Journal of the Torrey Botanical Society 133(3), 2006, pp. 449–459

Modifying distance methods to improve estimates of historical tree density from General Land Office survey records[1]

Roger C. Anderson[2,3], Suzanne L. Jones[4], and Richard Swigart

Department of Biological Sciences-4120, Illinois State University, Normal, IL 61790-4120

ANDERSON, R. C., S. L. JONES, AND R. SWIGART (Department of Biological Sciences-4120, Illinois State University, Normal, IL 61790-4120). Modifying distance methods to improve estimates of historical tree density from General Land Office survey records. J. Torrey Bot. Soc. 133: 449–459. 2006.—Distance sampling methods are widely applied to witness tree data from General Land Office (GLO) survey records to determine historic vegetation. Most researchers apply modifications of the point-centered quarter or random pairs distance methods to witness tree distances as if these data were collected according to the procedures required for the methods. Application of five methods (three modifications of the point-centered quarter method (Q_1, Q_2, and Q_1+Q_2) and random pairs with 180° or 203° exclusion angles) to GLO records from the 345,000 ha Shawnee National Forest Purchase Area in southern Illinois, resulted in tree density ranging from 117.8–177.5 trees ha^{-1}. We present a new procedure, the adjustable exclusion angle method, which empirically estimates the exclusion angle of the random pairs method based on the proportion of trees in quadrants opposite versus adjacent to the quadrant of the first witness tree. For our data, the distributions of witness trees in quadrants was best described as if surveyors used a random pairs method with an exclusion angle of 203° in their selection of witness trees. This method resulted in the highest estimates of tree density. There were significant differences ($P < 0.0001$) in the square root of the mean area among the five distance methods used. A surveyor bias for selecting trees near the center of the area between the ordinal directions was discovered.

Key words: distance methods, Government Land Office survey, historic vegetation, quarter method, random pairs, witness trees.

The General Land Office (GLO) survey records, also referred to as the Public Land Survey (PLS) records, are often the only source of information available to document historic vegetation patterns (Hutchinson 1988, Manies et al. 2001) and are considered to provide reliable information across landscapes (Bollinger et al. 2004). The GLO surveys were commissioned in 1785 for territories located to the northwest of the Ohio River, and were conducted when only sparse settlement by Europeans had occurred (Hutchinson 1988).

Studies using GLO survey data have many applications, including the description of historic vegetation (Kline and Cottam 1979, Grimm 1984, Nelson 1997, Bollinger et al. 2004), documentation of historic landscape disturbance patterns including fire and wind throw (Canham and Loucks 1984, White and Mladenoff 1994, Zhang et al. 1999, Zhang et al. 2000), and formulation of management or restoration plans that recover historic vegetation (Radeloff et al. 2000, Bolliger et al. 2004). Other studies have used GLO records to compare historic and current vegetation to evaluate landscape scale patterns of vegetation change over time (Curtis 1956, Radeloff et al. 1999, Dyer 2001, Cowell and Jackson 2002) and to associate historic vegetation patterns with specific site characteristics (Whitney and Steiger 1985, Fralish et al. 1991, Leitner et al. 1991, Delcourt and Delcourt 1996).

We present a new method, the adjustable exclusion angle method, which modifies the random pairs sampling method to estimate tree densities from GLO survey witness tree distances. Tree density estimates resulting from application of this new method are compared with those obtained using three modifications of the quarter method and the random pairs method with a 180° exclusion angle. Distance methods are commonly employed field sampling procedures used to determine tree densities from point-to-tree or tree-to-tree measurements (Cottam and Curtis 1949, 1955, 1956, Cottam et al. 1953). Inappropriate application of distance methods can lead to substantial errors in estimated tree densities from the GLO records. Because basal

[1] The USDA United States Forest Service funded this research.

[2] We thank M. Rebecca Anderson, James S. Fralish, and Dennis Nyberg for helpful reviews of this manuscript.

[3] Author for correspondence. E-mail: rcander@ilstu.edu

[4] Current address: 4189 NW Walnut Place, Corvallis, OR 97330.

Received for publication November 11, 2003, and in revised form December 19, 2005.

areas per unit area are calculated by multiplying mean tree basal area times tree densities, errors in density estimates also lead to errors in calculating tree basal area per unit area.

Mechanics of the GLO Surveys. Detailed reviews of survey instructions and procedures are available in several sources (e.g., Bourdo 1956, Hutchinson 1988). A summary of the instructions relevant to this paper follow. Surveyors were instructed to establish townships of six by six miles (9.7 × 9.7 km), which were subdivided into 36 one-mile square (1.6 × 1.6 km) sections. Surveyors marked section corners and quarter section points using one to four (usually two) witness trees that were likely to be healthy and long lasting so that the points could be relocated. This pattern results in useable data points being distributed at one-half mile (0.8 km) intervals along a grid system defined by the north-south and east-west section lines. The common name, estimated diameter at breast height, and distance and direction from section and quarter section points were recorded for each witness tree.

Surveyors also documented trees they encountered on the survey lines (line trees), recording their distance from the last survey point, diameter, and species. They noted general geological features such as cliffs, the width and direction of flow of streams and rivers, bodies of water, and changes in vegetation (e.g., transition from timber to prairie) and recorded their distances from the last surveyed point. At the end of each mile, or in some surveys one-half mile, they wrote a brief description of the land they had traversed with emphasis on general topography, the suitability of the land for agriculture, dominant tree species, and general vegetation type (e.g., timber, barrens, prairie, swamp). These notes have been used to document historic vegetation patterns in several studies (e.g., Kline and Cottam 1979, Swigart and Anderson 2000).

