

# Presettlement forests and fire in southern Alabama

S. Andrew Predmore, Josh McDaniel, and John S. Kush

**Abstract:** Although the loss of *Pinus palustris* P. Mill. (longleaf pine) dominated communities and the alteration of the presettlement fire regimes have been documented, there is little information on the ecology of the presettlement lower Coastal Plain forests of the southeastern United States. We used 12 637 witness trees, which were recorded by General Land Office surveyors between 1820 and 1846, to identify presettlement witness tree associations and to explore witness tree – environmental variable relationships. Detrended correspondence analysis (DCA) was used to identify three witness tree associations including a *Pinus* spp. – *Quercus marilandica* (L.) Muenchh. association, a *Quercus* spp. – *Carya* spp. association, and a *Persea* spp. – *Fagus grandifolia* Ehrh. association. Canonical correspondence analysis and contingency tables were used to describe and test witness tree relationships with slope, elevation, and soil drainage. Additionally, bearing distances, used as an indicator of forest density, were compared among the witness tree associations. Species orientation shown by the DCA ordination diagram was interpreted as a gradient of fire frequency. This interpretation of a fire gradient was supported through the analysis of bearing distances, which showed high bearing distances associated with witness trees located on the high fire frequency end of the gradient. The relationships between witness trees and environmental variables as well as relationships between witness trees and bearing distances suggest that fire-dependent longleaf communities dominated the presettlement study area.

**Résumé :** Bien que la perte de communautés dominées par *Pinus palustris* P. Mill. (pin des marais) et la modification des régimes des feux qui prévalaient avant la colonisation aient été documentées, il existe peu d'information sur l'écologie des forêts qui occupaient la basse plaine côtière du sud-est des États-Unis avant la colonisation. Nous avons utilisé 12 637 arbres témoins, recensés par les arpenteurs du Bureau général des terres entre 1829 et 1846, pour identifier les associations d'arbres témoins qui existaient avant la colonisation et explorer les relations entre les arbres témoins et les variables environnementales. L'analyse des correspondances redressée a été utilisée pour identifier trois associations d'arbres témoins incluant une association de *Pinus* spp. et *Quercus marilandica* (L.) Muenchh. , une association de *Quercus* spp. et *Carya* spp. et une association de *Persea* spp. et *Fagus grandifolia* Ehrh. L'analyse canonique des correspondances et des tables de contingence ont été utilisées pour décrire et tester la relation des arbres témoins avec la pente, l'altitude et le drainage. De plus, la distance des relèvements, utilisée comme indicateur de la densité de la forêt, a été comparée entre les associations d'arbres témoins. L'orientation des espèces illustrée par le diagramme d'ordination de l'analyse des correspondances redressée a été interprétée comme un gradient de la fréquence des feux. Cette interprétation d'un gradient de la fréquence des feux était supportée par l'analyse de la distance des relèvements qui a montré que les relèvements dont la distance était élevée étaient associés aux arbres témoins situés à l'extrémité supérieure du gradient de la fréquence des feux. Les relations entre les arbres témoins et les variables environnementales aussi bien que les relations entre les arbres témoins et la distance des relèvements indiquent que les communautés de pin des marais tributaires du feu dominaient la zone d'étude avant la colonisation.

[Traduit par la Rédaction]

## Introduction

The loss of longleaf pine (*Pinus palustris* P. Mill.) dominated communities is at the forefront of management issues in the southeastern Coastal Plain of the United States. These communities, and their unique floral and faunal components,

have declined dramatically since European settlement (Frost 1993; Engstrom 1993; Guyer and Bailey 1993; Folkerts et al. 1993). Habitat losses subsequent to European settlement are largely attributable to the clearing of land for agriculture, logging, and the alteration of presettlement fire regimes (Cowdrey 1983; Cowell 1998; Frost 1993). These losses have been considerable, including 98% of longleaf pine forests and 78% of bottomland hardwood forests (Noss et al. 1995). Given these considerable changes in the landscape, sources of information on presettlement forests can provide valuable information on the historical ecology of native plant communities. From a land-management perspective, this information is also relevant to restoration efforts and the associated need to understand the historic range of variability of ecosystems (Swetnam et al. 1999).

One commonly used data source on presettlement forests has been witness trees. The terms witness tree and bearing

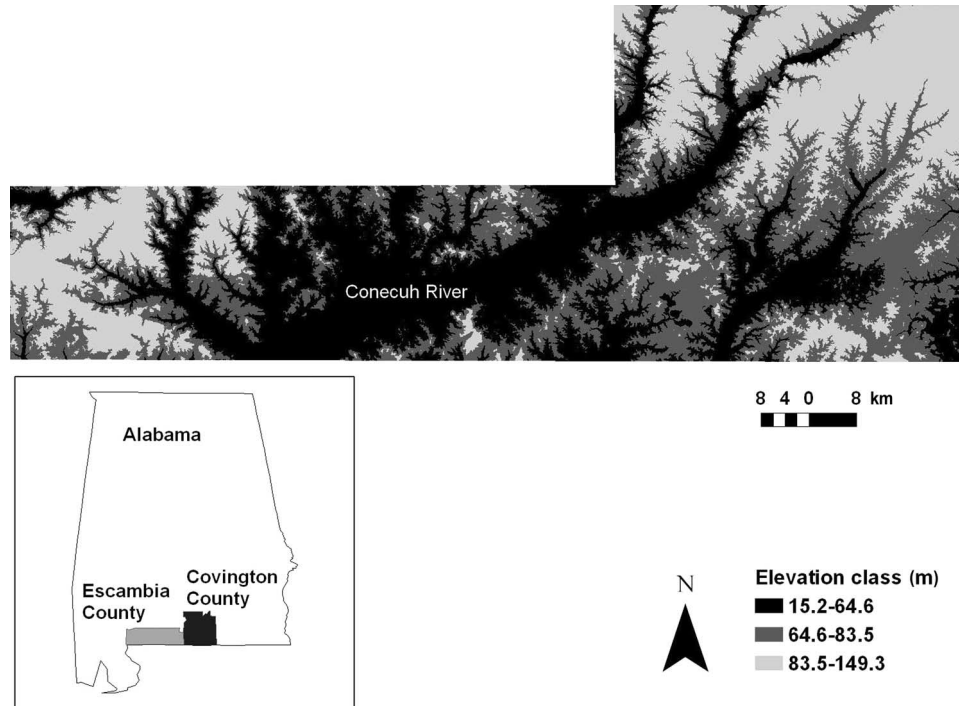
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**Fig. 1.** Study site map and elevation classification used for contingency table analysis in Escambia and Covington counties, Alabama.



tree are used interchangeably and refer to trees marked by land surveyors to identify parcels of land in preparation for sale (Bourdo 1956). The majority of research using witness tree data has come from the General Land Office (GLO) public land surveys. Researcher preference for GLO data is a direct result of their relative standardization and acceptance as a quantitative source of presettlement ecological data. Despite the general acceptance of this data source, the records are not devoid of problems. Potential difficulties with GLO records as ecological data include surveyor bias towards certain species, surveyor fraud, inaccurate tree identification, inconsistent tree identification, and failure to identify to species level (Black et al. 2002; Bourdo 1956). With the acknowledgment of some of these difficulties, GLO witness tree data are still one of the best available data sources regarding presettlement tree distributions (Bourdo 1956; Black et al. 2002; Schwartz 1994).

In this study, we describe the presettlement forests of Escambia and Covington counties, located in southern Alabama (Fig. 1). Many of the first recorded vegetation descriptions were similar in describing a region dominated by vast savannahs or open woodlands, with longleaf pine being the dominant tree (Harper 1914; Bartram 1791). These early descriptions are supported by the work of Frost (1993), who used Census of Agriculture data and early state maps to map the presettlement vegetation of the southeastern United States and depict southern Alabama as dominated by fire-dependent longleaf pine. The idea of pine dominance, and particularly that of longleaf pine, is further supported by modern witness tree studies. For example, in the upper Coastal Plain of Alabama, Black et al. (2002) found that a pine – blackjack oak (*Pinus* spp. – *Quercus marilandica* (L.) Meunchn.) community dominated sites of comparatively high

elevation and rugged topography. Additionally, Plummer (1975) found the frequency of pine to range from 71% to 99% in the lower Coastal Plain of Georgia.

