DEVELOPING A STAND DENSITY MODULE IN LANDIS TO IMPROVE SIMULATION REALISM OF STAND DYNAMICS

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ABSTRACT

Long-term landscape modeling is dependent on various forest dynamics including large-scale disturbances, environmental effects, land management and stand-scale succession. The stand density module was designed for LANDIS to link stand-level processes with large-scale landscape phenomena. The stand density module design is built based on the simple models of ecosystem processes which are suitable for large-scale landscape modeling. The stand density module is invented as a module that requires minimal parameterization and can be calibrated with empirical stand data. The stand density module predicted the basal area very accurately based on comparisons with the field data in spite of the simple model framework. The stand density module can interact with other modules in LANDIS reciprocally, thus the combined results allowed us to analyze the effects of various management regimes, inter- and intra-specific competition and interactions between disturbances on stand-level ecological processes. Finally, the stand density module in LANDIS provides feedbacks between stand dynamics and large-scale ecological processes.

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1. Introduction

Forest landscape models have emerged as crucial tools for understanding large-scale and long-term landscape processes such as seed dispersal, windthrow, climate change, forest harvest and fuel treatment (Willson et al., 1993; Tews et al., 2004; Wallace et al., 2008). Modeling techniques make it possible to describe the modeled objects mathematically and logically and deduce simulation results that cannot otherwise be investigated, especially at broad spatial and long temporal scales (Turner et al., 1995; Gardner et al., 1999; Mlandenoff and Baker 1999; Chumachenko et al., 2003; He et al., 2004). Landscape modeling is a viable way to analyze the large-scale ecological processes because experiments and observational studies are limited in spatial extent, temporal scope, or the number and levels of variables that can be assessed (Caswell, 1988; Baker, 1989). Therefore, landscape modeling is utilized to predict ecosystem change across large areas and over long time periods for providing a framework for synthesizing information.

Ecological theory and concepts provide foundations for forest landscape modeling which involves estimating forest ecosystem dynamics with the interactions of a variety of factors and processes, such as succession (Odum 1969; Pickett et al. 1987), disturbance (Pickett and White 1985; Pickett et al. 1989; Clark, 2001; Turner et al. 1997) and management. Many of the concepts developed over the past century in ecology include concepts of succession stages, the effects of disturbance in natural systems, and long-term influences of human managements on ecosystems. These concepts and principles on succession and forest disturbance are incorporated in landscape modeling to describe stand development patterns such as crown closure, self-thinning (Graney et al., 1985; Bi et al., 2000; Turnblom et al., 2000; Boncina et al. 2007; Peltola et al., 2007) and the maximum size-density relationships which are defined in terms of tree size and stand density (Reineke, 1933; Gingrich, 1967; Drew et al., 1979; Bi et al., 2001; Bechtold et al., 2003; Fraser et al., 2005; Kurinobu et al., 2007). These ecological concepts and principles add feedback mechanisms and simulation realism to forest landscape models.

Models that simulate changes of a landscape have largely evolved over the past decades, building on advanced technologies such as computing power and geographic information systems (GIS) software, and the availability of broad-scale spatial datasets. The increasing accessibility for those advanced technologies has resulted in major paradigm shift from non-spatial approaches to spatially explicit landscape modeling methods (Wimberly, 2003). With spatial modeling, the heterogeneity of environment, patterns of landtypes and various ecosystems components can be illustrated more realistically with the movement of organism and ecosystem components than non-spatial modeling. Spatially explicit simulations provide critical feedback about the important system properties that are not fully expressed in non-spatial models and are profoundly influenced by spatial heterogeneity. However, spatially explicit simulation models still bring uncertainty in model specification and parameterization because some ecosystem processes such as tree growth (Waterworth et al., 2007) and seed dispersal (Soons et al., 2004) are very difficult to estimate. For providing realistic simulation results with spatial modeling, multiple parameters describing species attributes and environmental characteristics are required and obtaining sufficient data over large heterogeneous landscapes is crucial.

LANDIS is a spatially explicit landscape model designed to simulate forest landscape change over large spatial and long temporal scales (Mlandenoff et al.1996, Mlandenoff and He 1999). The simulation by LANDIS describes the interactions of tree species, site conditions, and disturbances in relation to succession. LANDIS differs from most landscape models in that it deals with multiple landscape processes in combination with the simulation of succession dynamics at the tree species level (He et al, 2005). Thus, LANDIS can explain how disturbance and succession interact to change forest spatial patterns across large, heterogeneous landscapes and how alternative practices are likely to alter future landscape. Succession is a non-spatial, site level and competitive process driven by species life history attributes such as longevity, age of sexual maturity, shade tolerance class, fire tolerance class, maximum age of vegetative reproduction, sprouting probability, and effective as well as maximum seeding distance. When seed dispersal is simulated for a given site, a random number is drawn to decide if seed can establish. A species has a unique establishment coefficient for a site, which expresses the relative ability of the species to grow on different site categories or land types. When the establishment coefficient is greater than the random number for a given site, new establishment is allowed. Growth is increased in all species by 10 year time step and death occurs when the species age cohort reaches its longevity.

The current LANDIS (version 4.0) does not simulate forest landscape change using quantitative stand attributes such as stand density and basal area, and thus it is hard to simulate effects of competition and stocking level of stands accurately. Without quantitative stand attributes, LANDIS cannot explicitly simulate the cohort growth in terms of basal area or biomass of the cohort and stand development in combination with landscape processes. Without quantitative attributes describing stand density, it is not easy to evaluate the ecological and economic values of stands since we do not have information on the number or size of trees at each site over the landscape. Regeneration density also has huge effects on succession of stands but it is not capable of describing the amount of new seedlings without quantitative stand attributes. LANDIS currently incorporates only presence/absence and age data for each cohort, thus it has limitations in describing the stand dynamic changes linked with large-scale ecological processes. Therefore, it is an essential process to link stand dynamics to large-scaled ecological phenomenon and provide feedback between disturbances and succession with quantitative stand attributes. Including quantitative stand attributes in LANDIS will allow us to make more effective management prescriptions using tools that relate stand density to stand growth such as the density management diagram (Jack and Long, 1996; Stankova et al., 2007). Quantitative stand attributes will also better simulate succession in multiple species cohorts and various stand structures. Finally, adding quantitative estimates of stand density to LANDIS can provide valuable information about stand dynamics that are correlated with succession, growth, mortality and disturbances to model management schemes for various purposes over large landscapes

To enhance the simulation realism of LANDIS, I designed a stand density module to include quantitative stand attributes such as stand density, number of trees per unit area, and quadratic mean diameter (DBHq) of a tree cohort. The stand density module will be used to estimate the change of basal area in each cohort or stand and it will be utilized to estimate biomass which will better represent the effects of environment in combination with stand-level processes (Fang et al.,2001; Fang et al.,2007; Dillen et al., 2007; Cabaco et al., 2007). I also modified the seed dispersal design which is suitable for the stand density module to quantify regeneration density. These additions and modifications are expected to improve the simulation realism of stand dynamics, provide useful knowledge for forest management and feedback between succession and disturbances over large spatial scales (10^3~10^7 ha) and long temporal intervals (10^1~10^3 years) in forested landscapes.

1.1 Research Objectives

The primary objective of this study is to develop a stand density module for LANDIS to quantify stand basal area that will provide more realistic characterization of stand development and feedback among stand dynamics, disturbance, and harvest. The stand density module is expected to describe the changes of stand density (number of trees) at the individual grid cell level within the LANDIS model paradigm in interaction with large-scale landscape processes. I intend to use the quantitative stand attributes to simulate stand-level dynamics and to derive reasonable and realistic simulation results in stand basal area to describe stand development such as cohort growth and mortality into the current version of LANDIS. Specifically, I intend to

1. Design a stand density module based on species composition, age structure and stand development patterns generic to various environmental settings to estimate basal area of stands, relative density, number of trees per acre, and DBHq of stand.

2. Design the stand density module to be suitable for calibration and parameterization with empirical stand development data.

3. Quantify the effects of disturbance and harvest on stand density, species composition, and age structure at the level of the individual grid cell.

4. Conduct stand density module evaluation including module parameterization and uncertainty analysis with empirical data.

2. Review of LANDIS Model Family

Landscape ecologists have a comprehensive understanding of the strengths and limitations of different modeling approaches, along with an understanding of how modeling assumptions and parameterization errors may influence model behavior. There were several approaches incorporating quantitative stand attributes at the grid cell level for LANDIS (Schumacker et al., 2003; Pennanen et al., 2004; Scheller et al. 2004). Each approach has its strengths and limitations in how to simulate the change in succession dynamics at the stand scale. In general, the more specified and realistic simulation of stand dynamics, the more parameters of species traits, physical site conditions and disturbance regimes are required. However, it is impossible to incorporate all parameters representing species' attributes and landtype of stands and it is difficult to get sufficient data to provide initial condition for running model over large spatial landscape. Thus, stand level processes in combination with site physical condition for the landscape model need to be simplified enough to work efficiently with available datasets over large scale landscape and under current computational capacity. These limitations in parameterization make landscape modeling face some degree of skepticism that the simulation results really provide a useful representation of how real forest landscapes behave. Through the review of LANDIS model family, I seek to describe the objectives, the assumptions and methodology, the strong point and weakness in each approach. Based on the review, I address the verification of the stand density module in terms of accuracy and efficiency of model runs.

