growth is harder to detect. That might be due to the fact that grain angles become more pronounced in dead trees, which could be due to a loss of moisture (Lowery and Erickson 1967; Koch and Schlieter 1991). Therefore, spiral grain might not be an indicator of tree age, as dendrochronologists assume, but an indicator of how long a tree has been dead.

The established method of Brazier (1965), which takes only one diagonal on a cross-section to determine grain angles in a growth layer at a specific height, seems to lack accuracy for some species (Wobst *et al.* 1994). Although Brazier (1965) found a high correlation between different diagonals on one cross-section in Larch (*Larix* spp.), this observation was not confirmed by Wobst *et al.* (1994), who used Ash (*Fraxinus* spp.) and Douglas fir (*Pseudotsuga menziesii*). Therefore, Brazier's method should not be universally applied to all species as has been done by many studies (*e.g.* Cown *et al.* 1991, Burdon and Low 1992, Cameron *et al.* 1995). In this study, I tried to determine whether Brazier's method is applicable to white oak trees.

Chapter 2

BACKGROUND

2.1. History

Spiral grain growth has interested scientists for over 150 years. The earliest research was conducted in the 19th century in Germany (Braun 1854, Hartig 1895). At that time, scientists were concerned with endogenous factors such as longitudinal cell division (Hartig 1895). Hartig (1895) suggested that spiral grain growth is the normal growth pattern while straight grain is the anomaly. He also suggested that the direction of the longitudinal cell division is the cause for spiral grain patterns. Working with pines (*Pinus* spp.), Hartig (1895) also recognized the pattern of spiral grain growth in conifers that has been repeatedly verified by scientists (Champion 1925, 1927a, Rault and Marsh 1952, Kennedy and Elliott 1957, Northcott 1957). Although the timescale varies, spiral grain pattern over time in conifers can be described as follows: while in general young conifers spiral to the left, this spirality changes over time to straight grain and goes over to right spiral grain in older trees. This change is permanently recorded in trees in each growth layer.

In the first half of the 20th century, research was done on endogenous and exogenous factors. However, Noskowiak (1959) observed researchers often looked at or under the bark to test hypotheses of spirality. Noskowiak (1959) suggested that grain angles under the bark were not representative of average grain angles over the life of the tree. Other researchers such as Hartig (1895), Harris (1989), and Wobst *et al.* (1994) have supported this hypothesis. Even though spiral grain in the outer xylem does not represent the spiral grain pattern in the whole stem, it is an accurate measure of spirality at that point in time.

In his extensive work on spiral grain, Noskowiak (1959) summarized factors that have been studied as causes for spiral grain growth. His summary includes the "analogy to other spiral phenomena in nature" (pg.77), longitudinal cell division, genetic factors, and environmental factors such as rotations of the Earth, wind, light and solar movement, aspect, altitude, soils, density, snow and wind damage, site quality, and biotic factors. These factors continue to be studied today. However, no conclusive results have been presented to date, but the consensus of most researchers is that genetic components play an important role (Harris 1989, Kubler 1991, Danborg 1994).

More recent studies focus on consequences of the use of spiral-grained trees (Bechtel *et al.* 1990, Koch and Schlieter 1991). For example, while early studies of spiral grain studied grain angles for their own sake (Knigge and Schulz 1959, Bannan 1966), current research is focused on the effects on service poles (*e.g.* telephone poles or poles used in construction) or silvicultural management (*e.g.* the effect of thinning on spiral grain growth).

2.2. Hypotheses of Spiral Grain Formation

Spiral grain is defined as the alignment of wood fibers (tracheids) to the longitudinal (vertical) axis of the tree (Figure 2.1). Left spiral grain is usually denoted with positive grain angles (angles larger than zero) and right spiral grain usually with negative grain angles (angles smaller than zero) (Costa-e-Silva *et al.* 2000).

Scientists agree that spiral grain growth is the normal growth pattern in trees, and straight grain (*i.e.* grain with zero degree deviation from the tree axis) is not the common growth pattern (Harris 1989, Kubler 1991, and Danborg 1994). However, it is not clear

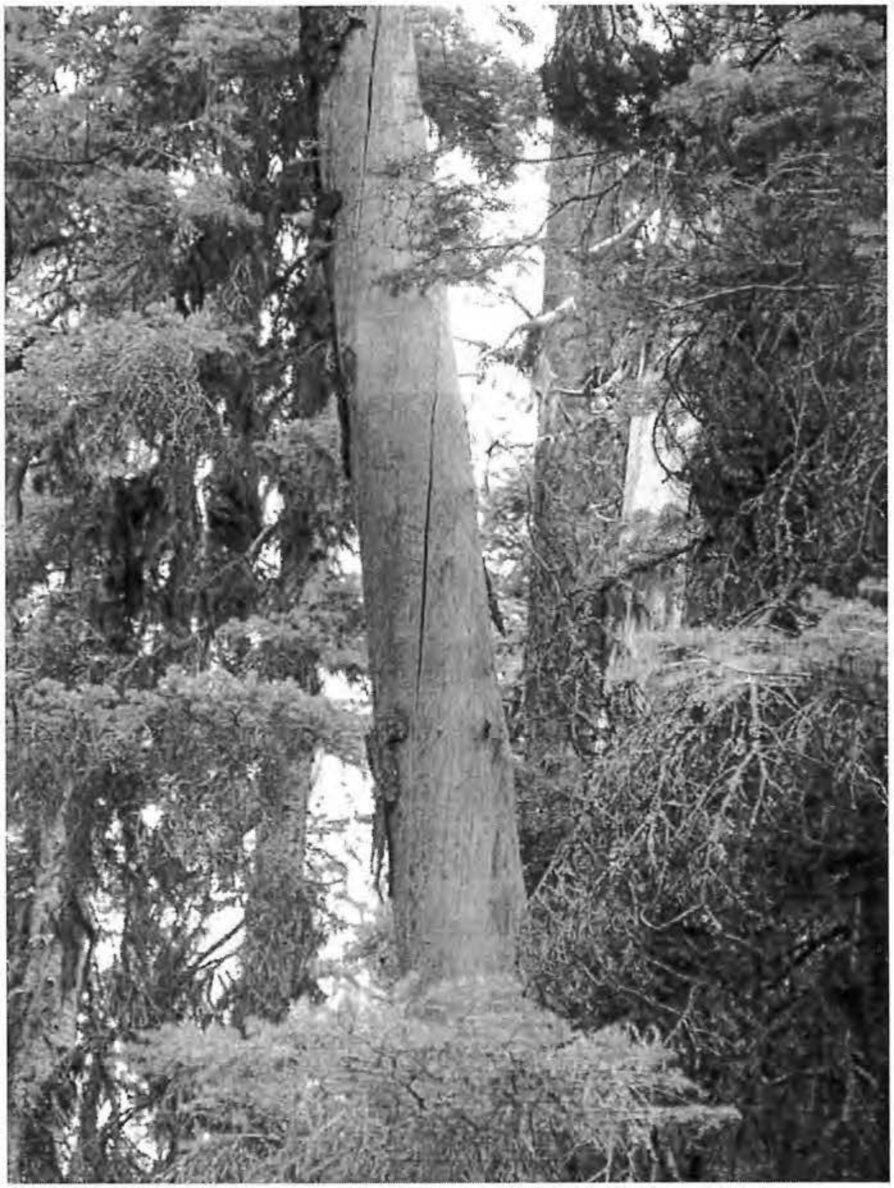

Figure 2.1. Right spiral grain in Glacier National Park (possibly white bark pine [*Pinus albicaulis]*).

why spirality is advantageous to trees and straight grain provides a disadvantage, nor is the causality of spiral grain growth clear. Several researchers suggested, as summarized by Noskowiak (1959:77), that "spiral grain in trees is still another manifestation of an essential 'spirality' in nature, *i.e.*, that many living things exhibit a spiral organization in their structure, form or movement" (Schaeffer 1931, Seifiz 1933a, 1933b, Iterson 1953).

Several authors summarized hypotheses for causes of spirality in trees (Noskowiak 1959, Harris 1989, Kubler 1991, Danborg 1994). Noskowiak (1959) distinguished between endogenous and exogenous factors, but he did not use these terms. He discussed cambial cell division (also known as longitudinal cell division [Hartig 1895]) and the influence of genetics as endogenous factors, and the environment as an exogenous factor.

2.2.1. Endogenous Factors

Hartig (1895) was one of the first to study growth and division of longitudinal cells (tracheids) as a cause of spiral grain. He found a positive correlation between direction of cell division and spiral grain growth. Later research by Bannan (1966) and Hejnowicz and Zagorska-Marek (1974) supported this hypothesis. Tracheids grow longitudinally and circumferentially. When growing, longitudinal tracheids divide in various ways and then extend up or down. By extending vertically, the tips of adjacent cells slide along each other (in opposite directions) with the lower tip to right or left of the upper tip (Figure 2.2). This process is believed to result in spiral grain growth (Hartig 1895, Bannan 1966, Hejnowicz and Zagorska-Marek 1974).

Heredity is the second endogenous factor. A common view today is that spiral grain growth is initiated by genetic factors (Harris 1989, Kubler 1991, Danborg 1994). Cahalan

(1985) showed that spiral grain growth in Sitka spruce (*Picea sitchensis*) is under strict genetic control. However, these trees still show differences in spiral grain growth that could be due to environmental factors.

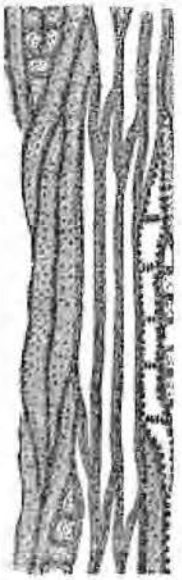

Figure 2.2. Tracheids grow longitudinally and circumferentially. After dividing, the tips of adjacent cells slide along each other in opposite directions, which results in spiral grain after Hartig (1895) (picture from Carrington 2004, New flowering plant features).

2.2.2. Exogenous Factors

Different environmental factors are believed to influence spiral grain growth such as gravity, wind, light and solar movement, aspect, slope, soil, altitude, water distribution, or injuries to the tree (Noskowiak 1959, Harris 1989, Danborg 1994). Gravity could be a factor because trees have to "pump" water and nutrients up the stem, and by spiraling the cells around the tree, it might be more efficient for the tree to distribute water and nutrients up to the crown. However, the fact that spiral grain growth also occurs in roots and branches does not support this hypothesis (Kubler 1991).

Although several research projects on how wind affects spiral grain growth have been conducted (*e.g.*, Wentworth 1931, Yeager 1931, and Howard 1932), results do not seem to be conclusive. Eklund and Sall (1999) found significant correlation between wind (did not specify whether direction or speed) and spiral grain growth. Mattheck and Kubler (1997) argued that wind induces spiral grain growth because it would reduce lever arms. However, trees within stands and in sheltered places also have a high proportion of spiral grain, and this fact is not explained (Kremple 1970). Harris (1989:81) mentioned that although wind might not be a primary factor for the twisting of trees, it "deserves some consideration" as a contributor to spiraling grain angles.

Studies on light and solar movement as well as movement of the Earth and their influence on spiral grain growth have been reviewed by Noskowiak (1959) and Harris (1989). Both concluded based on previous studies that these two factors are not responsible for spiral grain formation. Both cited, for example, Butler (1931) who thought heliotropism was responsible for spiraling grain, *i.e.*, trees follow the sun like a sunflower does and therefore induces spiral grain. However, as Noskowiak (1959) pointed out, Butler (1931) analyzed tree stems for spiral grain and ignored the pattern within the stem. Also, Noskowiak (1959) and Harris (1989) mentioned a hypothesis by A. H. Kennedy (as referenced to in a paper by Thunell [1951]). Kennedy believed that because of Earth's rotation, an atmospheric vortex is created producing greater velocities on the southern side of trees in the northern hemisphere and on the northern side of trees in the southern hemisphere. This spiraling movement of the air affects branches and therefore induces spiral grain. Kennedy's hypothesis was not supported by later studies and observations.

Aspect and slope are two other factors that have been suggested to affect spiral grain that was not supported by subsequent research. Smythies (1915) observed that trees on southern and western slopes have more pronounced spiral grain than trees on eastern and northern slopes. Using the same species, Rault and Marsh (1952) found no correlation between spiral grain angles and aspects. Van Oye (1926) suggested that spiral grain in trees on slopes was less pronounced than on flat land. As summarized by Harris (1989), he believed that lateral roots are produced generally along contours and therefore neutralize the effect of spiral grain growth. His hypothesis was rejected by Champion (1927b) and has not been mentioned in the spiral grain literature since.

