Site Index Determination Techniques for Southern Bottomland Hardwoods

Brian Roy Lockhart

ABSTRACT

Site index is a species-specific indirect measure of forest productivity expressed as the average height of dominant and codominant trees in a stand at a specified base age. It is widely used by forest managers to make informed decisions regarding forest management practices. Unfortunately, forest managers have difficulty in determining site index for southern US bottomland hardwood stands because of a lack of available information for many tree species, outdated information for several techniques, and a lack of knowledge in the application of other techniques for specific site conditions. Techniques to determine site index in bottomland hardwood stands include species trials, site index curves, soil-site equations, soil series, and expert systems. Each technique is reviewed here, including recent advances if available, advantages, disadvantages, and application to bottomland hardwood stands.

Keywords: species trials, soil-site index equations, soil series, expert systems, Baker/Broadfoot system

Site index is a species-specific indirect measure of forest productivity expressed as the average height of dominant and codominant trees in a stand at a specified base age (Helms 1998). It is the most widely used measure of forest productivity to meet specific management objectives (Jones 1969, Carmean 1975). Site index is used to (1) determine the suitability of a site for growing specific tree species in afforestation and reforestation efforts; (2) predict wildlife habitat quality and quantity, including cover, browse, hard mast, and soft mast; (3) predict quality and quantity of timber production; (4) predict tree biomass production; (5) assess impacts of land-use activities, such as harvesting and flood control, on future production of desired products; and (6) estimate monetary values of property during litigation proceedings.

Forest managers have difficulty in determining site index for southern US bottomland hardwood stands because of a lack of available information for many tree species, outdated information for several site index techniques, and a lack of knowledge in the application of other techniques for specific site conditions. Furthermore, no single source exists describing site index techniques for bottomland hardwood species. Therefore, a need exists to provide a comprehensive review of available site index techniques for bottomland hardwood managers. My objective in preparing this review is to focus on techniques applied to natural stands or afforested/reforested stands with long-term management objectives. Hardwood plantations where mechanical and chemical site preparation, herbaceous and woody competition control, and fertilizers are used to shorten rotations for fiber production are beyond the scope of this review.

Techniques available to determine a species site index for bottomland hardwood stands include species trials, site index curves, soil-site index equations, soil series, and expert systems. A review of each of these techniques includes use, advantages, disadvantages, recent advances if available, and examples for bottomland hardwood stands.

Species Trials

One technique to determine site index is to plant tree species of interest on a particular site and periodically evaluate their growth and development over time. Species trials are a logical way to determine site index for a species because they offer the ultimate ground truth (Francis 1984). Unfortunately, few species trials exist to determine site index of many bottomland hardwood species.

Two additional drawbacks to species trials are time and expense. It takes several decades to generate reliable information relating growth and development of a species to specific sites. Furthermore, these results relate only to the species used and the sites on which the trials were conducted. They may not be applicable to other species, sites, or natural stands. The time and expense of species trials, along with the many combinations of sites and species in bottomland hardwood stands result in their limited value for site index determination. Species trials in bottomland hardwoods have focused on short-rotation shade-intolerant, fast-growing species, such as eastern cottonwood (*Populus deltoides* Bartram ex Marsh.) and American sycamore (*Platanus occidentalis* L.), to determine optimal spacings for biomass production (Belanger 1973, Krinard and Johnson 1984).

Site Index Curves

A site index curve is a graphical representation of tree height growth over time. Tree height is used because it is considered the single best tree measure related to site productivity for a given species (Spurr and Barnes 1980). Tree height growth is also considered independent of stand density, except at the extremes of low and high

Manuscript received May 12, 2009; accepted August 22, 2011. http://dx.doi.org/10.5849/sjaf.09-027.

Brian Roy Lockhart (blockhart@fs.fed.us), USDA Forest Service, Southern Research Station, Stoneville, MS. *Andy Ezell, Emile Gardiner, John Hodges, Henry McNab, Steve Meadows, Edgar Mersiovsky, George Rheinhardt, Lyn Townsend, and Jim Walters provided constructive comments to earlier versions of this article. The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the USDA Forest Service of any product or service to the exclusion of others that may be suitable.*

density (Gingrich 1967, Lanner 1985). A site index curve is developed by plotting height and age data for a given species and forming a height-age growth curve (Avery 1975). A series of harmonized curves is then plotted, usually at 10-ft intervals at the base age, to generate a series of anamorphic site index curves (Schnur 1937). Users can then plot tree height and age data collected from the stand onto species-specific curves and determine site index. Husch et al. (1982) reinforced that site index varies according to species on a given site and that site index curves are prepared for individual species. Furthermore, index trees, or the trees from which total height and age are measured, were not suppressed from an overstory canopy during their lifetime; otherwise, the productive potential of the site for a particular species would be underestimated.