2.1 LANDCLIM

Schumacher et al. (2004) modified an earlier version of LANDIS (ver. 3.6) and modeled the influence of competition by adding a tree succession sub-module that included quantitative attributes of forest structure and parameters; (1) biomass, (2) number of trees and (3) maximum plant size on tree population dynamics to account for the influences of competition. The modified model introduced a more specific description of the properties of tree cohorts (e.g., biomass and number of trees) of tree cohorts; incorporated new formulations for tree growth and succession and added routines describing the physical environment such as light availability, temperature, and soil moisture. The modified model, LANDCLIM incorporate more mechanistic formulations of growth and competition then current LANDIS. The modifications of current LANDIS were conducted with the objectives: (1) to able to research the influence of a changing disturbance regime on landscape properties, (2) to able to investigate the effects of changing climatic parameters on landscape dynamics and (3) to study landscape properties that relevant for ecosystem management, with variables relating to stand biomass, species composition, and stand structure (Schumacher et al., 2004).

In this model, stand structure is modeled based on detailed quantitative information of tree age cohorts which means groups of tree of the same species and age. These cohorts are characterized by multiplying the average biomass of an individual tree and the number of trees in the cohort. The growth model is based on a logistic growth relation for individual trees, not a model of population-level dynamics. The growth rate is calculated with three growth-limiting factors, including light availability, the sum of degree-days and a drought index. In estimation of growth rate, Liebig's "Law of the Minimum" is adopted to combine these growth response factors. Based on Liebig's "Law of the Minimum", growth is controlled not by the total of resources available, but by the scarcest resource (limiting factor). Also, maximum tree size is added as a function of environmental condition which is related to degree-days and drought. Liebig's "Law of the Minimum" is also adopted to estimate maximum tree size. The yearly mortality rate is estimated based on a growth dependent component, a density-dependent component and intrinsic component. Tree regeneration is simulated with seed availability and environmental conditions. Seed availability in each cell is checked every decade with the original LANDIS seeding routine (He and Mladenoff, 1999). Establishment potential of available seeds is estimated as a function of environmental conditions, which are checked in two steps each year. The first step is calculation of biomass which is newly established at the end of a given decade and the second step is determined of the fraction years that have been favorable for establishment. Mortality which is implemented in LANDIS as an age-dependent function is adopted with endogenous mechanism and mortality caused by exogenous sources which are windthrow, fire and forest harvesting is also simulated in landscape scale process. Parameter sets describing tree species, physical site conditions and disturbance regimes are required in this model.

Based on various simulations over a range of possible future climate and disturbance scenarios, the application of this model can trace the change from weakly to strongly disturbed landscape, the impacts of climatic changes on forested landscape and the effects of such change of vegetation structure which current LANDIS cannot easily estimate. However, tree and stand-scale ecological processes in this model are mostly derived from approaches in widely used gap models. Adjusting this approach of gap modeling in a landscape-scale model requires too specific and detailed information of the various parameters such as; 1) light availability, 2) minimum temperature for establishment, 3) drought tolerance of species and 4) soil moisture. Such specific detailed data are not accurate when spatial extents are large and the temporal simulations are so long, thus the simulation results are not credible as the results of gap models. In the growth model, a logistic growth relation for individual tree was adopted, which is not suitable for describing population level of stand dynamics and the growth of cohort that LANDIS include as a basic unit for tree group because the effects of site condition on individual tree is not same as the effects of site condition on a cohort. For example, the light availability on an individual tree is different to the light availability on a cohort in a stand. In estimation of density-dependent mortality, Schumacher et al. (2004) assume that density-dependent mortality occurs if total stand biomass exceeds maximum stand biomass.

However, in real ecological process, density-dependent mortality works even when total stand biomass does not exceeds maximum stand biomass and total stand biomass become close to the maximum stand biomass. Thus, it does not describe real density-dependent mortality. Also, in stand growth and mortality model, minimum and maximum laws were adopted respectively even though various data for growth and mortality were collected. However, even though Liebig's law of minimum routinely applied to organisms, populations and communities, adopting the minimum law across these different scales is questionable. It is founded that unlike single species, communities are likely to adjust their stoichiometry to that of their resources by prediction of a resource ratio conceptual model and with an experimental test carried out in microcosms with bacteria (Danger et al., 2008). The results question the applicability of the Liebig's law of the minimum at the community level, and the relevance of ecosystem models relying on this principle (Danger et al., 2008). Finally, it is more recommended to adopt this approach in a relatively small-scale area and over a short-term period than a large-scale landscape.

2.2 LANDIS II

Scheller and Mladenoff (2004) developed a biomass module (living and dead biomass for a cohort) that describes quantitative analysis of forest growth, structure and composition and the biomass module allows landscape processes like large-scale disturbance to show their cumulative effects on biomass. The biomass module quantify the aboveground living biomass (Mg ha^{-1}) for each tree species-age cohort and calculates the rates of ecosystem process. LANDIS II is modified with three-fold objectives: (1) to integrate ecosystem process, aboveground living biomass, and dead biomass for landscape change, (2) quantify the influence of multiple disturbances on aboveground biomass and species composition, and (3) evaluate model results and conduct a sensitivity analysis of the model parameters (Scheller and Mladenoff, 2004).

As the parameters for running the biomass module, aboveground net primary productivity (ANPP) and aboveground mortality (M) are incorporated. Dead woody biomass was also amalgamated into a single value for each cell. Mortality is designed as the rate of biomass transferred from the living biomass to the dead biomass pool. Maximum ANPP (ANPPmax) could be estimated from expert knowledge, Forest Inventory and Analysis (FIA) data (e.g., Brown and Schroeder, 1999; Jenkins et al., 2001), or empirically measured data (e.g., Crow, 1978). Scheller and Mladenoff (2004) assumed that ANPPact increased logarithmically and asymptotically approached ANPPmax as cohort biomass approached the maximum possible biomass for the cohort. For the calculation of mortality rate, Scheller and Mladenoff (2004) assumed that mortality increased logistically as biomass increased until reaching equilibrium with ANPP. Scheller and Mladnoff (2004) provided biomass estimates, including both living and dead with ecological processes that requires minimal parameterization. The design of living biomass is based on the same conceptual scale and same function unit, a cohort of same species and age in LANDIS. Dead biomass provides additional information and feedback between fire disturbances.

However, the biomass module is routinely a function of cohort biomass against cohort age, which means the biomass of old age cohort is higher than young age cohort in the same species and same ecoregion. In real stands, it is not always likely to be that. The biomass of a cohort is the addition of all tree's biomass in the cohort thus the cohort biomass is decided by the number of trees and mean biomass of trees in the cohort. Even though simplification is required in large-scale landscape modeling, main predictor variable to estimate biomass of a cohort is average biomass of tree and number of trees. Therefore, the biomass module in LANDIS II leaves some problematic simulation results in specific cases of natural stands such as small number of old cohort and large number of young cohort in a stand.

As one of shortcomings in LANDIS II, the biomass module does not provide accurate relative stand density information especially in multiple stands. Scheller and Mlandnoff (2004) estimated maximum possible biomass for a species in an ecoregion as a 30-fold increase over ANPPmax. However, the maximum possible biomass in multiple cohorts is not clearly defined in this module. The potential biomass is also derived from the maximum possible biomass thus the ambiguousness of maximum biomass in multiple cohorts brings out crucial problems in the accuracy of simulation results. For the calculation of shade, two assumptions were made to define the percentage of full sunlight as a function of relative biomass. The first assumption is that a negative linear correlation between the natural log of percent full sunlight and the natural log of time (years) since complete disturbance (Howard and Lee, 2002) and the second assumption is that Scheller et al (2004) assumed that the natural log of relative living biomass (the ratio of actual to maximum site biomass, B_{AM}, ranging from 0.1 to 1) increase linearly with the natural log of time, again over two hundred years. Even though the first assumption was made based on the real data (Howard and Lee, 2002), the data is not enough data to make an assumption because some species' longevity is shorter than 200 years and in that cases the percent full sunlight can decrease dramatically before reaching 200 simulation year. The second assumption also lacks ecological background because it is made based on the simulation results of aboveground living biomass by LANDIS II. To be a reasonable assumption, more field data should be utilized to prove the second assumption correctly illustrate the stand developments in various stand composition and age structures. Based on two assumptions, the percentage of full sunlight as a function of relative biomass was estimated. With species shade tolerance and those two assumptions, a maximum relative living biomass for each species shade tolerance class is produced. However, the relationship between species shade tolerance and a maximum relative living biomass is doubtable.