Studying the influence of soil conditions on spiral grain is a complicated task. Soil influences plant growth with its many characteristics such as nutrient availability and water holding capacity. Harris (1989) pointed out that the idea of harsh growing conditions favoring spiral grain formation is a widely accepted one, and in fact, trees growing on mountain sides show pronounced spiral grain angles (personal observations). It is difficult to pinpoint the mechanism for how poor soil conditions, lack of water, or the age of the trees induces spiral grain growth. Few researchers have studied the effect of nutrients on spiral grain formation. Raunecker (1957, as summarized by Noskowiak 1959 and Harris 1989) found a correlation between the chemical composition of soils and grain angles. The majority of researchers (*e.g.*, Rault and Marsh 1952, Fielding 1967, and Whyte *et al.* 1980), however, did not support Raunecker's findings supporting the influence of soil composition on spiral grain. It is very important to mention, though, that although soil composition might not be a primary cause for spiral grain, the possibility that lack of nutrient availability might influence grain angle cannot be discounted.

As with soils, it is very hard to single out altitude as a factor influencing spiral grain growth. Most researchers studying the effects of altitude concluded that altitude alone does not influence the formation of spiral grain (*e.g.*, Mayer-Wegelin 1956). However, harsh climate, poor soil condition, or old age may reinforce the stressor of high elevation possibly making spiral grain more pronounced (Champion 1929, Thunell 1951, Mayer-Wegelin 1956).

Water distribution within trees was also suggested as a cause for spiral grain. Vité (1967) suggested that spiraling grain helps to distribute transpiration water evenly throughout the stem when it is lacking on one side of the tree. Webb (1967) and Kremple (1970) supported that hypothesis. Hartig (1895) and Liese and Ammer (1962) found more pits in spiral-grained trees than in straight-grained trees, which suggests that water flow is not necessarily along the cells only but also through those pits. This supports the water distribution hypothesis because water does not only follow the grain, but it is truly diffused by spreading through the pits as well. Therefore, water can be distributed vertically as well as horizontally.

Injuries also cause spiraling grain (Mattheck and Kubler 1997); however, this deviation of grain angles to the stem axis is not the spiral grain that is studied by most researchers. This deviation from the "normal" grain angle, with the "normal" grain angle being spiral grain itself, is only around a particular injury, branch, or root and has nothing to do with the growth pattern of spiral grain on the whole stem (Mattheck and Kubler 1997).

2.3. Spirality and Tree Age

A common belief, at least in the dendroecological community, is that right spiral grain (Figure 2.1) is an indicator of greater tree age (Fritts 2001). However, studies have shown that this is not necessarily the case particularly in hardwoods (*e.g.*, Noskowiak 1959). In conifers, a general pattern has been established. When young, trees usually spiral to the left, and with age straighten out and finally spiral to the right (Champion 1925, 1927a, Rault and Marsh 1952, Northcott 1957). In hardwoods, however, the opposite might be true, but exceptions to this rule are far more often reported than with softwoods (Noskowiak 1959). According to Noskowiak (1959), there are three reasons for the difficulty "to assign a general pattern to the hardwoods" (pg.54): (1) Hardwoods are more complex in their anatomical structure. (2) Branching between hardwoods and softwoods is very different. In contrast to conifers, deciduous trees initiate branching throughout the whole stem, and it is hard to find an area that is not affected by this branching pattern (*i.e.*, an area where grain angles are not distorted by branching). Softwoods, however, produce internodal areas that are long, equally spaced, and not affected by the branching habit. (3) Spiral grain growth has not been studied as much in hardwoods with conifer studies far outnumbering hardwood studies.

Danborg (1994) found trees that started spiraling to the right as early as ring number 12 (from pith) and on average in ring number 38. Other authors found similar results where the shift from left-handed spirality to straight grain and right-handed spirality occurred in a relatively young age (Harris 1989, Cown *et al.* 1991).

Spiral grain seems to become more pronounced in dead trees (snags and service poles) due to loss of moisture (Lowery and Erickson 1967). This loss of moisture could explain why pronounced right spiral grain can mostly be seen in dead trees (personal observation). The fact that pronounced spirality is often recognizable in dead trees could also be explained by the loss of the bark with mortality. Several authors stated that it is not possible to conclude on spirality pattern within the stem by looking at (or under) the bark (Knigge and Schulz 1959, Bues 1992, Kliger 2001).

2.4. Spiral Grain In Dead Trees and Poles

Spiral grain in living trees is hard to recognize and most of the time it is not visible in the outermost layer of the bark. When searching for spiral grain in the field, the eye usually sees spiral grain on fallen trees or standing snags. Lowery and Erickson (1967) are two of the few scientists who studied how grain angles in trees change after trees have died. They conducted an extensive study on three different species: Douglas fir, logdepole pine (*Pinus contorta*), and western larch (*Larix occidentalis*). Using examples of different direction and severity of grain angle, moisture content, and seasoning (air seasoned and green cut), Lowery and Erickson confirmed that spiral grain became more pronounced after trees died. The more severe spiral grain in living trees the more poles twist. Lowery and Erickson (1967) also tested bending strength of straight-, right-, and left-grained poles for Douglas fir and western larch. The results indicated that right-grained poles are almost as strong as poles with straight grain. Left-grained poles, however, are only about half as strong as poles with straight grain.

Lowery and Erickson (1967) traced the cause of this enhancement of existing spirality back to the moisture content of the trees/poles. Poles stop to spiral as soon as they reach an equilibrium in moisture content with the surrounding atmosphere. After the equilibrium is reached, grain angles varies due to seasonal climatic variations.

2.5. Difference of Spiral Grain Between Hardwood and Softwood

According to Noskowiak (1959) there are two certainties when talking about spiral grain patterns in hardwoods and softwoods: (1) Spiral grain is considered to be the normal condition in trees, and (2) spiral grain growth varies between individual trees, species, and the two groups (hardwood and softwood). Wobst *et al.* (1994) found variations in spiral grain along a stem, between different growth layers, and even within one growth layer at one height.

The main difference regarding spiral grain between conifers and hardwood is the predictability of spiral grain pattern. As Harris (1984: 395) stated, "in many conifers patterns of changing spirality are sufficiently predictable". Although the pattern might be predictable, the severity is not (Cown *et al.* 1991). The pattern in conifers, spiraling to the left when young and changing to straight grain and later right grain when getting older, has been found in many species and is generally accepted among scientists for conifers (Braun 1854, Hartig 1895, Champion 1925, Burger 1941). However, variation in how spiral grain occurs is great. Northcott (1957), for example, found in Douglas fir that only 64% of his samples exhibited the general pattern, 19% never changed the initial left spiraling grain and continued to increase the grain angle to the left, and 17% exhibited some other combinations. Also, the timing of the shift from left to straight to right spiral grain is different from tree to tree and species to species (Harris 1989, Cown *et al.* 1991, Danborg 1994).

For hardwood trees, a pattern is even harder to find. Noskowiak (1959: 55) made a "cautious statement" regarding the general spiral pattern: it could be the opposite of the softwood pattern, but variations are even greater and exceptions more numerous. When young, grain angles in hardwoods are to the right, straightens out, and then changes to left grain with age. Kennedy and Elliott (1957) and Northcott (1957) verified this pattern but also found great variations.

2.6. Established Methodologies

There are several established methods for studying spiral grain in trees. Destructive sampling is the most common and most rewarding technique, because grain angles vary at different heights, in different growth layers (tree rings), and even in one growth layer at a certain height (Hartig 1895). Consequently, in order to get a full picture of the grain angle in the whole tree, discs along the height of a tree have to be taken and examined. In most extensive studies on spiral grain (*e.g.* Lowery and Erickson 1967, Gjerdrum *et al.* 2002), numerous trees were cut down, and several discs along the stem were taken and examined.

A less destructive method was developed by Noskowiak (1968) and Harris (1984). Noskowiak (1968) demonstrated that the standard increment borer, which extracts a 4.5 mm sample, is unsuitable for such a study. Not only does the core twist easily, the area available to read the angle is too small to get an accurate measurement. After sanding the core for dating purposes, the readable area can be as small as 2 to 3 mm.

As Harris (1984) mentioned, Noskowiak's (1968) method of using 10 mm cores to measure grain angles has a major drawback: the core must maintain its orientation relative to gravity after it has been extracted from the tree. In order to be able to handle the core freely after taking it out of the tree, it would be useful to know the grain angle before extracting the core. With that knowledge, it is possible to reconstruct the position of the core within the tree under the microscope in the lab.

Harris (1984) suggested that to accurately measure spiral grain in the field the following procedures need to be conducted. A small window has to be cut into the bark of the tree and the bark has to be removed, which exposes the last growth layer just under the cambium. Using a device with a freely pivoting needle, a line can be scribed along the fibers exposing the grain angle. The grain angle can then be measured with a protractor leveled with a spirit level. The spirit level responds to gravity but not to the axis of the tree; however, spiral grain is defined as the deviation of the grain from the tree axis (Harris 1989). Brazier (1965) proposed to take measurements at two opposite radii to calculate the average grain angle at that height. By doing this, the problem of not considering the angle of the leaning tree and the problem of coring off of the perpendicular axis of the tree is avoided. Harris (1984), who made suggestions to improve on Noskowiak's method (1968) but did not actually conduct a study based on his suggestions, did not mention the problem of leaning trees. However, he suggested taking an increment core along the whole diameter (and with that it is possible to average angles on opposite radii).

Different methods have been used to measure grain angles on cross-sections. The most common one is to remove one growth layer after the other with a chisel, and measure grain angles at each exposed growth layer with a protractor. Brazier (1965) introduced the idea that as long as you measure grain angles at two opposite radii, you would minimize sampling errors like not coring or sawing vertically to the stem axis. Brazier did compare grain angles of pairs of diagonals. Using statistical analyses, he found a correlation coefficient of 0.90 between the diagonals of a cross-section for Larch and concluded that two radii would be an adequate measure of the average grain angle in a tree ring. Danborg (1994) found a similar correlation coefficient (0.87) for Norway spruce (*Picea abies*). The majority of researchers adopted Brazier's method (1965). It should be noted that, Hartig (1895) mentioned that there are indeed differences in grain angles in one growth layer at one height at different radii in pine trees (*Pinus* spp.). Wobst *et al.* (1994) reported in their study on Brazier's method using Ash (*Fraxinus excelsior* L.) and Douglas fir (*Pseudotsuga menziesii*) that in contrast to Brazier (1965) and Danborg (1994) it is necessary to have more than just one pair of radii in order to get an accurate picture of the average grain angle at a certain height. Using 32 radii and averaging 16 opposing radii, they found that there is a difference of several degrees within one growth layer at one height.

Chapter 3

METHODS

3.1. Site Description

The samples were taken on private property (owned by Mr. Allscheid) south of Waterloo, Monroe County, Illinois (Figure 3.1). Elevation ranges from 150 to 190 m above sea level and a small ephemeral stream runs through the property. Near the site under a sandstone rockshelter, archaeological deposits were found, which show that this area had been intensively used by Native Americans from ca. 4700 B.C. to A.D. 1400 (Arntzen, unpublished data).

Selective logging has been conducted on this site since the 19th century; however, the dominant species, oak (*Quercus* spp.) and hickory (*Carya* spp.) can be as old as 200 years (Speer, unpublished data). The understory consists mainly of dogwood (*Cornus nuttalli*) and ironwood (*Ostrya virginiana*).

The soil is relatively thin and rock can be found at one meter depth. The O-horizon is non-existent to very thin and the A-horizon is on average 10 cm thick. The soil is classified in the Seaton-Hickory-Eden association (steep and very steep, well drained, moderately permeable and slowly permeable, silty and loamy soils; formed in loess, glacial till, and residuum) (Soils Survey of Monroe County, Illinois 1987).