Several problems exist when using index trees for site index determination. Spurr and Barnes (1980) noted that assigning dominant and codominant crown classes to individual trees for site index determination is subjective and not necessarily repeatable, though Meadows et al. (2001) developed a crown classification system to quantify bottomland hardwood tree crowns on the basis of crown position and condition. Furthermore, tree canopy status changes over time as individuals drop from a dominant or codominant crown class to lower crown classes through competition, reducing the repeatability of measuring the same index trees (Raulier et al. 2003). Determining tree heights accurately also may be difficult because of dense leaf layers in tree tops during the growing season. McNab (1989) noted that age is particularly difficult to measure accurately in hardwoods. Furthermore, questions arise as to how many index trees are needed to accurately determine site index (Mailly et al. 2004). Finally, there is a temptation to use site index curves beyond the range of data used to develop the height-age relationships.

Additional problems have been noted using anamorphic site index curves (Tesch 1980). First, an assumption is made in developing anamorphic curves that height development of a species is similar across a variety of age classes and site conditions. Many authors have showed this to not be true (e.g., Carmean 1956, 1972, Hilt and Dale 1982). Curtis (1964) and Carmean (1972) indicated that harvesting was more likely to occur on good sites than poor sites because trees would reach merchantable size earlier on good sites. Therefore, older age classes in site index curve development would mostly be represented by trees growing on poor sites.

Second, Carmean (1972) found different patterns of height growth for upland oak species, based on stem analysis data, compared with height development based on anamorphic site index curves; therefore, he used polymorphic height growth patterns to better explain differences in height growth within a species. Anamorphic site index curves are proportional curves that have a constant ratio between heights regardless of tree age (Carmean 1972). Polymorphic site index curves are not proportional; therefore, they will have different height ratios depending on the age at which heights are compared. For example, Carmean (1972) showed differences in height growth in black oak (*Quercus velutina* Lam.) in later years depending on site quality. These differences would not appear in anamorphic site index curves, but they do appear in polymorphic site index curves. Carmean et al. (1989) published one of the most comprehensive sets of hardwood site index curves, with 53 curves for 31 species or species groups. Table 1 lists all known site index curves for southern bottomland hardwood species. Other curves are available for several of these species but were developed for sites outside of the southern United States. Of the 16 site index curves

Table 1. Published site index curves for southern bottomland hardwood species (updated from Francis 1984).

Species	Source area (states)	Reference
American sycamore	MS, LA	Briscoe and Ferrill (1958)
Cherrybark oak	AR, AL, LA, MS, TN	Broadfoot (1961)
	MS	Clatterbuck (1987)
Eastern cottonwood	IL, IN, KY, MO	Neebe and Boyce (1959)
	AR, KY, LA, MS, TN	Broadfoot (1960)
	LA, MS	Alexander (1976)
	MS	Cao and Durand (1991)
Green ash	AR, AL, LA, MS, TN	Broadfoot (1969)
Nuttall oak	AR, AL, LA, MS, TN	Broadfoot (1969)
Swamp blackgum[a]	GA	Applequist (1959)
Sweetgum	AL, FL, MS, SC	Winters and Osborne (1935)
	AR, LA, MS, TN	Broadfoot and Krinard (1959)
	AL	Lyle et al. (1975)
	MS	Clatterbuck (1987)
Water tupelo[b]	GA	Applequist (1959)
Water oak	AR, AL, LA, MS, TN	Broadfoot (1963)

[a] *Nyssa biflora* Walt.
[b] *Nyssa aquatica* L.

available for 9 species, only 3 have been published since 1976. Clatterbuck (1987) published site index curves for cherrybark oak (*Quercus pagoda* Raf.) and sweetgum (*Liquidambar styraciflua* L.) as part of a stand development study on old-field floodplain sites, and Cao and Durand (1991) published site index curves for eastern cottonwood plantations growing in the Lower Mississippi Alluvial Valley.

The reasons for little site index information for southern bottomland hardwood species are four-fold. First, development of site index curves is expensive. Considerable effort is required to locate stands that fit the assumptions for site index determination: relatively undisturbed, even-aged stands. Second, minor changes in elevation strongly influence flooding, sedimentation, soil texture, and soil pH. These changes strongly influence species composition and productivity (Hodges 1997, Wall and Darwin 1999), making site index determination difficult. Third, bottomland hardwood forests have been greatly altered through harvesting practices such as indiscriminate high grading, leading to few stands containing suitable index trees. Finally, changes in hydroperiod from levee/road construction and urban development have resulted in bottomland sites that are constantly changing, making site index a fluid rather than a static value.

Site index curves will remain the most popular technique to determine site index, which is a well established measure in the literature and in forest managers' training. Furthermore, site index is a key variable in many of today's growth and yield models (Hilt 1985). Forest managers must be aware, though, of the limitations in using site index curves.