The quantification of seed dispersal was not designed in the biomass module. Instead, the initial biomass is calculated with the maximum biomass for the ecoregion as the function of the current total biomass for the site. The initial biomass of a new cohort should be designed with more variables to decide the real quantification of new seedlings such as the amount of seeds reaching the site, establishment coefficients and relative density if it is to describe cohort reproduction in more realistic way.

2.3 Q-LAND

Q-LAND (Pennanen et al., 2004) adds quantitative cohort attributes and calculation of seed production and dispersal to the FIN-LANDIS design (Pennanen and Kuuluvainen, 2002) which was designed by modifying and expanding the LANDIS model through adding details to the simulation of tree regeneration, stand structure and fire behavior. The simulation operates in time steps of fixed length (e.g., 5 or 10 years). The objective of Q-LAND is to incorporate forest stand processes to estimate not only economical values but also ecological values. As the specific targets of the sub-model, Q-LAND tracks the basal area and volume of each tree species and simulates the amount of seed dispersal and tree regeneration. Q-LAND intends to simulate stand-replacing disturbances as well as non-stand-replacing disturbances.

As the solution to the problem of linking the details of the tree to landscape dynamics, growth tables were used as a model input with a simple idea that simulated tree cohorts follow the growth tables (Pennanen et al., 2004). The quantitative attributes of the tree cohorts, such as basal area, volume and tree dimensions as a function of cohort age, tree species and site quality are acquired in growth table and used as parameters in Q-LAND. Even though the growth tables were made in even-aged and single-species stands the growth tables are regarded as providing useful information in heterogeneous stands. Q-LAND tracks the proportion of territories that each cohort occupy, which is called density. The number of seedlings and asexual sprouts presents determine the initial density of a cohort. The density of cohort may only decrease without regeneration and the shade tolerant tree may survive in the same territories as understory when shade intolerant species located in the territories at a time thus Q-LAND can have a separate set of understory cohort in an each cell. Ecosystem process such as growth and mortality depends on the competitive environment by controlling the rate of cohort development along the path defined by the growth based on the age structure of each cohort. Stand level prediction of basal area, tree volume and seed dispersal were designed to describe stand development, leading to detailed results.

An advantage of using the growth table can be that the estimates of quantitative stand details are restrained to proper levels even though somewhat inaccurate parameters were provided. About seed dispersal, Pennanen et al. tried to incorporate most realistic seed production and dispersal model and regeneration density following verified and relevant equations with proper assumptions. However, although Q-LAND allows addressing various theoretical questions such as basal area prediction and seed dispersal estimation, Q-LAND is dependent on just growth table in the simulation of stand development. Using only growth tables, stand dynamics such as inter-specific competition in multiple stands cannot be simulated adequately. In the case of multiple stands, Q-LAND has a limitation in describing the stand development process which results in a rigid simulation. Because a growth table usually starts with initial stand density as 100 percent, it is not easy to describe the change of a poorly stocked stand. As another shortcoming of this model, the processes for species regeneration and seed dispersal are too complex to be adapted to large-scale landscape modeling. Q-LAND tries to distinguish the differences between good seedbeds, poor seedbeds and seed number is designed as a function of the terminal velocity of the seed, the median horizontal wind speed and the seed release height. It requires many specific equations and parameters for calculating seed dispersal and regeneration density. This complexity can be somewhat burdensome considering current computational capacity and acquiring detailed initial data such as terminal velocity of each species, the proportions of seeds that are deposited within the source cell and seedling survival on poor seedbeds relative to survival on good seedbeds are not easy for large-scaled landscape.

2.4 Forest Vegetation Simulator

The Forest Vegetation Simulator (FVS) is a model for predicting forest stand dynamics and is used extensively in the United States (Dixon, 2008). Forest managers have utilized FVS for summarizing and predicting future stand conditions under various management alternatives. The objectives of FVS are to analyze the effect of forest management on stand structure and composition to determine the suitability of stands for wildlife habitats and to predict losses from fire and insect outbreaks.

FVS is a semi-distant-independent individual tree growth and yield model (Dixon, 2008). A stand is treated as the population unit and standard forest inventory data are used for FVS. As the growth model, local growth rates are adjusted to model growth relationship, which is one of distinguishing features in FVS. FVS is designed to portray lots of forest types and stand structures, such as even and uneven aged stands and single to mixed species. As sources of input FVS utilize the existing inventory methods and produce initial estimates of volume and growth. FVS treat stands as the basic unit of management and the growth of model is dependent on the interactions of tree in a stand.

However, FVS is designed to predict forest stand dynamics for relatively small landscapes (10 ~ 10^3 ha). Thus, it requires various parameters specific to each species, landtype and environmental factors. The ecological processes such as growth, mortality and regeneration are more detailed for describing stand-scaled dynamics. To link this model with large-scaled landscape model like LANDIS, the equations and parameters for running FVS are too complex for species attributes and landtype property, making it difficult to connect large-scaled landscape results with stand level models. The linkage between large-scale landscape models and stand-level models is made difficult by the large quantity of data that is required which results in run-times that are extremely long. In order for stand dynamics to be effectively used with large, landscape-scale models stand-level data needs to be more simplified and streamlined with reasonable assumptions even though it may provide less accurate simulation results.

2.5 Justifications of a new stand density module for the LANDIS model

In contrast to the above models, I opted to incorporate stand density (number of trees) and relative density to provide the quantification of current stand density. Even though my approach simulates the change in stand density and tree diameter and can calculate relative density and basal area, I considerably simplified the process of parameter estimation using minimized variables and reasonable assumptions to the extent that users can acquire data on DBHq, number of trees and basal area from Forest Inventory and Analysis (FIA) data or other sources and link them to the LANDIS model. With reasonable assumptions describing realistic ecological processes, I used simple and relevant mathematical equations which describe growth, inter-specific competition and seed dispersal under the LANDIS framework and realistic simulation results of stand quantitative details will be expected. Based on simplified stand density module with DBHq and tree number, crucial stand quantitative details such as basal area will be estimated and simulated in combination with large-scale landscape processes, producing valuable feedback between stand development and landscape dynamics such as disturbances over large spatial and long temporal scales.

I did not adopt minimum law or maximum law in growth and mortality models utilized by LANDCLIM, which means that I used more factors which have effects on stand dynamics with minimized parameterization simultaneously. I did not utilize individual tree growth and mortality models that are utilized by LANDCLIM but invented a population-level growth and mortality models. In contrast to LANDIS II, I tried to incorporate stand density (number of trees) using reasonable assumptions and statistical technology. Based on real stand density, the accuracy of stand quantitative details will be heightened and the simulation results will provide valuable information for forest management. I intended to integrate the mortality induced by self-thinning based on estimated relative density. Because the mortality by self-thinning is strongly affected by relative stand density, the mortality by self-thinning based upon relative density is expected to describe the real stand dynamics. Compared with Q-LAND, I made more general simplifications on growth and mortality model instead of using just growth tables. This will make the models more flexible to describe the stand dynamics in various species mixtures and stand structures. In the model of seed dispersal and regeneration density, I tried to invent a simpler design which is suitable for large-scale landscape modeling than the design of Q-LAND. Such simplification will reduce computational burden. With a newly designed stand density module in LANDIS including valuable stand quantitative details based on reasonable simplification, the simulation realism of stand dynamics may be enhanced with linkage of large-scale and long-temporal landscape modeling.

3. Stand Density Module Design

3.1. General approach

The stand density module assesses current density of each individual forest stand (all trees in a grid cell) on a site over the simulated landscape. The stand density module tracks number of trees and DBHq of each cohort and finally simulate basal area of each cohort (tree group with same species and age class in a stand) and stand on each site (grid cell). Ths stand density module incorporate a stand density index (SDI) (Reineke, 1933; Moore et al., 1992; Woodall, 2003; Woodall, 2005; VanderSchaaf et al., 2007) to calculate stand relative density with estimated maximum stand density.

The stand density module includes various stand development patterns based on diverse factors of forest stand dynamics. Growth, mortality, seed dispersal and new seedling establishment are redesigned for LANDIS and a variety of stand development patterns are modeled as a function of stand relative density with quantitative stand attributes. Quantitative stand attributes in stand density module such as number of trees per acre, DBHq and basal area can be readily converted into volume, biomass, and carbon as model output.