Studies using contemporary data on longleaf pine forests in Gulf Coastal Plain identify two distinct communities: the xeric longleaf woodlands and the more common subxeric longleaf woodlands (Peet and Allard 1993; Christensen 2000). The primary difference between the two communities is an increase in the abundance of xeric hardwoods in the subxeric longleaf woodlands compared with the xeric longleaf woodlands (Peet and Allard 1993; Christensen 2000).

Linked to the dominance of longleaf pine is the idea that, without chronic low intensity fires, longleaf pine forests lose their characteristic open structure because of invasion and eventual replacement by hardwoods (Garren 1943; Gilliam and Platt 1999). As a result, one can infer that the importance of presettlement fire would have been twofold: it served to maintain fire-dependant longleaf pine and limited the extent of presettlement hardwoods. Quarterman and Keever (1962) confirmed this secondary role of fire by noting modern increases in upland mixed hardwoods due to fire suppression.

Although other witness tree studies have explored the presettlement landscapes of the southeastern Coastal Plain, few have concentrated on the lower Coastal Plain, and no studies have been conducted in this physiographic portion of Alabama (Schwartz 1994; Delcourt and Delcourt 1977). This study examines whether contemporary understandings of lower Coastal Plain forests are consistent with the information provided by the witness tree data in southern Alabama. The main objectives of this study are (i) to determine the abundance of overstory species across the study area and identify witness tree associations and (ii) to define relation-

ships between witness trees and important environmental variables. Finally, results will be discussed in the context of the role of fire in presettlement forests.

## Materials and methods

### Study area

The study area includes Escambia and Covington counties, which cover approximately 5000 km<sup>2</sup> in south-central Alabama (Fig. 1). Within the broader lower Coastal Plain physiographic province, the region is divided into four distinct physiographic belts: Southern Pine Hills, Dougherty Plain, Buhrstone Cuesta, and the Southern Red Hills (Fenneman 1938). The topography in Escambia County ranges from level to moderately steep. The majority of the relief throughout both counties is only gently sloping and primarily occurs along streams and rivers, with the exception of noticeable shallow depressions or sinks (Fenneman 1938). The elevation within the study area ranges from 15.2 to 149.3 m above sea level (USDA Natural Resources Conservation Service 1994).

The climate for both counties is impacted by the moist tropical air from the Gulf of Mexico. Mean yearly rainfall for the two counties is very similar, ranging from 148.6 cm in Covington County to 155.7 cm in Escambia County (Mattox 1979; Cotton 1984). Summers are hot, with the mean daily maximum temperature above 32 °C in June, July, and August (Mattox 1979; Cotton 1984). Summer thunderstorms are primarily responsible for the rainfall, and it is estimated that they impact the study area approximately one-half of all summer days (Mattox 1979; Cotton 1984). In the late summer and early autumn months, the region is periodically impacted by tropical depressions or hurricanes originating in the Gulf of Mexico. Winters are mild with only approximately 45 days per year experiencing a temperature below 0 °C (Mattox 1979; Cotton 1984).

### Witness tree data

The area composing Covington and Escambia counties was divided into the GLO township and range system. Each township contains 36 square miles, divided into a grid of 36 sections, each covering 1 square mile (2.59 km<sup>2</sup>). Four witness trees were recorded at each section corner, one in each quadrant (northeast, northwest, southeast, and southwest). Two additional trees were marked at each quarter corner, located at the section line midpoint, 0.5 miles (0.80 km) from the section corner (Schulte and Mladenoff 2001). For each witness tree, the surveyor recorded the direction and distance to witness trees from section corners and quarter corners, hereafter referred to as the bearing and bearing distance. All 12 surveyors which worked in the study area were very consistent in following this protocol, with the exception of one township, 6 North, 15 East, in which quarter corner witness trees were not recorded.

The witness tree data used for this study were gathered from surveyor field notes held by the Alabama State Archives, Montgomery, Alabama. Witness tree common names, bearing, and bearing distance were entered into a database. Witness tree common names presented two problems related to the interpretation of the data. First, with many common names, the name provided may reference several

tree species. In the interest of maintaining information, common names were retained and used in analysis. A table is provided listing all possible species related to a given common name (Table 1). The only common names that were grouped were “bay” and “green bay,” because we could not differentiate the species associated with these two common names (Table 1). In all subsequent analysis, common names are used, with the term “bay” referring to the bay – green bay grouping.

All surveys were conducted between 1820 and 1846, with over 98% of all witness tree points recorded between 1820 and 1826. Creek Indians did not officially surrender this land until 1814 (Ward 1991). It was not until 1819 that Alabama gained statehood, and the Cahaba and Sparta land districts were established to begin surveying the area (Ward 1991). Land sales to white settlers were limited until the late 1830s and early 1840s (Ward 1991). In light of this timeline, the surveys are indeed representative of the forests prior to any substantial European land use.

### GIS methods

The witness tree database, including common name, bearing, and bearing distance was joined with a GIS coverage of all township and range section corners, digitized from 1:100 000 US Geological Survey digital line graphs. A series of equations within ArcMap, ArcGIS 8.3 (ESRI, Redlands, California) produced witness tree locations based on all available spatial information (see Appendix A, eq. A1).

Three types of environmental data, each of importance in the distribution of tree species in the Coastal Plain, were used for this study including slope, elevation, and soil drainage (Table 2) (Frost 2000, Christensen 2000). The source for soil drainage data was 1:250 000 state soil geographic database (STATSGO) (USDA Natural Resources Conservation Service 1994) (Table 2). Elevation data were taken directly from USGS 1:24 000, thirty meter resolution digital elevation models. Slope data were derived from the digital elevation models using ArcGIS spatial analyst (ESRI, Redlands, California). Each of these GIS data sets were overlaid with the witness tree points and sampled using the ArcGIS script Gridspot (ESRI, Redlands, California) producing an output file that contained environmental attribute values for each witness tree.

### Identification of witness tree associations

Classification of witness trees into forest types or communities has been a common goal among witness tree studies (Black et al. 2002; Batek et al. 1999; Cogbill et al. 2002). Witness tree classification efforts generally start with a sample by species matrix, and in many cases, the samples used have been of a broad spatial extent. For example, Black et al. (2002) used a 1 km<sup>2</sup> grid, whereas Batek et al. (1999) used grid cells which were 511 m × 511 m to produce samples. The large spatial extent of these samples increases the number of witness trees per sample but, at the same time, may identify associations among witness trees that do not exist. For example, a spatially large sample could straddle both a bottomland and upland habitat but, nonetheless, would group all species in one sample. This study addresses this concern by forming samples at each section corner and quarter corner, producing 4730 samples, consisting of either