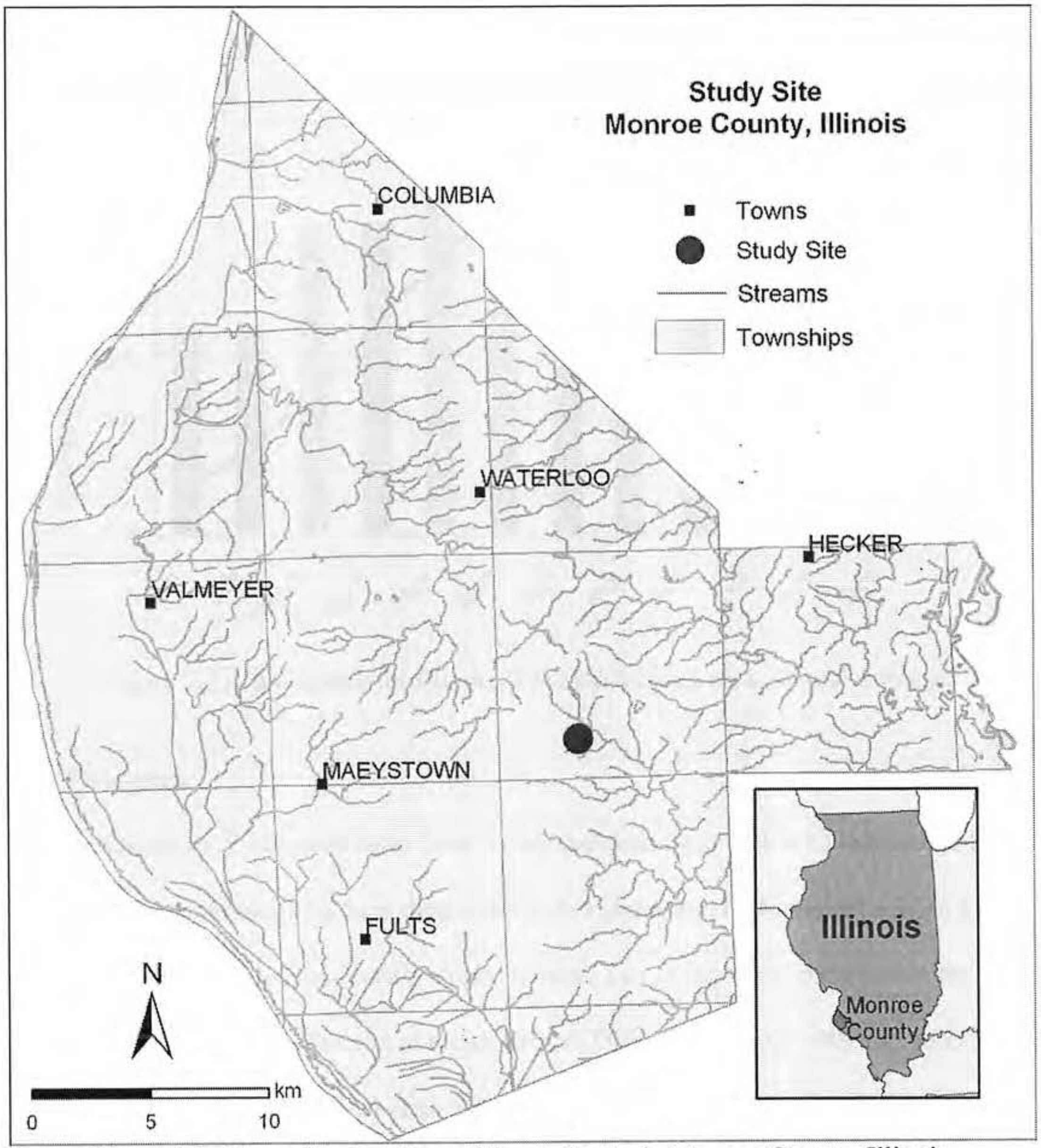

Figure 3.1. Map of the location of the study site in Monroe County, Illinois.

Precipitation in southeastern Illinois (Division 8) has a bimodal distribution with less precipitation during September, January, and February. The warmer part of the year coincides with a decrease in precipitation (Figure 3.2).

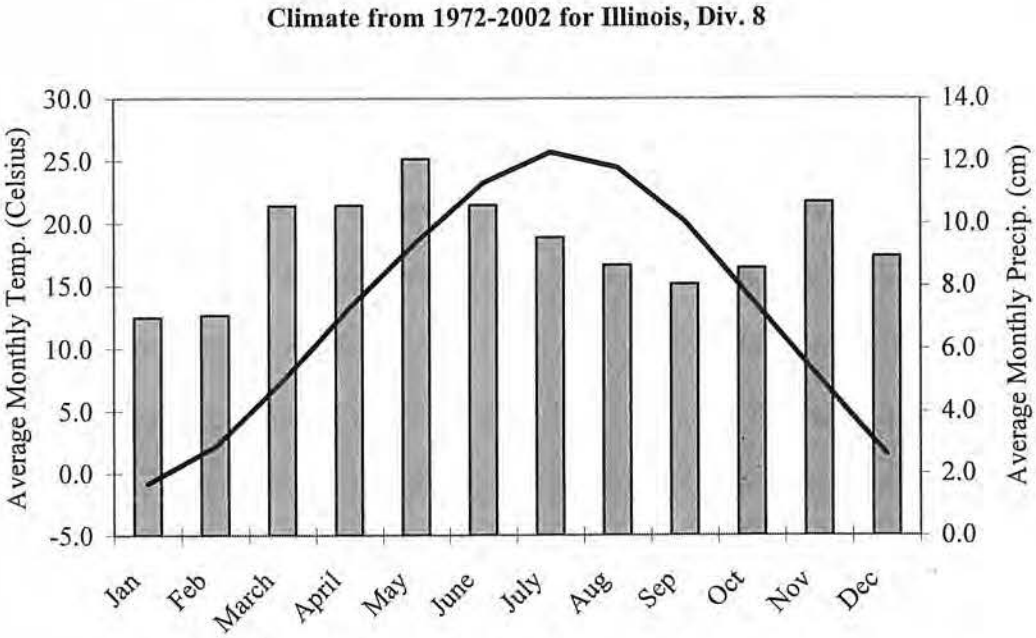

Figure 3.2. Climograph for Illinois, Division 8 based on a 30-year average.

3.2. Fieldwork

For this study, I removed cores from living and dead trees with a 12 mm increment borer and cut cross-sections from dead trees with a chainsaw. I established a 50 m by 50 m plot (Figure 3.3) on a moderately sloped terrace. Ten living white oaks within the plot with greater than 25 cm diameter at breast height (DBH) were cored with a 12 mm increment borer (Table 3.1). All dead trees in the plot that met certain requirements were cut using a chainsaw, and two cores were taken at breast height using a 12 mm increment borer. The requirements the trees had to fulfill included a sufficient stable structure, its root crown located within the plot, and DBH of at least 15 cm (Table 3.2).

While all dead trees in the plot were sampled, I was only able to sample and process a small number of living trees. The intention was to core every white oak in the plot; however, it soon became apparent that this would not be feasible for reasons mentioned under 5.3 (Studying Spiral Grain with Increment Borers). Therefore, the sampling of living trees was stopped after the tenth tree (Figure 3.3).

Before taking samples, a 10 cm by 10 cm window was cut into the bark of the living trees, the bark was chiseled off exposing the outermost growth layer, and grain angles were then measured with a freely pivoting needle and a protractor that was leveled with a spirit level. Two cores on opposite sides of the tree were then taken through the scribe mark so that the cores could be aligned to their right grain angle later in the lab. Without testing his own method, Harris (1984) suggested taking just one core over the whole diameter. In the field, however, I found it impossible to take a core over the whole diameter of oak trees with the larger 12 mm increment borer. Therefore, two cores on opposite sides of the trees were taken.

Also, the lean of the tree axis from vertical (gravity) and the degree of spiral grain in the bark were measured. To make sure that all increment cores maintained their field moisture level, they were stored in cling wrap and zip-lock bags. Coordinates of the trees relative to the plot and the UTM coordinates for the four corners of the plot were also recorded.

Alive	x (m)	y (m)	DBH (cm)
T3	3.0	9.5	46.1
T4	1.0	15.0	65.0
T5	7.0	29.0	52.5
T8	3.0	38.0	39.2
T10	14.0	49.0	42.5
T11	14.0	37.0	29.0
T12	15.0	37.0	34.4
T14	14.0	31.0	28.4
T20	20.0	38.0	42.0
T22	22.0	34.5	28.4

Table 3.1. DBH and location (x, y) in the 50 by 50 m plot for the living trees.

Dead	x (m)	y (m)	DBH (cm)	Comments
D1	8.0	1.5	38.1	damp, decay in sapwood
D2	15.0	20.0	35.0	standing snag, only above 1.5m fallen, dry, little decay
D3	5.5	33.5	27.7	outside ring on one side
D4	20.5	33.0	20.8	little bit of bark still on, left spiral evident on bark and wood
D5	21.5	45.0	19.9	little bark still on
D6	38.0	43.0		only cross-section (no cores) because of decay
D7				rotten inside
D8	42.0	28.0	19.7	

Table 3.2. DBH, location (x, y) in the 50 by 50 m plot, and comments for the dead trees.

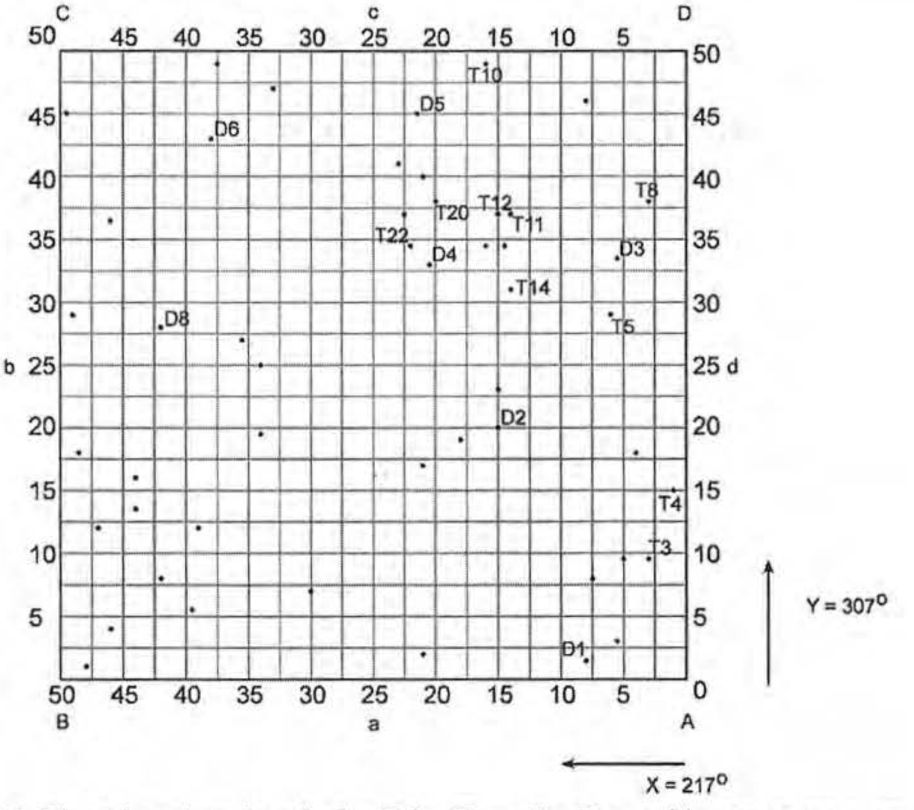

Figure 3.3. Plot of tree locations in the 50 by 50 m plot. Dots without text represent living trees of the species white oak or hickory (*Carya* spp.) with a DBH greater than 25 cm.

3.3. Lab Work

In the laboratory, a plane surface was cut along the cores with a razor blade, which was used to date samples and to measure ring width. The standard procedure of sanding the cores was not used because heat is generated when sanding cores and this heat would change moisture content of the samples. Cross-sections were sanded, because cross-sections are more robust than cores and do not twist as easily.

After cutting or sanding the cross-sectional surface, the samples were crossdated. Using skeleton plots and by matching up marker years (*i.e.*, years that are very dry and hence the ring width very small), it is possible to determine the year of formation of every ring (Stokes and Smiley 1968). This pattern of wide and narrow rings can then be used to date the samples. On skeleton plots, marker years are given a value from one to ten in relation to the surrounding tree rings: the smaller the ring width the higher the number. It is assumed that in dry years all trees are affected and show some sign of ring-width reduction. Skeleton plots of different samples were matched up and dates were assigned to the different inside and outside years of the samples. The ring width was then measured using a Velmex measuring machine and the Measure J2X program. The dating was then checked using COFECHA (Grissino-Mayer 2001).

