OAK GROWTH AND RESPONSE TO THINNING

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Abstract—Oak growth and yield is simultaneously influenced by tree-, stand-, and landscape-scale factors. At the tree scale oak diameter growth varies by tree species (typically n. red oak >= scarlet oak > black oak > white oak > chestnut oak > chinkapin oak > post oak), but oak diameter growth is even more strongly influenced by crown class. Oak stands go through up to 5 stages of development that differ in tree size structure and stand dynamics. Knowing a stand's developmental stage helps guide the application of thinning practices and other silvicultural techniques. Periodic thinning beginning at age 30 in oak stands can double board foot yield over a rotation relative to unmanaged oak stands. This results from capturing volume that would otherwise be lost through mortality and from reallocating growing space to desirable trees. The greatest increases in yield occur when a series of periodic thinnings is started when the stand enters the stem exclusion stage of development. Stump sprouts require even earlier treatment to maximize growth. Estimating future growth and yield in even-aged stands is often facilitated by application of mathematical models; models are a necessity for growth estimation in uneven-aged stands and stands with a large non-oak component.

INTRODUCTION

Traditionally, interest in forest growth and yield has been associated with timber production. However, growth and yield is simply one aspect of the broader subject of stand dynamics that deals with changes in stand size structure and species composition over time. These changes can be related to timber yield, but they can also be related to yield in wildlife habitat, quantity of mast production, aesthetic qualities, or even ecological services such as storing carbon or maintaining species diversity. Like timber yield, yield of these other products and amenities changes over time and in response to management activities. Yield tables or growth models can aid in estimating future quantities of all these outputs.

Growth and yield can be evaluated and analyzed at different spatial resolutions. Stand growth and yield (per acre) is often of primary interest, but stand growth is the composite outcome of growth and survival of thousands of individual trees. Hence, growth of individual trees as affected by species, size, and competition is also often of interest, particularly for stands with mixed species and multiple age classes. Likewise, the composite growth and yield of multiple stands in a geographic region, their spatial arrangement, and their anticipated change over time can be important in forest planning, locating a new wood using facility, or dealing with insect or disease problems.

Major factors that affect growth and yield of oak trees and oak stands are presented in this paper. Particular emphasis is given to response to thinning, changes in stand structure, and changes in species composition over time.

OAK TREE GROWTH

There are clear differences among species in diameter growth rates (fig. 1). For example, mean growth rates for scarlet oak in Missouri are approximately twice those for post oaks of comparable diameter. Over several decades these differences can result in substantial differences in tree diameter (and often a tree's height and crown position). However, tree longevity also plays a role, and over many decades the faster growing black and scarlet oaks are less likely to survive than white or post oaks, other factors being equal (Shifley and Smith 1982, Smith and Shifley 1984). Hence, in the long run, persistent oaks such as white oaks can often capture dominance from faster-growing, shorter-lived trees in the red oak group. We probably underestimate the influence of periodic droughts and other infrequent but severe external stressors in affecting longevity and species composition over the life of a stand. Such events may only occur once or twice during a rotation, but they can radically change stand species composition (e.g., the disproportionate loss of red and black oaks during drought-induced oak decline).