Other modules in LANDIS such as fire, harvest, wind, biological disturbance agent, and fuel will interact with the stand density module. The interaction between the stand density module and other modules in LANDIS will allow various ecological processes (e.g., succession and disturbances) to influence the stand density at both stand-level and landscape-level. The new version of LANDIS will include the information on quantitative stand attributes as an integral part with upgraded disturbance modules (He et al., 2004; Yang et al., 2004 Shang et al., 2004). The advanced LANDIS version with a stand density module is designed to provide realistic results of stand dynamics and feedback among quantitative stand attributes and large-scale ecological process.

3.2. Estimation of relative density of stand using stand density index

As one of the crucial factors representing stand development, relative density (the ratio of actual stand density to a maximum stand density attainable in a stand) can be utilized to describe the relationship between density and growth based on various validated field experiments using tools that relate stand density to stand growth such as the density management diagram (Figure 3.1). Briegleb (1952) and Tadaki (1964) have drawn general conclusions on how stand growth is related to density indices that are comparable to relative density, so the information on relative stand density will bring crucial information about the stand development stages and changes in quantitative details of the stand, .

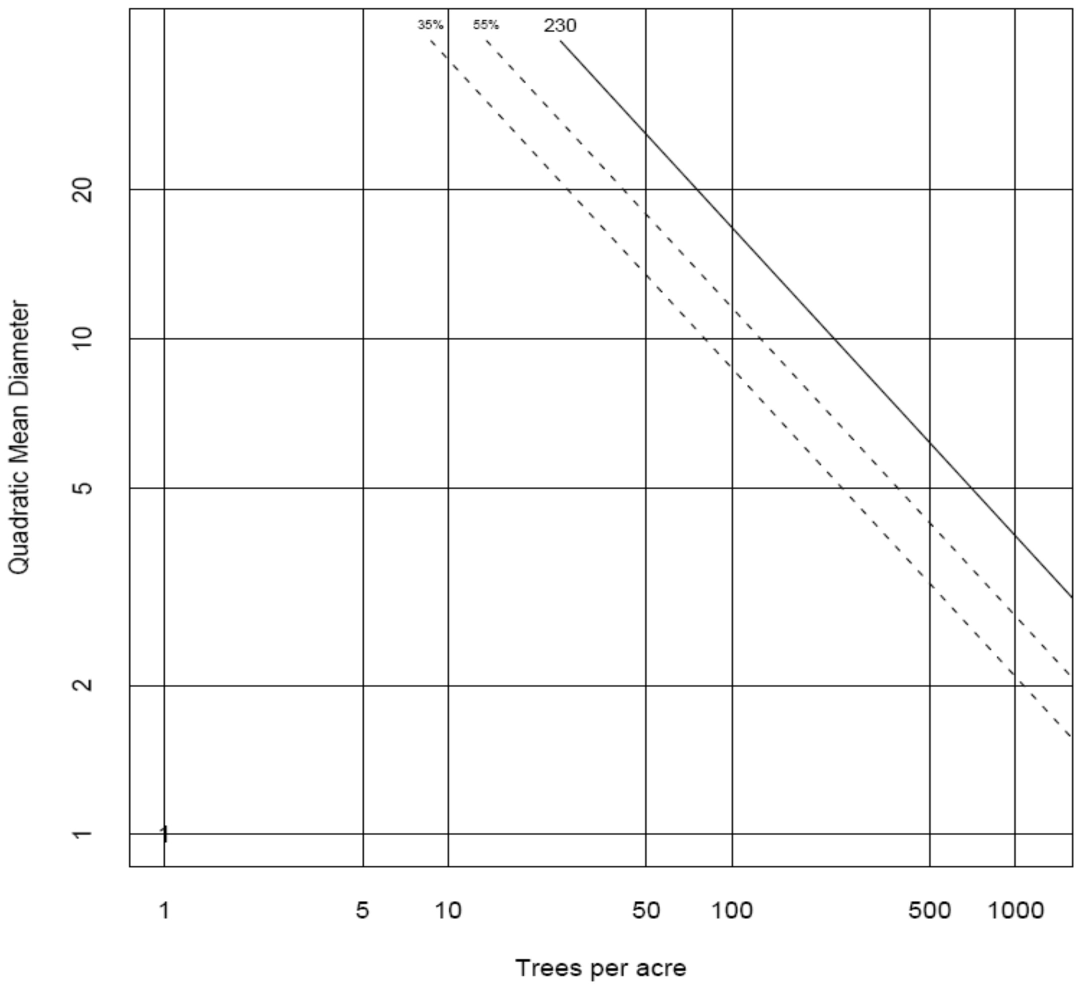


Figure 3.1 Density Management Diagram of Upland Oak (Figure is taken from Larsen et al., 2001). Dark line labeled 230 indicates the line of maximum stand density and 230 indicates a maximum stand density for upland oak (number of trees at 10 inch in DBHq per acre). Dotted lines indicates the percentages relative to a maximum stand density

Various measures of stand density were suggested but each way has pros and cons. In the stand density module, I consider two approaches of defining relative density. One is a measure of relative density by tree number per estimated maximum SDI and the other is a measure of relative density by space occupied by average-size trees per unit area. After evaluation of both approaches to empirical data and comparing the results, a final approach is adopted for the LANDIS stand density module.

3.2.1 Estimation of relative density based on the number of trees per unit area

Stand density index (SDI) is a relative measure of stand density that converts a stand's current density into a density at a reference size (10 inches of DBHq). Stand density index was presented by Reineke (1933) and can be defined as

$$\mathrm{SDI} = \mathrm{TPU}\,[\mathrm{Dq}/10]^{1.605} \quad \text{Eq. 3.1}$$

where; SDI is Stand Density Index,

Dq is the quadratic mean diameter (inch),

and TPU is tree number per unit area.

The only way to appropriately determine SDI in stands with non-normal diameter distributions is to determine the SDI for individual DBH classes and then add them for the entire stand (Long and Daniel, 1990). The SDI summation methods is

$$\mathrm{SDI} = \sum_1^j \sum_1^i \mathrm{TPU}_{ij}\,(\mathrm{Dq}_{ij}/10)^{1.605} \quad \text{Eq. 3.2}$$

where; Dq_{ij} is the quadratic mean diameter of trees in the *i*th diameter class (inch) and *j*th age class,

TPU_{ij} is the number of tree per unit area in the *i*th diameter class (Long and Daniel, 1990; Long, 1995; Shaw, 2000)

and *i* represents a species present in a cell and *j* represents age class

Relative density (RD) is a quantification of current density of forest stand in comparison to some maximum level and can be defined as

RD = SDIcurrent / SDImax Eq. 3.3

where SDIcurrent is current stand density index,

and SDImax is maximum stand density index.

Specific gravity is the ratio of the density of a given substance to the density of water. Dean and Baldwin (1996) found that a species' specific gravity explained much of the variation in maximum SDI among tree species and found that a species' specific gravity was inversely related to its *SDImax.* A strong relationship was found between the mean specific gravity of all trees in a stand and the 99th percentile of the observed distribution of stand SDI's by classes of mean stand specific gravity (Woodall et al., 2005).

$E\ (SDI99) = b_0 + b_1\ (SGm) + e_i$ Eq. 3.4

where; E (SDI99) is statistical expectation of the upper 99 th percentile of stand specific gravity,

SGm the mean specific gravity for trees on a site,

e_i the random error term,

and b_0 and b_1 are parameters to be estimated.

For predictions of 99 th percentile SDI, Woodall et al. (2005) found that SGm explained 92% of the variation in SDI99 (p-value < 0.001, RMSE = 53.1, $\widehat{b_0}$ = 2057:3, $\widehat{b_1}$= 2098.6). (Fig.3.2)

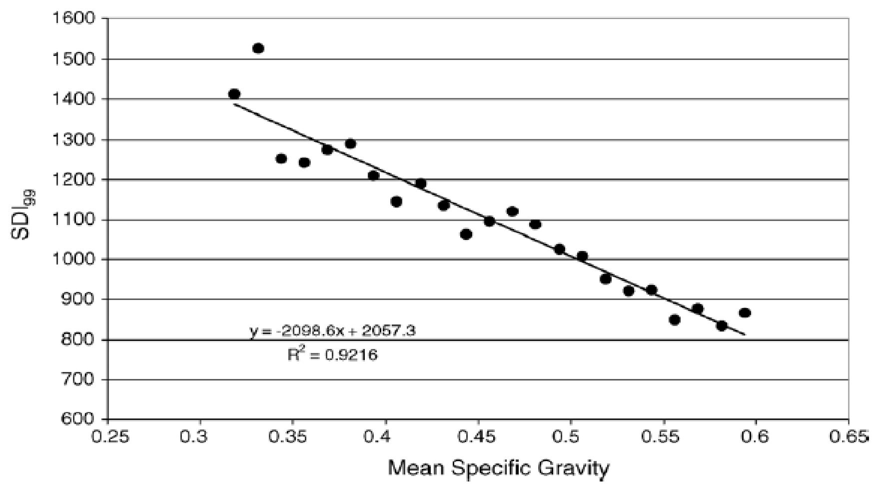


Figure 3.2. Mean stand specific gravity explained 92% of the variation of SDI99, 99th percentile of the observed distribution of SDI (copied from Woodal et al., 2005).