Application of Distance Methods to GLO Survey Data. The distance methods (Cottam and Curtis 1949, 1956; Cottam et al. 1953) utilize the distances from a point to trees or from tree to tree, to estimate the square root of the mean area of a tree. Because the mean area is the amount of space occupied by a single tree, the square root of the mean area is squared and divided into the appropriate unit area (e.g., acre, hectare) to calculate tree density. Modifications of quarter method and the random pairs method are often used to calculate tree densities from the witness tree data.

Point-Centered Quarter Method. In application of the quarter method, the distance from a sampling point to the nearest tree in each of four quadrants around the point is measured (Fig. 1A) (Cottam and Curtis 1949, 1956; Cottam et al. 1953). The distance to the nearest tree is Q_1, the distance to the next nearest is Q_2, and so on. The average of the four measured distances [$Q_m = (Q_1 + Q_2 + Q_3 + Q_4)/4$] equals the square root of the mean area of a tree. However, each distance bears a specific relationship to the square root of the mean area: $Q_1 = 0.50$, $Q_2 = 0.81$, $Q_3 = 1.12$, $Q_4 = 1.57$ and $Q_m = (0.50 + 0.81 + 1.12 + 1.57)/4 = 1.00$ of square root of the mean area. Any of the four distances, separately or in combination, can be used to estimate the square root of the mean area. For example, when two witness trees are recorded, one can assume they are Q_1 and Q_2, and take their average distance and divide it by a correction factor of 0.66 (average of 0.50 and 0.81, correction factors for Q_1 and Q_2, respectively), to calculate the square root of the mean area. Following the same procedure when three witness trees are recorded, the distances can be treated as Q_1, Q_2, and Q_3 and the average distance equals 0.81 of the mean area. The average distance would be divided by a correction factor of 0.81 to calculate the square root of the mean area (Cottam and Curtis 1949, 1956; Cottam et al. 1953).

Random Pairs. In the random pairs method (Fig. 1B), an exclusion angle of 180° is typically used with a line between the sampling point and the tree nearest to the point bisecting the angle, although exclusion angles of other sizes can be used. Trees occurring inside the exclusion angle are excluded from the sample. The distance between the first tree and the tree closest to it outside of the exclusion angle is measured. The average of the tree-to-tree distances is equal to 125% of the square root of the mean area and is multiplied by a correction factor of 0.80 to calculate the square root of the mean area (Cottam and Curtis 1949, 1956; Cottam et al. 1953).

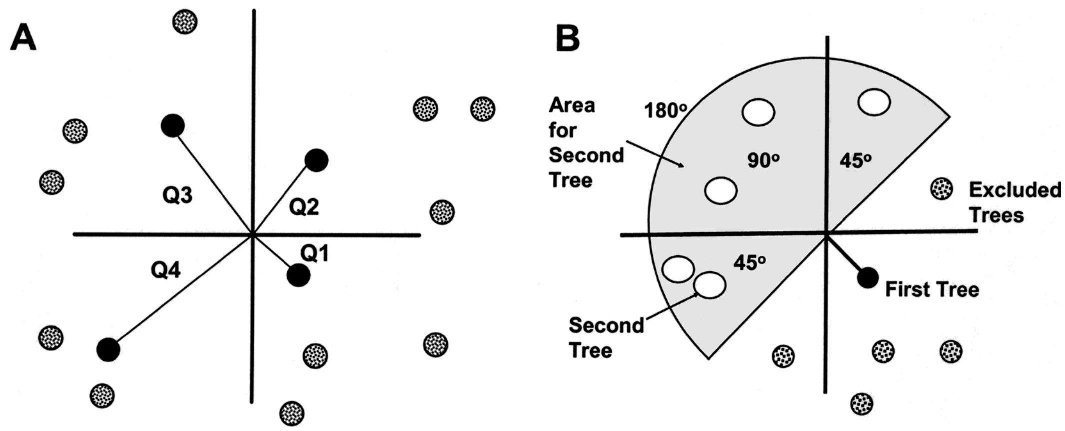

FIG. 1. (A) Representation of the procedure used to measure tree distances at each sampling point with the point-centered quarter method. Darkened circles represent the nearest tree in each quadrant and Q_1 through Q_4 represent the longest to the shortest measured distance at the point, respectively. (B) Representation of the procedure used to measure the tree to tree distance with the random pairs with a 180° exclusion angle. Darkened area indicates area available for the second tree.

LIMITATIONS OF DISTANCE METHODS. The distance methods assume that trees are randomly distributed, and erroneous estimates of tree densities can result if the population of trees deviates from random distributions (Risser and Zedler 1968, Mueller-Dombois and Ellenberg 1974). Procedures for determining if tree samples are derived from randomly distributed populations of trees are given in Cottam et al. (1957), but there is no statistical significance determined for these results. Additionally, a single tree can be measured only once, which is a potential problem in areas with low tree densities if sample points are not widely spaced (Newsome and Dix 1968).

TESTING ASSUMPTIONS OF THE DISTANCE METHODS FOR WITNESS TREE DATA. The witness tree data should meet specific criteria for a particular distance method to be applied (Anderson and Anderson 1975). The assumptions of the distance methods are tested empirically by examining the way in which surveyors actually selected trees. For the random pairs and quarter methods, if the area around the point is divided into four quadrants (NE, SE, SW and NW), the trees should be equally distributed in the four quadrants. Equal distribution of trees would assure that the surveyors did not have a bias for tree selection with respect to the direction of the four quadrants around the survey point. Additionally, both distance methods require that no more than one witness tree may occur in a quadrant. If both trees occur in the same quadrant, the most parsimonious decision would be to treat the shorter of the two distances as Q_1 of the quarter method (Rodgers and Anderson 1979).

TESTING ASSUMPTIONS OF THE QUARTER METHOD. For the two witness tree distances to be treated as Q_1 and Q_2, the second tree should occur twice as often in the quadrants adjacent to the quadrant of the first tree as in quadrants opposite the quadrant of the first tree (Fig. 1A). This relationship exists, because after the first tree is chosen there are two adjacent and one opposite quadrant in which the second tree can occur (Anderson and Anderson 1975).