After dating and measuring the samples, spiral grain angles were measured. The cores were mounted in clamps with the cross-sectional view facing up. One growth layer after the other was chiseled off using a chisel and hammer, and on the exposed tree rings, grain angles were measured using a microscope with a protractor reticle to 1° precision. The outside grain angles measured in the field were either added or subtracted to measurements of grain angles for each year measured in the laboratory. This study follows the common notation for grain angles, which is negative values for the right grain angles and positive values for the left grain angles.

Four diameters (eight radii) were measured on cross-sections. Each growth layer was chiseled off around the whole cross-section and grain angles were measured under the microscope. After Brazier (1965), grain angles on two opposing radii were averaged.

3.4. Data Analysis

Statistical analysis was used to determine correlation and significance. (1) COFECHA, a standard program in dendrochronology was used to check whether the cross-dating of the samples was correct. In addition, the data were run through ARSTAN (another statistical tool in dendrochronology) to standardize the tree ring series and create a master chronology, which was then used in a climatic analysis of the spiral grain data. Sixty six climatic variables where used, specifically monthly PDSI, temperature, and precipitation and the lagged months for the previous growing season for the period from 1895 to 2002 to examine the climatic response of these trees and of spiral grain. The program ARSTAN was used to compile the standard, residual, and arstan chronologies for the climate analysis (Cook and Holmes 1986). The raw ring width measurements have an age-related growth trend, (*i.e.* younger tree rings are naturally wider than older tree rings because the tree has a greater volume to cover with the same amount of wood as the tree grows larger). To remove this age-related growth trend, ARSTAN applies a smoothing spline and computes index values in three different chronologies: standard, residual, and arstan. The values in these chronologies reflect the growth response of the trees to the environment and not the age-related growth. For the ARSTAN analysis, a conservative negative exponential curve with a minimum spline rigidity of 64 years was used to detrend the data. The minimum spline rigidity keeps the negative exponential curve from being too steep and leveling out too soon. (2) A correlation analysis was used to determine differences between spiral grain in cores and cross-sections from dead trees (with the core being taken directly above the cross-sections) to determine the usefulness of data received from cores and the possibility of using cores to study spiral grain growth in trees. For studying how useful increment borers are in spiral grain studies, cross-sections and cores from the same tree and preferably same height and same compass-direction have to be examined. Therefore, dead trees were cored and subsequently cut using a chainsaw right above the borehole from the increment borer. Cores a and b of each tree correspond to radii A and E on the cross-sections whereby the direction of radius A is equivalent to core a and radius E to core b. The radii might deviate from the exact direction of the core by one or two centimeter because of a knot area or a break within the cross-section. (3) Regression and correlation analysis were used to analyze the relationship of spiral grain to age of tree. (4) Due to low sample size, a statistical analysis could not be used to determine differences between spiral grain in cores from living trees and cores from dead trees to determine if spiral grain becomes more pronounced after trees die. Instead, the data were graphed and visually compared. (5) Regression and correlation analysis was used to examine the differences between several series of grain angles (diagonals) on one cross-section to determine if Brazier's method (1965) is applicable to white oaks.

3.4.1. Data Preparation for the Analysis of Brazier's Method

In order to reduce the time spent in the lab working on cross-sections, Brazier (1965) introduced the idea that it would be enough to just look at one diagonal on a cross-section to get an overall picture of grain angles at that specific height in the tree. He supported his hypothesis statistically. However, Wobst *et al.* (1994) had contrary results using different species. For this study, grain angles in eight radii on several cross-sections from white oaks were measured and the four resulting diagonals (averaged opposing radii) were compared with each other. The initial grain value could not be accurately measured in the field; therefore, the first measurement of each averaged value was set to zero and subsequent grain angles were calculated accordingly. In addition, the first measurement (that was set to zero) was considered to be a year that had all grain angles represented (Tables 3.3 and 3.4). By doing so, it is possible to compare trends from one growth layer to the next. However, results do not reflect absolute spirality, *i.e.*, it cannot be concluded on when the direction of spiral grain growth changes, but merely that there is a change in direction during the life of a tree. In addition, grain angles measured in knot areas were deleted.

year	H	G	F	E	D	C	B	A	r(A,E)	r(B,F)	r(C,G)	r(D,H)	Age
1914	Pith	Pith	Pith	Pith	Pith	Pith	Pith	Pith	Pith	Pith	Pith	Pith	1
1915													2
1916	4	-5	-8	-6		3	10	9	1.5	1	-1		3
1917	4	-5	-7	-9	-3	3	9	9	0	1	-1	0.5	4
1918	1	-5	-9	-7	-5	4	8	6	-0.5	-0.5	-0.5	-2	5
1919	0	-6	-11	-8	-4	3	9	5	-1.5	-1	-1.5	-2	6
1920	1	-6	-11	-6	-2	3	9	5	-0.5	-1	-1.5	-0.5	7

Table 3.3. Sample data chart of absolute grain angles before the reorganization of the data (cross-section 5).

year	H	G	F	E	D	C	B	A	r(A,E)	r(B,F)	r(C,G)	r(D,H)	Age
1914													
1915													
1916													
1917	0	0	0	0	0	0	0	0	0	0	0	0	4
1918	-3	0	-2	2	-2	1	-1	-3	-0.5	-1.5	0.5	-2.5	5
1919	-4	-1	-4	1	-1	0	0	-4	-1.5	-2	-0.5	-2.5	6
1920	-3	-1	-4	3	1	0	0	-4	-0.5	-2	-0.5	-1	7

Table 3.4. Sample data chart of relative grain angles after reorganization of the data (cross-section 5).

3.4.2. Data Preparation for the Analysis of Grain Angles in Living and Dead Trees

Although data were available for the cross-sections (dead), these were not included in this part of the analysis, because cross-section from living trees were not available for this study. Even though the cores might not be a good representation of absolute grain angles (will be analyzed), for this study the assumption is made that the cores and their angles change under the same forces and therefore are among themselves comparable. Sample size is low for this analysis: four dead trees and seven living trees, and for those samples, the same problem arose as for the examination of Brazier's method: the lack of initial grain angles in the dead trees. To avoid this problem, all years that did not have grain angles (in both radii) represented were deleted. In addition, grain angle data were deleted to match the beginning years on the cores from the living and dead trees. Also, grain angle measurements in the start year of the data set were set to zero and subsequent grain angles were adjusted accordingly (example in Table 3.3 and 3.4).

3.4.3. Spatial analysis of Spirality

For this analysis, I classified the correlation coefficient for all living and dead samples (tree age vs. grain angle) in three classes, gave each class a symbol, and plotted the classes on Figure 3.3: high for r ≥ 0.800 with the symbol "+", medium for 0.800 > r > 0.300 with the symbol "o", and low for r ≤ 0.300 with the symbol "-". Two maps were produced: on the first map, correlation coefficients were plotted regardless of direction (negative or positive), and on the second map, the direction of the correlation was considered with negative correlation being part of the last class (low).

Chapter 4

RESULTS

4.1. COFECHA, Climate, and Ring Width

COFEHCA is a standard statistical tool in dendrochronology to check visual cross dating. Ring width measurements of all cores are compiled into a master chronology and then each core is removed and correlated back to the master to produce a correlation value representing the strength of the dating. A 40-year segment with a 20-year lag was chosen because some of the cores were as short as 57 years and on average 105 years old (Grissino-Mayer 2001). These settings adjust the value for the critical correlation at the 99% confidence level to 0.3665. The series intercorrelation of 0.649 (mean sensitivity 0.231) is considered high for dendrochronological applications.

The availability of a master chronology by Speer (unpublished data) created another opportunity to check the accuracy of the data. With 157 cores in that series, the standard option for the segment length was used: 50-year segments with 25-year lags. The critical correlation at the 99% confidence level is 0.3281. The series intercorrelation improved to 0.663 (with a mean sensitivity of 0.260).

The standard, residual, and arstan chronologies produced by the program ARSTAN were correlated against the 66 climatic variables. To be significant on the 99% level, correlation coefficients have to be higher than 0.403 and higher than 0.312 for the 95% confidence level (Table 4.1 and Appendix A). The climatic conditions in June play an important role in the life of trees at the Allscheid site. Although June precipitation is best correlated with the residual chronology, June PDSI is significantly correlated at the 99% level with the standard as well as the residual chronology. Therefore, June PDSI was used for a regression analysis against the residual chronology (Figure 4.1). The variance explained ($r^2 = 0.220$) is relatively low but nevertheless significant. June PDSI was also used to examine the relationship between climate and grain angles (computed on a subset of the whole data set: living trees); however, a low correlation of 0.022 (not significant) was found. The averaged grain angles of all living trees were also correlated with all climate variables. February temperature and the lagged September temperature from the previous year are significantly correlated to spiral grain angles ($r = 0.318$ at the 0.01 level [2-tailed] and $r = -0.211$ at the 0.05 level [2-tailed], respectively). However, these two variables are not significantly correlated with the chronologies computed by ARSTAN (Appendix A).

In addition, ring width and its relationship with spiral grain angles were examined. Again using a subset of the whole data set, living trees, a significant (at the 0.01 significance level) but low correlation coefficient was computed ($r = -0.303$). This suggests that a smaller ring develops more spiral grain.

Sign. Climatic Variables	*meaSTD*	*meaRES*	*meaARS*
May PDSI	0.328	0.307	0.275
June PDSI	0.424	0.469	0.374
July PDSI	0.402	0.436	0.366
August PDSI	0.364	0.401	0.340
September PDSI	0.297	0.329	0.260
Growing Season PDSI	0.407	0.436	0.363
June Precipitation	0.385	0.541	0.362
Growing Season Precipitation	0.337	0.391	0.308
June Temperature	-0.215	-0.403	-0.188
Growing Season Temperature	-0.326	-0.373	-0.303

Table 4.1. Significant correlation coefficients for 10 climate variables (dark gray: significant at the 99% confidence level; light gray: significant at the 95% confidence level).

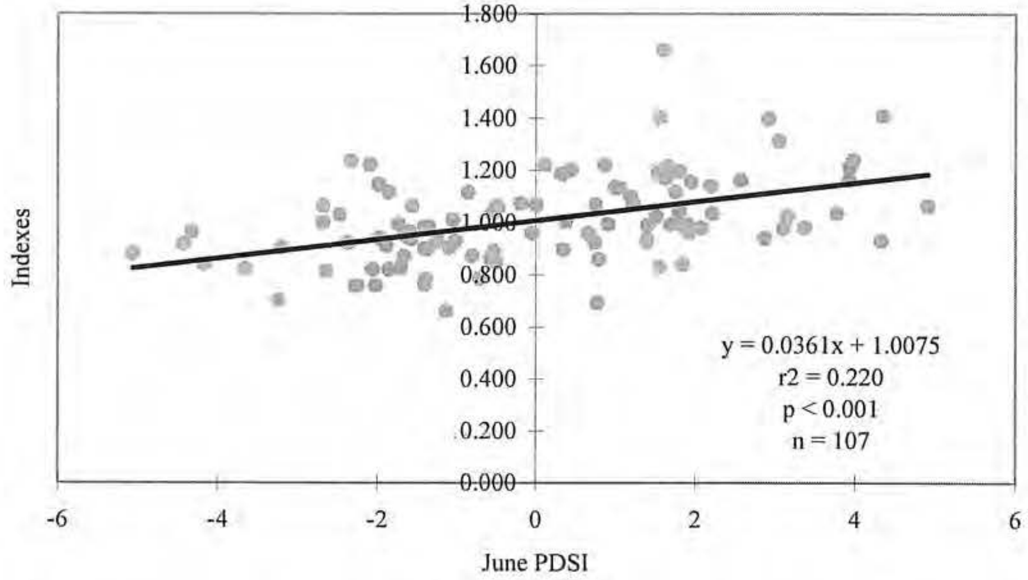

Figure 4.1. Regression analysis with June PDSI and ARSTAN's Residual Chronology.

4.2. Studying Spiral Grain with Increment Borers

For this part of the study, cross-sections and cores from the same tree, approximately same height, and same compass-direction were examined. In this analysis I used the measured grain angles and not the cumulative grain angles. The highest correlation between the averaged spiral grain data from the cores and the averaged spiral grain data from the cross-section (from just one diagonal with the same compass-direction) is 0.335 (dead tree 1) and the lowest is 0.120 (dead tree 3, Table 4.2). Dead tree 8 was excluded from this analysis because of low sample depth (low number of years with spiral grain measurements). For the dead trees number 2, 6, and 7, spiral grain angles could not be measured because of rotten wood.