Soil-Site Index Equations

Soil-site index equations provide a quantitative means to estimate site index based on soil and site variables that directly or indirectly influence tree height growth. Variables may include depth of topsoil, soil texture, presence or absence of pans, topography, and aspect. Several reviews of soil-site index equations based on older literature have been published (Carmean 1975, 1977).

Soil-site index equations have been developed for several hardwood species on upland and bottomland sites. Equations for upland hardwoods have greater correlation with site index determined from index curves ($r^2 = 0.61$ to 0.86) than those for bottomland hardwoods ($r^2 = 0.38$ to 0.68), primarily because of the strong influence

Table 2. Species and literature sources for bottomland hardwood soil-site index equations (updated from Francis 1984).

Species	Source area (states)	Reference
Cherrybark oak	TN	Hebb (1962)
	AL, AR, LA, MS, TN, TX	Broadfoot (1969)
Eastern cottonwood	AL, AR, LA, MS, TN, TX	Broadfoot (1969)
Green ash	AL, AR, LA, MS, TN, TX	Broadfoot (1969)
Nuttall oak	AL, AR, LA, MS, TN, TX	Broadfoot (1969)
Swamp blackgum	GA	Applequist (1959)
Sweetgum	TN	Hebb (1962)
	NJ	Phillips and Markley (1963)
	AL, AR, LA, MS, TN, TX	Broadfoot (1969)
Water tupelo	GA	Applequist (1959)
	AL, AR, LA, MS, TN, TX	Broadfoot (1969)
Water oak	AL, AR, LA, MS, TN, TX	Broadfoot (1969)
Willow oak	AL, AR, LA, MS, TN, TX	Beaufait (1956)
	AL, AR, LA, MS, TN, TX	Broadfoot (1969)

of slope position and aspect on upland tree height growth (e.g., Trimble 1964, Graney 1977, Woolery et al. 2002). Aspect is less important on bottomland sites because of relatively level topography. However, Beaufait (1956) found that differences of only a few inches in elevation strongly influenced silt and clay content, flooding depth and duration, and soil aeration, thus correlating these topographic features with site index.

Broadfoot (1969) advocated against using soil-site index equations in bottomland hardwood forests, especially for investment purposes. These equations have little practical application because of high variability in bottomland soils, and some soil attributes, such as chemical properties, are difficult to measure in the field.

Soil-site equations do allow for a better understanding of the influence of various soil and site characteristics on tree height growth. For example, Broadfoot (1969) developed the following site index equation for water oak (*Quercus nigra* L.):

$$SI_{50} = 87.11 - 13.34(X_1) + 1.558(X_2) - 0.0264(X_3) \tag{1}$$

where SI_{50} = site index, base age 50 years; X_1 = presence (1) or absence (0) of a fragipan; X_2 = depth of topsoil in inches; and X_3 = exchangeable sodium in pounds per acre at the 0–4-in. soil depth.

In Equation 1, the presence of a fragipan reduced site index by 13 ft, indicating that water oak is sensitive to soils with dense horizons. Each 1-in. increase in topsoil depth increased site index 1.6 ft. Also, an elevated level of exchangeable sodium, which is an indication of poor internal drainage, decreased site index. In this equation, r^2 was 0.57.

Table 2 lists species and literature sources for bottomland hardwood soil-site index equations. These equations were developed prior to 1970, using multiple regression techniques. Today, with greater knowledge of tree growth and soil development processes, improved computer technology, and more sophisticated statistical models, soil and site data can be used to develop potentially more accurate soil-site index equations. For example, Grimley et al. (2008) successfully applied volumetric magnetic susceptibility, a measure of ferimagnetic minerals in soil, such as maghemite and magnetite, that are sensitive to soil aerobic and anaerobic conditions, to tree species flood tolerance ranking. Soil chemical properties that are now easily measured in the field and soil physical properties may provide the additional detail necessary to more accurately determine site index for bottomland hardwood species. Additionally, regression programs, such as TableCurve 2D and TableCurve 3D, provide enhanced tools to analyze data in greater detail than was available when the original soil-site index equations were developed.

Soil Series

Identification of the soil series that occurs on a site is another way to determine site index for bottomland hardwood stands. The Natural Resource Conservation Service (NRCS) has classified soils across most of the United States and developed a series of publications describing the soils in each county. Each county soil survey contains information on tree productivity, including site index. Tree heights and ages on a given soil series were measured and used to determine site index from published site index curves. A list of site index curves used by NRCS is maintained in the National Register of Site Index Curves (hereafter called the Register) found in the *National Forestry Manual* (NRCS 1998).

In 2005, the NRCS launched the Web Soil Survey (WSS), which placed information from county soil surveys onto the World Wide Web in digital format (NRCS 2011). Managers can develop user-defined tract boundaries based on satellite imagery and develop tract maps containing soil series, common tree species, site index, volume of wood fiber for select species, and recommended species to manage on the site. The Web Soil Survey was recently updated to version 2.2.6.

