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RESEARCH REPORT

AGE DEPENDENCE OF SPIRAL GRAIN IN WHITE OAKS (*QUERCUS ALBA* L.) IN SOUTHWESTERN ILLINOIS

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ABSTRACT

Dendrochronologists have used the presence of spiral grain as an indicator of old trees for most of the history of the field, although this relationship has been little studied. We examined cross-sections from dead trees and used a 12-mm Haglof Swedish Increment borer to collect cores from living white oak (*Quercus alba* L.) trees in an Eastern Deciduous Forest stand in southwestern Illinois. Spiral grain is the alignment of wood fibers to the longitudinal axis of trees and is driven by patterns of initial cambial cell division. In this study, we examine environmental factors that may affect spiral grain severity, the usefulness of non-destructive sampling methods (using the 12-mm increment borer), and the relationship between tree age and spiral grain. We tested Brazier's method (1965) of averaging the spiral grain angle from two radii taken 180 degrees apart (*i.e.* one diameter in the tree) to get representative grain angles for the whole circumference of a tree at a certain height. The 12-mm increment borer did not produce consistent results in this study; therefore, the collection of cross-sections is advised for the study of spiral grain in white oaks. Brazier's method should not be used in white oaks and should not be applied universally to all tree species. The severity of spiral grain is expressed in the xylem and may not be expressed in the bark of the tree. Left spiral grain does generally increase in white oaks with age, although this relationship is not always consistent, so a tree without severe spiral grain is not necessarily young.

Keywords: spiral grain, dendrochronology, age dependence, white oak.

Dendrochronologen haben die Präsenz von Drehwuchs als Indikator fuer alte Bäume genutzt, obwohl diese Verhältnis wenig erforscht wurde. Wir untersuchten Querschnitte von toten Bäumen and nutzten einen 12-mm Zuwachsborer der schwedischen Marke Haglof, um Holzproben von lebenden weissen Eichen (*Quercus alba* L.), die in einem Laubwald im Südwesten von Illinois zu finden sind, zu sammeln. Drehwuchs ist der Verlauf der Holzfasern im Vergleich zur Stammachse eines Baumes und wird von einer kambialer Zellteilung initiiert. In dieser Studie haben wir die Umweltfaktoren, die den Drehwuchs eventuell beeinflussen, die Nützlichkeit von nicht zerstörerischen Probeentnahmeverfahren (mit dem 12-mm Zuwachsborer), das Verhältnis zwischen Baumalter und Drehwuchs, und Brazier's Methode (1965) untersucht. Brazier's Methode ist das Analysieren des Drehwuchses entlang zweier Radien, die in einer Geraden liegen (also ein Durchmesser von einem Baum), um repräsentative Drehwuchswinkel für den ganzen Umfang auf einer bestimmten Höhe eines Baumes zu erhalten. Der 12-mm Zuwachsborer produzierte keine stimmigen Resultate in dieser Studie. Deshalb werden zerstörerische Probeentnahmeverfahren, wie das Entnehmen von Querschnitten eines Baumes, nahegelegt, um den Drehwuchs in weisser Eiche zu bestimmen. Braziers Methode sollte nicht in der weissen Eiche benutzt und sollte auch nicht universell für jede Baumart angewandt werden. Die Stärke des Drehwuchses wird im Xylem zum Ausdruck gebracht und nicht in der Baumrinde. Linker Drehwuchs nimmt im Allgemeinem im Alter in weisser Eiche zu, obwohl dieses Verhältnis nicht immer existiert, so dass ein Baum ohne starken Drehwuchs nicht unbedingt jung ist.

Schlüsselwörter: Drehwuchs, Dendrochronologie, Weisse Eiche, Holzfaserorientierung.

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INTRODUCTION

Spiral grain, the alignment of wood fibers (tracheids) to the longitudinal axis of trees, has fascinated scientists for over 150 years. Visible in trees and poles, spiral grain and its possible causes are of interest to foresters, botanists, and dendrochronologists. 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 because of 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).