TESTING ASSUMPTIONS OF THE RANDOM PAIRS. The 180° angle excludes from selection as the second tree all trees that occur in the quadrant of the first tree and those trees in one-half of the area of the two adjacent quadrants. Therefore, the area in which the second tree can occur is limited to the quadrant opposite the quadrant of the first tree and one-half of the area of the two adjacent quadrants (Fig. 1B). Consequently, the second tree should occur as often in the opposite quadrants as in adjacent quadrants to meet the assumptions of the random pairs with an exclusion angle of 180° (Anderson and Anderson 1975).

Modifying the Random Pairs Method. While modifications of the Quarter Method have been applied to GLO survey witness tree distances, there has been no modification of the Random Pairs Method applied to these data. However, because tree densities can be calculated for exclusion angles other than 180°, this flexibility in the size of exclusion angles provides for the possibility of using the Random Pairs Method when criteria for the Quarter Method or Random Pairs Method with a 180° exclusion angle are not met. Application of modification of the Random Pairs with an appropriate exclusion angle is dependent upon determining the pattern of second tree selection relative to the position of the first tree.

Methods. Study Area. We used GLO records (1806–1810) for the 345,000 ha Shawnee National Forest Purchase Area, which extends across the unglaciated southern tip of Illinois. The purchase area is located about 525 km south of Chicago, Illinois USA between 37°10″ and 37°52″ N latitude and between 88°4″ and 89°40″ W longitude. Climatically, the purchase area is within the Humid Temperature Domain/Hot Continental Division, which is characterized by pronounced hot summers and cool or mild winters (Bailey 1996). At Dixon, Illinois, located within but east of the center of the purchase area, mean annual temperature and precipitation are 14.5 °C and 122 cm, respectively. Mean temperatures for the warmest and coldest months are 26 °C (July) and 1.1 °C (January), respectively (Angle 2002). The purchase area is bounded by the Ohio and Wabash rivers on the east and the Mississippi River on the west. Elevation varies from about 90 m to 310 m a.s.l.

The study area is primarily in the Shawnee Hills Natural Division of Illinois (260,620 ha) that is divided into two subdivisions, the Greater and Lesser Shawnee Hills. The Greater Shawnee Hills subsection (173,631 ha) is the northern of the two subdivisions and is characterized by a high east-west escarpment of Pennsylvanian age sandstone. The Lesser Shawnee Hills subsection (86,989 ha) averages 61 m lower in elevation than the more dissected Greater Shawnee Hills, with Mississippian age limestone as the primary surface bedrock. The remainder of the purchase area is included in the Ozark Division (50,000 ha), an extension of the Ozark Plateau that is separated from the main part of the plateau by the Mississippi River; bottomlands associated with the Mississippi, Ohio, Wabash, and Cache rivers (34,380 ha); and the Cretaceous Hills (9,589 ha), a series of low hills that are underlain with Cretaceous age sand, gravels, and clays (Willman and Frye 1970, Schwegman 1973). Most of the soils were derived from loess that originated primarily from the Mississippi flood plain (Fahrenbacher et al. 1968, Willman and Frey 1970).

The study area was included in the Western Mesophytic region by Braun (1950) and is largely characterized by oak-hickory forest on upland sites and mesic forests dominated by sugar maple (*Acer sacharrum*) and American beech (*Fagus grandiflora*) in sheltered locations, with a diversity of tree species occupying bottomland sites (Voigt and Mohlenbrock 1964, Fralish 1994). Detailed information about forest composition and structure is provided in the literature (e.g., Thomson and Anderson 1976, Fralish 1988, 1997; Fralish et al. 2002).

Data Collection and Analysis. From the GLO records, the following data were recorded: township number; range number; assigned x, y coordinates for each section and quarter section point within a township; and common name, distance and direction (azimuth degrees) from the section or quarter-section point for each witness tree. To determine if there was a random selection of trees with respect to direction from the survey points, we used Chi-square to test for equal number of trees per degree of azimuth, within 36 ten-azimuth-degree sectors, and within four quadrants [NE (1–90°), SE (91–180°), SW (181–240°), and NW (241–360°).

Based on the quadrant of occurrence for the first witness tree, the second tree was recorded as being in a quadrant opposite or adjacent in relation to the first. Using chi-square, we tested these results against the assumptions of the occurrence of the second witness tree in quadrants opposite or adjacent to the quadrant of the first witness tree for the random pairs with a 180° exclusion angle (equal number of second trees in opposite and adjacent quadrants) and the quarter method (twice the number of second witness trees in adjacent quadrants as opposite). These results, and examination of the number of witness trees by degrees of azimuth and in 36 ten-azimuth-degree sectors, suggested that surveyors preferred using trees located near the center of quadrants as witness trees over those located near ordinal directions. To further test for surveyor bias in witness tree selection, we used two-way ANOVA to test for differences in mean witness tree distances between first and second witness trees that occurred within plus or minus ten degrees of ordinal directions (0, 90, 180, and 270 azimuth degrees) or within plus or minus ten degrees of the center of each of the four quadrants (45, 135, 225, and 315 azimuth degrees). Data were log normal transformed to achieve normality.

The random pairs method uses tree-to-tree measurements to calculate tree densities. Because survey records contain point-to-tree distances, and the angle between the trees (alpha) can be determined using their azimuths from the point, the distance between the two witness trees at a point can be calculated. A triangle is formed using the known distances as two of the sides and the unknown tree-to-tree distance, which is opposite the angle alpha, as the third side. The tree-to-tree distance is calculated using the equation:

$$D_t = \left[\begin{array}{l} (\text{distance}_1)^2 + (\text{distance}_2)^2 \\ - \left(\begin{array}{l} 2 \times \text{distance}_1 \\ \times \text{distance}_2 \times \cos \alpha \end{array} \right) \end{array} \right]^{-2}.$$

Once the distance between trees is determined the mean distance is obtained and multiplied times the appropriate correction factor (0.80) for the 180° exclusion angle to yield the square root of the mean area.