Several difficulties should be noted when using soil surveys for site index (Carmean 1967, Jones 1969). Soil mapping was based on soil profile characteristics and pedogenic processes, which are loosely associated with forest productivity. Studies that measured site index by soil series produced a wide range of site indices within a given series (Phillips and Markley 1963, Covell and McClurkin 1967). Furthermore, soil mapping in floodplains was conducted at a broader scale than in uplands, especially when the floodplain was forested. Groninger et al. (2000) compared site indices from soil surveys with those produced through the Baker/Broadfoot system (Baker and Broadfoot 1979). They found site indices were significantly lower using the Baker/Broadfoot system (described in more detail in the Expert Systems section below) than those given for species recommended for planting by soil surveys.

Another difficulty with soil surveys is the lack of published site index curves for many bottomland hardwood species. The Register uses site index curves in Broadfoot (1963) for eight oak species (laurel [*Quercus laurifolia* Michx.], overcup [*Quercus lyrata* Walt.], swamp chestnut [*Quercus michauxii* Nutt.], water, Nuttall [*Quercus nuttallii* Palmer], pin [*Quercus palustris* Muenchh.], willow [*Quercus phellos* L.], and Shumard [*Quercus shumardii* Buckley] oaks). Unfortunately, Broadfoot (1963) contains site index curves only for water oak. As previously mentioned, site index varies by species on a given site and site index curves are prepared for individual species (Husch et al. 1982). Noteworthy among the oaks for which the Register uses the water oak site index curves are overcup and Shumard oaks. These oaks occur on vastly different sites, with overcup oak found on low flats and shallow sloughs (clay soils) and Shumard oak most often found on high ridges with moist but well-drained soils (silt loams). Site index curves developed for one species can be used for another species only when height growth or site index relationships between the two species have been established (Carmean 1979). Such relationships do not exist between water oak and the other oak species listed above. Broadfoot (1970) did publish height and site index relationships between sweetgum and green ash (*Fraxinus pennsylvanica* Marsh.), eastern cottonwood, cherrybark oak, Nuttall oak, water oak, and willow oak, with r^2 values ranging from 0.30 to 0.58.

A second difficulty with the Register involves missing site index curves. The *National Forestry Manual* (which contains the Register) was published in 1998. Therefore, new curves may exist that need to be included in the Register. Broadfoot (1969) published site index curves for Nuttall oak and green ash, but these curves are not included in the Register. Furthermore, Clatterbuck (1987) contains site index curves for cherrybark oak and sweetgum. Although the Register does have citations for site index curves for these latter species, it does not list the more recent Clatterbuck (1987) curves. Although the Register is one of the most comprehensive listings of site index curves available, it is in need of updating. Efforts are currently underway to update the Register (George Rheinhardt and Lyn Townsend, pers. comm., NRCS, Oct. 6, 2008).

Broadfoot (1976) presented information on 40 soil series that occur across the mid-South region. A measured site index was presented for several species along with a calculated site index using Broadfoot's (1970) sweetgum conversions. Broadfoot (1976) also presented an estimated range of site index for many bottomland hardwood species for a given soil series, although the range between high and low site index is 20 ft.

The use of soil series for determining site quality is common. WSS provides forest managers with a Web-based tool to quickly obtain site index for a particular tract of land. The inherent problems involved in using soil series for site index must be recognized by forest managers. Site index values for a soil series may be better used to provide a qualitative assessment of site productivity. For example, site index can be used to determine whether a site is suitable for planting a particular species. Furthermore, these numerical values can be used to determine broad productivity classes (e.g., good, medium, or poor) for a particular species (George Rheinhardt, pers. comm., NRCS, Mar. 30, 2009). As new site index information is developed, it can be quickly incorporated in WSS (Lyn Townsend, pers. comm., NRCS, Oct. 6, 2008).

Expert Systems

Expert systems are tools that can be used by forest managers to quantitatively estimate site index. These systems typically involve few mathematical functions, instead relying on summation of points tied to important soil and site characteristics to determine site index (Baker and Broadfoot 1977, 1979, Harrington 1986). At present, only one expert system has been developed for bottomland hardwood stands. The Baker/Broadfoot system for determining site index relies on four key soil factors and associated soil and site properties to determine site index for 14 bottomland hardwood species (Baker and Broadfoot 1979).