**Table 1.** Common names provided by surveyors and likely corresponding species (Godfrey 1988).

Common name	Scientific name	Frequency	
		No.	Percent
Ash	<i>Fraxinus americana</i> L., <i>Fraxinus caroliniana</i> Mill., <i>Fraxinus pennsylvanica</i> Marsh., <i>Fraxinus profunda</i> (Bush) Bush	17	0.13
Bay, green bay	<i>Gordonia lasianthus</i> (L.) Ellis, <i>Magnolia grandiflora</i> L., <i>Magnolia virginiana</i> L., <i>Persea borbonia</i> (L.) Spreng., <i>Persea palustris</i> (Raf.) Sarg.	360	2.85
Beech	<i>Fagus grandifolia</i> Ehrh.	84	0.67
Birch	<i>Betula nigra</i> L.	4	0.03
Black gum	<i>Nyssa sylvatica</i> Marsh.	38	0.30
Blackjack oak	<i>Quercus marilandica</i> (L.) Muenchh.	255	2.02
Black oak	<i>Quercus velutina</i> Lam.	72	0.57
Cedar	<i>Chamaecyparis thyoides</i> (L.) B.S.P., <i>Juniperus virginiana</i> L.	2	0.02
Chestnut	<i>Castanea dentata</i> (Marsh.) Borkh.	48	0.38
Chinquapin	<i>Castanea pumila</i> (L.) Mill., <i>Castanea ashei</i> Sudw. in Ashe, <i>Castanea floridana</i> (Sarg.) Ashe	12	0.09
Cucumber	<i>Magnolia acuminata</i> L.	6	0.05
Cypress	<i>Taxodium ascendens</i> Brongn., <i>Taxodium distichum</i> (L.) L.C. Rich.	26	0.21
Dogwood	<i>Cornus alternifolia</i> L.f., <i>Cornus asperifolia</i> Michx., <i>Cornus foemina</i> Mill., <i>Cornus amomum</i> Mill., <i>Cornus florida</i> L.	149	1.18
Elm	<i>Ulmus alata</i> Michx., <i>Ulmus americana</i> L., <i>Ulmus rubra</i> Muehl., <i>Planera aquatica</i> J.F. Gmel.	8	0.06
Fetterbush	<i>Leucothoe racemosa</i> (L.) Gray, <i>Lyonia lucida</i> (Lam.) K. Koch	4	0.03
Gum	<i>Nyssa aquatica</i> L., <i>Nyssa sylvatica</i> Marsh. var. <i>biflora</i> (Walt.) Cory, <i>Nyssa sylvatica</i> Marsh.	65	0.51
Hackberry	<i>Celtis laevigata</i> Nutt.	4	0.03
Haw	<i>Crataegus</i> spp.	4	0.03
Hickory	<i>Carya aquatica</i> (Michx. f.) Nutt., <i>Carya glabra</i> (Mill.) Sweet, <i>Carya ovata</i> (Mill.) K. Koch, <i>Carya pallida</i> (Ashe) Engl. & Graebn., <i>Carya tomentosa</i> Nutt.	73	0.58
Holly	<i>Ilex opaca</i> Ait.	75	0.59
Hornbeam	<i>Ostrya virginiana</i> (Mill.) K. Koch	21	0.17
Ironwood	<i>Carpinus caroliniana</i> Walt.	16	0.13
Laurel	<i>Kalmia latifolia</i> L.	7	0.06
Linden	<i>Tilia americana</i> L.	1	
Magnolia, bull bay	<i>Magnolia grandiflora</i> L., <i>Magnolia macrophylla</i> Michx., <i>Magnolia tripetala</i> L.	3	0.02
Maple	<i>Acer rubrum</i> L., <i>Acer saccharinum</i> L., <i>Acer saccharum</i> Marsh.	45	0.36
Mulberry	<i>Morus rubra</i> L.	2	0.02
Myrtle	<i>Myrica cerifera</i> L., <i>Myrica inodora</i> Bartr., <i>Ilex myrtifolia</i> Walt.	6	0.05
Oak	<i>Quercus alba</i> L., <i>Quercus austrina</i> Small, <i>Quercus muehlenbergii</i> Engelm., <i>Quercus michauxii</i> Nutt., <i>Quercus stellata</i> Wangeh., <i>Quercus margareta</i> Ashe, <i>Quercus chapmanii</i> Sarg., <i>Quercus virginiana</i> Mill., <i>Quercus geminata</i> Small, <i>Quercus minima</i> (Sarg.) Small, <i>Quercus pumila</i> Walt., <i>Quercus hemishperica</i> Bartr. ex Willd., <i>Quercus laurifolia</i> Michx., <i>Quercus phellos</i> L., <i>Quercus myrtifolia</i> Willd., <i>Quercus incana</i> Bartr., <i>Quercus nigra</i> L., <i>Quercus marilandica</i> , <i>Quercus laevis</i> Walt., <i>Quercus falcata</i> Michx., <i>Quercus pagoda</i> Raf., <i>Quercus velutina</i> Lam., <i>Q. rubra</i> , <i>Quercus shumardii</i> Buckl., <i>Quercus nuttallii</i> Palmer, <i>Quercus coccinea</i> Muenchh.	202	1.60
Open	Section corners or quarter corners recorded as "open" in the survey	41	0.32
Persimmon	<i>Diospyros virginiana</i> L.	5	0.04
Pine	<i>Pinus echinata</i> Mill., <i>Pinus elliotti</i> Engelm, <i>Pinus glabra</i> Walt., <i>Pinus palustris</i> Mill., <i>Pinus serotina</i> Michx., <i>Pinus taeda</i> L.	10558	83.55
Plum	<i>Prunus americana</i> Marsh., <i>Prunus angustifolia</i> Marsh., <i>Prunus umbellata</i> Ell.	1	0.01
Poplar	<i>Populus deltoides</i> Bartr., <i>Populus heterophylla</i> L., <i>Liriodendron tulipifera</i> L.	28	0.22
Post oak	<i>Q. stellata</i> , <i>Q. margareta</i>	110	0.87
Red bay	<i>P. borbonia</i>	3	0.02
Red oak	<i>Q. rubra</i> , <i>Q. falcata</i>	74	0.59
Sassafras	<i>Sassafras albidum</i> (Nutt.) Nees	9	0.07
Sourwood	<i>Oxydendrum arboretum</i> (L.) DC.	28	0.22
Spanish oak	<i>Q. falcata</i>	2	0.02
Swamp oak	<i>Q. laurifolia</i> , <i>Q. michauxii</i> , <i>Q. pagoda</i>	3	0.02

**Table 1** (concluded).

Common name	Scientific name	Frequency	
		No.	Percent
Swamp-privet	<i>Forestiera acuminata</i> (Michx.) Poir. in Lam.	4	0.03
Sweetbay	<i>Magnolia virginiana</i> L.	9	0.07
Sweetgum	<i>Liquidambar styraciflua</i> L.	38	0.30
Sycamore	<i>Platanus occidentalis</i> K.	4	0.03
Tupelo gum	<i>N. aquatica</i>	4	0.03
Water oak	<i>Q. nigra</i>	12	0.09
White oak	<i>Q. alba</i>	32	0.25
Willow oak	<i>Q. phellos</i>	18	0.14
Whortleberry	<i>Ilex cf. pauciflora</i>	5	0.04
Unknown tree		28	0.22
Illegible		3	0.02
Descriptions given rather than common name	Such as swamp or cypress swamp	9	0.07

**Note:** The only exception to the use of Godfrey was with regards to the common name “whortleberry,” in which Schwartz (1994) was consulted.

**Table 2.** Environmental variables used and the categories derived for contingency table analysis.

Variable	Category	Range
Elevation (m a.s.l.)	Low elevation	15.2–64.6
	Mid-elevation	64.6–83.5
	High elevation	83.5–149.3
Slope (%)	Flat-gradual	0.00–1.37
	Gradual	1.37–3.08
	Steep	3.08–14.11
Drainage	Well drained	Somewhat excessively drained to well drained
	Moderately drained	Moderately well drained to somewhat poorly drained
	Poorly drained	Poorly drained to very poorly drained

**Note:** Slope and elevation ranges were derived to produce equal samples for each category.

two or four witness trees. In doing so, we sacrificed depth of sample to assure that witness trees in a sample were near one another on the landscape, which improves the likelihood of finding authentic associations in the witness trees.

Detrended correspondence analysis (DCA), an eigenvector ordination technique, was performed using CANOCO version 4.5 (Plant Research International, Wageningen, The Netherlands) to identify natural species associations in the witness tree data (Black et al. 2002; McCune and Grace 2002). Only section corner samples, consisting of four witness trees, were used in the DCA because we felt a slightly deeper sample would produce a better indication of species associations. In addition, only species occurring >30 times in the witness tree surveys were included in analysis.