Distance methods assume that distances between trees or from points to trees are measured to the center of the tree (point to trees) or trees (tree to tree) (Ashby 1972). To accommodate this assumption one-half of the tree diameter(s) was added to each distance measurement. Ninety of 7892 trees lacked diameter estimates and one-half of the mean tree diameter was added to the distances for these trees. Tree densities calculated from the square root of the mean area were subsequently converted to metric units. Comparisons among methods were based on the square root of mean areas and not tree densities calculated for each point, because tree densities are calculated by squaring the mean areas after they are averaged for the population. Consequently, mean tree density calculated by averaging tree densities across points is not equal to the density for the population of trees, whereas averaging the square root of the mean area across points is equal to the square root of the mean area for the population of trees.

The square root of the mean area for the data set was calculated using five methods: (1) three modifications of the quarter method (using the shorter tree distance and longer tree distance as Q_1 and Q_2, respectively, and Q_1 plus Q_2), (2) the random pairs method with a 180° exclusion angle, and (3) random pairs with a 203° exclusion angle for reasons described later. Distances of the first and second recorded witness tree do not always correspond to the shortest and longest distances, so these data were sorted before analysis. The square root of the mean area was calculated using the following equations: shortest distance × 2, longest distance × (1/0.81), and [((shortest distance + longest distance)/2) / 0.66] for the modifications of the quarter method. For the random pairs method, the tree-to-tree distance was calculated and multiplied by 0.80 or 0.74, for the 180° and 203° exclusion angle, respectively. All interior section and quarter section points with two witness trees were included in the analysis for all methods.

One-way ANOVA was used to determine if there were significant differences among the square root of the mean areas owing to method. We calculated a mean square root of the mean area for the five methods at each point. This mean was subtracted from the square root of the mean area calculated for each method at the point and the deviates were used as the dependent variable in the one-way ANOVA with method as a fixed effect. Differences among means were tested using Ryan-Einot-Gabriel-Welch multiple range tests, which controls for Type I statistical error. All statistical analysis of data was done using SAS (1999–2001).

Results. NATURE OF THE HISTORIC VEGETATION. The dominant forest type in the study area at the time of the GLO surveys was oak-hickory forest with the leading tree species in the Greater and Lesser Shawnee Hills, Ozark, and Ohio-Wabash Natural Divisions being white oak (*Quercus alba*) with Importance Values [IV = (Relative Density + Relative Dominance)/2] of 43.4, 45.5, 26.0, and 20.3 in the four Divisions, respectively. Black oak (*Quercus velutina*) was the second leading species in the Greater and Lesser Shawnee Hills and Ohio-Wabash Divisions (IV = 16.0, 19.1, 15.3, respectively) and it was the third leading species in the Ozark Division (9.3). Beech was the second most important species in the Ozark Division (IV= 25.4). In the Mississippi bottoms, the three leading taxa were ash (*Fraxinus* spp.), elm (*Ulmus* spp,), and hackberry (*Celtis occidentalis*). Hickory (*Carya* spp.) was the third most important species in the Greater and Lesser Shawnee Hills (IV = 7.4 and 6.1, respectively). Estimates of tree density, based on the random pairs with a 203° exclusion angle, ranged from a high of 215 trees ha^{-1} in the Ozark Division to a low of 128 trees ha^{-1} in the Lesser Shawnee Hills. These two Divisions also had the greatest variation in basal area being 16.7 and 27.7 m^2 ha^{-1} for the Lesser Shawnee Hills and the Ozark Divisions, respectively. Separate mean tree basal areas were calculated for each of the Divisions and used in calculating basal area per ha.

TESTING FOR THE ASSUMPTIONS OF THE DISTANCE METHODS. Surveyors had a biased selection of witness trees on eastern and southern boundaries of townships. Trees inside the township being surveyed were selected in preference to those in adjacent townships. For eastern boundaries surveyors chose trees more often in the SW and NW quadrants than the NE and SE quadrants (NW = 619, SW = 586, SE = 80, and NE = 76, and χ^2 = 810, P < 0.0001, df = 3) and for southern boundaries they preferentially chose trees from the NE and NW quadrants (NW = 663, NE = 626, SW = 133, SE = 101, and, χ^2 = 733, P < 0.0001, df =3). These data were excluded from the analyses described here.

The remaining data set did not have witness trees equally distributed, by degrees of azimuth (χ^2 = 860.179, P < 0.001, df = 359), in the 36 10-degree sectors (χ^2 = 143.557, P < 0.001, df = 35) or in the four quadrants (χ^2 = 9.584, P = 0.022, df = 3). A plot of number of witness trees by ten-azimuth-degree sectors demonstrated that the surveyors had a preference for selecting trees near the center of each of the four quadrants (Fig. 2). Comparison of number of trees by quadrant indicated that there were 1905, 2059, 1906, and 2022 trees in the NE, SE, SW, and NW quadrants, respectively. The data set was large (3946 survey points and 7892 witness trees), and although the departure from an equal distribution (1973 trees/quadrant) was significant at the 0.05 level, the actual numerical deviation from equal distributions is small ranging from 49 to 86 trees/quadrant (2.5–4.4%). Consequently, it is reasonable to apply the distance methods for analysis to this data set based on the small number of trees deviating from the expected distribution. The alternative would be to use the shorter of the two distances as Q_1 of the quarter method and this would result in the loss of one-half of the available distance data (Rodgers and Anderson 1979). The consequences of this alternative were evaluated with our data set.