Traditional techniques for determining bottomland hardwood site index involve the use of heights and ages of selected index trees. Unfortunately, index trees may not be available in the following situations: (1) the species of interest not present, (2) pastures or agricultural fields under row-crop production, (3) forests where potential index trees have been harvested, especially in high graded stands, and (4) forests managed under the uneven-aged silvicultural system where potential index trees may have undergone a period of suppression early in life. Without suitable index trees, the Baker/Broadfoot system was developed to determine site index for bottomland hardwood species based solely on soil and site characteristics. Advantages of the Baker/Broadfoot system include that it (1) provides estimates of site index under any soil or site condition associated with bottomland hardwoods; (2) can be applied throughout the southern US hardwood region except in mountainous areas, where aspect influences site index; (3) does not require identification of soil series; and (4) provides guidelines for soil ameliorative treatments (Baker and Broadfoot 1979). Furthermore, sensitivity analyses can be used to determine the relative importance of specific soil and site properties on site index of selected species (Baker and Broadfoot 1978). The Baker/Broadfoot system does require knowledge of soil features, such as texture and physical structure, to properly evaluate a site. This knowledge can be easily acquired through a standard soils text and field instruction.

Table 3. Major soil factors and associated soil and site properties used in the Baker/Broadfoot System (Baker and Broadfoot 1979).

Physical condition	Moisture availability	Nutrient availability	Aeration
Soil depth	Water table depth	Geologic source	Soil structure
Texture	Pans	Past use	Swampiness
Compaction	Topographic position	Organic matter	Mottling
Soil structure	Microsite	Depth of topsoil	Soil color
Past use	Soil structure	Soil age	
	Texture	pH	
	Flooding		
	Past use		

Baker and Broadfoot (1979) indicated that height growth of hardwoods is dependent on four major soil factors: soil physical condition, moisture availability during the growing season, nutrient availability, and aeration (Table 3). The basis for the Baker/Broadfoot system is that each of these major soil factors is responsible for a certain percentage of tree growth. These percentages are then multiplied by an assumed maximum site index on an ideal site for each species to produce site quality values (actual feet of site index) for each major soil factor (Table 4).

The proportion of site index accounted by each major soil factor is composed of the contributions made by individual soil and site properties (Table 3). A site quality value is assigned to each soil and site property for each of three possible conditions (best, medium, and poor). Values assigned to the best category, when summed across all soil and site properties for each major soil factor equals the maximum site index value for that species, although exceptions have been discovered for green ash, Shumard oak, and swamp chestnut oak (Table 4). The number of site evaluations to make on a particular site is related to the variability of the site. In general, one evaluation should be conducted for each specific site condition (Dr. Jim Baker, pers. comm., 1999).

When using the Baker/Broadfoot system, difficulties are often encountered in interpreting the meaning of several soil and site properties in the field. Baker and Broadfoot (1979) provided a brief explanation of several soil and site terms and an example application using the system for eastern cottonwood. A more detailed explanation of each soil and site property is warranted, including how each is interpreted in the field (Table 5). An example using Nuttall oak in a former agricultural field in the Lower Mississippi Alluvial Valley (LMAV) is also provided (Tables 6 and 7).

Example

An example of evaluating a site with the Baker/Broadfoot system is provided below. The site is located north of Highway 35 near Dermott in Drew County, Arkansas, about one-quarter mile east of Cutoff Creek in the LMAV. The field was planted with hardwood

Table 4. Site quality values (actual feet of site index) and associated percentage contributions of each major soil factor to individual tree species site index. Values used are from Baker and Broadfoot (1979).

Species	Maximum site index	Minimum site index	Major soil factors			
			Physical condition	Moisture availability	Nutrient availability	Aeration
Eastern cottonwood	130[a]		46 (35)[b]	46 (35)	26 (20)	12 (10)
Green ash	105 (104)[c]	65	21 (20)	47 (45)	26 (25)	10 (10)
Hackberry/sugarberry[d]	100	55	25 (25)	25 (25)	25 (25)	25 (25)
Cherrybark oak	125	70	31 (25)	38 (30)	25 (20)	31 (25)
Nuttall oak	120	75	24 (20)	42 (35)	30 (25)	24 (20)
Shumard oak	120 (122)[c]	70	31 (25)	32 (26)	29 (24)	30 (25)
Swamp chestnut oak	110 (109)[c]	65	28 (26)	31 (28)	24 (22)	26 (24)
Water oak/willow oak	115	70	29 (25)	34 (30)	23 (20)	29 (25)
Sweet pecan[e]	115	70	27 (24)	30 (26)	30 (26)	28 (24)
Sweetgum	120	75	30 (25)	36 (30)	24 (20)	30 (25)
American sycamore	130	70	32 (25)	20 (15)	39 (30)	39 (30)
Yellow-poplar[f]	125	70	40 (32)	30 (24)	25 (20)	30 (24)

[a] Base age 30 years for eastern cottonwood, 50 years for all other species.
[b] Percent contribution to maximum site index.
[c] Actual maximum site index based on summation of major soil factor contributions.
[d] *Celtis laevigata* Willd. and *Celtis occidentalis* L.
[e] *Carya illinoensis* Wangenh.
[f] *Liriodendron tulipifera* L.