In Table 4.2, I also included the correlation coefficients between the measured grain angles and the age of the trees. The difference between cores and cross-sections are also visible in these coefficients: while grain angles on the cross-sections correlate highly with age, the cores have comparably low correlation coefficients (see 4.5, 5.6, and 6.5 for the results, discussion, and conclusion on age dependency).

	Age	*CORE01*
CORE01	0.808	1
CROSS01	0.593	0.335

	Age	*CORE03*
CORE03	0.361	1
CROSS03	0.737	0.120

	Age	*CORE04*
CORE04	0.261	1
CROSS04	0.971	0.244

	Age	*CORE05*
CORE05	0.470	1
CROSS05	0.909	0.239

Table 4.2. Correlation coefficient for averaged spiral grain data from cores (CORE) and averaged spiral grain data from cross-section (from just one diagonal with the same compass-direction; CROSS) including correlation coefficients against age (spiral grain angles vs. tree age).

4.3. Accuracy of Brazier's Method for White Oak

For this analysis, correlation coefficients were computed for each diagonal on a cross section and then compared between the four sets of diagonals. Only one out of five cross-sections had high correlation coefficients (0.9) between the diagonals (dead tree 4, Table 4.3 and Figure 4.2). The other four cross-sections exhibited great variations among the correlation coefficients (for example dead tree 1, Table 4.4 and Figure 4.3).

It should be mentioned that two of the five trees had two piths. While in one tree (#3) this problem was cancelled out by averaging the radii along a diagonals, in the other tree (#1) the piths were very close to each other (and therefore might not have influenced grain angles individually). Nevertheless, in at least two other trees, the correlation was low (Appendix B).

	year	*r(A,E)*	*r(B,F)*	*r(C,G)*	*r(D,H)*
r(A,E)	0.977	1.000			
r(B,F)	0.939	0.961	1.000		
r(C,G)	0.941	0.959	0.967	1.000	
r(D,H)	0.950	0.965	0.962	0.961	1.000

Table 4.3. Correlation coefficient in dead tree 4 between the diagonals.

	Year	*r(A,E)*	*r(B,F)*	*r(C,G)*
r(A,E)	0.270	1		
r(B,F)	0.219	0.216	1	
r(C,G)	0.459	0.483	0.644	1
r(D,H)	-0.357	0.071	-0.174	-0.081

Table 4.4. Correlation coefficient in dead tree 1 between the diagonals. Although some of the correlation coefficients are high, not all of them are consistently so; therefore, the diagonals do not relate very well with each other.

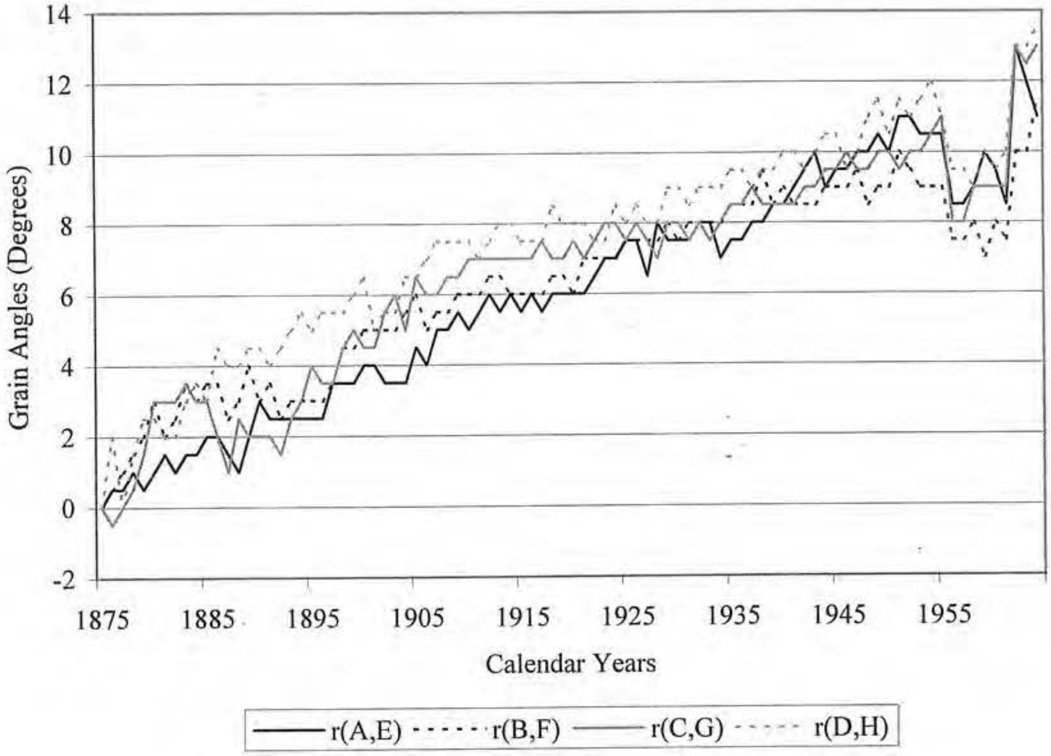

Figure 4.2. Graph of the four diagonals in dead tree 4.

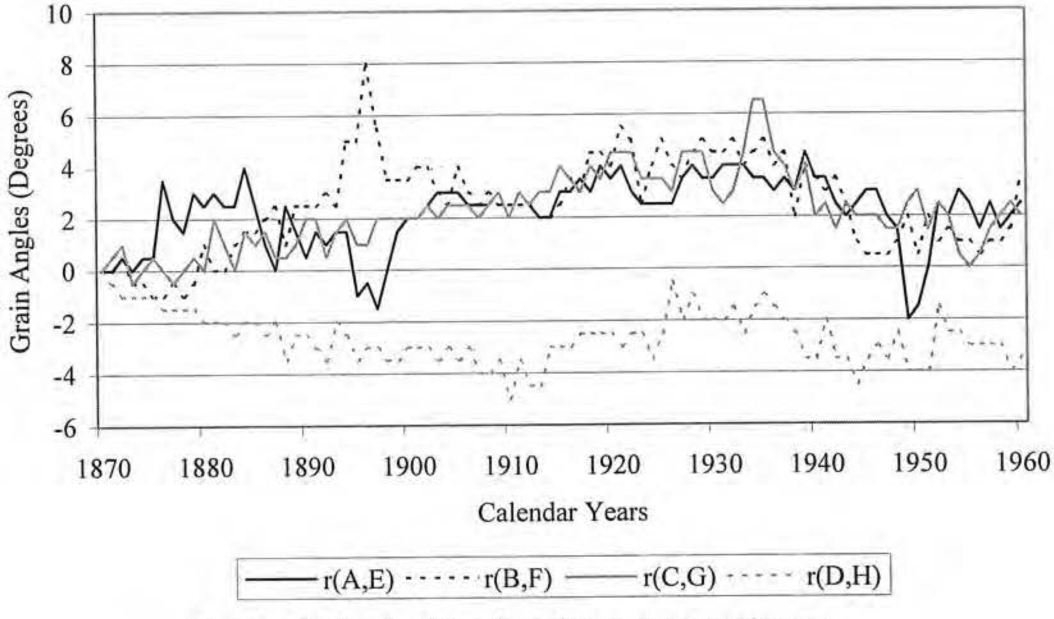

Figure 4.3. Graph of the four diagonals in dead tree 1.

4.4. Grain Angles in Dead Trees vs. Living Trees

In this analysis, I compared samples of living and dead trees to examine if grain angles differ due to mortality and subsequent desiccation of the tree. The sample size is low for this analysis: four dead trees and seven living trees. Therefore, a statistical analysis was not possible. Visual comparison was done with graphs of the grain angles compared to the age of the trees (Figure 4.4). Cumulative grain angles were plotted. While three out of four dead trees have right (negative) grain angles (these are not absolute but relative grain angles), four out of seven living trees have left (positive) grain angles. Also, two dead trees have lower (right) grain angles than six of the living trees. This difference becomes more apparent in the graph plotting the average grain angles of living and dead trees (Figure 4.5).

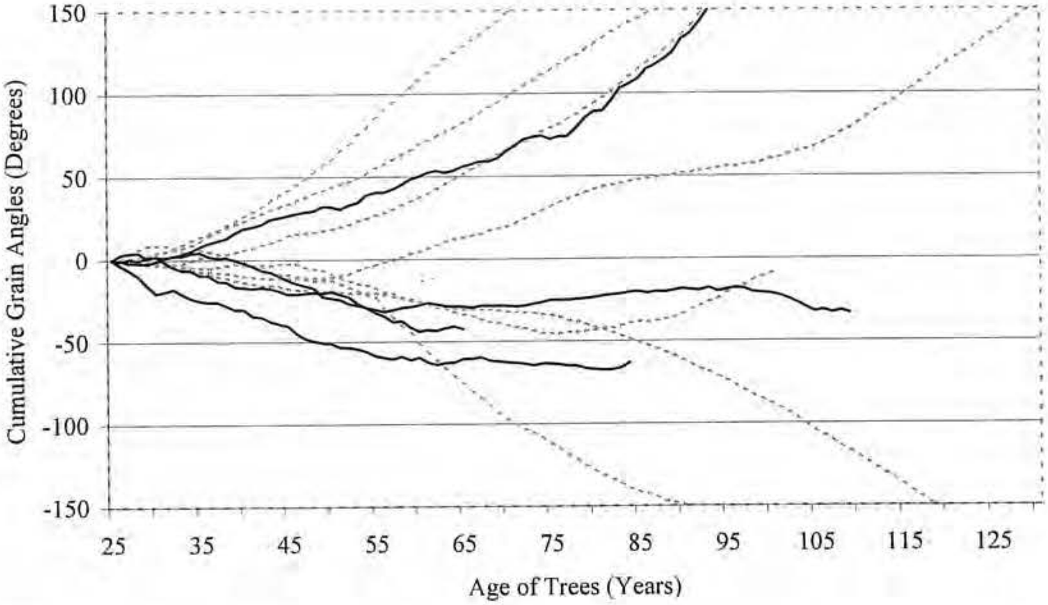

Figure 4.4. Cumulative grain angles of living and dead trees plotted against the age of the trees (averages of two cores per tree, dashed: living trees, solid: dead trees).

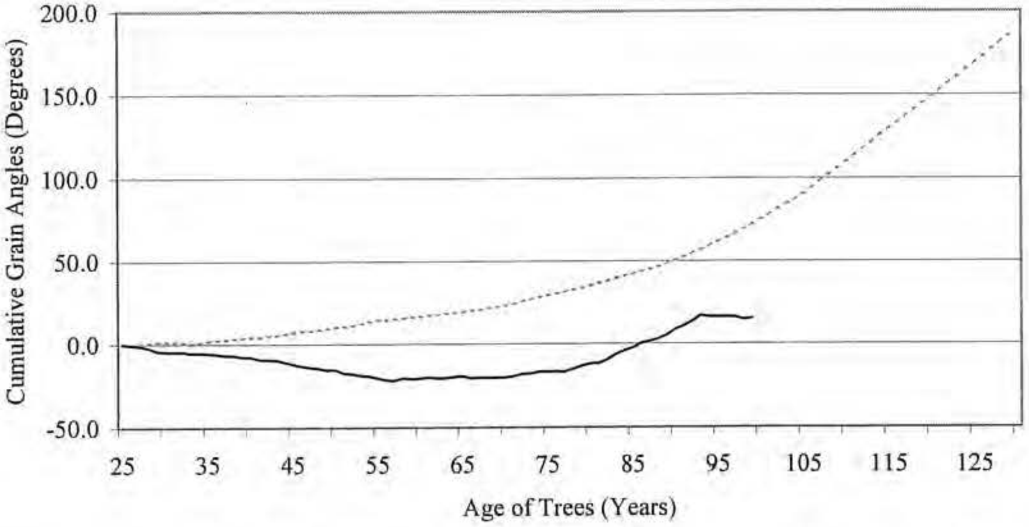

Figure 4.5. Cumulative grain angles of living and dead trees plotted against the age of the trees (overall averages of all trees, dashed: living trees, solid: dead trees).

4.5. Spiral Grain as an Indicator of Age

For this analysis, data from cross-sections and from living cores were used. Although cores do not necessarily represent spiral grain angles as they are found in cross-sections (see section 4.2), the assumption was made that the cores twist similarly and therefore a similar trend might be visible. Also for this analysis, measured grain angles were used and not cumulative grain angles.