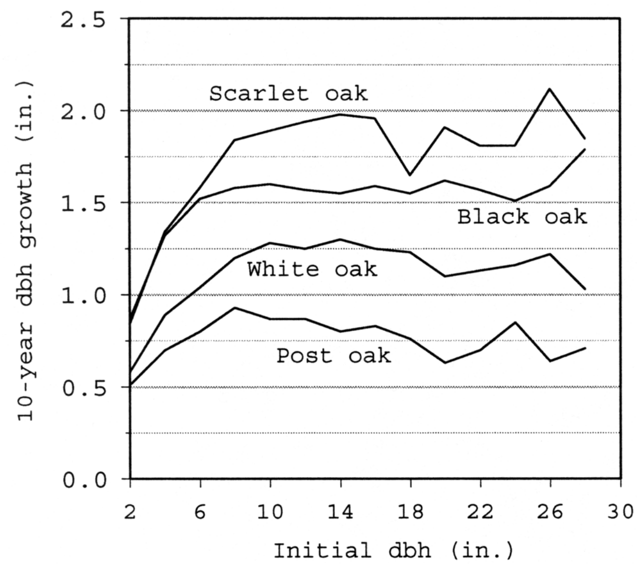

Figure 1—Mean periodic tree diameter-at-breast-height growth for black (*Quercus velutina* Lam.), scarlet (*Q. coccinea* Muenchh.), white (*Q. alba* L.), and post oaks (*Q. stellata* Wangenh.) in Missouri (based on Shifley and Smith 1982).

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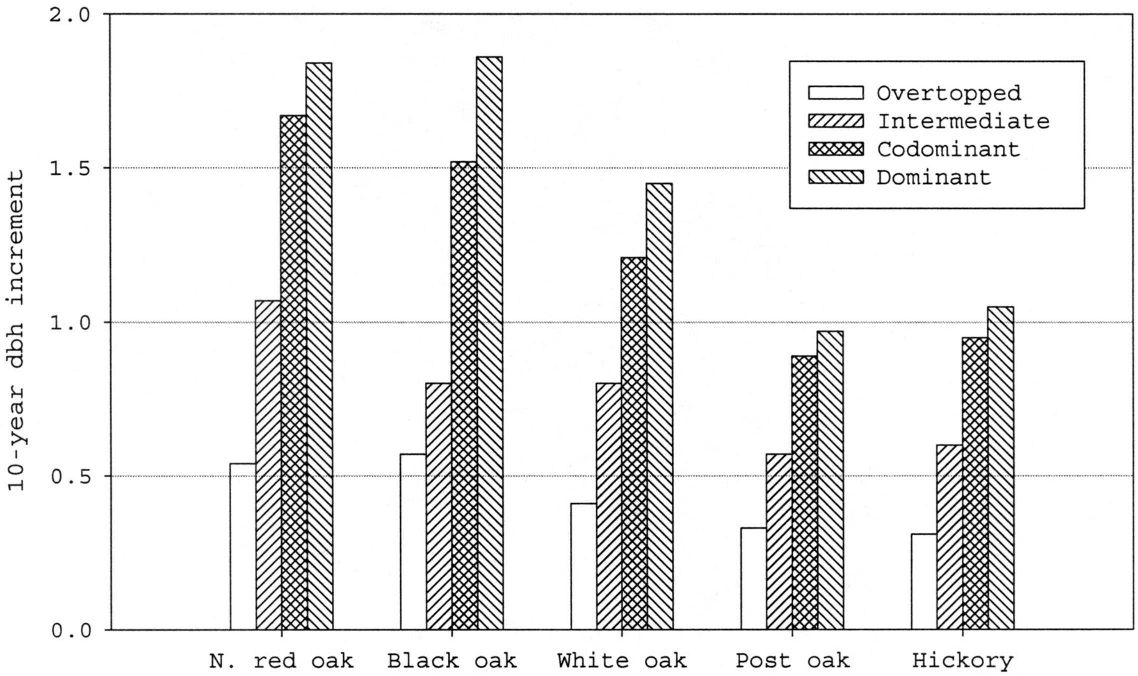

Figure 2—Effect of tree crown class on diameter growth for oaks and hickories in Missouri. The hickory group is a composite of all *Carya* spp. (based on Shifley and Smith 1982).

Crown position is even more influential than species in controlling diameter growth. A tree's crown class (dominant, codominant, intermediate or overtopped) can completely overshadow differences among species (fig. 2). Trimble (1969) stated that crown class is the single most important factor in tree diameter growth, and it is clear that a dominant or codominant oak of nearly any species will, on average, grow faster in diameter than an overtopped or intermediate oak of any other species.