Table 5. Detailed explanation of each soil and site property used in the Baker/Broadfoot System, including how each is interpreted in the field.

Property	Description
Soil depth	Floodplain soils are usually considered deep (>4 ft.) because of their alluvial origin Exceptions include the presence of a tight plowpan, a fragipan, or a high water table
Artificial or inherent pan	Plow pan is a compacted soil layer due to tillage operations Inherent pan is a natural dense soil layer often referred to as a fragipan
Texture	Based on the proportion of sand, silt, and clay in the soil Broad texture classes can be determined by the "ribbon" test
Compaction	Refers to the arrangement of soil particles and its impact on soil pore space Clayey, nonmontmorillionite soils are strongly compacted because of the lack of shrinking and swelling like montmorillionite clays, such as Sharkey clay
Soil structure	Refers to the arrangement of primary soil particles and are found in standard soil texts A stratified structure indicates that no soil profiles have developed, just layers of different soil texture exist Different texture layers, especially if several layers are clay, have good water holding capacity
Past use	The phrase "near virgin forest cover" should be ignored; intent was to represent a maturing or mature forest
Water table depth	Depth to a nonstagnant "true" water table during the growing season Determine by looking at water elevation in a nearby stream; water table will be 1 to several ft above the water in a stream Loessial hills are difficult because the water table is typically >10 ft, but these silt loam soils have good moisture holding capacity; score 7–10 ft
Topographic position	Floodplain or stream bottom refers to first bottoms Terraces refer to second bottoms Lower slopes refers to the transition area between uplands and bottomlands
Microsite	Concave means a general depression of the site that holds more moisture Convex means a general rise of the site
Flooding	Based on the long-term flooding pattern for the site Determined by past experience, discussion with local residents, or river gauge records
Geologic source	Refers to the origin of the soil Mississippi River, loess, and blackland soils are high in native fertility Coastal plain soils are relatively low in native fertility Headwaters of steam and small rivers would be consider coastal plain origin; as they progress they may become mixed (e.g., mixed with loess going through the loessial hill region in Mississippi)
Organic matter	Mature forests will usually have 1–2% organic matter Agriculture fields or recently abandoned agriculture fields will have <1% organic matter
Topsoil depth	Depth of surface soil or depth to the B-horizon Darker in color and coarser in texture than subsoil
Soil age	Based on degree of soil profile development; the more distinguishable the profile, the more mature the soil Young soils have no profile development (layering is not considered profile development) Medium or moderate profile development will show signs of profiles along a soil pit wall Older soils will have readily distinguishable profiles
pH	Minor rivers and streams tend to have acidic soils (4.0–6.5) Young soils on major rivers tend to have basic soils (7.0–8.5)
Swampiness	Visual indication of the amount of pore space for root gas exchange Wet in winter only allows for ample pore space during the growing season Wet from January to July limits pore space to one-half the growing season Waterlogged indicates little pore space throughout the growing season
Mottling	Spots or blotches of different color (e.g., gray, yellow or light brown) caused by poor internal drainage and poor aeration
Soil color	A black, brown, or red soil indicates well-aerated soil with good moisture availability Yellow or brownish-gray soil indicates water saturation part of the year Gray soil indicates extended period of water saturation with little oxygen available for tree roots

Table 6. Site evaluation guide for Nuttall oak[a] (from Baker and Broadfoot 1979).