Spiral grain from all diagonals on the cross-sections demonstrated a significant age-spirality correlation ($r^2 = 0.873$ with $p < 0.001$; $r = 0.935$). Looking at the results for individual trees, great variations can be seen (Table 4.5). Having a closer look at the graphs, some trees show the same distinct pattern as tree 4 (Figure 4.6). Those trees start with right spiral grain in their youth and change the direction of the spiral grain growth to the left when they get older.

A similar pattern can be seen in cores from living trees when comparing grain angles and tree age. Averaging all cores into one value gives a significant result using regression analysis ($r^2 = 0.529$, $p < 0.001$) and a relatively high correlation coefficient using correlation analysis ($r = 0.727$). Averaging the two cores from each tree and analyzing those values results in a low but still significant correlation ($r^2 = 0.110$, $p < 0.001$, $r = 0.331$). Again looking at individual trees, great variation between the trees can be seen (Table 4.6). As with the cross-sections, some trees have this distinct pattern: negative (right) grain angles for younger years and more pronounced positive (left) grain angles with tree age (Figure 4.7).

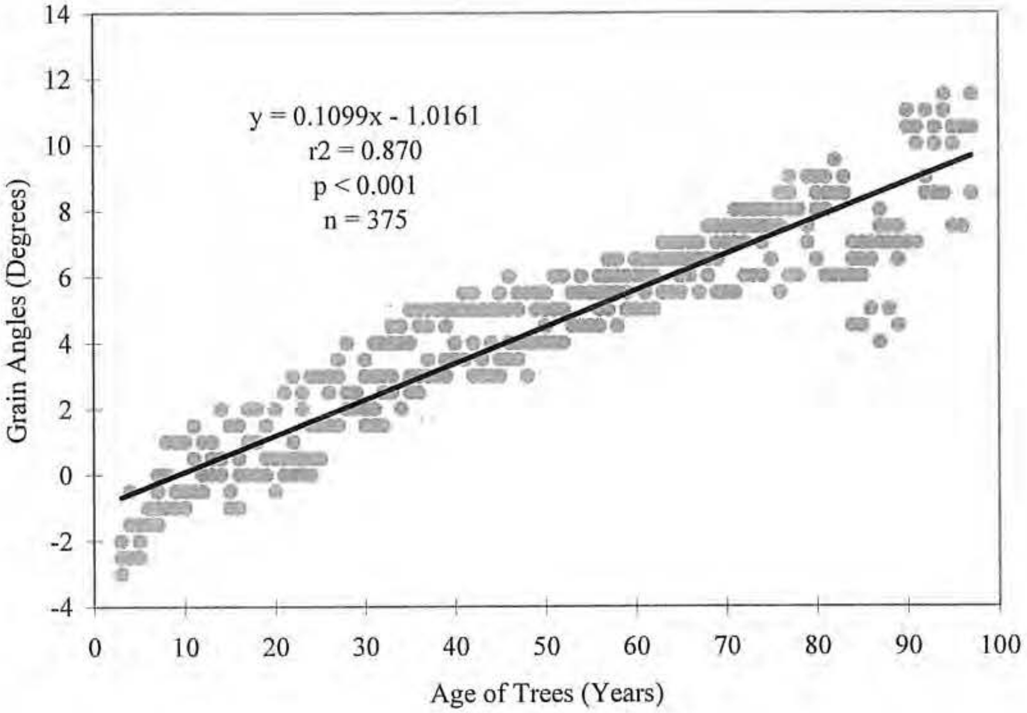

Figure 4.6. Regression analysis: tree age vs. grain angles (four diagonals, dead tree 04).

	r^2	p	n	r
JMTD01	0.011	0.028	451	0.103
JMTD03	< 0.001	0.808	308	-0.014
JMTD04	0.870	< 0.001	375	0.933
JMTD05	0.611	< 0.001	179	0.783

Table 4.5. Results for the regression and correlation analysis for cross-sections (tree age vs. grain angles).

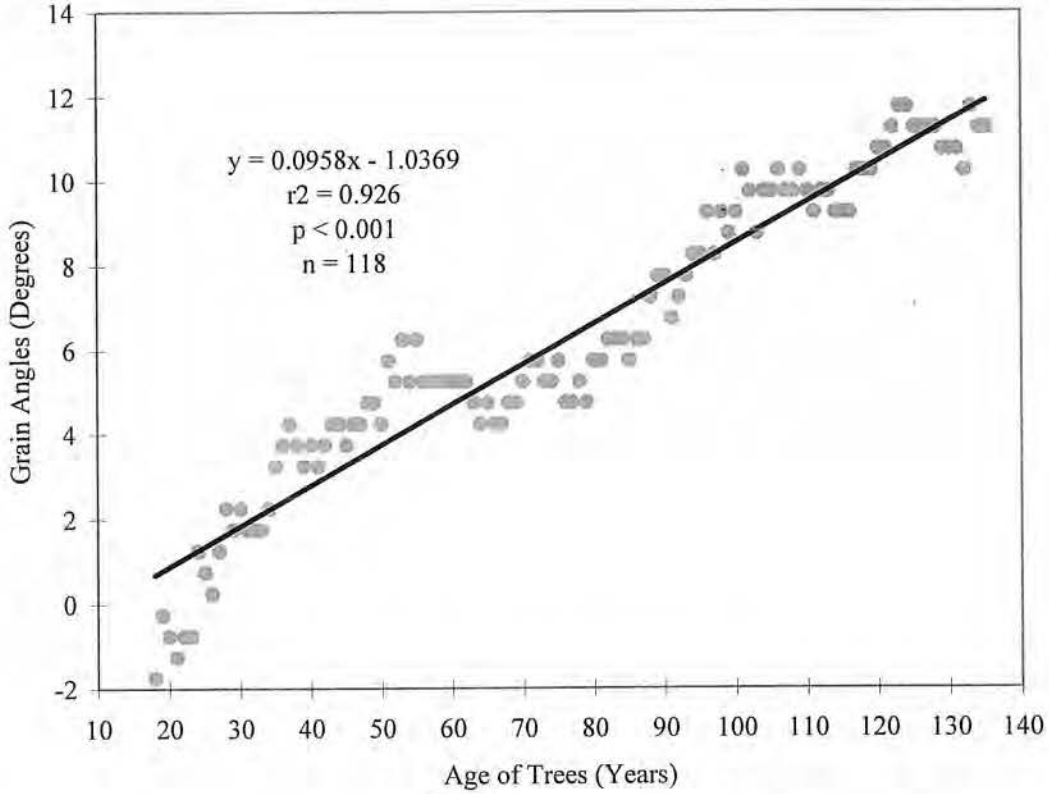

Figure 4.7. Regression analysis: tree age vs. grain angles (living tree 22).

	r^2	p	n	r
JMT08	0.288	< 0.001	81	-0.536
JMT10	0.250	< 0.001	83	0.500
JMT11	< 0.001	0.906	124	0.011
JMT12	0.805	< 0.001	126	-0.897
JMT14	0.483	< 0.001	122	0.695
JMT20	0.899	< 0.001	117	0.948
JMT22	0.926	< 0.001	118	0.962

Table 4.6. Results for the regression and correlation analysis for living trees (tree age vs. grain angles).

4.6. Spatial Analysis

In an attempt to explain the diverse correlation coefficients, a visual spatial analysis was done. The location of all trees can be seen in Figure 3.3. For this analysis, I focused on the part of the plot where most of the trees (10 out of 11) are located (Table 4.7, Figure 4.8, and Figure 4.9). Looking at both maps, a cluster of high correlation coefficients can be seen while medium and low correlation coefficients are more dispersed. It is, however, not possible to determine whether that is a random effect due to low sample size or a true pattern.

	r	Marked in Figure 4.8. as:	Marked in Figure 4.9. as:
D1	0.103	-	-
D3	-0.014	-	-
D4	0.933	+	+
D5	0.783	o	o
T8	-0.536	o	-
T10	0.500	o	o
T11	0.011	-	-
T12	-0.897	+	-
T14	0.695	o	o
T20	0.948	+	+
T22	0.962	+	+

Table 4.7. Results for the correlation analysis for living (T) and dead (D) trees (tree age vs. grain angles) including the correlation coefficient classification (high [+], medium [o], and low [-]).

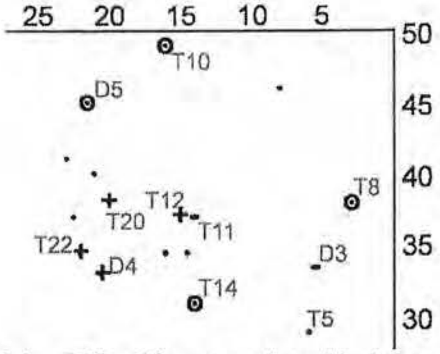

Figure 4.8. Case 1: Part of the 50 by 50 meter plot with the tree location and the symbol as shown in table 4.7. In this case trees with high (+), medium (o), and low (-) correlation coefficients regardless of direction (positive/negative) are shown. Dots symbolize trees of the species white oak or hickory that were not included in this study.

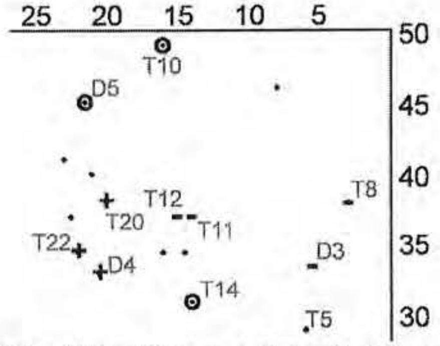

Figure 4.9. Case 2; Part of the 50 by 50 meter plot with the tree location and the symbol as shown in table 4.7. In this case trees with high (+), medium (o), and low (-) correlation coefficients considering the direction (positive/negative) are shown. Negative correlation coefficients are classified as a low correlation coefficient. Dots symbolize trees of the species white oak or hickory that were not included in this study.

Chapter 5

DISCUSSION

5.1. Problems with the Data Set

Several problems arose during the work with this data set. For example, due to the method of measuring grain angles in the field, it was not always possible to rely on absolute grain angles. As already mentioned by Noskowiak (1959), measurements are very subjective. Therefore, instead of using absolute grain angles, the first years of the spiral grain measurements were (during the statistical analysis) set to zero and the following grain angles calculated accordingly. Because of that it was not always possible to analyze the absolute grain angles but rather the trends of the grain angles. Often, it was important that compared samples that start in the same year (calendar year or age), which required the truncation of measurements in some samples where not every core had spiral grain measurements. This approach reduced the data available for the analyses in some instances considerably.

Also, with a core being broken, the data collected after the break could in most cases not be used because angles could not be referenced to the previous ring. The same happened with samples where grain angles could not be measured because the ring width was too small and rings could not be chiseled off adequately.

Another problem for some of these analyses was the absence of the pith. The pith is important to obtain the age of the tree. Of ten living trees, three had to be excluded because it was impossible to estimate the pith date. Two out of seven trees had precise pith dates because at least one of the two cores had the pith present. The other five pith dates were estimated using the diameter of the tree and an average of the inside 10 or 20 ring widths of the cores. Where concentric rings were visible on the cores, these estimates were double-checked using the pith indicator (Applequist 1958) and believed to be a reliable estimate.

Observations in the field indicate that the averaging of grain angles from two opposing radii might result in the loss of valuable grain data. In several trees, I observed different directions of the grain angles in opposing radii. So, 10° right spiral grain on one end of a diagonal and 10° left spiral grain on the other end of the diagonal would result in zero degree grain angles and would not represent the actual grain angles of the tree. A method has to be developed that allows for the researcher to adjust the cross-section in the lab when measuring grain angles to the vertical axis of the tree.

5.2. COFECHA, Climate, and Ring Width

Spiral grain appears to be somewhat controlled by preceding temperature conditions (lagged September and February temperature). However, these variables are not significantly correlated with the chronologies computed by ARSTAN (Appendix A). Therefore, the most limiting factor for tree growth is not the factor that controls spiral grain in trees. The significant but low correlation coefficient ($r = -0.303$) between spiral grain angles and ring width could be a sign of a relationship, suggesting that grain growth spirals more when the tree is stressed. This would support the hypothesis of water transport around the tree as being a driving factor for spiral grain growth. However, a more accurate method of measuring grain angles in the field has to be used to verify a relationship.