Spiral grain formation is the normal pattern of wood growth in most trees and is driven by division of cambial initials to the right in most conifers and division to the left in most hardwoods. 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* (Bong.) Carr.) is under strict genetic control. Hartig (1895) found a positive correlation between direction of cell division (pseudotransverse anticlinal division in the vascular cambium and the following intrusive cell growth) and spiral grain growth. This finding has been supported by Bannan (1966), Hejnowicz and Zagorska-Marek (1974), and Hejnowicz and Romberger (1979). Also, ethylene production in the wood itself is suggested to influence or even initiate spiral grain growth (Telewski and Jaffe 1986a; Eklund *et al.* 2003). As studied by several authors, spiral grain might strengthen the tree to protect it from breakage when external mechanical loads like bending and torsion are applied (Quirk *et al.* 1975; Telewski and Jaffe 1986b; Skatter and Kucera 1998).

Various environmental factors are believed to influence spiral grain growth, including gravity, wind, light and solar movement, aspect, slope, soil, altitude, water distribution, or injuries to the tree (Noskowiak 1959; Harris 1989; Danborg 1994; see Rauchfuss (2004) for a full description of the various hypotheses). 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 easier 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). Wind has been suggested as another factor that could drive spiral grain formation although there is little consensus on the mechanisms involved (Wentworth 1931; Yeager 1931; Howard 1932; Kremple 1970; Harris 1989; Mattheck and Kubler 1997; Eklund and Säll 1999). Mattheck and Kubler (1997) and Telewski and Jaffe (1986a) 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 (Kremple 1970). Studies on light, sun angle, and the Earth’s rotation to determine their influence on spiral grain growth have concluded that heliotropism (*e.g.* Butler 1931) is not a major contributor to tree growth and that the Coriolis force (*e.g.* Thunell 1951) is too broad scale to affect individual tree growth (Noskowiak 1959; Harris 1989).

Early studies tested the effect of slope and aspect on the occurrence of spiral grain in trees with mixed results, ending in the conclusion that there is no consistent pattern (Smythies 1915; Van Oye 1926; Champion 1927b; Rault and Marsh 1952). Soil influences on plant growth (*e.g.* nutrient availability and water holding capacity) have been suggested as possible controlling factors of spiral grain development but repeated studies of this mechanism have not supported any definite conclusions (Rault and Marsh 1952; Raunecker 1957; Fielding 1967; Whyte *et al.* 1980; Harris 1989). Altitude has also been studied as a possible cause of spiral grain production in trees but most researchers have concluded that altitude alone is not enough to cause spiral grain, but it may be when combined with harsh climate, lower vapor pressure, poor soil condition, increased exposure to ultraviolet energy caused by a thinner atmosphere, or old age to reinforce these stresses on trees (Champion 1929; Thunell 1951; Mayer-Wegelin 1956). The water distribution hypothesis suggests that spiral grain helps to distribute transpiration water evenly throughout the stem when it is lacking on one side of the tree and is supported by the finding that more pits occurred in spiral grain trees than in straight grained trees (Hartig 1895; Liese and Ammer 1962; Vité 1967; Webb 1967; Kremple 1970). Injuries also cause spiral grain (Mattheck and Kubler 1997). However, this deviation of grain angles to the stem axis is not part of the ultimate cause of spiral grain as these are just deviations around local anomalies.

Destructive sampling methods (*i.e.* cutting cross-sections with a chainsaw) have mainly been used for the determination of grain angles in research studies (Harris 1989; Koch and Schlieter 1991; Danborg 1994). Non-destructive methods for analyzing grain angles in a tree (*i.e.* use of a sampling method that does not kill the tree) are desirable. Noskowiak (1959) tried to use a 4.5-mm increment borer to study spiral grain but was not successful because of deformation of the core after removal from the tree because of the diameter of the core. Noskowiak (1968) later successfully tested the use of a 10-mm increment borer and concluded that the method was useful although his measuring of grain angles was rather complex. Assessing the usefulness of such non-fatal and time-saving methods is a crucial emphasis for spiral grain research.