Tree crown class is the result of the competitive sorting that takes place as trees increase in size and vie for a finite amount of growing space. The average annual diameter at breast height (d.b.h.) growth for a stand decreases as stand age and basal area increase, but those dominant and codominant trees that are well positioned in the canopy continue to grow rapidly at the expense of trees that have smaller or crowded crowns. Trees rarely improve their crown class over time unless a timber harvest or other significant stand disturbance occurs to release growing space. Thus, if a tree achieves a dominant or codominant crown class, it must maintain that canopy position or it will eventually lose out to competitors. Thinning manipulates crown classes and growing space to favor trees that satisfy management objectives.

Compared to diameter growth, the height growth of dominant and codominant trees is less affected by stand density. Hence, height growth of trees that have continuously remained in these two crown classes is used to measure site quality via site index. Previous studies have shown that on the same site the site index (i.e., height in feet at age 50) for scarlet oak is 3 feet greater than for black oak which is in turn 4 feet greater than for white oak (McQuilken 1974).

However, oaks have different height growth patterns. Scarlet and black oak get off to a rapid start but slow after 50 or 60 years. When the trees reach 100 years, white oaks in the upper canopy will often be 10 to 15 feet taller than black oaks (Carmean 1971). Tree height growth and site index are, of course, closely linked to volume growth of trees and stands.

In contrast to trees in the upper canopy, height growth of trees in subordinate crown classes is greatly affected by competitors, and oaks that fail to maintain a favorable crown position usually face an early demise, barring some disturbance to the overstory that increases available growing space. One of the few oak height models based on tree diameter and age (regardless of crown class) was published by Hilt and Dale (1982) as part of the OAKSIM model.

Over long periods of time, oaks that are persistent (e.g., through sprouting or through greater shade tolerance than competitors) are sometimes able to survive, despite the presence of faster growing competitors. For example, white oak (which is slower growing but longer lived and slightly more shade and drought tolerant than black, red, and scarlet oak) may eventually achieve dominance opportunistically. This may be the result of a designed timber harvest, or it may occur by chance when shorter lived species reach the end of their life span or when the droughts or other disturbances (that inevitably occur over the course of a long rotation) take their toll on other species. As the number of sites monitored continuously over many decades gradually increases, the importance of extreme events (e.g., drought, ice, fire, partial harvest) in triggering changes in species composition is increasingly apparent.

TREE RESPONSE TO THINNING

Controlling tree crown class through thinning is the single most important thing a manager can do to increase tree growth and stand yield over time. Studies in oak stands have demonstrated that dominant and codominant oaks will respond to increased thinning intensity with increased diameter growth across a wide range of diameters and ages, even if stand stocking is reduced to 30 percent or less (Dale 1972). Note, however, that oak management guides for timber production generally recommend keeping minimum stocking above 50 percent to avoid development of epicormic branching and to fully utilize the growing space per acre. At lower stocking levels, diameter growth of individual trees is increased, but stand growth is typically not maximized. Significant thinning effects have been reported for red, black and scarlet oaks up to 90 years old in Connecticut (Ward, 2002).

It often takes two years for tree diameter growth to achieve maximum response to thinning, and the effects of thinning on individual overstory trees may persist for as long as two decades. When trees are given a competitive advantage through thinning, they are often able to maintain that advantage by increasing their crown area and capturing growing space which allows them to maintain the faster growth rate for years. There are two general exceptions to this response to thinning. First, trees with small, poorly formed crowns (e.g., intermediate and overtopped crown classes) may not respond at all to thinning, or the response may be delayed by three to five years as tree crowns gradually enlarge to capture the growing space release by thinning. Second, oaks in stands less than 10-years old may not increase their diameter growth in response to thinning. In young stands crown classes are not firmly established, and the growing space released by the removal of a young tree is small relative to the ability of surrounding trees to expand and capture growing space. The rapid growth of vegetation relative to tree size in young stands means the effect of thinning is generally short-lived. Thus, the potential benefits of thinning in seedling/sapling stands can be quickly erased by crown expansion in residual trees and a flush of herbaceous growth. Consequently, diameter growth of dominant and codominant trees less than 10 years old has shown a variable response to thinning. When stands are very young, the intermediate and overtopped trees are actually more likely to respond to thinning with increased diameter growth than are larger trees. Herbicides applied to cut trees may increase the duration of the thinning effect in young stands (Johnson and others 2002).