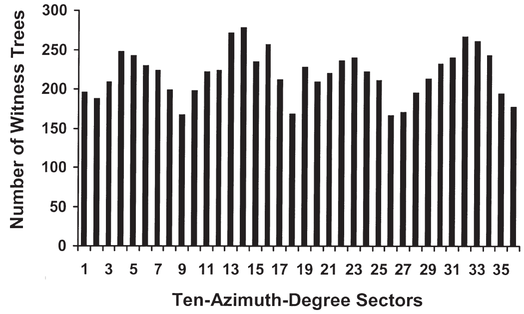

FIG. 2. Number of first and second witness trees in 36 ten-azimuth-degree sectors beginning with 0–9° in the first category and ending with 350–359° in the last category.

There were no significant (F = 1.63, P = 0.2025, df = 1, 3707) differences in mean (mean ± SE) witness tree distances for trees within plus or minus ten degrees of the center of each quadrant (5.83 ± 0.10 m, N = 2,107) or within plus or minus ten degrees of the ordinal directions (5.81 ± 0.14 m, N = 1,605). First witness trees had significantly (F = 105.79, P < 0.0001, df = 1, 3,707) shorter mean distances than second witness trees (5.15 ± 0.10 and 6.47 ± 0. 13 m, for first and second trees, respectively). There were no significant (F = 0.16, P = 0.69, df = 1, 3607) two-way interactions between tree position (near ordinal directions or the center of quadrants) and order of tree measurement. Distances for first witness trees were 5.14 ± 0.16 m and 5.16 ± 0.12 m for ordinal and center trees, respectively, and distances for second trees were 6.53 ± 0. 0.23 m and 6.43 ± 0.15 m for ordinal and center trees, respectively.

The distribution of the second witness tree in relation to the first were 57.3% ($N = 2262$ trees) in opposite quadrants and 42.7% ($N =$ 1,685 trees) in adjacent quadrants and did not meet criteria for either the random pairs (50% in opposite quadrant, 50% in adjacent quadrants, $\chi^2 = 84$, $P < 0.005$, df = 1) or quarter method (1/3 in opposite quadrant, 2/3 in adjacent quadrants, $\chi^2 = 1019$, $P < 0.0001$, df = 1). Departure of the data from stated criteria for random pairs method justifies modification of the method of calculating mean area to more precisely estimate tree densities.

THE ADJUSTABLE EXCLUSION ANGLE METHOD. An exclusion angle of 180°assumes an equal distribution of second witness trees in quadrants opposite and adjacent to the quadrant of the first tree. An exclusion angle >180° would be necessary to fit the distribution of sample data (57.3% of second trees in quadrants opposite the first and 42.7% adjacent to the first). With a larger exclusion angle, as long as it is less than 270°, the entire opposite quadrant (90° azimuth) would be available for second tree selection. However, the areas in each of the two adjacent quadrants would occupy less than 45 azimuth degrees. The proportion of the total trees in opposite and adjacent quadrant should be equal to the proportion of the azimuth degrees in opposite and adjacent quadrants. This relationship exists because the number of trees in opposite and adjacent quadrants should be equal to the area available for the trees to occur in each. And the areas in opposite and adjacent quadrants is proportional to the degrees of azimuth in these quadrants. Because the azimuth degrees in the opposite quadrant are fixed at 90°, the degrees of azimuth in the two adjacent quadrants combined are given by the following relationship: [90° × (proportion of total trees in adjacent quadrants/ proportion of total trees in the opposite quadrants)].

Calculating degrees of azimuth in adjacent quadrants for our data becomes:

$$[90^\circ \times (0.427/0.573) = 67^\circ].$$

Thus, using the distribution of sample data in opposite and adjacent quadrants after the first tree was selected, it was determined that an exclusion angle of 203° [360° − (90° (in the opposite quadrant) + 67° (in the two adjacent quadrants)] would describe this distribution.

By sampling an artificially generated random population, Cottam et al. (1953) reported a linear relationship between the mean distances for selected exclusion angles between 0° and 260° and their percentage of the square root of the mean area. Linear regression indicated a significant relationship between these selected exclusion angles (0, 30, 60, 100, 140, 180, 220, and 260 degrees) and the percentage of the square root of the mean area represented by their mean distances ($Y = 0.3703X + 59.687$; $R^2 = 0.9989$, $P < 0.001$, where Y = percentage of the square root of the mean area and X = exclusion angle). From the regression, the exclusion angle of 203° calculated for this data set had a mean distance that was 135% of the square root of the mean area, which resulted in a correction factor of 0.74 (100% / 135% = 0.74). Because mean distances become longer as the size of the exclusion angle increases (125% vs. 135% of the mean area for random pairs 180° vs. 203°, respectively), the correction factor for the 203° exclusion angle (0.74) is smaller than the correction factor for the 180° exclusion angle (0.80).

Use of the adjustable exclusion angle method will be unique to each GLO survey data set. A hypothetical application of the procedures used to determine an appropriate exclusion angle is shown in Fig. 3.

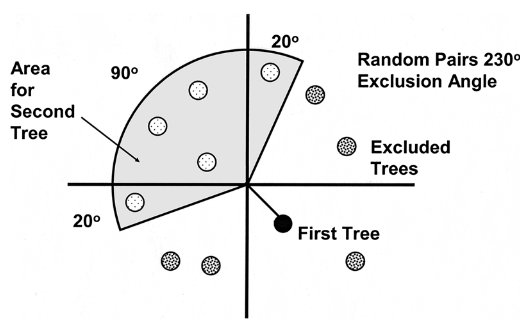

FIG. 3. Hypothetical example for a GLO survey data set that resulted in an exclusion angle of 230°. The darkened area indicates the region within which the second witness tree occurred after the first witness tree was selected. For this example, 90 azimuth degrees were available for the occurrence of the second tree in the opposite quadrant and 20° in each of the adjacent quadrants. Of the second witness trees, 69.2% [(90°/130°) × 100], occurred in the quadrant opposite the first tree and 30.8% [(40°/ 130°) × 100] in the two adjacent quadrants. Application of this exclusion angle results in a mean distance equal to 144.86% [$Y = (0.3703 \times 230) + 59.687$] of the square root of the mean area and a correction factor of 0.69 (100%/144.86%).