I used 99^{th} percentile of the observed distribution of stand SDI as an estimate of maximum stand density indes and current stand density index was calculated using the SDI summation methods based on the cohort's DBH classes as described in equation 3.2.

3.2.2. Estimation of relative density using the space occupied by average-sized tree per unit area

The relative density can be also calculated by the growing spaces occupied by average-sized trees per unit area in stand density module. Based on DBHq of each cohort, the average size of tree was estimated using SDI in comparison to maximum number of average tree size per unit area (Table 3.1). In this approach, maximum value of a stand density is a unit area where the users define and the definition of maximum value of a stand density is more intuitive than the other approach described above especially in multiple cohorts and we can estimate the portion of each cohort in a stand with more reasonable arithmetic approach. Relative density using the space where occupied by average-sized tree per unit area is defined as

$$RD = \left(\sum_{1}^{j} \sum_{1}^{i} S_{ij}\right)/ua \quad \text{Eq. 3.5}$$

where *s* represents average tree size, *i* represents a species present in a cell and *j* represents age class and ua represents unit area.

Table. 3.1 Suggested Maximum SDI by species and source. English units are number of 10-inch trees per acre. Metric units are number of 25.5cm trees per hectare. (Taken from Larsen et al., 2001)

Species	**Maximum SDI (English)**	**Maximum SDI (Metric)**	**Source**
White fir	830	2050	Reineke, 1933
Red fir	1000	2470	Reineke, 1934
Mixed conifer for CA	750	1850	Reineke, 1935
Douglas-fir for WA-OR	595	1470	Reineke, 1936
Douglas-fir for CA	600	1480	Reineke, 1937
Eucalyptus	490	1210	Reineke, 1938
Redwood	1000	2470	Reineke, 1939
Ponderosa Pine	800	1980	Reineke, 1940
Loblolly Pine	450	1110	Reineke, 1941
Longleaf Pine	400	990	Reineke, 1942
Slash Pine	400	990	Reineke, 1943
Shortleaf Pine	400	990	Reineke, 1944
Upland Oak	230	570	Schnurr, 1937
Ponderosa Pine	830	2050	Long, 1985
Lodgepole Pine	690	1700	Long, 1986
Douglas-fir	587	1450	Long, 1987
Western Hemlock	790	1950	Long, 1988

3.3. Cohort growth and mortality

3.3.1 The growth of cohort

The growth of a cohort in the stand density module is simulated by the increase in quadratic mean diameter breast height (DBHq) with time. The growth of a cohort occurs as the age of the cohort increases until tree reaches longevity. Quadratic mean diameter is the measure of average tree diameter conventionally used in forestry (Robert et al, 2000) and it is used to estimate height, basal area and volume. For simplicity, I assumed that DBHq of a cohort reached the average of maximum DBHq at the average longevity of species, and I modeled this relationship using the Gompertz curve (Gompertz, 1825). The average of maximum DBHq means the arithmetic mean of the values of maximum DBHq at average longevity over study area and it is estimated with FIA, field data and the output of stand-scale modeling. The average longevity means the average lifespan in years of live trees which are not removed by disturbance, harvest and self-thinning. In other words, the average longevity represents the average lifespan of tree species when trees are protected from external disturbances and all essential factors for living such as space, water and nutrients are sufficient.

We cannot track the trajectories of DBHq of the species which has long longevity over large-scale study area because some trees have very long longevity (e.g., White Oak) and the landscape modeling is very large-scaled (10^3~10^7ha),. Thus, we need reasonable assumption to estimate DBHq of a cohort which will be used to estimate other quantitative details of cohorts such as basal area and relative density. Among various growth equations, the Gompertz (1825) equation is applied as one of many possible growth models (Winsor, 1932), and Nokoe (1978) concluded that this equation demonstrates sufficient flexibility to warrant its use. For example, the Gompertz equation can be used for describing population in a confined space, as birth rates first increase and then slow as resource limits are reached. Many researchers (Causton and Venus, 1981; Laird et al, 1965; Zweifel and Lasker, 1976; Zullinger et al. 1984) found that the Gompertz curve is appropriate in biological work such as tree growth and it was deduced theoretically by Medawar (1940) that growth should follow the Gompertz curve (Zeide, 1993). Thus,

$$DBHq = DBHqamax * e^{a * e^{kt}} \quad \text{Eq. 3.6}$$

where *DBHq* represents current quadratic mean diameter of a cohort and *DBHqamax* represents the average of maximum DBHq per unit area over study landscape and *t* represents time (year). The *a* and *k* are growth coefficients. For simplicity in the stand density module the coefficient *a* and *k* are adopted with the average of fitted values for overall species to describe the change of DBHq in most species. However, coefficients can be developed for a certain degree of classification (e.g., hardwood and softwood), if desired (Figure 3.3).

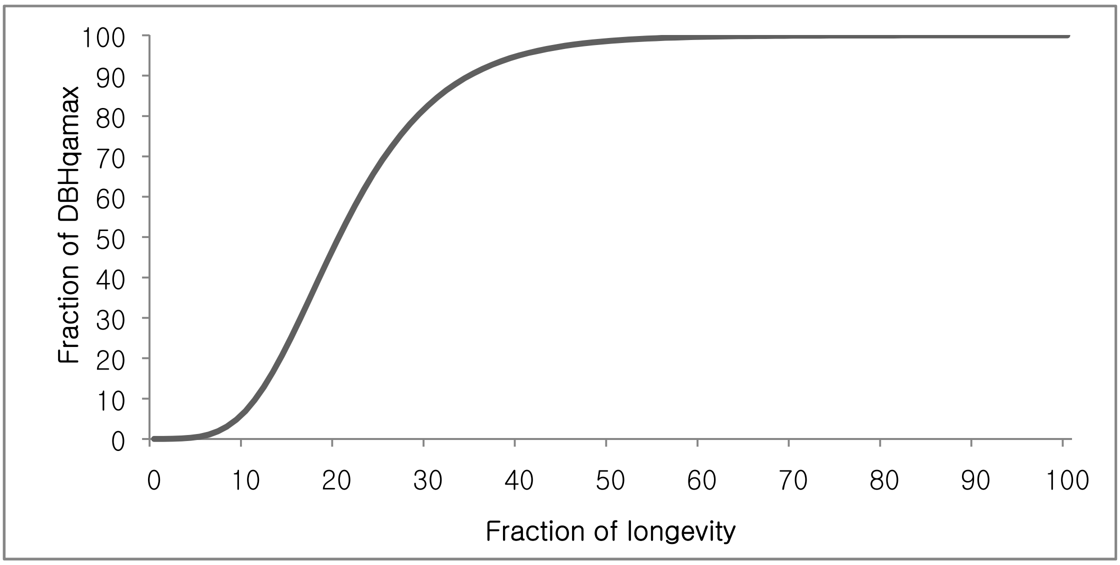


Figure 3.3 Modeled relationships between DBHq and Longevity based on Gompertz Equation (Eq. 3.6).

3.3.2 The mortality of a tree cohort

The mortality of trees is caused by self-thinning (growth and density based mortality), ageing, harvest, and various disturbances in LANDIS. The range, intensity and period of mortality are decided by the each module's algorithm of current LANDIS. Those factors are operated mutually to produce combined results in tree cohort mortality over large-scale landscape.

The mortality by self-thinning is modeled as the function of stand relative density and mortality (Percent of number of trees dead in a stand per one year) by self-thinning. Several assumptions were made to describe the mortality by self-thinning. I assumed that self-thinning mortality increase lineally as the relative stand density increases.

Mortality = j * RD + b Eq. 3.7

where RD is stand relative density and j and b are the coefficients.