5.3. Studying Spiral Grain with Increment Borers

Although Noskowiak (1968) and Harris (1984) suggested the usefulness of a 10 mm increment borer when studying spiral grain, results of the statistical analysis in this study suggest that the increment borer might not be an appropriate tool for studying spiral grain in white oaks. Both thought that it would be possible to examine spiral grain on this larger core through the whole diameter of the tree. Using a 4.5 mm increment borer in hardwoods is very strenuous; using the 12 mm increment borer for coring hardwoods is almost impossible. Two people turning the borer are necessary to get the borer past the pith. I concluded that coring the whole diameter with a 12 mm borer is physically impossible in large hardwoods, particularly white oak.

Another major problem with the increment borer compared to chain sawing cross-sections is the need to hit pith. Hitting pith is very important to obtain the age of the tree; yet, it is an "art" (Grissino-Mayer, personal communication). There are several possibilities to estimate the age of the tree; however, as was the case in this study, three out of ten cores had to be excluded from the analyses because no decent estimates were possible for these cores.

As already mentioned by Noskowiak (1959), measuring the angle of the tree to vertical, the lean of the tree, is a very subjective task. Yet, this measurement is crucial to later assign absolute grain angles to the cores in the laboratory. The method used in this study (using a protractor with freely moving measurement stick that reacts to gravity) could be improved by additionally using a one-meter board or stick and holding it against the tree to avoid measuring errors due to fissures in the bark. Averaging multiple measurements (as has been done in this study) improves readings.

In addition, it is not always possible to core at exactly the same height and at exactly 180° from the other borehole. In fact, the height of the second core must be a few centimeters above or below the first coring height to avoid the hole that is created from the first core. Therefore, cores are not as accurate as cross-sections.

Another analysis in this study suggests that the grain angles in just one diagonal at a certain height are not representative of the grain angles around the whole tree at that height (see next section 5.4), *i.e.* two cores would not be enough to get a representative picture of spiral grain (at least in white oak).

5.4. Accuracy of Brazier's Method for White Oak

Brazier's method is very desirable for spiral grain studies because it saves a lot of time when measuring spiral grain. Although Brazier's method does not seem to be wrong as evidenced in Dead Tree 4 with the high correlation coefficients between the four diagonals, the results show that this method cannot be applied universally to all individual trees and tree species.

5.5. Grain Angles in Dead Trees vs. Living Trees

The results in this analysis indicate a difference in grain angles between living and dead trees. The results in this analysis were derived from visual comparison of the data and could not be verified with a statistical analysis because of a low sample size. However, personal observations in the field support these results. For a sound analysis, though, more samples have to be added and a statistical analysis would be advantageous. Causes of differing spiral grain between living and dead trees cannot be ascertained from this study, however, Lowery and Erickson (1967) concluded in their research that moisture content affects the degree of spiral grain (section 2.4).

5.6. Spiral Grain as an Indicator of Age

My analyses support Noskowiak's (1959) findings for a complex pattern of spiral grain in hardwoods. While softwoods spiral to the left in the juvenile phase, they change direction of the grain angles to the right when they get older. Although not every softwood has this grain pattern, exceptions are not numerous and this pattern is thought of as the general pattern. In contrast, it is much harder to find a general pattern in hardwoods, and Noskowiak (1959: 55) only dared to make a "cautious statement" because of the great variability of patterns. Hardwoods might spiral to the right when they are young but change direction to finally spiral to the left when they get older. Variations are much greater, though, compared to softwoods, and data in this study also reflect this aspect of Noskowiak's finding. At least half of the trees show this distinct pattern of spiral grain to the right when young and switch to a counter-clockwise (left) direction when older. However, variations are high and for two trees the pattern is even the opposite.

5.7. Spatial Analysis

In this analysis, only a small number of samples were available. A spatial pattern of the trees that demonstrate high amount of spiral grain is visible. It is not clear whether this is a true pattern or a random construct due to low sample size. If this is a true pattern, a cause could be found in the topography of the plot. The part around the "high correlation" trees was relatively steep while the part of the plot above (northwest) and on the right (northeast) side of that cluster was more level. However, this is pure speculation at this point and further analyses need to be conducted to examine this possible cause.

Chapter 6

CONCLUSIONS

The climate analysis with the ARSTAN data suggests a relationship between tree growth and climate, especially with the climatic conditions in June. However, spiral grain growth is correlated with February and the previous September temperature which indicates that the limiting factor for tree growth may not be the cause of spiral grain growth. Further studies with a more accurate method to measure grain angles in the field are necessary to conclude on the relationship between ring width and spiral grain. The low but nevertheless significant correlation coefficient suggests a relationship.

Although a non-fatal sampling method is desirable from an environmental as well as organizational standpoint, it has to be concluded from the results and the problems mentioned (in section 5.3), that the use of cross-sections is a better and more rewarding approach (at least with the methods, tools, and tree species used in this study).

As expected from field observations, Brazier's method of using just one diagonal on a cross-section to get an average grain angle for the whole circumference of that cross-section is not applicable for white oaks. I conclude that Brazier's method cannot be applied universally to every tree species. Before using Brazier's method on an untested species, appropriate tests in at least two preferably three cross-sections should be conducted.

Even though a statistical analysis was not possible for this experiment, a cautious conclusion is possible. From the data that was available, a difference in grain angles between living and dead trees was visible. It seems that dead trees have higher grain angles in a clockwise direction (to the right) than living trees. Besides increasing the sample size to validate the results, the use of cross-sections instead of cores could prove to be more effective.

The findings in this analysis support Noskowiak's (1959) findings for hardwoods. A majority of the trees show this distinct pattern of spiral grain to the right when young and switch to a left when older. However, variations are high and two trees have an opposite pattern. Increasing the sample size should be a major goal for future studies. That, of course, means an increased amount of time in the laboratory. Lab time, however, should not be decreased by just measuring every second or fifth growth layer. This method could result in the loss of valuable data.

Looking at the location of the trees used in this analysis, a cluster with a pronounced spiral grain pattern seem to be noticeable, although, this is pure speculation at this point. With a larger sample size, a sound spatial, including a topographic, analysis should be possible to clarify whether this pattern is a real one or just a product of low sample size.

Unfortunately, the 12 mm increment borer did not produce consistent results in this study; therefore, destructive sampling is necessary to study spiral grain in white oaks. Brazier's method (1965) should not be used in white oaks and should not be applied universally to all tree species. Samples from living and dead trees vary in severity and direction of spiral grain. The climatic factors that are most limiting to tree growth do not influence spiral grain growth in white oaks in this stand. Severe spiral grain does in general seem to be an indicator of age in white oaks, although most trees have severe left spiral grain and not right spiral grain. However, a tree without severe spiral grain is not necessarily young. To judge the severity of spiral grain, grain angles have to be examined in the outermost layer of the wood and not in the bark.

APPENDIXES

APPENDIX A

Table A.1. Correlations coefficients for 66 climate variables with average grain angles of all living cores and the different chronologies that ARSTAN creates from the averaged ring width measurements (meaSTD – standard chronology, meaRES – residual chronology, meaARS – Arstan Chronology).

Climate Variables	r for Grain Angles	r for meaSTD	r for meaRES	r for meaARS
lag May PDSI	0.081	0.049	-0.177	0.030
lag June PDSI	0.084	0.059	-0.236 (*)	0.034
lag July PDSI	0.075	0.086	-0.183	0.063
lag Aug. PDSI	0.064	0.145	-0.074	0.125
lag Sep. PDSI	0.048	0.177	0.029	0.147
lag Oct. PDSI	0.088	0.148	0.019	0.122
lag Nov. PDSI	0.097	0.165	0.055	0.138
lag Dec. PDSI	0.072	0.137	0.066	0.106
Jan. PDSI	0.054	0.114	0.086	0.082
Feb. PDSI	0.061	0.205 (*)	0.138	0.163
March PDSI	0.000	0.191 (*)	0.142	0.147
April PDSI	0.040	0.216 (*)	0.135	0.171
May PDSI	0.071	0.328 (**)	0.307 (**)	0.275 (**)
June PDSI	0.075	0.424 (**)	0.469 (**)	0.374 (**)
July PDSI	0.067	0.402 (**)	0.436 (**)	0.366 (**)
Aug. PDSI	0.054	0.364 (**)	0.401 (**)	0.340 (**)
Sep. PDSI	0.056	0.297 (**)	0.329 (**)	0.260 (**)
Oct. PDSI	0.091	0.242 (*)	0.252 (**)	0.213 (*)
Nov. PDSI	0.119	0.241 (*)	0.257 (**)	0.211 (*)
Dec. PDSI	0.076	0.200 (*)	0.274 (**)	0.178
lag Growing Season PDSI	0.079	0.116	-0.143	0.090
Growing Season PDSI	0.069	0.391 (**)	0.395 (**)	0.345 (**)
lag May Precipitation	0.059	0.067	-0.111	0.049
lag June Precipitation	0.088	0.041	-0.201 (*)	0.017
lag July Precipitation	0.017	-0.002	-0.107	0.004
lag Aug. Precipitation	-0.054	0.165	0.232 (*)	0.151
lag Sep. Precipitation	-0.096	-0.024	0.029	-0.033
lag Oct. Precipitation	0.143	-0.030	-0.004	-0.024
lag Nov. Precipitation	0.151	0.108	0.104	0.103
lag Dec. Precipitation	0.083	0.039	0.045	0.040

Jan. Precipitation	-0.079	0.052	0.119	0.037
Feb. Precipitation	0.074	0.159	0.082	0.148
March Precipitation	-0.145	0.031	0.073	0.008
April Precipitation	0.048	0.089	0.038	0.064
May Precipitation	0.066	0.271 (**)	0.238 (*)	0.237 (*)
June Precipitation	0.111	0.385 (**)	0.541 (**)	0.362 (**)
July Precipitation	0.000	0.138	0.134	0.149
Aug. Precipitation	-0.047	0.009	0.022	0.006
Sep. Precipitation	-0.053	-0.076	-0.085	-0.089
Oct. Precipitation	0.121	-0.071	-0.078	-0.061
Nov. Precipitation	0.191 (*)	0.081	0.078	0.078
Dec. Precipitation	0.015	0.031	0.068	0.053
lag Growing Season Prec	0.016	0.114	-0.074	0.086
Growing Season Precipitation	0.044	0.337 (**)	0.391 (**)	0.308 (**)
lag May Temperature	-0.039	0.076	0.138	0.078
lag June Temperature	0.022	0.003	0.109	0.036
lag July Temperature	-0.023	-0.146	0.022	-0.132
lag Aug. Temperature	-0.039	-0.176	-0.141	-0.169
lag Sep. Temperature	-0.211 (*)	-0.153	0.065	-0.142
lag Oct. Temperature	-0.009	0.105	0.109	0.108
lag Nov. Temperature	0.045	0.018	-0.002	0.009
lag Dec. Temperature	0.049	0.080	0.123	0.088
Jan. Temperature	0.010	-0.032	-0.030	-0.048
Feb. Temperature	0.318 (**)	0.143	0.027	0.159
March Temperature	0.028	0.004	-0.004	-0.018
April Temperature	0.131	0.137	0.068	0.157
May Temperature	-0.020	-0.084	-0.120	-0.080
June Temperature	-0.003	-0.215 (*)	-0.403 (**)	-0.188
July Temperature	0.031	-0.217 (*)	-0.133	-0.200 (*)
Aug. Temperature	-0.035	-0.163	-0.199 (*)	-0.163
Sep. Temperature	-0.121	-0.286 (**)	-0.240 (*)	-0.265 (**)
Oct. Temperature	-0.084	0.030	0.078	0.043
Nov. Temperature	0.019	0.046	0.095	0.035
Dec. Temperature	0.020	-0.013	-0.043	-0.002
lag Growing Season Temp	-0.108	-0.127	0.073	-0.105
Growing Season Temp	-0.058	-0.326 (**)	-0.373 (**)	-0.303 (**)

n = 107 for all correlations

** Correlations significant at the .01 level (2-tailed).

* Correlations significant at the .05 level (2-tailed).