Oaks often originate as stump sprouts, and sprouts present a different situation with respect to thinning young trees. Thinning has been demonstrated to be effective in increasing diameter growth on sprouts that were as old as 25 years, but the sooner sprout clumps are thinned to a single stem (down to 5 years of age), the greater the gain in diameter growth relative to unthinned clumps (Johnson and others 2002). Early thinning of stump sprouts to a single stem can double diameter growth relative to sprouts in unthinned clumps; diameter increases of 30 to 60 percent are common, depending on site index and initial tree size (Johnson and Rogers 1980). Although retaining the single largest sprout typically results in the largest future tree, smaller sprouts released at an early age can perform nearly as well. Consequently, retaining sprouts based on form rather than tree size will result in relatively little loss in future size (Johnson and others 2002).

STAND GROWTH AND RESPONSE TO THINNING

As even-aged oak stands develop over time they go through five stages of stand development: (1) stand initiation, (2) stem exclusion, (3) understory reinitiation, (4) complex, and (5) mixed stage (fig. 3) (Johnson and others 2002, Oliver and Larson 1996). These stages are defined by the population dynamics governing the tree community at each stage of development. For upland oaks in the Central Hardwood Region, the stages of development are associated with a characteristic range of stand ages. The stand dynamics at each stage govern the efficacy of thinning and the stand response to thinning. Thus, knowledge of a stand's stage of development is useful in understanding when, why, and how to thin.

Following a stand initiating disturbance (e.g., clearcut or stand-replacing fire) even-aged oak stands enter the stand initiation stage of development (fig. 3). New trees are added to the stand, tree crowns expand rapidly relative to their initial size, and trees compete intensely for growing space. Woody vegetation is often dense and "brushy". At this stage the growing space that is released by the death or removal of individual trees is rapidly occupied by the expanding crowns of surrounding trees. Consequently, thinning effects are short lived and highly variable. However, thinning stump sprouts is an exception. Because clumps of stump sprouts share the same growing space and the same root system, competition among them is much more intense than for seedlings or seedling sprouts with a single stem. Young sprout clumps respond with rapid growth when they are thinned to a single stem. In essence, clumps of stump sprouts begin life in the stem exclusion stage of development and stump sprout response to thinning is similar to that described below for stands in the stem exclusion stage of development.

As oak stands mature and move into the stem exclusion stage of development, the site is fully occupied and the number of trees in the stand naturally decreases as trees increase in size (fig. 4). Trees that are at a competitive disadvantage are eliminated from the stand. In the absence of a major disturbance, the number of trees per acre will decrease exponentially over time. This change can be expressed graphically as a function of age or in the format of a Gingrich-style stocking chart.

It is during the stem exclusion stage of development that managers can have the greatest impact on stand growth and yield. Thinning conducted during this stage of development can recover trees that will otherwise die and simultaneously reallocate growing space to the most desirable residual trees based on species, size, or form. Increased volume yield from thinning is the combined result of (1) utilizing trees that would otherwise die and (2) increasing the growth of selected residual trees (fig. 5). In his yield tables for thinned oak stands, Gingrich (1971a, 1971b) indicated that by thinning a stand early and often it is possible to double board foot volume yield relative to unthinned stands. The key is to