In addition, time-saving laboratory methods are also highly desirable. Harris (1984) suggested a simplified method that has not been tested (to be described later). To save time, Brazier (1965) 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. This method seems to lack accuracy for at least some species (Wobst *et al.* 1994). Although Brazier (1965) found a high correlation between different diameters 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* (Mirb.) Franco.). 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 our study, Brazier's method was tested in white oak (*Quercus alba* L.).

Spirality and Tree Age

A commonly held idea in the dendrochronological community is that spiral grain is an indicator of greater tree age (Fritts 1976). However, studies have shown that this is not necessarily the case, particularly in hardwoods (Noskowiak 1959). In conifers, a general pattern has been established. When young, conifer trees usually spiral to the left (*i.e.* when facing the tree, the grain slopes toward the left) and with age straighten out and finally spiral to the right (Champion 1925, 1927a; Rault and Marsh 1952; Northcott 1957; Harris 1989; Cown *et al.* 1991, Danborg 1994). In hardwoods, however, the opposite might be true, but exceptions to this rule are more often reported than with softwoods (Noskowiak 1959).

Grain angle is fixed in trees with the lignification of tracheids, but Lowry and Erickson (1967) have suggested that drying of the wood will cause standing trees to relax along the vertical axis (as a result of gravitational pull) with a loss of moisture enhancing the apparent spiral grain angle in dead snags and service poles. 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 assess the spiral pattern within the stem by looking at (or under) the bark (Knigge and Schulz 1959; Bues 1992; Kliger 2001).

The purpose of this study is to examine non-fatal sampling methods and to analyze spiral grain patterns in living and dead white oak trees. The ultimate goal is to determine if a high degree of spiral grain truly suggests trees of exceptional age. In particular, the objectives of this study are to:

1. examine the extent to which different climate variables affect the growth of spiral grain;
2. test whether an increment borer can be used to study spiral grain;
3. assess the applicability of Brazier's method of averaging two radii on a cross-section at a certain height for the average spiral grain angle in white oak trees; and,

4. test whether spiral grain angles correlate with the age of the tree.

METHODS

Site Description

Sampling was conducted on private property just south of Waterloo, Monroe County, Illinois (Figure 1). Elevation ranges from 150 to 190 m above sea level and a small ephemeral stream runs through the property. Selective logging has been conducted on this site since the 19th Century; however, representative trees within 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* Audubon ex. Torr. & Gray) and ironwood (*Ostrya virginiana* (Mill.) K. Koch). The soil is relatively thin and rocks can be encountered 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 to very steep, well drained, moderately permeable to slowly permeable, silty and loamy soils; formed in loess, glacial till, and residuum) (Soil Survey of Monroe County, Illinois 1987). Precipitation in southeastern Illinois (NOAA Climate 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.

Field Methods

For this study, we removed cores from living and dead trees with a 12-mm diameter Haglof Swedish Increment borer and cut cross-sections from dead trees with a chainsaw. We established a 50 m by 50 m plot on a moderately sloped terrace. Ten living white oaks within the plot with greater than 25 cm diameter at breast height (DBH) were cored. All dead trees (seven total) in the plot that met certain requirements (sufficient stable structure, root crowns located within the plot, and a DBH of at least 15 cm) were cut using a chainsaw, and two cores were taken at breast height using a 12-mm increment borer.

Before taking samples, a 10 cm by 10 cm window was cut into the bark of the living trees, and then the bark was chiseled off to expose the outermost growth layer. The grain angles were then measured with a freely pivoting needle and a protractor that was leveled with a spirit level. With a sharp nail-like instrument, scribe marks were cut along the grain into the exposed outermost layer to make the grain more visible. Two cores on opposite sides of the tree were taken through the scribe marks so that the cores could be aligned to their proper grain angle later in the lab. Without testing his own method, Harris (1984) suggested taking just one core through the whole diameter of the tree. In the field, however, we found it impossible to take a core through 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 wrapped with plastic wrap and stored in air-tight zip-lock bags.