**Witness tree association with environmental variables**

The DCA was followed by a canonical correspondence analysis (CCA), a technique that constrains species data by a multiple linear regression on environmental variables. CCA was used to identify species interactions with slope, elevation, and soil drainage without consideration of species associations (McCune and Grace 2002). Because species associations are not considered by the CCA, we were less concerned with depth of sample, and both quarter corner and corner section samples were used. Slope and elevation were averaged for each sample, and these data were continuous

rather than categorical. All six STATSGO categories of soil drainage were left uncombined for the CCA (Table 2).

In following the DCA with CCA, one can discern whether pure gradients in species and species associations, as shown through DCA, are similar to those produced through a direct gradient analysis using environmental variables included in the CCA (Ter Braak 1995; McCune and Grace 2002). Ordination diagrams produced through CCA show the orientation of species in environmental space, where environmental variables are drawn as vectors indicative of the strength and direction of correlation between species and environmental variables (Ter Braak 1995). As with the DCA, only species occurring >30 times in the survey were included in the CCA.

Whereas CCA orients species according to select environmental variables, contingency table analysis was used to test species associations with categories of environmental variables (Table 2). In this analysis, the environmental data were used for each witness tree rather than each sample. Two by three presence–absence tables were constructed for each species recorded >30 times in the surveys and for each environmental variable. The two rows produced were for species presence or absence, whereas the three columns were for the three categories of slope, elevation, or soil drainage (Table 1). The *G* statistic, calculated from observed and expected frequency data, was used to test the null hypothesis of independence between species and environmen-

tal variables (Strahler 1978). Standardized residuals were used to illustrate positive and negative associations with environmental variables (Strahler 1978). For a complete description of these techniques, consult Black et al. (2002) and Strahler (1978).

### Analysis of bearing distances

To explore differences in forest structure, bearing distances were separated by witness tree species and witness tree associations identified through the DCA. Because surveyors may have selected larger, potentially longer lived species, bearing distances and subsequent density calculations are best interpreted as indices of density (Bourdo 1956; Nelson 1997). Delcourt and Delcourt (1977) compared bearing tree distances across witness tree communities in north-central Florida and found little evidence of surveyor bias in the selection of witness trees. In describing tributary bottomland hardwoods, significant differences in bearing distances were found across species, and Delcourt and Delcourt (1977) acknowledged that this difference could be result of differing stand densities. Other studies, although recognizing the potential role of bias, have used bearing distances to interpret tree density in relation to fire and to estimate density (Grimm 1984; Nelson 1997).

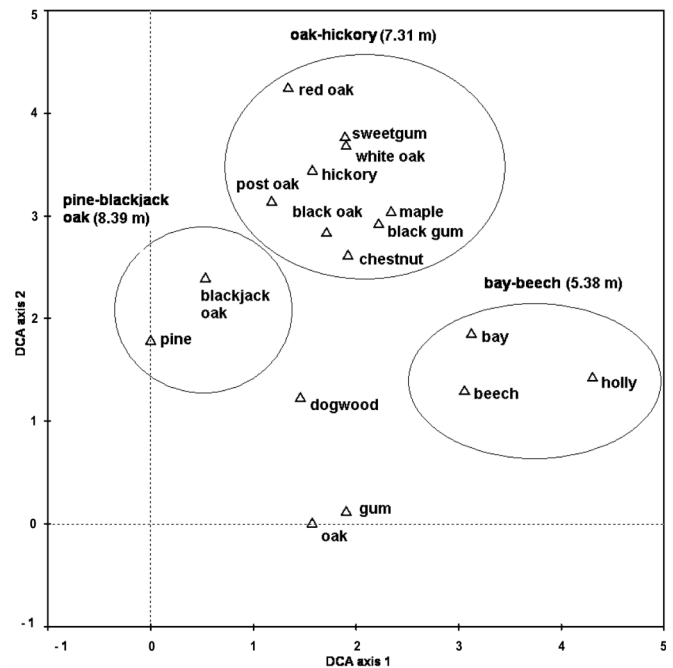
In this study, the Mann–Whitney test, the nonparametric equivalent of an independent sample *t* test, was used to determine if differences in bearing distances, were significant among witness tree associations or among common species. The Mann–Whitney test converts data to ranks and tests a different null hypothesis compared to the *t* test; rather than testing the equality of means, it tests whether the medians of two samples are equal (Howell 1999). Pairwise Mann–Whitney tests were only conducted after finding significant differences in bearing distances among all groups using the nonparametric Kruskal–Wallis test (Neter et al. 1996). The familywise error rate was controlled in multiple testing using the Bonferroni correction (Howell 1999). In addition, mean bearing distances were used to calculate density (trees per hectare) for the entire study area using section corner samples. The equation for the point-centered quarter method was used to calculate density (Barbour et al. 1999; Cottom and Curtis 1956).

## Results

Pine was the most frequently listed common name in the field note data, accounting for approximately 84% of the total sample (Table 1). Of the 3295 quarter corner samples, 2638, or over 80%, were composed of pine only. For the 1435 section corners, 1083 or 75% of the samples, pine was the only witness tree recorded. In sum, samples composed of only pine account for 9608 of the pines reported in the survey notes, or approximately 91% of all pines. Unfortunately, there was no attempt by surveyors to distinguish pine species, with the exception of one surveyor who listed ‘long leaved pine’ in his timber descriptions.

The DCA indicates that pine distribution is most closely related to blackjack oak, producing the pine – blackjack oak association (Fig. 2). When pines were found in samples with other species, they were most often found in association with blackjack oak and to a lesser extent post oak and dog-

**Fig. 2.** Detrended correspondence analysis (DCA) of witness tree species which were identified >30 times in the surveys. Three associations are identified including pine–blackjack oak, oak–hickory, and bay–beech. For each association, the mean bearing distance is given in parentheses. Axis one accounts for 11.5% of the species variance, and axis 2 explains 8.5% of the species variance.

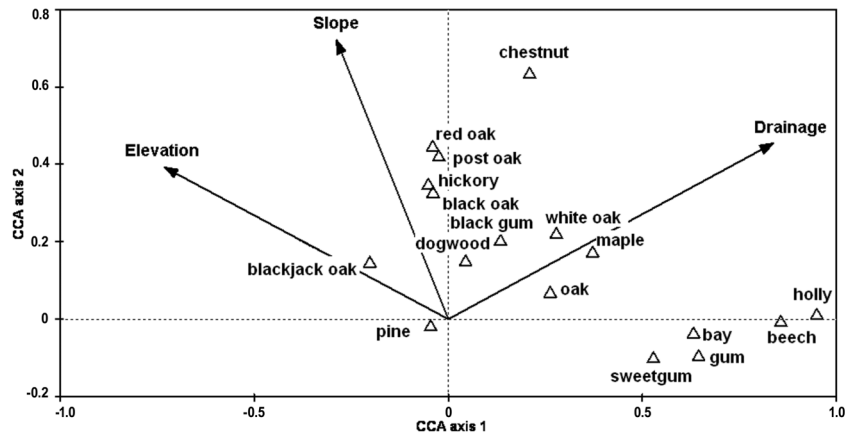


wood (Fig. 2). From the DCA, an oak–hickory association and a bay–beech association are also well-defined (Fig. 2). Gum and oak do not clearly fit into any of the three main associations; however, because they are identified only to the genus level, it is not surprising that they are oriented towards the center of axis 1.

The association of species shown in the DCA is largely mirrored in the CCA. This result is expected given that slope, elevation, and drainage are important drivers of site moisture and fire frequency (Christensen 2000; Frost 2000). Pine and blackjack oak are both associated with well-drained sites (Fig. 3; see Fig. A1 in Appendix A). The CCA illustrates subtle differences in distribution of pine and blackjack oak with respect to environmental variables, and these differences are confirmed by contingency table analysis. Pine was associated with only gradual slopes and moderate to high elevations within the study site, whereas blackjack oak is associated with steep slopes and only the higher elevation upland sites (see Figs. A2 and A3 in Appendix A). Of the oaks listed, only blackjack oak is associated with only well-drained soils (see Fig. A1 in Appendix A).