Table 1. Comparison of square root of mean areas (mean ± SE), density (trees ha^{-1}) and basal area (m^2 ha^{-1}) calculated using various distance methods with or without one-half of witness tree diameters added to distances.

Distance Method	(Q_1)	(Q_2)	(Q_1+Q_2)	RP[a] 180°	RP 203°
SQRT mean area (m)					
With ½ tree diam.	8.47 ± 0.100	9.22 ± 0.100	8.86 ± 0.091	8.36 ± 0.088	7.74 ± 0.082
Without ½ tree diam.	8.13 ± 0.100	8.99 ± 0.100	8.59 ± 0.091	8.11 ± 0.088	7.51 ± 0.081
Tree Density (stems ha^{-1})					
With ½ tree diam.	139.4	117.8	127.4	143.0	167.1
Without ½ tree diam.	151.4	123.8	135.4	151.9	177.5
Tree Basal Areas (m^2 ha^{-1})					
With ½ tree diam.	17.2	14.6	15.7	17.7	20.6
Without ½ tree diam.	18.7	15.3	16.7	18.8	21.9

[a] RP = Random Pairs

COMPARISON OF FIVE DISTANCE METHODS. One-way ANOVA indicated significant differences in square roots of mean areas owing to method (F = 356.94, P < 0.0001, df = 4, 19,725). The square roots of the mean area were significantly different among all five methods. When one-half of the tree diameters were added to the distances, the square roots of the mean areas ranged from 7.74 ± 0.08 m for the random pairs with a 203° exclusion angle to 9.22 ± 0.10 m for the Q_2 distance and corresponded to tree densities of 167.1 and 117.8 trees per ha for the two methods, respectively (Table 1). Multiplying tree densities for the two methods by the mean tree basal area of the sample (1,236 cm^2) yielded basal areas of 14.6 and 20.6 m^2 ha^{-1} for the Q_2 distance and random pairs 203° exclusion angle, respectively. Without adding one-half of the tree diameters to witness tree distances, tree densities and basal areas were higher than if diameters were added to distances and ranged from 123.8 to 177.5 trees per ha and 18.7 to 21.9 m^2 ha^{-1}, respectively (Table 1).

Discussion. Many studies have addressed some of the problem issues and limitations associated with using the GLO survey records to determine historic vegetation (Bourdo 1956, Nelson 1997, Manies et al. 2001, Schulte and Mladenoff 2001). Among the commonly cited issues is witness tree selection. Witness tree selection prescribed by the surveyor general, "…the distances measured to two or more adjacent trees in opposite directions, as nearly as may be…" (Tiffin 1815, reported in Bourdo 1956), probably had more than one interpretation and may have been difficult to administer in the field. Bias toward particular species and sizes of trees was also present, as surveyors were instructed to choose trees that were likely to be healthy and long lasting (Tiffin 1815, reported in Bourdo 1956). Manies et al. (2001) found evidence for differences in witness tree selection among surveyors for size and species. In our data set surveyors recorded trees less than 12.7 cm (5 inches) in diameter including 5, 10, and 125 trees that were 5.1, 7.6, and 10.2 cm (2, 3, and 4 inches), respectively. Nelson (1997) notes that while use of a distance method assumes unbiased distance measurements, this assumption, when using GLO records, is unrealistic. Our data support this conclusion and shows that surveyors selected trees near the center of the distance between the ordinal directions in preference to trees that were near ordinal directions.

In some instances, this preference could have resulted in surveyors not measuring the tree nearest to the section or quarter section point, because trees near the center of the quadrant were preferentially used as witness trees even though trees near the ordinal directions were closer to the point. If surveyors only used trees adjacent to the ordinal directions when trees in the center of the quadrants were at substantially longer distances than those occurring adjacent to the ordinal directions, this bias would have resulted in shorter distances for witness trees occurring adjacent to the ordinal directions than those near the center of the quadrants. However, our results indicate that even though there was a biased selection of trees there was no difference in the mean distances for witness trees selected near the center of the quadrants or close to the ordinal directions. The lack of significant differences in distances between the two groups of witness trees suggests that surveyors likely chose trees close to the center of the quadrant over those close to ordinal directions only when the distances between the two trees were similar. This pattern of selection results in more witness trees being chosen near the center of quadrants than near ordinal directions, as shown by our data; however, there is no indication of effects of this choice on distance. Preference for trees near the center of quadrants also explains why there were more second witness trees occurring in quadrants opposite the quadrant of the first trees than would be expected if a random pairs method with an 180° exclusion angle was used. If the first witness tree is preferentially selected to be in the center of the quadrant, a tree opposite the first is more likely to be in the quadrant opposite to the quadrant of the first tree than in the quadrant adjacent to the quadrant of the first tree.

While the witness tree data from survey records may be somewhat lacking in accuracy and precision, it is the best record of historic vegetation available, and is well suited for quantitative analysis (Curtis 1959, Schulte and Mladenoff 2001). To ensure that quantitative measures, like tree density, are as representative of historical conditions as possible, the attributes of the witness tree data should be carefully examined before applying a particular distance method for analysis. Some researchers have used modifications of the quarter method (Rodgers and Anderson 1979, Fralish et al. 1991, Swigart and Anderson 2000, Bollinger et al. 2004), whereas others used the random pairs method (Leitner and Jackson 1981). These two methods have different assumptions for the selection of trees and distances measured. It is important that the appropriate method is applied depending on the distribution of witness trees. Otherwise, assumptions and predictions made about the resulting density data may have errors that could be reduced or eliminated by applying the most appropriate distance method. Adding one-half of the witness tree diameter to the measured distance to the tree should be done, because it meets the distance method criterion of distances being measured to the center of the tree and improves the estimate of tree density (Ashby 1972). Because of the pattern of second witness trees in quadrants opposite and adjacent to the quadrant of the first tree and the bias of selection trees in the center of quadrants by surveyors, we think that our adjustable exclusion angle method, which determines a corrected exclusion angle, gives more accurate representation of tree density than the other methods used in this study to estimate tree density.