Laboratory Methods

In the laboratory, a plane surface was cut along the cores with a razor blade. This finished surface 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 (Stokes and Smiley 1968). The ring width was measured using a Velmex measuring system and Measure J2X measuring software. The crossdating was checked using COFECHA (Grissino-Mayer 2001).

The cores were mounted in clamps with the cross-sectional view facing up. One annual growth layer after the other was chiseled off using a chisel and hammer, and on the exposed tangential surface of each ring, grain angles were measured using a

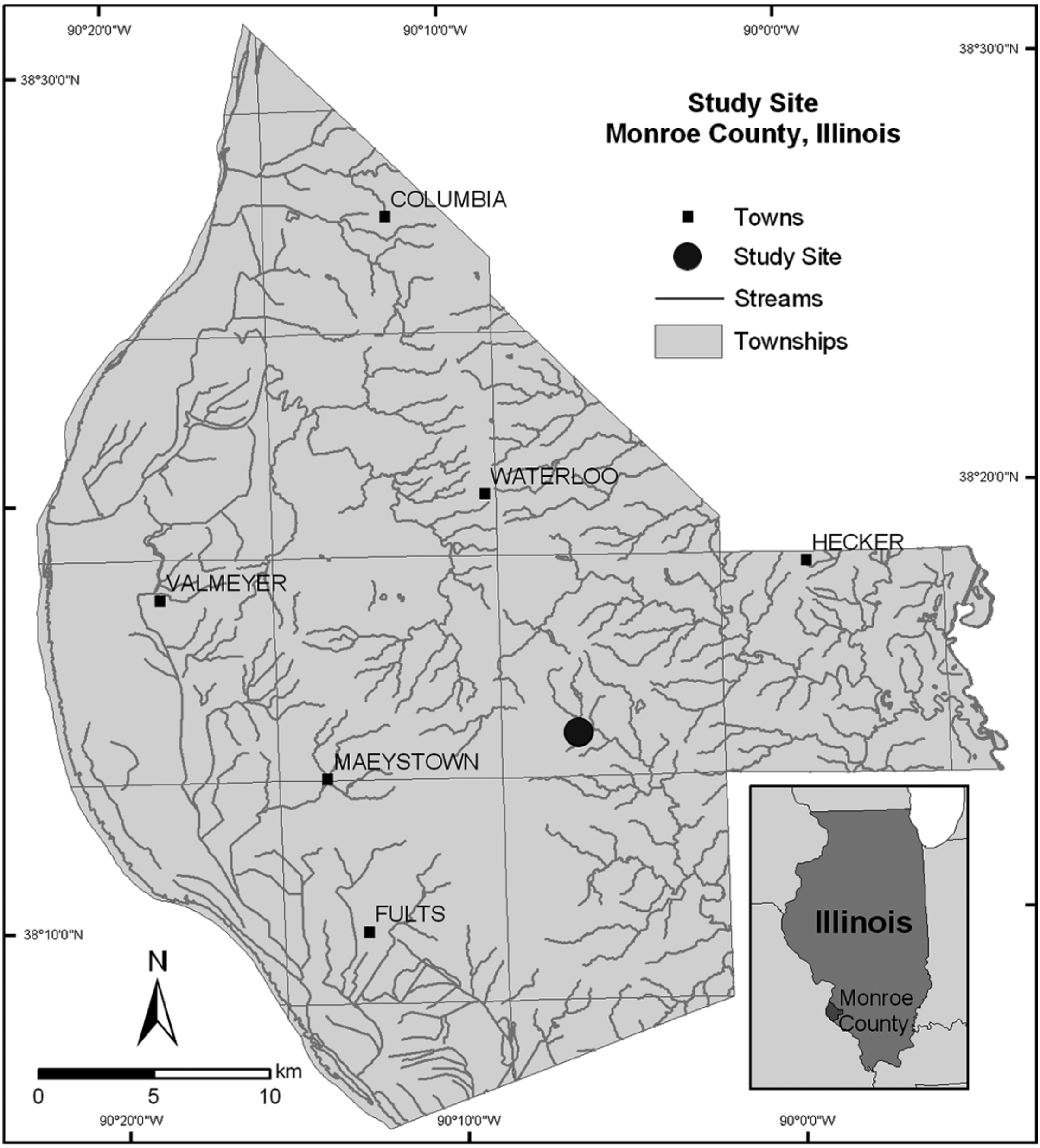

Figure 1. Map of the location of the study site in Monroe County, Illinois.

microscope with a protractor reticle to 1° precision. The outside grain angles measured in the field were either added or subtracted to measurements of each annual grain angle measured in the laboratory. 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.

The measurement data were run through ARSTAN (Cook and Holmes 1986) to standardize the tree-ring series and create a master chronology, which was then used in a climatic analysis. A correlation analysis was used to check for consistency in spiral grain between cores and cross-sections from dead trees (with the cross-section being taken directly above the borehole of the increment borer) to determine the usefulness of data received from cores and the possibility of using cores to study spiral grain growth in trees. Correlation analysis was used to examine the relationship between several series of grain angles (paired radii) on one cross-section to determine if Brazier's method (1965) is applicable to white oaks. A 95% confidence interval ($\alpha = 0.05$) was chosen for testing significance for all analysis unless otherwise stated. Correlation analyses were used to analyze the relationship of spiral grain to the age of tree.

The initial grain angle could not be precisely measured in the field because of the limitations of the precision of the markings on the spirit level. To test Brazier's method and analyze grain angles in living and dead trees, the first measurement of each averaged value was set to zero and subsequent grain angles were calculated accordingly. In addition, the first measurement (which was set to zero) was considered to be a year that had all grain angles represented. This assumption made it possible to compare trends from one growth layer to the next. However, results do not reflect absolute spirality, *i.e.