The majority of species grouped into the oak–hickory association by the DCA, including black oak, chestnut, dogwood, hickory, post oak, and hickory, are distributed similarly with respect to environmental variables according to contingency table analysis (see Figs. A1, A2, and A3 in Appendix A). These species are generally all associated with steep slopes, high elevations, and moderately to poorly drained soils (see Figs. A1, A2, and A3 in Appendix A). These species are also aligned similarly by the CCA with the exception of chestnut, which is strongly differentiated by its association with steeper slopes (Fig. 3).

**Fig. 3.** Canonical correspondence analysis (CCA) of the witness tree species, which were recorded >30 times in the surveys. The length of the vectors indicates the relative importance of environmental variables in explaining the species distributions. Axis 1 explains 76.4% of the species environmental-variable relation, and axis 2 explains 17.2% of species – environmental variable relation.



**Table 3.** Results of pairwise comparisons of bearing distances for witness tree associations using the Mann–Whitney test, with the  $\alpha$  level adjusted (0.0167) for multiple comparisons using the Bonferroni correction.

Comparisons of bearing distance (median, m)	Z	Two-sided p
Oak–hickory (5.83) versus pine–blackjack oak (7.24)	-6.75	<0.0001
Bay–beech (4.22) versus pine–blackjack oak (7.24)	-15.02	<0.0001
Bay–beech (4.22) versus oak–hickory (5.83)	-5.91	<0.0001

**Note:** An overall Kruskal–Wallis test for differences among the three groups was significant ( $\chi^2 = 262.28$ ,  $df = 2$ ,  $p < 0.0001$ ).

The CCA differentiates gum and sweetgum from the typical oak–hickory species (black oak, chestnut, dogwood, hickory, post oak, hickory) and orients them closely to bay, beech, and holly (Figs. 2 and 3). With respect to environmental variables, these species (bay, beech, holly, gum, and sweetgum) occupied low-elevation, flat or gradual slope sites with moderate to poor drainage (Fig. 3). Contingency table analysis confirms the patterns shown by the CCA (see Figs. A1, A2, and A3 in Appendix A). The CCA also differentiates white oak, maple, and oak from other oak–hickory species (Figs. 3). Contingency tables offer insights into which environmental variables distinguish the distribution of white oak, oak, and maple. These species are associated with either flat–gradual slopes or steeper slopes but not gradual slopes (see Fig. A1 in Appendix A). In contrast, species such as black oak, chestnut, dogwood, hickory, post oak, and red oak are uniformly identified with the steepest slopes (see Fig. A1 in Appendix A). Additionally, oak, white oak, and maple were typically found in low to middle elevations, whereas most other oak–hickory species are associated with only the higher elevations (see Fig. A2 in Appendix A).

The CCA shows bay, beech, holly, gum, and sweetgum as associated with more poorly drained sites compared with other species and species associations (see Fig. A1 in Appendix A). From examining the CCA diagram, it appears that gradual sloping to flat terrain and low elevation are the strongest factors differentiating this CCA grouping from other species (Fig. 3). This pattern is reflected in the contingency table analysis. Bay and sweetgum are associated with poorly drained soils, whereas beech and holly are more clo-

sely associated with moderately drained soils (see Fig. A3 in Appendix A). All species in this CCA grouping are positively associated with gradual sloping to flat areas and negatively associated with steeper sloping topography (see Fig. A1 in Appendix A). Bay, beech, holly, gum, and sweetgum all exhibit strong associations with low-elevation portions of the study area (see Fig. A2 in Appendix A). It is also worth noting that bay, when not found with holly or beech, was commonly located in stands composed of only bay. Of the 360 bays recorded, 150 (42%) were found in samples containing only bay.

Bearing distances across the entire study area ranged from 0.00 to 201.97 m, with an overall mean of 8.11 m. The mean bearing distance for all section corners was 9.75 m, from which we calculated a mean density for the entire study area of 105.19 trees/ha. Bearing distances varied significantly among tree species, indicating different forest densities across the study area (see Tables A1 and A2 in Appendix A). Pine had the greatest mean bearing distance, and the results of the Mann–Whitney tests showed significantly higher median bearing distance for pine compared with bay, holly, and maple (see Table A1 in Appendix A). In calculating mean bearing distances for species associations, a clear gradient in forest density exists, with the pine – blackjack association having the highest mean bearing distance and the bay–beech association having the lowest mean bearing distance (Fig. 2). The Kruskal–Wallis test comparing the bearing distances of witness tree associations showed significant differences between all groups (Table 3). The Mann–Whitney tests showed that the median pine – blackjack oak bearing

distance was greater than both the oak–hickory and bay–beech median bearing distances (Table 3).

## Discussion

The most useful way to discuss presettlement forest communities in the southeastern Coastal Plain is by examining each community in relation to the dominant disturbance agent, fire (Monk 1965; Frost 2000). Axis 1 of the DCA is best interpreted as a gradient of fire frequency, with the pine – blackjack oak association experiencing the most frequent fires. Witness tree associations with environmental variables also support the idea of a gradient of fire frequency. The influence of fire is further confirmed through the analysis of bearing distances. A known connection exists between stand density and fire in the southeastern Coastal Plain, with pyrogenic species and communities generally associated with lower densities compared with communities with longer fire return intervals (Frost 2000; Noel et al. 1998); as a result, bearing distances may be interpreted as an indicator of the presettlement fire regime.

Witness tree records from Escambia and Covington counties, Alabama, show that pine was even more dominant in the presettlement lower Coastal Plain of Alabama than it was in nearby regions (Schwartz 1994; Black et al. 2002; Dietz 1957). Much like the witness tree records of northern Florida, pine was often found at section corners and quarter corners with other pines (Schwartz 1994). Although the common name “pine” could refer to six different endemic species, occupying a broad range of sites, contingency table analysis showed pine strongly associated with well-drained, middle- to high-elevation, gradually sloping sites. The competitive advantage of longleaf pine on well-drained upland sites has been documented (Frost 1993; Peet and Allard 1993; Wade et al. 2000), suggesting that longleaf pine was dominant in the study area.

Compared with most other witness trees in the survey, pine generally exhibited higher bearing distances, which are indicative of lower density forests, a characteristic commonly associated with longleaf pine communities (Heyward 1939; Gilliam and Platt 1999). Noel et al. (1998) report that a regularly burned, old-growth longleaf pine stand in Georgia, excluding stems <10 cm DBH, has a density of 79–94 trees/ha. The exclusion of trees under 10 cm DBH is a conservative assumption, given that surveyor instructions in 1846 required witness trees to be 5 in. (12.7 cm) in diameter or greater (Bourdo 1956). Our study area density estimate likely includes higher density patches of bay, holly, or even various species of oak sprouts (Delcourt and Delcourt 1977; Quarterman and Keever 1962). Even with the inclusion of these higher density patches, our overall density estimate (105.19 trees/ha) is only slightly higher than the upper end of the range presented by Noel et al. (1998) for a longleaf pine forest. This suggests that an open forest structure was common within the study area. The idea of open forest structure is further supported by the fact that surveyors listed “open” for several quarter and section corners in which witness trees were not recorded (Table 2).

An active presettlement fire regime is the only plausible explanation for low stand densities and the dominance of pine. Without chronic low-intensity fires, longleaf pine loses its competitive advantage, and longleaf pine dominated

communities are invaded by hardwoods and other pines, leading to higher density stands and the eventual replacement of longleaf pine (Garren 1943; Quarterman and Keever 1962; Gilliam and Platt 1999). The fire tolerance of longleaf pine is a result of several traits including early development of thick bark, large buds with high heat capacity, buds protected by a sheaf of needles, and a bolting stage as juveniles, which quickly raises the terminal bud above surface fire flames (Gilliam and Platt 1999; Wade et al. 2000).