Stage of development		Typical thinning and regeneration practices to increase timber yield
1. Stand initiation stage. Typically age 0-20 years Seedlings or saplings	Results from a stand initiating disturbance--typically timber harvest, wind or fire. Brushy mass of woody vegetation often with abundant herbaceous growth. Basal area and trees per acre are increasing.	**Thin stump sprouts to maximize growth response. Other thinning or crop tree selection is often ineffective at this stage. Prescribed fire may favor oaks.**
2. Stem exclusion stage. Typically age 10 to 70 years Saplings to young sawtimber	Stand ceases to accumulate trees as the growing space is fully occupied. Stand develops overstory understory and subcanopy layers. The number of trees decreases exponentially as trees become larger in size. Subcanopy is densely shaded and subcanopy vegetation is sparse. Shade tolerant trees may persist in subordinate canopy layers.	**Begin periodic thinning for maximum growth response. Select crop trees. This is the earliest stage where stocking charts are relevant for prescriptions.**
3. Understory reinitiation stage. Typically age 50-100+ years; Mature sawtimber	Increasing overstory tree size leads to larger canopy gaps when overstory trees die or are cut. Those gaps in combination with a rising canopy level and greater spacing among trees allows more light to reach the forest floor than during the stem exclusion stage. New trees become established. Regeneration often favors shade tolerant trees. In some ecosystems oak reproduction may persist and accumulate in the understory by periodically dying back and resprouting.	**Continue thinning. Underplant or burn as needed to control species establishment. Consider regeneration for stands under even-aged regimes.**
4. Complex stage. Typically age > 100 years. Mature sawtimber or old growth. Regeneration in canopy gaps leads to uneven-aged stand.	Large canopy gaps are created by the loss of individual overstory trees. Gaps are too large to be completely filled through crown expansion of surrounding trees. New age cohorts (seedlings or advance reproduction) are established in the gaps and some new trees eventually reach the overstory. Shade tolerant reproduction is favored in mesic ecosystems. Oak reproduction may succeed in more xeric ecosystems. Includes mature forests that are lightly thinned and mature, managed uneven-aged stands. Includes old-growth as a special case.	**Regenerate or continue intermediate thinning for uneven-aged or long-rotation even-aged stands. Prescribed burning may increase species diversity or favor oak reproduction.**
5. Mixed stage. Typically age > 15 years (i.e., oldest cohorts are beyond stand initiation stage).	Results when a stand in the stem exclusion, understory reinitiation or complex stage is heavily disturbed, but not to the extent that an entirely new stand is regenerated. May be the consequence of wind, fire, insects, disease or harvest. Irregular age and tree size-class distribution. Over time the stand will move toward the complex stage of development.	**Salvage, timber stand improvement, sanitation cut, release, regeneration harvest.**

Figure 3—Stages of oak stand development with notes on thinning for increased timber production and on other management practices (based on Johnson and others 2002, illustrations by David Hamilton).