* no conclusion can be drawn regarding when the direction of spiral grain growth changes, only that there is a change in direction during the life of a tree. In addition, grain angles measured in knot areas were deleted.

RESULTS

COFECHA, Climate, and Ring Width

A 40-year segment with a 20-year lag was chosen because some of the cores were as short as 57 years and averaged 105 years (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 and mean sensitivity of 0.231 are high, suggesting that these series are sensitive to a stand level signal.

The climatic conditions in June are the dominant control of tree growth on this site. June Palmer Drought Severity Index (PDSI; data from the NOAA Climate Division 8 for Illinois) is significantly correlated with both the standard and residual chronologies produced in ARSTAN and explains 22% of the variance in the residual chronology. February temperature and lagged September temperature from the previous year were significantly correlated to spiral grain angles ($r = 0.32$ and $r = -0.21$, respectively). In addition, ring width and its relationship with spiral grain angles were examined using the living trees. A slight negative correlation was found between ring width and spiral grain angles ($r = -0.30$). This suggests that stressful growing conditions produce greater spiral grain formation.

Table 1. Correlation coefficients for averaged spiral grain data from cores (CORE) and averaged spiral grain data from cross-section (from just one diameter with the same compass-direction; CROSS) including correlation coefficients against age (spiral grain angles *vs.* tree age).

	Age	CORE01
CORE01	0.81***	
CROSS01	0.59*	0.34
	Age	CORE03
CORE03	0.36**	
CROSS03	0.74***	0.12
	Age	CORE04
CORE04	0.26*	
CROSS04	0.97***	0.24*
	Age	CORE05
CORE05	0.47**	
CROSS05	0.91***	0.24

*p < 0.05. **p < 0.01. ***p < 0.001.

Studying Spiral Grain with Increment Borers

For this part of the study, cross-sections and cores from the same tree, approximately the same height and same compass-direction, were examined. In this analysis, we 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 diameter with the same compass-direction) was 0.34 (dead tree 1) and the lowest is 0.12 (dead tree 3, Table 1).