The dominance of pure pine samples in the witness tree surveys, the clear associations of pines with well-drained uplands, and high bearing distances indicate that a xeric longleaf community, characterized by high fire frequency and very few xeric hardwoods, dominated the presettlement study area (Peet and Allard 1993; Rebertus et al. 1993). This finding contradicts those that suggest that subxeric longleaf woodlands, with longer fire-return intervals and increased numbers of xeric oaks, such as turkey oak and blackjack oak, dominated the presettlement landscape (Peet and Allard 1993). This subxeric longleaf woodlands community clearly existed in the study area, as shown by the pine – blackjack oak association identified through the DCA. Because blackjack oak commonly referred to all scrub oaks, this community likely included both *Q. marilandica* and *Quercus laevis* Walt. (Frost 2000; Black et al. 2002). The distribution of blackjack oak on steeper slopes compared with pines indicates upland, broken landscapes in which fire may have been compartmentalized and less common (Rebertus et al. 1993; Frost 2000). This finding confirms the idea of a longer fire-return interval in subxeric longleaf woodlands (Peet and Allard 1993).

Only a fraction of quarter corner or section corner samples in the study area (9%) contained a mixture of pine and other species, with only a portion of these occurring in mixture with blackjack oak. This suggests that subxeric longleaf woodlands were far less common than the xeric longleaf community (Peet and Allard 1993). However, this conclusion is not definitive, because surveyors may have avoided the less impressive looking “scrub oaks” in favor of pines. If surveyor selection of pines over “scrub oaks” was pervasive in the study, one would expect significantly higher bearing distances for pine compared with blackjack oak, which we found in the comparison of pine and blackjack oak bearing distances. However, the reason for this difference remains unclear; it could be a result of different densities associated with these witness trees or indicative of surveyor selection of witness trees. Although the exact proportion of the presettlement landscape in xeric versus subxeric longleaf woodlands is unresolved, the overall dominance of pyrogenic longleaf communities is indisputable.

Although fire is essential to maintaining longleaf pine dominated communities, presettlement fire was responsible for limiting the numbers of hardwoods and confining their distribution to steeply sloping areas, areas of relatively poor drainage, or low elevation areas in proximity to streams in rivers. This finding confirms the results of other studies regarding presettlement Coastal Plain communities, which noted that hardwoods were isolated in swamps, slopes, bottomlands, and perhaps upland flats and peninsulas (Frost 2000, Delcourt and Delcourt 1977, Schwartz 1994).

Using bearing distances as an indicator of forest density

and fire frequency, the oak–hickory association is second to the pine – blackjack oak association along the fire frequency gradient. The majority of species falling into the oak–hickory association showed strong associations with higher elevations, steeper slopes, and moderate to poor drainage, suggesting an upland hardwood association with reduced fire frequency compared with longleaf communities described by Peet and Allard (1993). Again, in reference to Frost's (2000) work on fire compartments, a reduced fire interval compared with pine – blackjack oak association would be expected. Similar to the pine – blackjack association or subxeric longleaf woodlands, oak–hickory species are in steeply sloping uplands. Unlike blackjack oak, a key component of the subxeric longleaf woodlands, witness trees in the oak–hickory association were associated with moderate to poorly drained soils. Our data suggest that differences in soils were responsible for a longer fire return interval in oak–hickory forests compared with subxeric longleaf woodlands.

It is important to note that the witness trees falling in the oak–hickory association were found with pine in some quarter corner and section corner samples. Even acknowledging a pine component of this association, the association was rare across the study area, a result similar to that found in northern Florida (Delcourt and Delcourt 1977; Schwartz 1994). There is some disagreement about which pine species were most common in this association, with *Pinus palustris* P. Mill., *Pinus taeda* L., and *Pinus glabra* Walt. being the most likely species. Species–site associations and an open forest structure indicate a habitat periodically affected by fire, suggesting that longleaf pine would have been the most common pine species within this association. These conclusions support Schwartz's (1994) hypothesis that the assemblage is either a transition zone between upland pine and oak–hickory forests or a stable longleaf pine – oak – hickory community. The idea of a transition zone seems most appropriate, because the species in this association were found to straddle a gradient identified by Frost (2000) from mesic pyrophytic woodlands to less fire susceptible mesophytic hardwood flats.

Several species grouped in the oak–hickory association by the DCA (white oak, maple, and oak) were grouped differently by the CCA, suggesting that they are best equated with the less fire prone mesophytic hardwood flats (Frost 2000). Associations with slope show that these species were located on both flats adjacent to rivers and streams and the bottomlands sloping away from water. Contingency tables show that elevation distinguishes these species from the rest of the oak–hickory association, with oak, maple, and white oak more often found in low-lying floodplains and stream valleys rather than in broken upland habitats occupied by the majority of species in the oak–hickory association. The conclusions regarding the site characteristics confirm those of Black et al. (2002) and suggest that these species were located in a transition area between upland pine–oak–hickory and the bay–beech association.

The bay–beech association defined by the DCA, like all hardwoods in the study area, was limited in number and extent and represents a mix of bottomland hardwood, bay swamps or bayheads, and wet savannahs in presettlement forests. Environmental gradients discriminating the distribution of these species and forest types are subtle and, thus,

difficult to discern using witness tree data (Quarterman and Keever 1962; Christensen 2000).

Based purely on composition of the bay–beech association (bay, beech, and holly), the majority of this association likely resembles bottomland hardwoods as described by Frost (2000) or similarly the tributary hardwoods described by Delcourt and Delcourt (1977). Within the study area, bay, beech, and holly were found in flat, low-lying areas with poor drainage and low bearing distances, indicating a fire-protected habitat. In describing the bottomland hardwoods in South Carolina, Frost (2000) drew similar conclusions regarding the influence of fire and environmental variables on bottomland hardwoods. Because *Magnolia grandiflora* L. was not consistently identified by any common name in the surveys, a portion of the bay sample may have referred to this species, leaving the possibility that the magnolia–beech forests described by Delcourt and Delcourt (1977) were also present in presettlement southern Alabama.

The strong association of bay with poorly drained soils, even compared with beech and holly, suggests that a portion of the bay sample was representative of bay swamps or bayheads described by Monk (1965). According to Monk, bayheads are typically found on poorly drained soils with high organic matter and are composed of evergreen hardwoods, like *Magnolia virginiana* L., *Persea palustris* (Raf.) Sarg., and *Gordonia lasianthus* (L.) Ellis, each of which could have been a component of the “bay” witness tree sample. The pure bay samples found were likely indicative of bay swamps on the presettlement landscape.

When species were oriented with respect to slope, soil drainage, and elevation, the common names sweetgum and gum were distributed most closely with bay, beech, and holly. These two species have relatively high median bearing distances indicative of low-density forests. Like the bay, gum and sweetgum are associated with moderately or poorly drained soils in flat areas. This landscape description fits well with modern descriptions of wet savannahs or flatwoods, which occupy a transition zone between xeric pine communities and bayheads (Christensen 2000).

In describing the wet savannahs of eastern Texas, Streng and Harcombe (1982) noted an open forest structure consisting of *Liquidambar styraciflua* L., *Nyssa sylvatica* Marsh., *M. virginiana*, as well as *Pinus palustris* and *Pinus taeda*. The association of sweetgum and gum with low-lying flat areas with poor drainage and with relatively high median bearing distances seems paradoxical. These relationships can only be explained in terms of a wet savannah. Further, the association of gum and sweetgum with bay is plausible given the possibility that bay may have referred to *M. virginiana*, a common species found in wet savannahs. Even if *M. virginiana* was not commonly referred to using the common name bay by surveyors, the association of bay with sweetgum is possible, because fire is known to produce sharp ecotones between bay swamps and wet savannahs (Christensen 2000). This close proximity could lead to sweetgum and bay swamps being captured by the same sample.

## Conclusions

This study largely confirms previous regional notions regarding the presettlement coastal plain. Witness tree associa-

tions mirror contemporary understandings of lower Coastal Plain vegetation in both species composition and distribution with respect to environmental variables. This study did reveal some ways in which Covington and Escambia counties differ from the general understanding of the region. Most notable among these differences is that open pine woodlands and pine savannahs appear to have been even more common in southern Alabama and that xeric longleaf woodlands were more common than subxeric longleaf woodlands.