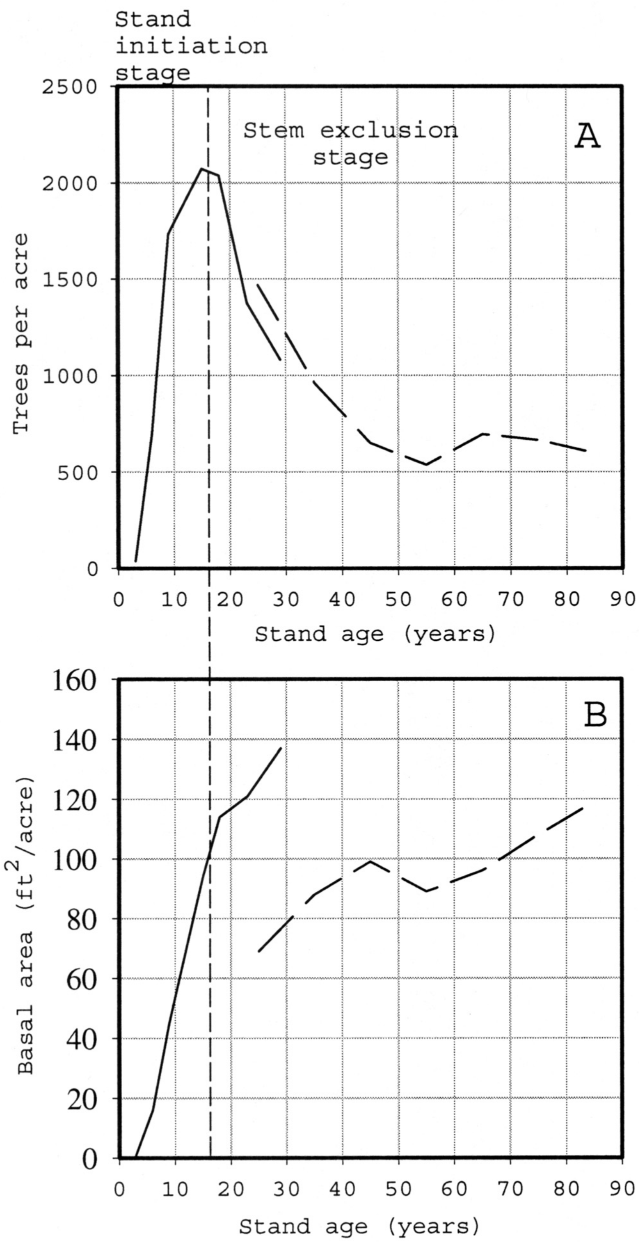

Figure 4—(A) The shift from the stand initiation stage to the stem exclusion stage of development is signaled by the change from increasing to decreasing trees per acre over time. This occurred at about age 17 in this example. (B) Basal area continues to increase. The solid line shows data for a bottomland sweetgum-red oak stand (Johnson and Krinard 1988) and the dashed line shows data for an upland oak-mixed hardwood stand in Connecticut (Ward and others 1999).

start thinning early in the stem-exclusion stage of development—approximately age 30 for eastern oak stands. The biggest net increases in total volume occur by thinning oak stands on excellent sites, but even on moderate and poor sites total yield can be doubled relative to unthinned stands.

During the understory reinitiation stage the stand is nearing economic maturity and silvicultural practices in oak stands generally concentrate on establishing desirable advance reproduction and maintaining tree quality. Thinning during

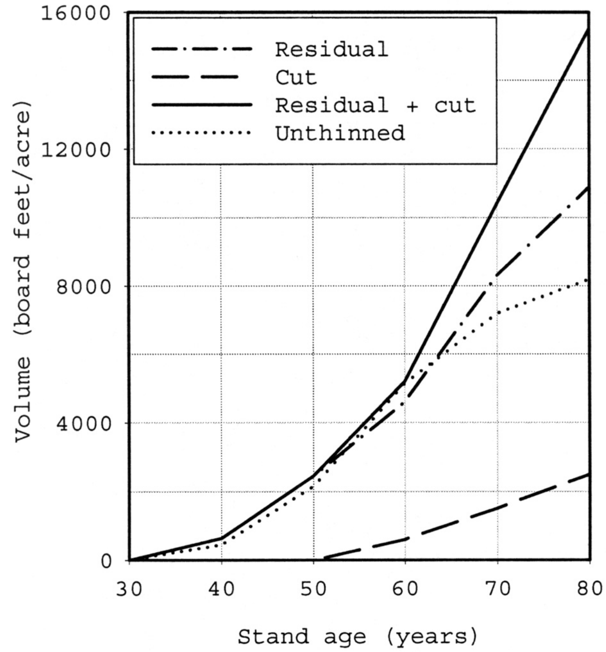

Figure 5—Yield of thinned and unthinned stands over time. With regular thinning, the combined yield of cut and residual trees can double the yield of an unmanaged stand (based on Gingrich 1971a).

this stage of development will result in faster growth of vigorous residual trees on good sites. Due to the relatively large tree crowns, removal of trees by thinning will also provide more light to the forest floor and canopy gaps will persist longer than at earlier stages of development. Economically the major concerns associated with thinning at this stage revolve around (1) minimizing epicormic branching, (2) minimizing mechanical damage of residual trees, (3) controlling future species composition, and (4) ensuring that thinning prior to overstory removal provides sufficient time (about a decade) to capture the response of residual trees. For oak stands that are to be managed on long rotations or to be converted to uneven-aged silviculture, commercial thinning through the stem exclusion stage of development will typically result in faster growth and greater total yield.