Table 2. Correlation coefficient in dead tree 4 between the diameters. Letters A through G represent the end points of each radius measured with the paired letters (*e.g.* A, E) representing one diameter.

	Year	r(A,E)	r(B,F)	r(C,G)
r(A,E)	0.98***			
r(B,F)	0.94***	0.96***		
r(C,G)	0.94***	0.96***	0.97***	
r(D,H)	0.95***	0.97***	0.96***	0.96***

***$p < 0.001$.

The difference between cores and cross-sections are also visible in the correlation coefficients between the measured grain angles and the age of the trees (Table 1). While grain angles on the cross-sections correlate highly with age (average r = 0.80), the cores have comparably low correlation coefficients (average r = 0.48).

Accuracy of Brazier's Method for White Oak

For this analysis, correlation coefficients were computed for each diameter on a cross-section and then compared between the four sets of diameters. Only one out of five cross-sections had a high correlation coefficient (r = 0.90) between the diameters (dead tree 4, Table 2). The other four cross-sections exhibited great variations among the correlation coefficients (*e.g.* Table 3).

Spiral Grain Relationship with Age

Averaged spiral grain from all diameters on the cross-sections demonstrated a significant age-spiral grain correlation ($r = 0.94$, $p < 0.001$). The results for individual trees display great variations (Table 4). When plotted, some trees show a distinctive pattern, starting with right spiral grain when young and changing the direction of spiral grain growth to the left when they grow older.

Table 3. Correlation coefficient in dead tree 1 between the diameters. Although some of the correlation coefficients are high, not all of them are consistently so; therefore, the diameters do not relate very well with each other.

	Year	r(A,E)	r(B,F)	r(C,G)
r(A,E)	0.27**			
r(B,F)	0.22*	0.22*		
r(C,G)	0.46***	0.48***	0.64***	
r(D,H)	−0.36***	0.07	−0.17	−0.08

*$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Table 4. Results for the correlation analysis for cross-sections (tree age *vs.* grain angles). The number of rings compared is represented by n.

	n	r	p
JMTD01	451	0.10	<0.05
JMTD03	308	−0.01	0.808
JMTD04	375	0.93	<0.001
JMTD05	179	0.78	<0.001

A similar pattern can be seen in cores from living trees when comparing grain angles and tree age. Averaging all cores into one value yielded significant results ($r = 0.73$, $p < 0.001$). Averaging the two cores from each tree and analyzing those values resulted in a low but still significant correlation ($r = 0.33$, $p < 0.001$). Again, looking at individual trees, great variation between the trees was observed (Table 5). As with the cross-sections, some trees have this distinct pattern: negative (right) grain angles during younger years and more pronounced positive (left) grain angles with increasing tree age.

DISCUSSION

Quality of the Chronologies

The series intercorrelation of 0.649 and mean sensitivity of 0.231 were relatively high compared to other chronologies developed in the eastern US

Table 5. Results for the correlation analysis for living trees (tree age *vs.* grain angles). The number of rings compared is represented by n.

	n	r	p
JMT08	81	−0.54	<0.001
JMT10	83	0.50	<0.001
JMT11	124	0.01	0.906
JMT12	126	−0.90	<0.001
JMT14	122	0.70	<0.001
JMT20	117	0.95	<0.001
JMT22	118	0.96	<0.001

(Dewitt and Ames 1978; Speer 2001). Furthermore the trees in this area have been documented at close to 200 years in age (Speer, unpublished data), suggesting that many of the trees in this region survived local logging at the turn of the century, making them a useful resource for further dendrochronological analysis.

Problems with the Data Set

Several problems arose during this research with this data set. For example, because of the method of measuring grain angles in the field, it was not always possible to rely on absolute grain angles. As already noted by Noskowiak (1959), measurements of the grain angle in the field are very subjective. Therefore, instead of using absolute grain angles, the first years of the spiral grain measurements were set to zero during the statistical analysis and the subsequent grain angles were calculated accordingly. As a result, it was not always possible to analyze the absolute grain angles, but we were able to analyze the trends of the grain angles. Often, it was important that compared samples 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 narrow 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 10 living trees, three had to be excluded because it was impossible to accurately calculate the pith date because of a lack of curved rings at the center of the core. Two out of seven trees had precise pith dates. 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 curvature of the rings was visible on the cores, these estimates were double-checked using pith indicators (Applequist 1958) and we believed these to be reliable estimates of tree age.