In general, it is reported that self-thinning starts around relative density 55% and self-thinning rate becomes higher as relative stand density increases (Drew et al., 1979; Lussier et al., 2002). Thus, I assumed that self-thinning mortality works only when the stand relative density is above the threshold (e.g., relative density = 55%). If the relative stand density falls below the threshold, the mortality by self-thinning stops (Figure 3.5). For Simplicity, after the relative stand density becomes over than 100%, the random number of self-thinning mortality that maintains the stand relative density ranging from 95% to 100% was designed. When the stand relative density becomes over than 100%, in the case of multiple stands including various cohorts, higher random mortality rate was adopted to young and shade-intolerant species within the stand relative density ranging from 95% to 100%

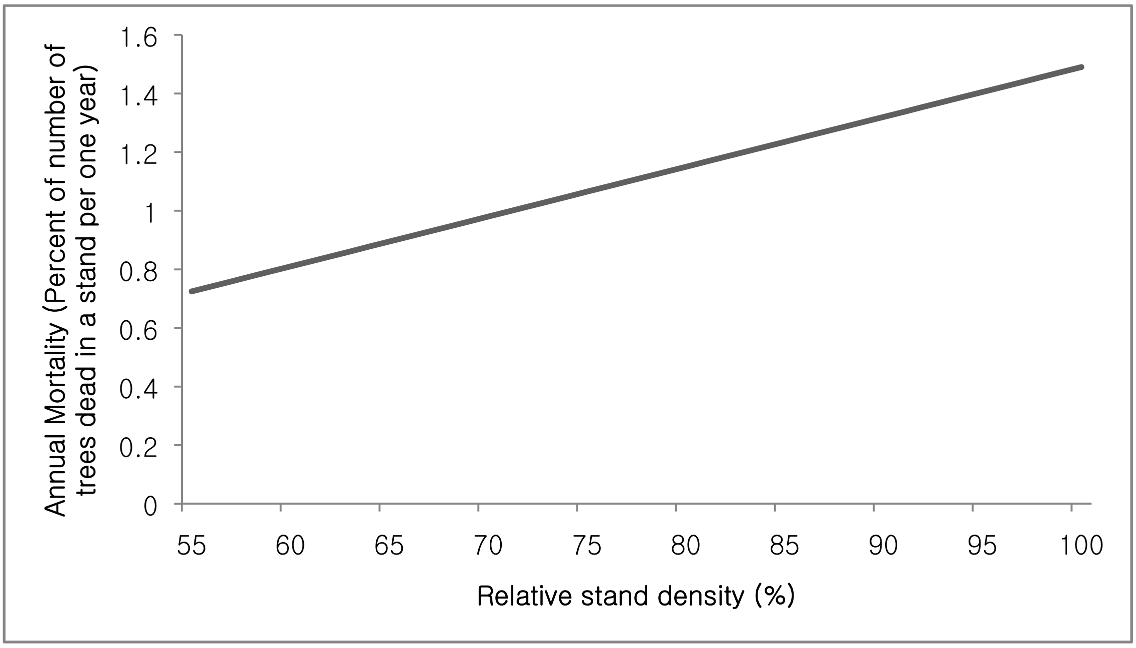


Figure 3.4 Relationship between relative stand density and mortality

3.4. Succession and seed dispersal

3.4.1 Seed dispersal and regeneration density

Seed production is designed based on the basal area of the source trees (Pennanen et al., 2004). The mean number of seeds produced annually (Q_0) is designed as;

$Q_0 = 3067Bm^{-0.58}$ Eq. 3.8

where B is the basal area of the source tree (m^2) and m the average mass (g) of one seed. The equation can be applied to a range of tree species (Greene and Johnson, 1994).

The dispersal kernel is described as a temporally constant input during dispersal season and decreases exponentially with distance from the source P (Nathan et al., 2000). The negative exponential curve is adopted in modeling seed dispersal because it generally fits observed seed shadows very well for a variety of plant species and dispersal agents (Wilson, 1993; Nathan et al. 2000). ;

$$Q(p) = \frac{2\alpha}{\pi D^2} exp(-\frac{2p}{D}) \quad \text{Eq. 3.9}$$

where α represents the total seed output, i.e. the total number of seed dispersed from the source towards any direction per unit time, *p* represents the distance from the source and *D* represents the mean distance travelled by dispersing seeds.

The establishment coefficient of a species for specific landtype in LANDIS was used by multiplying estimated seed dispersal number and final regeneration density is calculated by multiplying estimated seed number and establishment coefficient;

$$Nr = Q(p)\ est\ coef \quad \text{Eq.3.10}$$

where *Nr* is regeneration density, *Q(p)* is seed number and est coef is establishment coefficient

3.4.2 Establishment of new species.

In current LANDIS, shade-intolerant species (species with lower shade-tolerance class) cannot establish either by seeding or by vegetative reproduction on a site where more shade tolerant and mature species are present. In the new design of the LANDIS SDI module with the information about relative density, the establishment of shade-intolerant species is allowed when relative density is under the crown closure (0 < Relative Density < 15%) as a default. Crown closure is often used to approximate the initiation of inter-tree competition as opposed to the growth of noncompeting trees (Drew et al., 1979). Thus the relative density of crown closure is reasonable point that decides the establishment of shade-intolerant species. Even shade tolerant species cannot establish when growing space is deficient. As a default, any new establishment is rejected over full occupancy (Relative density >= 60%), thus even shade-tolerant species can establish only when relative stand density is below 60%.

3.4.3. Quantification of vegetative reproduction

In current LANDIS, vegetative reproduction may occur following the death of a species age cohort

(Hong et al., 2005). The species' sprouting probability is compared with a random draw from a uniform distribution to stochastically determine whether vegetative reproduction occurs. The number of trees by vegetative reproduction is determined by species' sprouting probability and the number of dead trees in a previous time step in the cases that species' sprouting probability is bigger than the random number;

$$Q(v) = sp * m \quad \text{Eq. 3.11}$$

where Q(v) is number of vegetative reproduction and sp is the species' sprouting probability and m is the number of dead trees in the year of vegetative reproduction

4. Parameter estimation and landscape initialization

Caswell (1976) distinguished two major types of model objectives. One is to provide accurate predictions of the behavior of system and the other is to gain insight into how the system operates. The objective of an ecological model helps determine what we need in terms of data and how to evaluate the model. Based on the objectives of my research, parameterization for LANDIS was conducted to simulate succession of five species in the Boston Mountains of Arkansas. It will provide basic information for species attributes and landtype properties. The parameterization process was done using ArcGIS for LANDIS 4.0. It also gives insight into the relationship between species composition change and quantitative stand attributes change in the new LANDIS stand density module.

For deriving simulation results with the stand density module, estimates of coefficients for growth and mortality were made with empirical data for one hundred years in sample plots using R, a language and environment for statistical computing and graphics. The empirical data used for the estimations came from yield, stand and volume tables for even aged upland oak forests (Schnur, 1937) and in the further step, FIA and FVS simulated results will be used for the parameterization process. The estimated parameters can be used to determine the rate of growth, self-thinning and regeneration related parameters.

4.1 Growth coefficient

As one source of empirical data, yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937) were utilized to estimate growth coefficient. For the estimation of coefficients for the growth model, I modeled DBHq by age for 100 years (Table 4.1) using equation 3.6. I used the change of DBHq at site index 60 as the average of environmental site condition.

Table 4.1 DBHq change of upland oak at site index 60 by age per acre (Schnur, 1937)

Age	DBHq
0	1.4
20	2.5
30	4.0
40	5.3
50	6.3
60	7.2
70	8.0
80	8.8
90	9.4
100	10.1

Table 4.2 Summary table of non linear regression analysis with data in Table 4.1 and equation 3.6.

Parameters:

	Estimate	Std. Error	t value	Pr(>|t|)
a	2.690096	0.122825	21.90	1.04e-07
k	0.030623	0.002067	14.82	1.53e-06