Additionally, determining how the surveyors actually selected witness trees may reveal other inherent problems in the data. For example, the purchase area covers an area of over 345,000 ha and provided the opportunity to examine and test statistically the way in which surveyors actually implemented the Surveyor General's instructions. The data set had one key problem at this level, which was the bias of surveyors to choose, on the eastern and southern boundaries of townships, witness trees that were in quadrants within the township being surveyed. Because of this preference for the two quadrants inside of the township, (390 vs. 2494 trees, outside and within townships, respectively), the two distances were not assumed to be Q_1 and Q_2. Within each of the two quadrants any distances could be Q_1, Q_2, Q_3, or Q_4 with equal probability Consequently, we considered the average of the two distances to be Q_m, based on the equal probability of a given witness tree distance being Q_1, Q_2, Q_3, or Q_4 (Sauer 2002). Because the square roots of the mean area are squared to yield mean areas, treating the mean distances from eastern and southern township boundaries as an average of Q_1 and Q_2, instead of Qm, would have increased the mean area and decreased the tree density by a factor of 2.2956 ($1/0.66 \times 1/0.66$) or 229%. For example, if tree densities of 100, 200, 400 trees per ha resulted when the average distance was treated as if it was Q_m, treating the mean distance as the average of Q_1 and Q_2 would result in densities of 44, 87, and 174 trees per ha, respectively.

Conclusions. The criteria for distribution of witness trees in quadrants around the survey points associated with the application of the distance methods should be evaluated before any method is used for calculation and analysis of the square root of the mean area. If necessary, the data set should be subdivided into points with similar information and patterns of witness tree selection. The distance methods should be modified and applied based on the actual characteristics of each data group. Additionally, results from quantitative analysis of GLO records should be verified with descriptions of the landscape recorded in the surveyor's field notes and current information known about the ecology and distribution of tree species.

Literature Cited

Angle, J. 2002. Historical Climate Data. Station: 112353 Dixon Springs Agr. Center. Illinois State Water Survey, 2204 Griffith Dr., Champaign, IL. <http://www.sws.uiuc.edu/atmos/statecli/Summary/112353.htm> (accessed Dec. 1, 2004).

Anderson, R. C. and M. R. Anderson. 1975. The presettlement vegetation of Williamson County, Illinois. Castanea 40: 345–363.

Ashby, W. C. 1972. Distance measurements in vegetation study. Ecology 53: 980–981.

Bailey, R. G. 1996. Ecosystem Geography. Springer-Verlag, New York, NY. 204 p.

Bollinger, J., L. A. Schulte, S. N. Burrows, T. A. Sickley, and D. J. Mladenoff. 2004. Assessing ecological restoration potentials of Wisconsin (U.S.A.) using historical landscape reconstructions. Restor. Ecol. 12: 124–142.

Bourdo, E. A., Jr. 1956. A review of the general land office survey and its use in quantitative studies of former forests. Ecology 37: 754–768.

Braun, E. L. 1950. Deciduous forests of eastern North America. Hafner Publishing Co., New York, NY. 596 p.

Canham, C. D. and O. L. Loucks. 1984. Catastrophic windthrow in the presettlement forests of Wisconsin. Ecology 65: 803–809.

Cottam, G. and J. T. Curtis. 1949. A method for making rapid surveys of woodlands by means of pairs of randomly selected trees. Ecology 30: 101–104.

Cotttam, G. and J. T. Curtis. 1955. Correction for various exclusion angles in the random pairs method. Ecology 36: 767.

Cottam, G. and J. T. Curtis. 1956. The use of distance measures in phytosociological sampling. Ecology 37: 451–460.

Cottam, G., J. T. Curtis, and A. J. Catana. 1957. Some sampling characteristics of a series of aggregated populations. Ecology 38: 610–622.

Cottam, G., J. T. Curtis, and B. W. Hale. 1953. Some sampling characteristics of a population of randomly dispersed individuals. Ecology 34: 741–757.

Cowell, C. M. and M. T. Jackson. 2002. Vegetation change in a forest remnant at the eastern presettlement prairie margin, USA. Nat. Areas J. 22: 53–60.

Curtis, J. T. 1956. The modification of mid-latitude grasslands and forests by man, p. 721–762. *In* C. Sauer, M. Bates, and L. Mumford [eds.], Man's role in changing the face of the earth. The University of Chicago Press, Chicago, IL.

Curtis, J. T. 1959. The vegetation of Wisconsin: an ordination of plant communities. University of Wisconsin Press, Madison, WI. 657 p.

Delcourt, H. R. and P. A. Delcourt. 1996. Presettlement landscape heterogeneity: Evaluating grain of resolution using General land Office Survey data. Landscape Ecology 11: 363–381.

Dyer, J. M. 2001. Using witness trees to assess forest change in southeastern Ohio. Can. J. For. Res. 31: 1708–1718.

Fahrenbacher, J., B. Ray, and J. Alexander. 1968. Illinois soils and factors in their development, p. 165–175. *In* R. Bergstrom [ed.], The Quaternary of Illinois. Special Publication 14. College of Agriculture, University of Illinois, Urbana, IL.

Fralish, J. S. 1988. Predicting potential stand composition from site factors in the Shawnee hills forest of Illinois. Am. Midl. Nat. 120: 79–101.