COFECHA, Climate, and Ring Width

Spiral grain appears to be somewhat controlled by preceding temperature conditions (lagged September and February temperature). These variables are not significantly correlated with the master tree-ring chronology, demonstrating that different environmental factors affect incremental wood accumulation and spiral grain formation. However, the significant but low correlation ($r = -0.30$) between spiral grain angles and ring width suggests that stressful conditions to tree growth may enhance spiral grain formation. This would support the hypothesis of water transport around the tree being a driving factor for spiral grain growth. However, a more accurate method of measuring grain angles in the field is needed to verify a relationship.

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 standard-sized 12-mm increment borer might not be an appropriate tool for studying spiral grain in white oaks. Both authors thought that it would be possible to examine spiral grain on this larger core through the whole diameter of the tree. Using the hand-driven 12-mm increment borer for coring hardwoods is almost impossible, especially for extracting a core all the way through the tree. Two people turning the borer were necessary to get the borer to the pith. We concluded that coring the whole diameter with a 12-mm borer is physically impossible in large hardwoods, particularly white oak. Some other instruments may be of use in collecting a whole core through the entire tree. A CSIRO Trecor™ Wood Corer can be used to take a 12-mm increment core using an electronic motor or an archaeological borer with a hole saw cutting tip could be used to take 12-mm diameter cores.

Another major problem with the increment borer compared to using a chain saw for cross-sections is the need to hit pith. Hitting pith is very important to obtain the age of the tree, but requires considerable skill. Several means exist 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 indicated 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 (*i.e.* 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 caused by fissures in the bark. Averaging multiple measurements (as was done in this study) improves readings.

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

Accuracy of Brazier's Method for White Oak

Brazier's (1965) method of averaging the grain angle between two radii taken 180 degrees apart for a representative grain angle of the tree is very desirable for spiral grain studies because it saves much time when measuring spiral grain. Although Brazier's method does not seem to be wrong (as shown in dead tree 4 with the high correlation coefficients between the four diameters), our results show that this method cannot be applied universally to all individual trees and tree species.

Observations in the field indicate that the averaging of grain angles from two opposing radii might result in the loss of valuable grain angle data. In several trees, we observed different directions of the grain angles in opposing radii. A 10° right spiral grain on one side of the tree and 10° left spiral grain on the other side of the tree would result in zero degree grain angles and would not represent the actual grain angles of the tree. These observations argue against the Brazier's (1965) method, as do our results of averaging across two opposing radii (a diameter) within a tree.

Spiral Grain Relationship to Age

Our analyses support Noskowiak's (1959) findings for a complex pattern of spiral grain in hardwoods. Hardwoods appear to spiral to the right when they are young but change direction to finally spiral to the left when they grow older. At least half of the trees show this distinct pattern. However, in the other half of the trees, variations are high and for two trees the pattern is the opposite. Overall, we observed a pattern of increased spiral grain associated with the age of the cambium.

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 temperature in February and the previous September, which indicates that the limiting factor for tree growth may not be the cause of spiral grain growth. Stressful conditions in February and the proceeding September may stress the tree and control cell division when it initiates in the spring.

Although a non-destructive sampling method is desirable from an environmental standpoint, we conclude from the results and the problems mentioned in this study 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 diameter on a cross-section to obtain an average grain angle for the whole circumference of that cross-section is not applicable for white oaks. The results show 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.

The results of 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 the left when older. However, variations are high and two trees have an opposite pattern. Severe left spiral grain does seem to be related to the age of white oak trees, however, a tree without severe spiral grain is not necessarily young.

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