APPENDIX B

	Year	*r(A,E)*	*r(B,F)*	*r(C,G)*
r(A,E)	0.270	1		
r(B,F)	0.219	0.216	1	
r(C,G)	0.459	0.483	0.644	1
r(D,H)	-0.357	0.071	-0.174	-0.081

Table B.1. Correlation coefficients in dead tree 1 between the diagonals. Consistently low correlation coefficients.

	year	*r(A,E)*	*r(B,F)*	*r(C,G)*
r(A,E)	0.709	1.000		
r(B,F)	-0.732	-0.288	1.000	
r(C,G)	0.919	0.780	-0.634	1.000
r(D,H)	-0.770	-0.408	0.732	-0.719

Table B.2. Correlation coefficients in dead tree 3 between the diagonals. Although some of the correlation coefficients are relatively high, they change their direction (neg./pos.).

	year	*r(A,E)*	*r(B,F)*	*r(C,G)*
r(A,E)	0.977	1.000		
r(B,F)	0.939	0.961	1.000	
r(C,G)	0.941	0.959	0.967	1.000
r(D,H)	0.950	0.965	0.962	0.961

Table B.3. Correlation coefficients in dead tree 4 between the diagonals. Consistently high correlation coefficients.

	year	*r(A,E)*	*r(B,F)*	*r(C,G)*
r(A,E)	0.880	1.000		
r(B,F)	0.699	0.758	1.000	
r(C,G)	0.769	0.833	0.607	1.000
r(D,H)	0.750	0.702	0.548	0.613

Table B.4. Correlation coefficients in dead tree 5 between the diagonals. Although some of the correlation coefficients are relatively high, they are not consistently so.

	year	*r(A,E)*	*r(B,F)*	*r(C,G)*
r(A,E)	-0.098	1.000		
r(B,F)	-0.218	0.393	1.000	
r(C,G)	0.302	0.464	0.370	1.000
r(D,H)	0.679	0.283	0.212	0.593

Table B.5. Correlation coefficients in dead tree 8 between the diagonals. Consistently low correlation coefficients.

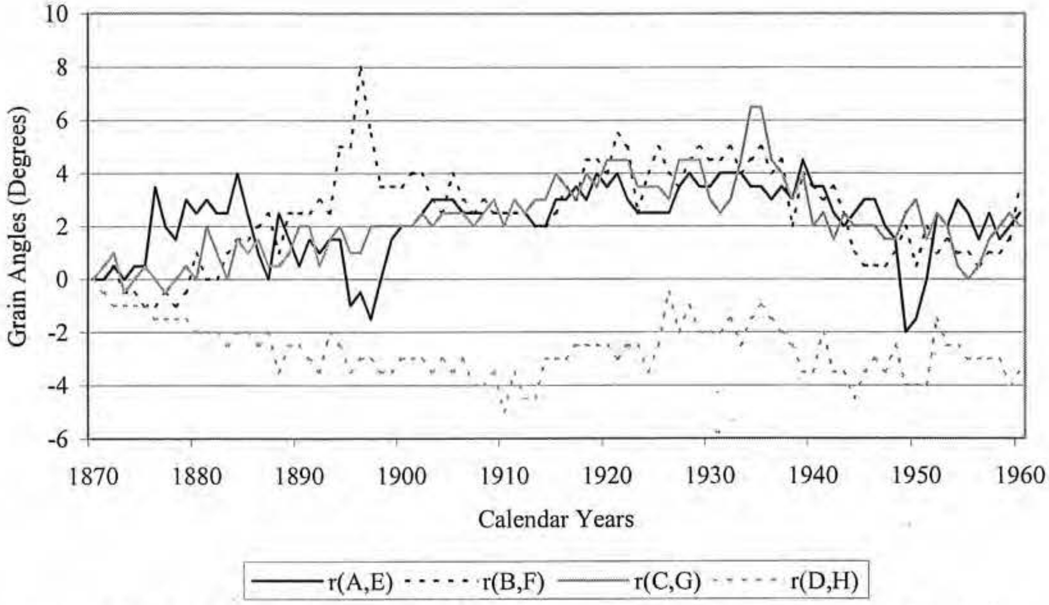

Figure B.1. Grain angles compared to calendar years (four diagonals, dead tree 1).

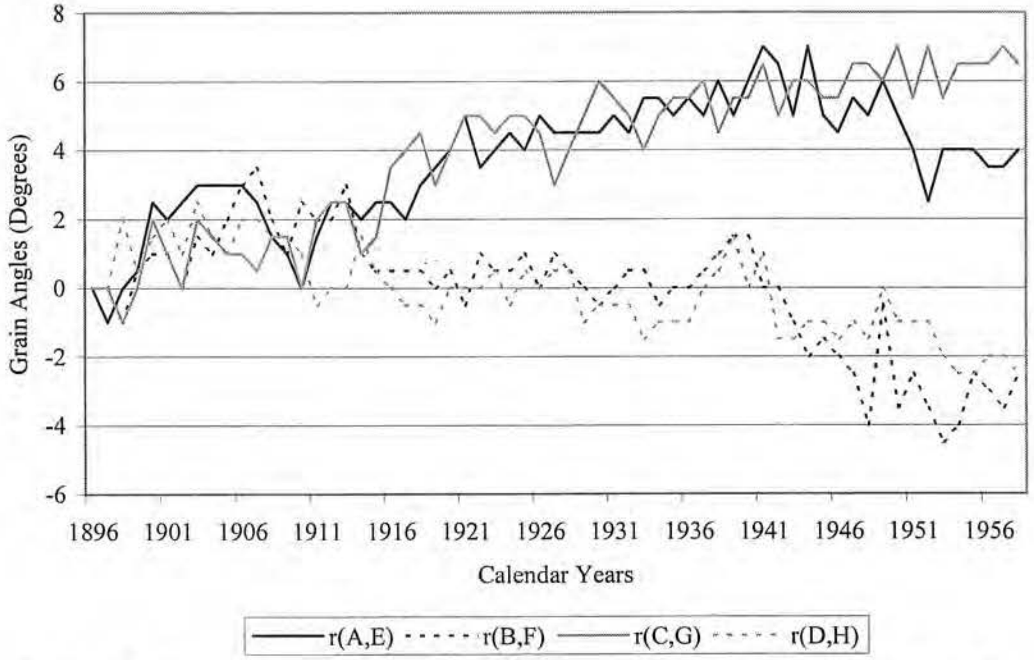

Figure B.2. Grain angles compared to calendar years (four diagonals, dead tree 3).

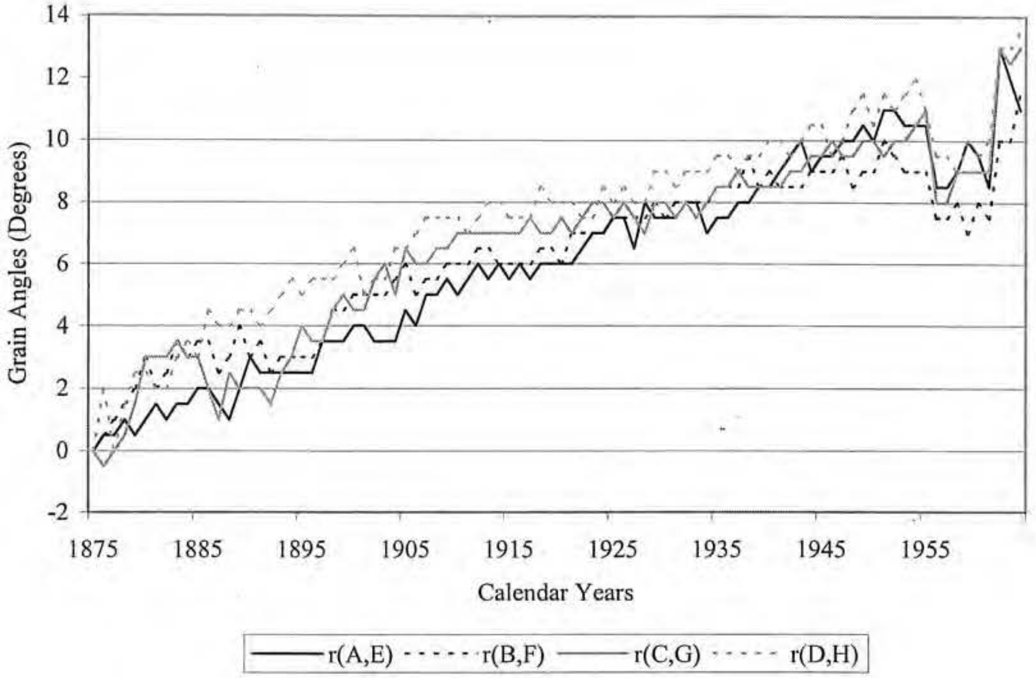

Figure B.3. Grain angles compared to calendar years (four diagonals, dead tree 4).

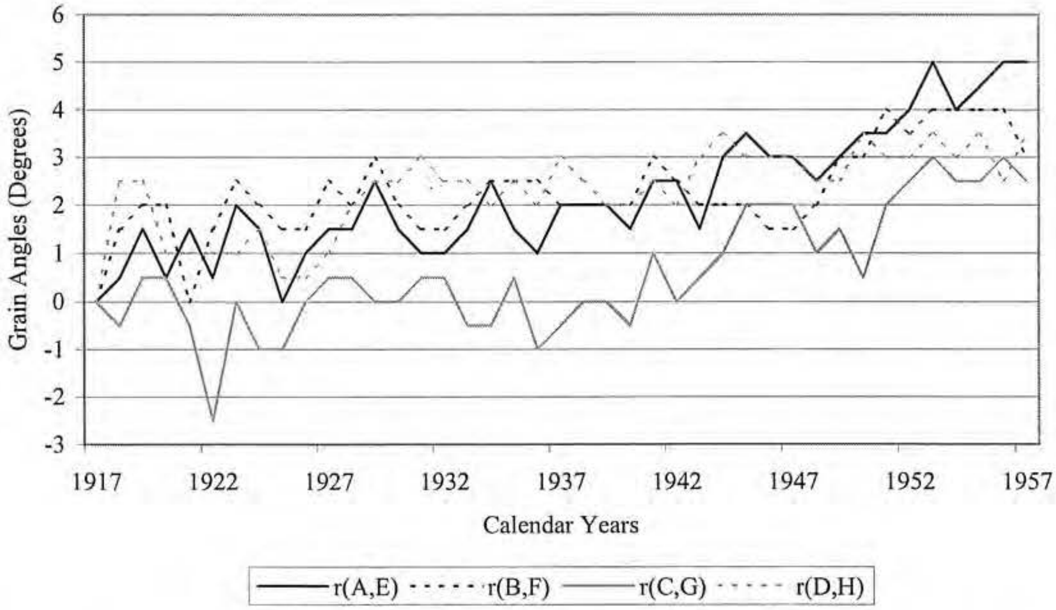

Figure B.4. Grain angles compared to calendar years (four diagonals, dead tree 5).

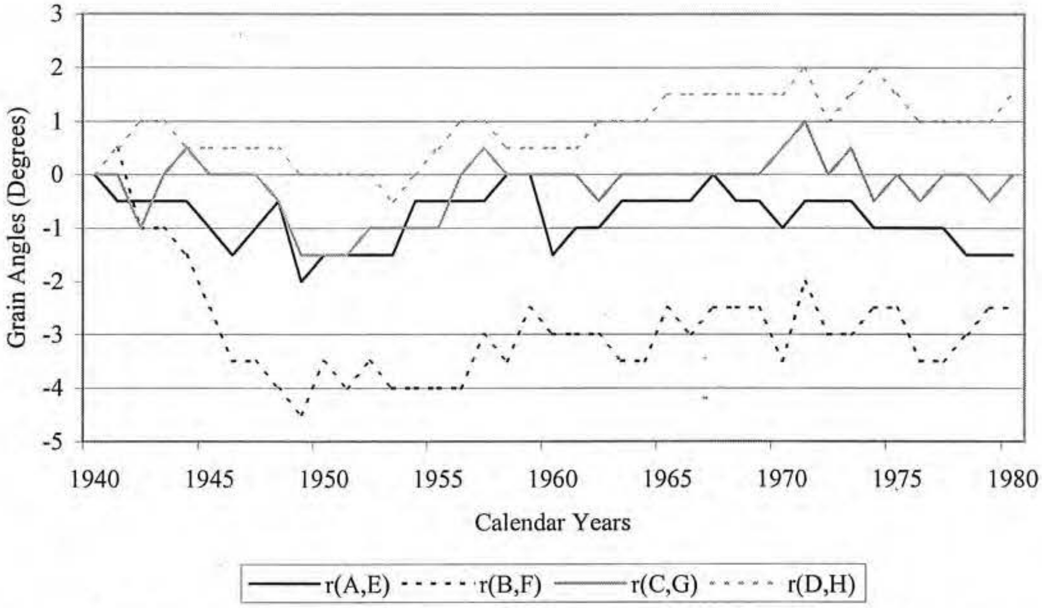

Figure B.5. Grain angles compared to calendar years (four diagonals, dead tree 8).

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