When a stand reaches the complex stage of development (fig. 3), it has become an uneven-aged stand because canopy gaps are sufficiently large to recruit new age cohorts. Thinning to promote overstory crop trees or thinning to promote the development of a balanced uneven-aged stand structure is warranted if the goal is uneven-aged management.

It is difficult to generalize about growth and yield for oak stands with mixed species and multiple age classes. Although the same basic principles apply with regard to how trees respond to stand density and crown class, the differential growth and survival rates among tree species and size classes can greatly affect the oak component of the stand. Estimating growth and yield for such stands requires the use of mathematical models. Mathematical models also facilitate exploring the outcome of alternative thinning practices on stand development. For example,

Table 1—Oak growth and yield models (excludes regeneration models)

Model type and name	Applicability	Notes
	Yield Tables	
Upland oaks (Schnur 1937)	Well-stocked, even-aged, unmanaged upland oak stands; geographic range is bounded by New York, southern Michigan, Missouri, Tennessee, and western North Carolina	Comprehensive yield, composition, and size structure information by site index and age; the primary reference for upland oak yield in fully stocked, unmanaged, minimally disturbed stands; good baseline source of comparison for managed stands
Oak woodlots (Gevorkiantz and Scholz 1948)	Even-aged, mixed oak stands in western and south-central Wisconsin	Comprehensive volume yield by age and site quality; good baseline for comparison of managed stands
Managed upland central hardwoods (Gingrich 1971a, 1971b)	Central hardwood region, even-aged upland stands that are managed or where management is contemplated	Good guidance on the broad-scale effects of thinning on stand yield by age, and site index; thinning prescriptions are linked to Gingrich (1967) stocking guide and management guides by Roach and Gingrich (1962, 1968)
	Stand-Level Models	
GROAK (Dale 1972, 1973)	Based on data from Ohio, Kentucky, Missouri, and Iowa; applicable to even-aged, upland mixed oaks stands	Predicts oak growth and yield as function of stand age, stand basal area, and site index; evaluates the effects of thinning on oak growth and yield; more versatile than yield tables for thinned oaks; models can be applied using spreadsheet software; also incorporated into the Northeast Decision Model (NED) (http://www.fs.fed.us/ne/burlington/ned/)
Upland oaks (Graney and Murphy 1994)	Boston Mountains region in northwest Arkansas	A recalibration and detailed evaluation of methodology used on GROAK as applied to the Boston Mountain region
Minnesota yield models (Walters and Ek 1993)	Oak-hickory forests in Minnesota	Predicts growth and yield as a function of stand age and stand basal area; based on statewide Forest Inventory and Analysis inventory data including stands with a wide variety of past disturbances; good indicator of regional "woods run" yields; part of a system of models for 14 Minnesota forest types
Appalachian hardwood mutltispecies model (Bowling and others 1989)	Appalachian hardwoods in the Blue Ridge ecoregion of North Carolina and Georgia	Predicts density, height, and volume for red oak, white oak, and other species groups, including d.b.h. frequency distribution by species
	Individual-Tree Models	
OAKSIM (Hilt 1985a, 1985b)	Even-aged upland oak stands aged 3 to 120 years in southern Ohio and eastern Kentucky	Estimates growth and survival of individual trees with overall stand growth constrained to be consistent with Dale's (1972) GROAK model; one of the few sources of oak height growth and taper equations (Hilt and Dale 1982); can be implemented using the NED http://www.fs.fed.us/ne/burlington/ned/
TWIGS Miner and others (1988), Bolton and Meldahl (1990a, 1990b), and Hilt and Teck (1989)	Even- and uneven-aged stands with pure or mixed species; four regional variants cover from Minnesota to Missouri to West Virginia to Maine, and Alabama, Georgia, and South Carolina	Software allows simulated thinning, volume estimation, and economic analysis; tree growth and survival models have been incorporated into FVS (see below) http://www.ncrs.fs.fed.us/pubs/Software
FVS (Forest Vegetation Simulator) http://www.fs.fed.us/fmsc/fvs/.	Regional variants (21) are applicable to major forested regions of the United States; variants applicable with oaks include Lake States, Central States, Northeast, Southeast, South, Central Rockies, Klamath Mountains, Pacific Northwest Coast, Westside Cascades, and Westside Sierra Nevada	Good software support and excellent integration with data management, scenario evaluation, output, and display tools; nationally implemented and supported; can be user-calibrated with local inventory data; applicable to all major species groups within a region; includes models for some western oak species groups; models governing species dynamics are from a variety of sources including PROGNOSIS (Stage 1973), TWIGS (see above), and those developed specifically for FVS
GHAT Harrison and others (1986, updated 2000)	Even-aged Appalachian mixed hardwoods in Blue Ridge physiographic province of Virginia, North Carolina, Tennessee, and Georgia	Height growth, diameter growth, volume growth, and survival following thinning; designed specifically to address response to thinning in mixed species stands; includes equations for white, black, northern red, scarlet, and chestnut oaks http://www.cnr.vt.edu/g&y_coop/ghat.pdf