This study presents a unique interpretation of bearing distance information to examine forest structure and the associated fire regime. Bearing distances associated with species and witness tree associations confirm modern expectations regarding the influence of fire on presettlement communities. The main conclusion being that more fire-protected communities would exhibit higher density forests compared with communities with frequent fire. The combination of results, including the dominance of pine and its association with environmental variables, suggest that the majority of the study area would have been open, fire-dependent, longleaf pine dominated communities.

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## Appendix A

Appendix A appears on the following page.

**Table A1.** Results of pairwise comparisons of bearing distances for witness trees occurring >30 times in the General Land Office surveys.

Witness tree (median bearing distance)	<i>z</i> Statistic and <i>p</i> value							
	Pine	Bay	Blackjack oak	Oak	Dogwood	Post oak	Beech	Holly
Pine (7.24 m)		-14.86, * <0.0001	-4.11, * <0.0001	-1.67, 0.0941	-3.33, <0.0009	-1.67, <0.0956	-2.62, 0.0087	-5.05, * <0.0001
Bay (3.82 m)			6.55, * <0.0001	8.04, * <0.0001	5.54, * <0.0001	5.69, * <0.0001	4.67, * <0.0001	1.39, * <0.0001
Blackjack oak (5.83 m)				1.60, 0.1102	-0.04, 0.9704	0.85, 0.3983	-0.07, 0.9472	-2.58, 0.0100
Oak (6.84 m)					-1.38, 0.1676	-0.32, 0.7455	-1.28, 0.2006	-3.61, 0.0004
Dogwood (5.63 m)						0.79, 0.4291	-0.03, 0.9744	-2.45, 0.0140
Post oak (6.64 m)							-0.75, 0.4515	-2.81, 0.0049
Beech (5.43 m)								-2.29, 0.0220
Holly (4.02 m)								
Black oak (6.64 m)	-1.44, 0.1494	3.84, * 0.0001	0.38, 0.7015	-0.47, 0.6412	0.37, 0.7135	-0.16, 0.8758	0.28, 0.7807	2.09, 0.0365
Red oak (5.83 m)	-2.38, 0.0174	4.35, * <0.0001	-0.06, 0.9557	-1.14, 0.2522	0.06, 0.9534	-0.68, 0.4980	0.04, 0.9711	-2.09, 0.0367
Hickory (6.44 m)	-2.68, 0.0073	3.92, * <0.0001	-0.37, 0.7138	-1.46, 0.1455	-0.38, 0.7061	-0.99, 0.3197	-0.27, 0.7855	1.71, 0.0878
Gum (5.63 m)	-2.29, 0.0217	3.28, 0.0010	-0.27, 0.7880	-1.24, 0.2149	-0.26, 0.7919	-0.85, 0.3947	-0.23, 0.8214	1.52, 0.1269
Chestnut (5.43 m)	-2.45, 0.0145	3.09, 0.0020	-0.52, 0.6062	-1.51, 0.1310	-0.33, 0.7414	-1.04, 0.3006	-0.29, 0.7696	1.39, 0.1654
Maple (3.82 m)	-4.92, * <0.0001	0.30, 0.7664	-2.95, 0.0032	-3.88, * 0.0001	-2.81, 0.0050	-3.20, 0.0017	-2.71, 0.0068	-0.66, 0.5087
Black gum (3.62 m)	-4.55, <0.0001	0.29, 0.7737	-2.86, 0.0042	-3.73, * 0.0002	-2.74, 0.0062	-2.94, 0.0033	-2.71, 0.0067	-0.59, 0.5519
Sweetgum (6.74 m)	-1.25, 0.2119	3.27, 0.0011	0.30, 0.7605	-0.48, 0.6329	0.20, 0.8405	-0.20, 0.8426	0.19, 0.8480	1.87, 0.0620
White oak (6.54 m)	-0.59, 0.5525	4.12, * <0.0001	0.93, 0.3518	-0.01, 0.9884	0.97, 0.3342	0.33, 0.7411	0.93, 0.3523	2.45, 0.0144

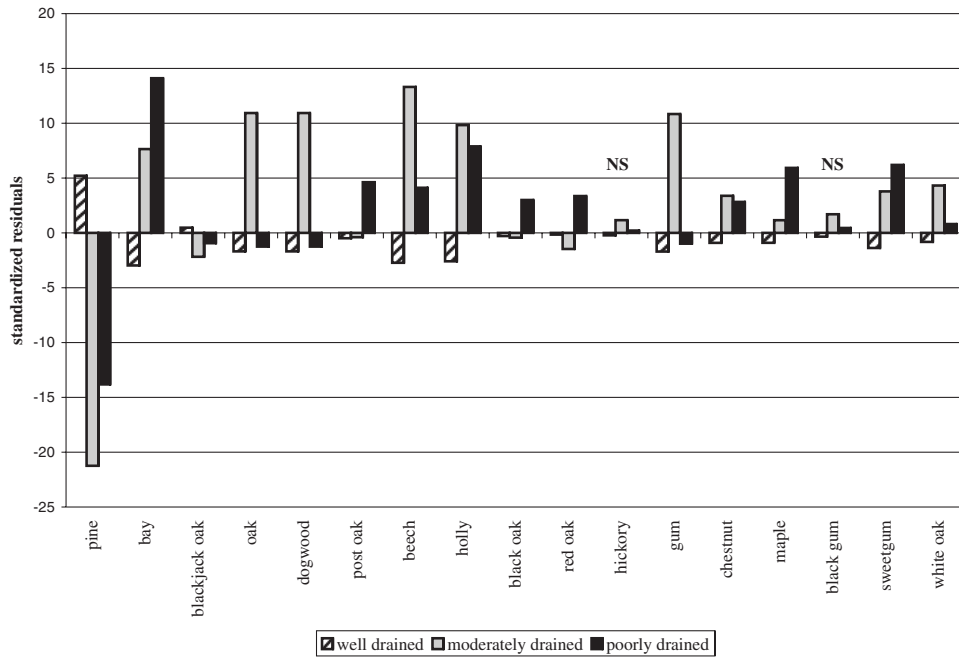
**Note:** The Mann–Whitney test was used for all comparison with the  $\alpha$  level adjusted (0.00038) for multiple comparisons using the Bonferroni correction. Each cell provides the *z* statistic followed by the *p* value. Pairwise comparisons were conducted after an overall Kruskal–Wallis test for differences among the 17 witness trees was significant ( $\chi^2 = 332.57$ ,  $df = 16$ ,  $p < 0.0001$ ).

**Table A2.** Results of pairwise comparisons of bearing distances for witness trees occurring >30 times in the General Land Office surveys.