Fralish, J. S. 1994. Composition, diversity, and environmental relationships of the central hardwood bottomland forest. p. 39–49. *In* S. Roberts and R. Rathfon [eds.], Management of Forested Wetland Ecosystems in the Central Hardwood Region. Publication FNR 151, Indiana Dept. of Forestry and Natural Resources, West Lafayette, IN.

Fralish, J. S. 1997. Community succession, diversity, and disturbance in the central hardwood forest, p. 234–266. *In* M. Schwartz [ed.], Conservation in highly fragmented landscapes. Chapman and Hall, New York, NY.

Fralish, J. S., F. B. Crooks, J. L. Chambers, and F. M. Harty. 1991. Comparison of presettlement, second-growth and old-growth forest on six site types in the Illinois Shawnee Hills. Am. Midl. Nat. 125: 294–309.

Fralish, J. S., A. Carver, R. C. Anderson, S. Sauer, C. Ruffner, D. D. Close, R. Swigart, and E. M. White. 2002. Presettlement, Present, and Projected Forest Communities of the Shawnee National Forest, Illinois. USDA, Forest Service, Shawnee National Forest, Harrisburg, IL. 145 p.

Grimm, E. C. 1984. Fire and other factors controlling the Big Woods vegetation of Minnesota in the mid-nineteenth century. Ecol. Monogr. 54: 291–331.

Hutchinson, M. D. 1988. A guide to understanding, interpreting, and using the Public Land Survey Field Notes in Illinois. Nat. Areas J. 8: 245–255.

Kline, V. M. and G. Cottam. 1979. Vegetation responses to climate and fire in the driftless area of Wisconsin. Ecology 60: 861–868.

Leitner, L. A. and M. T. Jackson. 1981. Presettlement forests of the unglaciated portion of southern Illinois. Am. Midl. Nat. 105: 290–304.

Leitner, L. A., C. P. Dunn, G. R. Guntenspergen, F. Stearns, and D. M. Sharpe. 1991. Effects of site, landscape features, and fire regime on vegetation patterns in presettlement southern Wisconsin. Landscape Ecology 5: 203–217.

Manies, K. L., D. J. Mladenoff, and E. V. Nordheim. 2001. Assessing large-scale surveyor variability in the historic forest data of the original U.S. Public Land Survey. Can. J. For. Res. 31: 1719–1730.

Mueller-Dombois, D. and H. Ellenberg. 1974. Aims and methods of vegetation ecology. John Wiley & Sons, New York, NY. 547 p.

Nelson, J. 1997. Presettlement vegetation patterns along the 5^{th} principle meridian, Missouri Territory, 1815. Am. Midl. Nat. 137: 79–94.

Newsome, R. D. and R. L. Dix. 1968. The forests of Cypress Hills Alberta and Saskatchewan, Canada. Am. Midl. Nat. 80: 118–185.

Radeloff, V. C., D. J. Mladenoff, H. S. He, and M. S. Boyce. 1999. Forest landscape change in the northwestern Wisconsin pine barrens from pre-European settlement to the present. Can. J. For. Res. 29: 1649–1659.

Radeloff, V. C., D. J. Mladenoff, and M. S. Boyce. 2000. A historical perspective and future outlook on landscape scale restoration in the northwest Wisconsin pine barrens. Restor. Ecol. 8: 119–126.

Risser, P. G. and P. H. Zedler. 1968. An evaluation of the grassland quarter method. Ecology 49: 1006–1009.

Rodgers, C. S. and R. C. Anderson. 1979. Presettlement vegetation of two prairie peninsula counties. Bot. Gaz. 140: 232–240.

SAS. 2001. SAS/STAT Users Guide. The SAS Institute, Cary, NC.

Sauer, S. L. 2002. Analysis of the historic vegetation using General Land Office survey records in the Shawnee National Forest, Illinois USA, MS Thesis, Illinois State University, Normal, IL.

Schulte, L. A. and D. J. Mladenoff. 2001. The original U.S. public land survey records: their use and limitations in reconstructing presettlement vegetation. J. For. 99: 5–10.

Schwegman, J. 1973. Natural Division of Illinois. Illinois Nature Preserves Commission, Rockford, IL. (Reprinted, Mohlenbrock, R. H. 1986. Guide to the vascular flora of Illinois, Southern Illinois University Press, Carbondale, IL).

Swigart, R. and R. C. Anderson. 2000. Historic vegetation of The Nature Conservancy's Chinquapin Preserve, Woodford County, central Illinois. Trans. Ill. Acad. Sci. 93: 185–199.

Thomson, Paul M., and Roger C. Anderson. 1976. An ecological investigation of the Oakwoods bottoms greentree reservoir, p. 45–64. *In* J. Fralish, G. Weaver, and W. Schlesinger [eds.], Proceedings of the first Central Hardwoods Conference. Southern Illinois University, Carbondale, IL.

Tiffin, E. 1815. Instructions for deputy surveyors. Indiana State Library, Indianapolis, IN.

Voigt, J. and R. Mohlenbrock. 1964. Plant communities of southern Illinois. Southern Illinois University Press, Carbondale, IL.

White, M. A. and D. J. Mladenoff. 1994. Old-growth forest landscape transitions from pre-European settlement to present. Landscape Ecology 9: 191–205.

Whitney, G. and R. J. Steiger. 1985. Site-factor determinants of the presettlement prairie-forest border areas of north-central Ohio. Bot. Gaz. 146: 421–430.

Willman, H. and J. Frye. 1970. Pleistocene Stratigraphy of Illinois. Illinois State Geological Survey Bulletin 94, Urbana, Illinois.

Zhang, Q., K. S. Pregitzer, and D. D. Reed. 1999. Catastrophic disturbance in the presettlement forests of the Upper Peninsula of Michigan. Can. J. For. Res. 29: 106–114.

Zhang, Q., K. S. Pregitzer, and D. D. Reed. 2000. Historical changes in the forests of the Luce District of the Upper Peninsula in Michigan. Am. Midl. Nat. 143: 94–110.