Soil-site property	Soil-site condition and relative quality		
	Best	Medium	Poor
Factor 1. Physical condition			
Soil depth and presence of artificial or inherent pan	Deep soil (>4 ft); without pan [8][b]	Medium depth (2–4 ft), or a soil with a plowpan [5]	Shallow soil (<2 ft), or a soil with an inherent pan [−3]
Texture (in rooting zone)	Medium-textured; silty or loamy [2]	Coarse-textured; sandy [1]	Fine-textured; clayey [−1]
Compaction (in surface foot)	No compaction; loose, porous, friable, bulk density <1.4 g/cc [6]	Moderately compacted; firm, moderately tight, bulk density 1.4–1.7 g/cc [3]	Strongly compacted; tight, bulk density >1.7 g/cc [0]
Structure (in rooting zone)	Granular; structureless, single-grained if sandy, massive if loamy or silty [3]	Prismatic; blocky [2]	Massive (if clayey);platy [0]
Past use and present cover	Undisturbed; near-virgin forest cover [5]	Moderate cultivation; cultivated <20 years, or open with grass cover [3]	Intensive cultivation; cultivated >20 years, or open and bare [1]
Factor 2. Moisture availability during growing season			
Water table depth	2–6 ft [9]	1–2 ft; 7–10 ft [6]	<1 ft [unsuitable] >10 ft [0][c]
Artificial or inherent pans	No pans [9]	Plowpan [4]	Inherent pan [−2]
Topographic position	Floodplain or stream bottom [8]	Stream terraces or lower slopes [5]	Upland [0]
Microsite	Concave; depression, pocket, trough [4]	Level; flat [2]	Convex; ridge, mound [0]
Structure (in rooting zone)	Granular; structureless, massive (if silty, loamy, or clayey); stratified [2]	Prismatic; blocky [1]	Structureless, single-grained (if sandy); platy [0]
Texture (in rooting zone)	Silty or loamy (or stratified) [2]	Clayey [1]	Sandy [0]
Flooding	Winter through spring [6]	Winter only [3]	None [0]; continuous [unsuitable]
Past use and present cover	Undisturbed; near-virgin forest cover [2]	Moderate cultivation; cultivated <10 years or open with grass cover [1]	Intensive cultivation; cultivated >10 years of open and bare [0]
Factor 3. Nutrient availability			
Geologic source	Mississippi River, loess, blackland [3]	Mixed coastal plain and other [1]	Coastal plain [−1]
Past use and present cover	Undisturbed; near-virgin, forest cover, cultivated <5 years [6]	Moderate cultivation; cultivated 5–10 years, or open with grass [3][d]	Intensive cultivation; cultivated >10 years, or open and bare [0][d]
Organic matter (A-horizon)	>2% [6]	1–2% [3]	<1% [0]
Depth of topsoil (A-horizon)	>6 in. or no profile development [6]	3–6 in. [3]	<3 in. [−3]
Soil age	Young, no profile development (Entisols) [3]	Medium, moderate profile development (Inceptisols) [1]	Old, well-developed profile, leached (Alfisols, Ultisols) [−1]
pH (in rooting zone)	4.5–5.5 [6]	5.6–7.5 or 4.0–4.4 [4]	<4.0 [−2]; >7.5 [unsuitable]
Factor 4. Aeration			
Soil structure (in rooting zone)	Granular, porous; structureless, single-grained if sandy, massive if loamy or silty [7]	Prismatic; blocky [5]	Massive (if clayey); platy [0]
Swampiness	Wet in winter only [7]	Wet January to July [5]	Waterlogged all year [unsuitable]
Mottling	None to 18-in. depth [5]	None to 8-in. depth [3]	Mottled to surface or gray mineral soil [1]
Soil color (in rooting zone)	Black, brown, red [5]	Yellow, brownish-gray [2]	Gray [0]

[a] 120 ft at 50 year maximum site index; 75 ft minimum acceptable site index.
[b] Each bracketed number indicates the site quality rating (feet of site index) of a particular soil-site condition.
[c] If the soil is a sand or loamy sand, then [−10].
[d] If cultural practices included annual fertilization, then [4].

Table 7. Example field sheet for the Baker/Broadfoot System with Nuttall oak example.

Site Quality Evaluation
Baker/Broadfoot System

Site Name: Dermott, Drew County
Pit Number: 1
Species: Nuttall oak

Date: March 2005
Weather: clear and cool
Evaluator(s): Brian Roy Lockhart

Physical Condition		Moisture Availability		Nutrient Availability		Aeration	
Soil depth	8	Water table	6	Geologic source	2	Structure	5
Texture	−1	Pans	6	Past use	4	Swampiness	6
Compaction	3	Position	8	Organic matter	0	Mottling	2
Structure	2	Microsite	2	Topsoil	6	Color	3
Past use	1	Structure	1	Soil age	3		
		Texture	1	pH	6		
		Flooding	6				
		Past use	0				
Total	13	Total	30	Total	21	Total	16

Site index = 80.
Notes: Percentages: maximum site index = 72% (86/120); physical condition = 54% (13/24); moisture availability = 71% (30/42); nutrient availability = 70% (21/30); Aeration = 67% (16/24).

seedlings as part of restoration effort under the Wetlands Reserve Program. The soil was classed as a Perry clay (very-fine, smectitic, thermic Chromic Epiaquerts) that formed in thick beds of clayey slack-water deposits by the Arkansas River (Soil Conservation Service 1976). A soil pit was excavated on a level area about 50 yards to the north of the highway. Using the Nuttall oak site evaluation table from Baker and Broadfoot (1979; Table 6), the following determinations were made for each soil and site factor (Table 7 lists this evaluation in a field sheet).

Physical Condition

The soil was considered deep because it was located in the LMAV and because it was near Cutoff Creek. The texture was clay based on the shape of a rubbed sample. The soil was moderately compacted because of the high clay content. The structure was blocky. Past use was agricultural row-crop production because the site was recently planted with tree seedlings. Discussion with a local resident indicated that it had been cleared of forests in the 1970s.