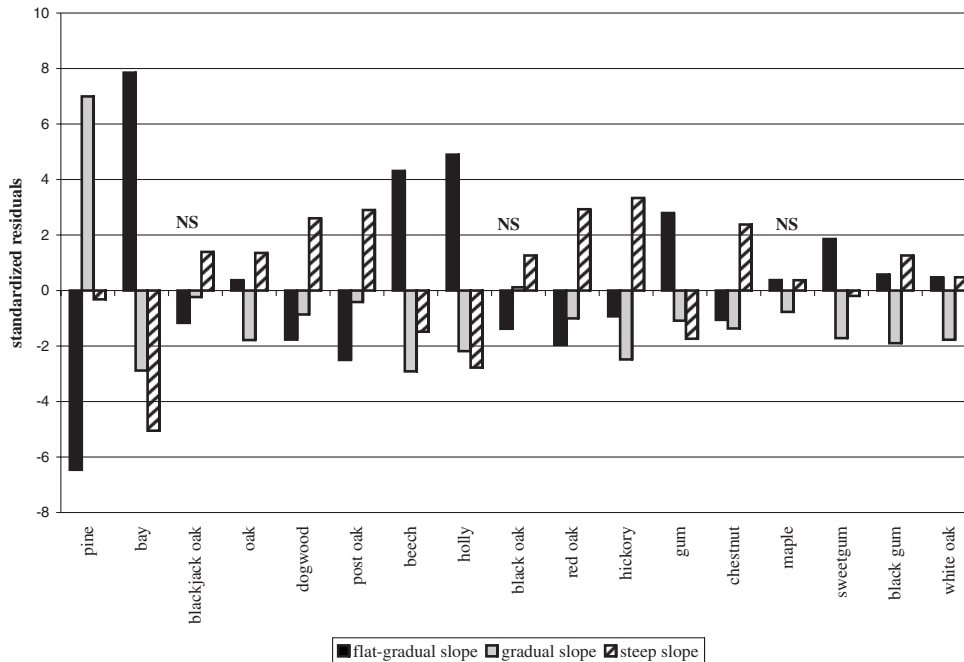
Witness tree (median bearing distance)	<i>z</i> Statistic and <i>p</i> value							
	Black oak	Red oak	Hickory	Gum	Chestnut	Maple	Black gum	Sweetgum
Black oak (6.64 m)		0.28, 0.7795	0.78, 0.4381	-0.58, 0.5605	-0.61, 0.5413	-2.43, 0.0150	-2.11, 0.0349	-0.11, 0.9149
Red oak (5.83 m)			-0.31, 0.7565	-0.23, 0.8163	-0.39, 0.6980	-2.56, 0.0105	-2.52, 0.0119	0.21, 0.8344
Hickory (6.44 m)				0.05, 0.9609	-0.34, 0.7325	-2.37, 0.0178	-2.17, 0.0297	0.55, 0.5822
Gum (5.63 m)					-0.12, 0.9029	-1.98, 0.0481	-1.95, 0.0517	0.39, 0.6993
Chestnut (5.43 m)						-1.97, 0.0489	-1.92, 0.0547	0.56, 0.5747
Maple (3.82 m)							-0.10, 0.9219	2.25, 0.0271
Black gum (3.62 m)								-2.12, 0.0172
Sweetgum (6.74 m)								
White oak (6.54 m)	0.42, 0.6754	0.88, 0.3812	1.00, 0.3163	0.97, 0.3334	1.30, 0.1937	2.99, 0.0028	2.82, 0.0048	0.46, 0.6431

**Note:** The Mann–Whitney test was used for all comparison with the  $\alpha$ -level adjusted (0.00038) for multiple comparisons using the Bonferroni correction. Each cell provides the *z* statistic followed by the *p* value. Pairwise comparisons were conducted after an overall Kruskal–Wallis test for differences among the 17 witness trees was significant ( $\chi^2 = 332.57$ ,  $df = 16$ ,  $p < 0.0001$ ).

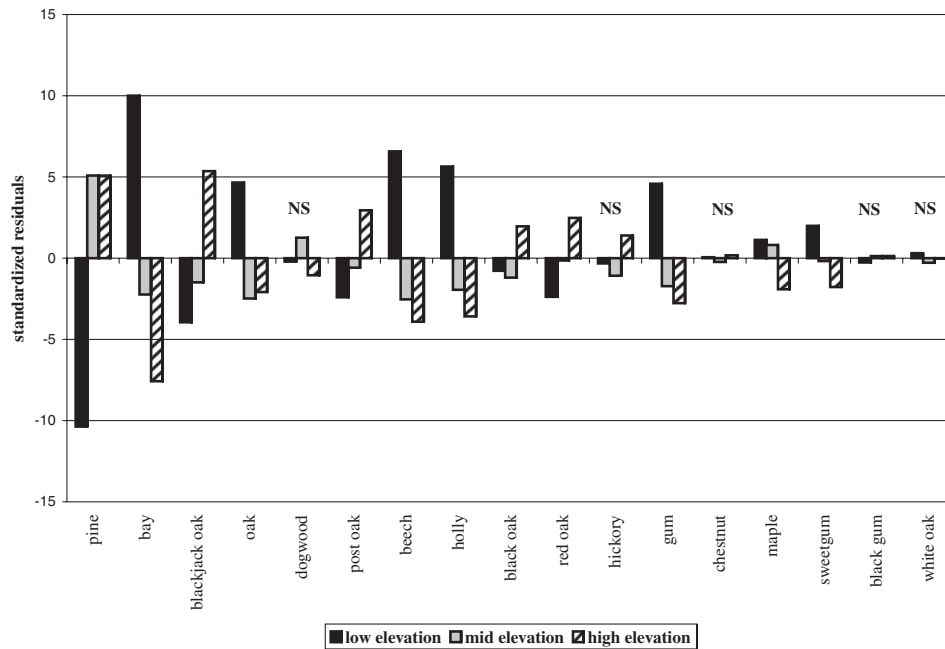
**Fig. A1.** Standardized residuals from contingency table analysis testing association between species and drainage categories. Only species recorded >30 times in the surveys were tested. NS, associations were not significant.



**Fig. A2.** Standardized residuals from contingency table analysis testing association between species and slope categories. Only species recorded >30 times in the surveys were tested. NS, associations were not significant.



**Fig. A3.** Standardized residuals from contingency table analysis testing association between species and elevation categories. Only species recorded >30 times in the surveys were tested. NS, associations were not significant.



Equations A1. Equations used within ArcMap (ArcGIS 8.3) to georeference witness tree data, based on direction of surveyor movement, Escambia and Covington counties, Alabama. GIS analysis was conducted in a Universal Transverse Mercator projection, with the North American datum 1983.

Surveyor movement east:

$$\begin{aligned} \text{Final } x \text{ coordinate} &= \text{section corner } x \text{ coordinate} \\ &+ \text{distance from corner} + \sin(\text{compass bearing}) \\ &\quad \times \text{bearing distance} \times \text{direction } x \end{aligned}$$

$$\begin{aligned} \text{Final } y \text{ coordinate} &= \text{section corner } y \text{ coordinate} \\ &+ \cos(\text{compass bearing}) \times \text{bearing distance} \\ &\quad \times \text{direction } y \end{aligned}$$

Surveyor movement west:

$$\begin{aligned} \text{Final } x \text{ coordinate} &= \text{section corner } x \text{ coordinate} \\ &- \text{distance from corner} + \sin(\text{compass bearing}) \\ &\quad \times \text{bearing distance} \times \text{direction } x \end{aligned}$$

$$\begin{aligned} \text{Final } y \text{ coordinate} &= \text{section corner } y \text{ coordinate} \\ &+ \cos(\text{compass bearing}) \times \text{bearing distance} \\ &\quad \times \text{direction } y \end{aligned}$$

Surveyor movement south:

$$\begin{aligned} \text{Final } x \text{ coordinate} &= \text{section corner } x \text{ coordinate} \\ &+ \sin(\text{compass bearing}) \times \text{bearing distance} \\ &\quad \times \text{direction } x \end{aligned}$$

$$\begin{aligned} \text{Final } y \text{ coordinate} &= \text{section corner } y \text{ coordinate} \\ &- \text{distance from corner} + \cos(\text{compass bearing}) \\ &\quad \times \text{bearing distance} \times \text{direction } y \end{aligned}$$

Surveyor movement north:

$$\begin{aligned} \text{Final } x \text{ coordinate} &= \text{section corner } x \text{ coordinate} \\ &+ \sin(\text{compass bearing}) \times \text{bearing distance} \\ &\quad \times \text{direction } x \end{aligned}$$

$$\begin{aligned} \text{Final } y \text{ coordinate} &= \text{section corner } y \text{ coordinate} \\ &+ \text{distance from corner} + \cos(\text{compass bearing}) \\ &\quad \times \text{bearing distance} \times \text{direction } y \end{aligned}$$

Note that the *x* and *y* directions were coded as 1 or -1 from the surveys: east = 1, west = -1 for direction *x* and north = 1 and south = -1 for direction *y*.