Residual standard error: 0.1722 on 7 degrees of freedom

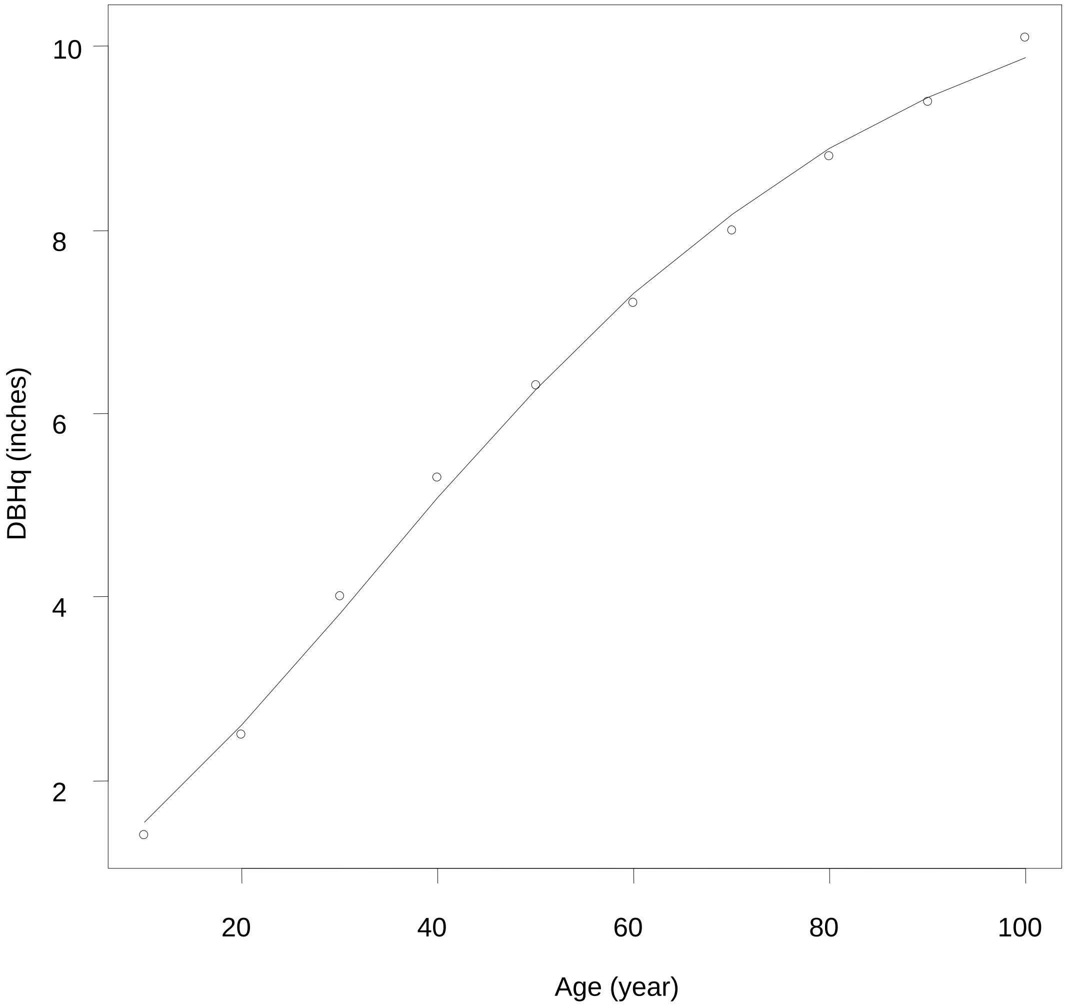


Figure 4.1 The fitted value with estimated coefficients (Dot = empirical data, Line = fitted line with growth equation).

Given results of summary in analysis using non linear regression (Table 4.2), it is statistically significant. The graph with empirical data and fitted line fits well, indicating the reasonable estimation of the relationship between age and DBHq for site index 60. Thus, the growth coefficient can be adopted for growth equation.

4.2 Mortality coefficient

For estimation of the coefficient for the mortality by self-thinning (Equation 3.7), empirical data, FIA and FVS can be utilized. I used the data of the relationship between annual mortality and relative density (Schnur, 1937; Lussier et al., 2002) to estimate the coefficients of the mortality curve (Table 4.3).

Table 4.3 The relationship between mortality rate and relative density (Average data taken from Lussier et al., 2002)

Relative Density Index	Mortality rate(%) per one year
0.06	0
0.12	0
0.3	0.11
0.47	0.29
0.62	1.29
0.67	0.77

Based on relative density and mortality rate (Lussier et al., 2002), linear regression analysis was conducted to estimate the mortality coefficients in the equation 3.7. These estimated coefficients for mortality by self-thinning can be used as a default for softwood. Given the results derived by linear regression (Figure. 4.2, Table 4.4), it is statistically significant and these coefficients can be used for the mortality equation 3.7.

Table 4.4 Summary of linear regression analysis with empirical data (Lussier et al., 2002) fit to equation 3.7.

Parameters

	Estimate	Std. Error	t value	Pr(>|t|)	
b	-0.2141	0.1068	-2.005	0.0493	*
j	1.7164	0.2084	8.236	1.38e-11	***

Residual standard error: 0.4982 on 63 degrees of freedom

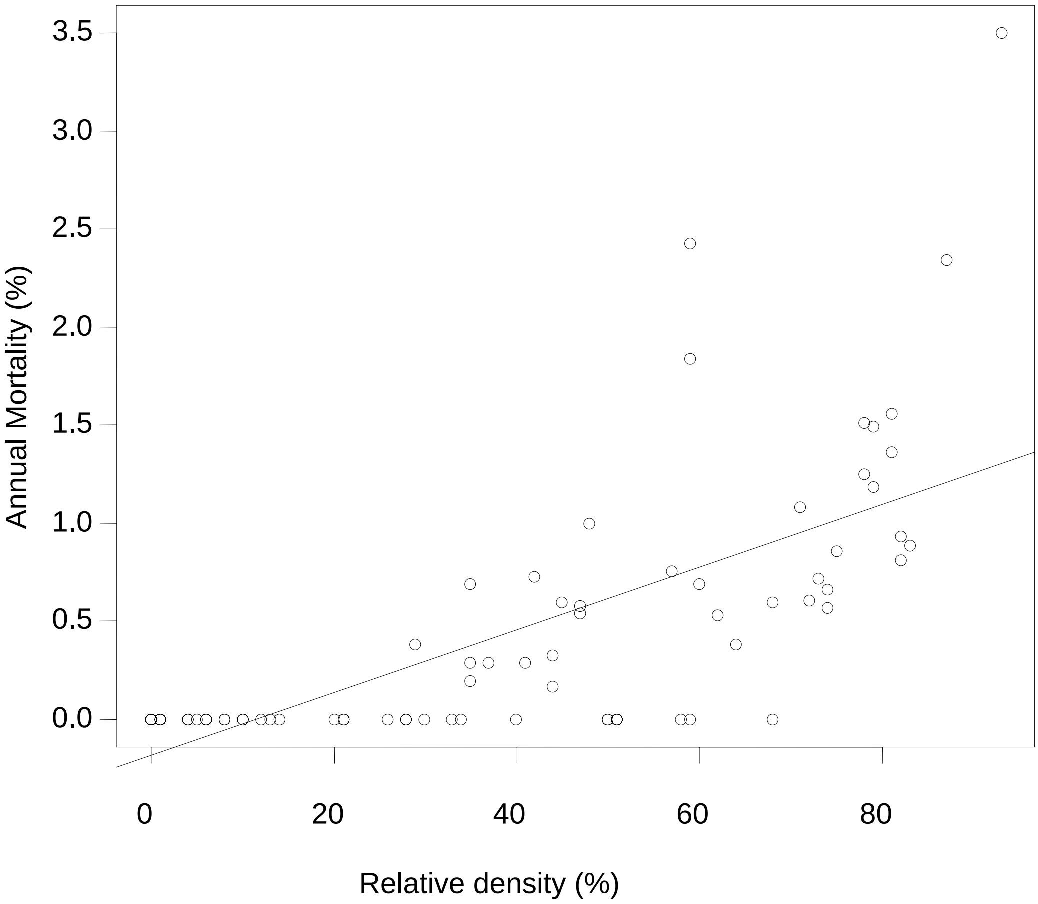


Figure 4.2 The graph of fitted value with estimated coefficients (Dot = empirical data, Line = fitted line with equation 3.7).

For estimation of the mortality coefficient that can be used as a default for overall species, I used the empirical yield, stand and volume tables for even-aged upland oak forest (Schnur, 1937) with the field data of black spruce (Lussier et al., 2002). Given the results derived by linear regression (Table 4.5), it is statistically significant and these coefficients can be used for the mortality equation 3.7 for overall species in multiple stands.

Table 4.5 Summary of linear regression analysis with empirical data (Schnur, 1937, Lussier et al., 2002) fit to equation 3.7.

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
b	-0.09524	0.13788	-0.691	0.491	
j	1.55598	0.17606	8.838	1.19e-15	***

Residual standard error: 0.8361 on 170 degrees of freedom

4.3. Study area

Our study area is The Boston Mountains in the Buffalo Ranger District of the Ozark National Forest in northern Arkansas. The Boston Mountains are the highest, southernmost member of the Ozark Plateau physiographic province (Fenneman, 1938) and is the southernmost lob of the central hardwood region (Merritt 1980, p. 108). The Boston Mountains are among the most difficult sites to regenerate oak (Graney and Rogerson, 1985; Sander and Graney, 1993; Graney and Murphy, 1997).

The range of elevation is from 1900 to 2500 feet. Rocks are sedimentary and predominately of Pennsylvanian age. Most ridges and spurs are generally less than one-half mile wide and the plateau is sharply dissected. March, April, and May are the wettest months and annual precipitation averages 46 to 48 inches in the portion within Arkansas. Extended summer dry periods are common and autumn is usually dry. The frost-free period ranges from 180 to 200 days long. The tops are flat to gently rolling and the sides are composed of an alternating series of steep simple slopes. In ridge and upper slope positions, soils are medium-textured and derived from sandstone residuum. In side slopes, soils are fine-texture and derived from shale residuum. Soils common to bench positions are deep, well-drained, medium-textured soils derived from sandstone and shale colluviums (Graney, 1977).