Moisture Availability

The water table depth, based on the depth of a nearby drainage ditch, was considered to be between 7 and 10 ft, though this is subjective with clay soils. No distinct plowpan could be detected, and digging with a shovel indicated that the soil was somewhat more compact beginning at about 18 in. (assigned 6 points instead of 9 points for no pans—the ability to interpolate between conditions is another advantage of the Baker/Broadfoot system). The site was located on an active floodplain and was level (probably because of land-leveling practices). The soil structure was blocky and texture was clay. Flooding appears to occur in the winter through early spring (personal observations). Past use was intensive cultivation for more than 10 years.

Nutrient Availability

The geological source of the sediments was considered mixed coastal plain, although 2 points were given instead of 1 because of the potential for some Mississippi River deposition and the location near the Bartholomew Escarpment, which contains a loess cap on its soils. Past use was intensive cultivation, although the area was believed to have been annually fertilized. Topsoil depth was less than 6 in., whereas organic matter content was judged less than 1%. No profile development was observed. pH, measured using a standard field kit, was 5.0 to 5.5.

Aeration

The soil structure was blocky. The site was considered wet January through May but not to July (assigned 6 points). A few reddish-gray mottles were detected at 5 in. depth, and soil color was reddish brown.

Summary

A summary of the total site quality values for each major soil factor indicate site index for Nuttall oak in this former agricultural field is 80, which is considered marginal for timber production objectives but acceptable for wildlife habitat objectives. No site index was listed in the Drew County soil survey for Nuttall oak on Perry clay, although water oak had a site index value of 80. Web Soil Survey listed cherrybark oak with a site index of 80, green ash at 72, and sweetgum at 92. The physical condition of the soil, in particular texture, compaction, structure, and past use, was the most limiting of the soil and site properties for Nuttall oak.

Additional Notes

Blackmon (1979) indicated that site index values from Broadfoot (1976) were tested against site quality values predicted from the Baker and Broadfoot (1977) version of the system, with correlation coefficients ranging from 0.93 for sweetgum to 0.99 for eastern cottonwood. He further mentioned that the Baker/Broadfoot system should provide estimates of site index within 5 ft of measured values 99% of the time if all soil and site properties are accurately measured (Blackmon 1979). Furthermore, accuracy of the Baker/Broadfoot system has been tested against published site index curves for cherrybark oak, with few differences found between the methods (Aust and Hodges 1988, Belli et al. 1998). The other species in the Baker/Broadfoot system have yet to be rigorously tested against published site index curves.

The species tables in Baker and Broadfoot (1979) allow for only one species to be evaluated at a time. SITEQUAL was developed so that all the species could be evaluated simultaneously using a designated form (Harrington and Casson 1986). Advantages of SITEQUAL include (1) completeness, (2) speed, and (3) use for sensitivity analyses to evaluate the relative sensitivity of specific hardwood species to past land use practices (e.g., row-cropping systems) or proposed future practices (e.g., construction of a drainage system). A disadvantage of SITEQUAL is the inability to interpolate between successive conditions within individual soil or site properties, thereby reducing model robustness. Furthermore, because all 14 species are evaluated simultaneously, a species will be evaluated whether or not it naturally occurs on the site in question. SITEQUAL compensates by footnoting a species if its rating falls below a minimum acceptable value or when a specific soil or site property makes the site unsuitable. Finally, SITEQUAL is a DOS-based program developed before Microsoft Windows. Therefore, managers will need to go to the DOS prompt and then initiate SITEQUAL.

Expert systems provide an avenue between researchers and forest managers. They are relatively simple to use and can provide accurate results. The Baker/Broadfoot system can be used for determining site index in bottomland hardwood forests. Additional research is needed with species besides cherrybark oak to verify the Baker/Broadfoot system against published site index curves. Future research should include other species, such as American elm (*Ulmus americana* L.) and black willow (*Salix nigra* Marsh.), to provide a more complete listing of species available for site index evaluation in bottomland hardwoods. Efforts are under way to fit the Baker/Broadfoot system with Web Soil Survey (Terry Clason, NRCS, pers. comm., Mar. 27, 2009).

Conclusions

Many techniques are available to determine site index for bottomland hardwood sites, including species trials, site index curves, soil-site equations, soil series, and expert systems. Each technique has its advantages and disadvantages, but much work remains. Site index curves need to be developed for many bottomland hardwood species. Most current bottomland hardwood site index curves are anamorphic and need to be compared with polymorphic curves. New site index curves and a thorough review of the literature are needed to update the NRCS National Register of Site Index Curves. Finally, 13 of the 14 species used in the Baker/Broadfoot system need to be verified against published site index curves (if they exist).

This verification will provide greater confidence in using the system when index trees are not present. The research community must awaken to these needs and provide timely information. Greater knowledge of site index through proven evaluation techniques will allow managers to make more informed decisions to manage bottomland hardwood forests to meet specific landowner objectives.

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