thinning or other cultural treatments that target particular tree species such as the oaks (favorably or adversely) can greatly alter future growth, yield, species composition and value. It often takes decades for the oak cohorts in a mixed species stand to succeed or fail, and models are the only practical tools available to address growth and yield for the infinite range of mixed stands that occur. Growth and yield models applicable to oaks and oak mixtures are summarized in table 1. Models accommodate a wide range of initial stand conditions, can evaluate alternative management regimes, produce repeatable results, and are increasingly used as a component of larger simulation and management systems. Examples include the Northeast Decision Model (NED) (http://www.fs.fed.us/ne/burlington/ned/), and national forest planning efforts based on the Forest Vegetation Simulator (FVS) (http://www.fs.fed.us/fmsc/fvs/).

ECONOMIC CONSIDERATIONS

Simulation models also facilitate economic analysis of thinning alternatives. Some models have integrated economic analysis capabilities. Predicted outcomes can also be analyzed in stand-alone economic analysis software which is widely available. Professional judgment and field experience are still required to evaluate potential effects of thinning on tree quality. In economic terms potential changes in tree grade can supercede the effects of total volume growth, and the available models have little or no capacity to predict changes in tree grade. Reported economic returns from thinning vary greatly depending upon the condition of the stand prior to thinning, growth response, and alternative rates of return (Johnson and others 2002). However, given the uniformly low alternative rates of return currently available, investment in hardwood thinning is as attractive an investment as at any time in the past several decades.

SUMMARY

Thinning has the potential to as much as double total yield over a rotation by capturing volume that would otherwise be lost to mortality. However, to maximize the effect, thinning should begin early in the stem exclusion stage of stand development and be repeated until one or two decades prior to a regeneration harvest. In addition to increasing total merchantable yield, thinning can increase tree quality and value. Tree conditions (species, crown class), stand conditions (stage of development, density, species mixture), and even landscape conditions (e.g., potential risk of disturbance by pathogens or fire) are all important considerations in thinning decisions. Perhaps most important is an understanding of the stand's stage of development. The stage of development (stand initiation, stem exclusion, understory reinitiation, complex, or mixed) provides important information on the stand's natural dynamic. Thinning is usually most effective when the silviculturist or resource manager works with, rather than against, the stand's natural dynamic (e.g., thinning to increase volume growth when the stand is in the stem exclusion stage, thinning to facilitate advance regeneration when the stand is in the understory reinitiation stage, etc.) Most effective thinning practices are designed to work in concert with the stands natural dynamic and to accelerate change to meet ecological or economic objectives. A wide range of simulation models are available to explore alternatives for specific stand conditions.

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