4.5. Estimation of initial quantitative stand attributes

The stand density module requires parameter sets describing quantitative stand attributes and seed dispersal. For initial quantitative stand attributes, stand age structure (McNeill et al., 2005), stand basal area, cohort basal area, density of cohort (Martinez et al., 1998), quadratic mean diameter of cohort and coefficients for growth and mortality are estimated and calculated. This study did not parameterize all the study area with the quantitative stand attributes, because the SDI design needs to be fully programmed and implemented in the LANDIS model before landscape simulations can be carried out. However, I provide general thought of how landscape scale parameterization can be done for the parameters used in SDI module.

The plot and tree data provided by the USDA Forest Service are used to derive initial quantitative stand attributes and seed dispersal. For the estimation of density in the study area, the basal area or biomass per each stand (all trees in a grid cell) and cohort (tree group of same species and same age class in a stand) in study area can be estimated using FIA data, remote sensing data (Bortolot et al., 2005; Feldpausch et al., 2006; Hall et al., 2006; Hyde et al., 2007; Muukkonen et al., 2007; Popescu et al., 2007) and landtype using the relationship between basal area and diameter as a practical stand density measure (Reid et al., 2006; Tewari et al., 2007).

Basal area of a stand = f (landtype, neighboring cell's basal area, remote sensing data) Eq. 4.1

Given the estimated basal area in each grid cell, the each cohort's basal area to whole basal area of stand in a cell is estimated based on species composition and age structure of cohort.

Basal area of a cohort = f (species composition, age structure) Eq. 4.2

The initial number of tree in each cohort is calculated using age-dependent diameter estimation based on a regression analysis (Eq. 3.6) with estimated basal area of cohort (Eq. 4.2)

$BA = 0.005454\ (DBHq)^2$ Eq.4.3

where BA(ft^2) is basal area and DBHq is quadratic mean diameter of breast height (inches) per acre.

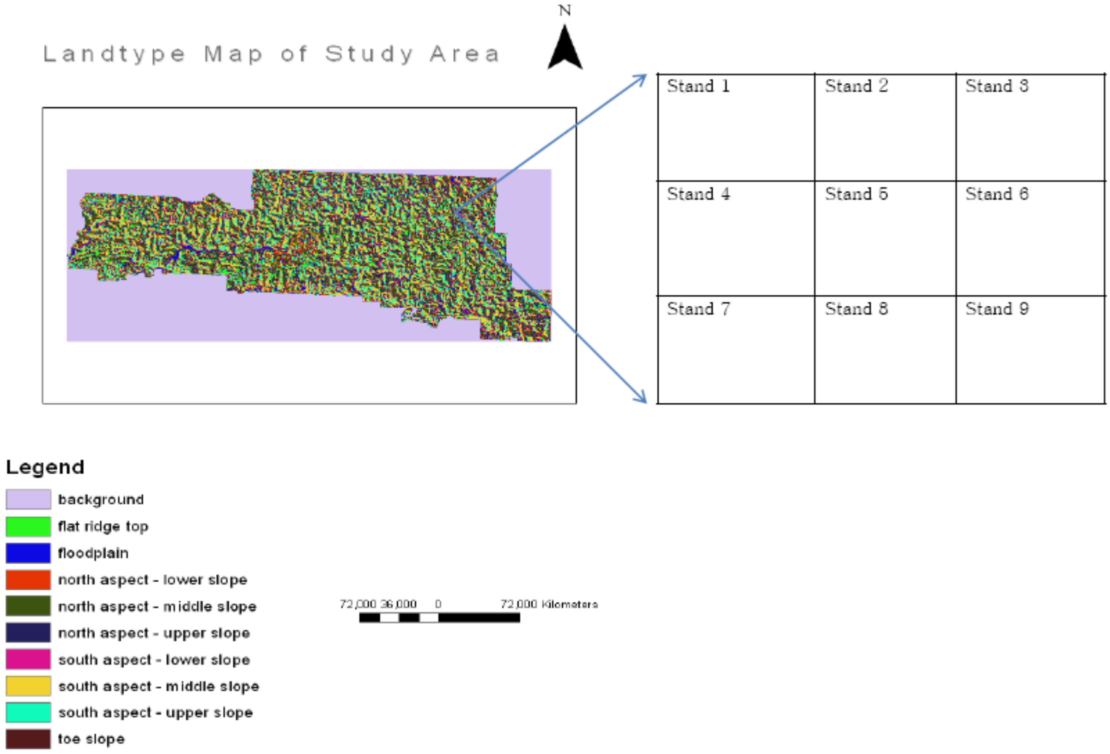


Figure 4.3 Spatial descriptions of artificial stands and the unit area of each stand is an acre.

5. Evaluation, sensitivity analysis and verification of the Stand Density Module

Proof of concept is used to verify the module design. In the LANDIS modeling framework, a new idea is often undertaken to prove that the core ideas are workable and feasible, before the design is programmed into the LANDIS software. This use of proof of concept helps establish technical issues, and overall direction of ecological modeling, as well as providing feedback for modeling.

Based on the stand density module, the evaluation, sensitivity analysis and verification for proof of concept were designed within limited condition of stands to verify its correctness and feasibility of the approach and to prove that module is workable in various situations, including pure even-aged and multiple uneven-aged stands with regeneration, harvest, disturbances and species settings.

5.1 Evaluation of the Stand Density Module with self-thinning mortality model in even-age stand without disturbance, regeneration, and harvest.

The relative stand density and basal area were simulated based on the stand density module designed by self-thinning mortality model (Eq. 3.7) with the scenario of various initial numbers of trees in single-species even-aged stand of white oak at age 10 years. Disturbance, regeneration, and harvest are controlled to investigate the simulated response driven by the differences of initial number of trees. It is assumed that the physical site conditions are same and no influence by exterior changes in all simulation experiments. The simulation time-step was 1 year and the duration of simulation is 90 years

5.2.1 Single-species even-aged stand with the initial number 50

Based on estimated growth and modified mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 50 at age 10 were simulated for 90 years. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand at age 10 with the initial number 50 starts from 1% and increases steadily because of trees growth over time (Fig. 5.1). For simulation year 90, there was no decrease or fluctuation in the change of relative density because self-thinning did not work under the threshold which is designed as a starting point in self-thinning mortality by the stand density module. The calculation of relative density is done using equation 3.3 and the current SDI was calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. My design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data

(Schnur, 1937; Drew et al, 1979).

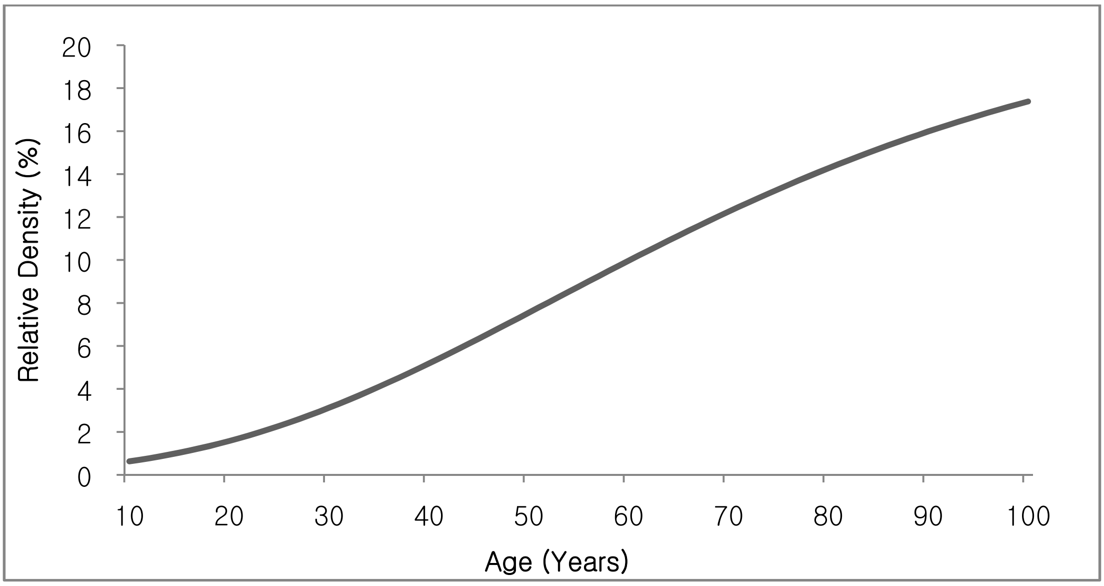


Figure 5.1 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand at age 10 with the initial number 50 starts from 1.0 square feet per acre and increases steadily because of tree growth over time (Fig. 5.2). Its trajectory showed a similar pattern to that of relative density (Fig. 5.1). For simulation year 90, there is no decrease or fluctuation because self-thinning did not work due to low relative density. At age 100, the basal area becomes 21 square feet per acre and it is the maximum basal area for the simulation year 90. The pattern of change of basal area over time also matches the pattern of the basal area in growth and yield table of Schnur (1937).

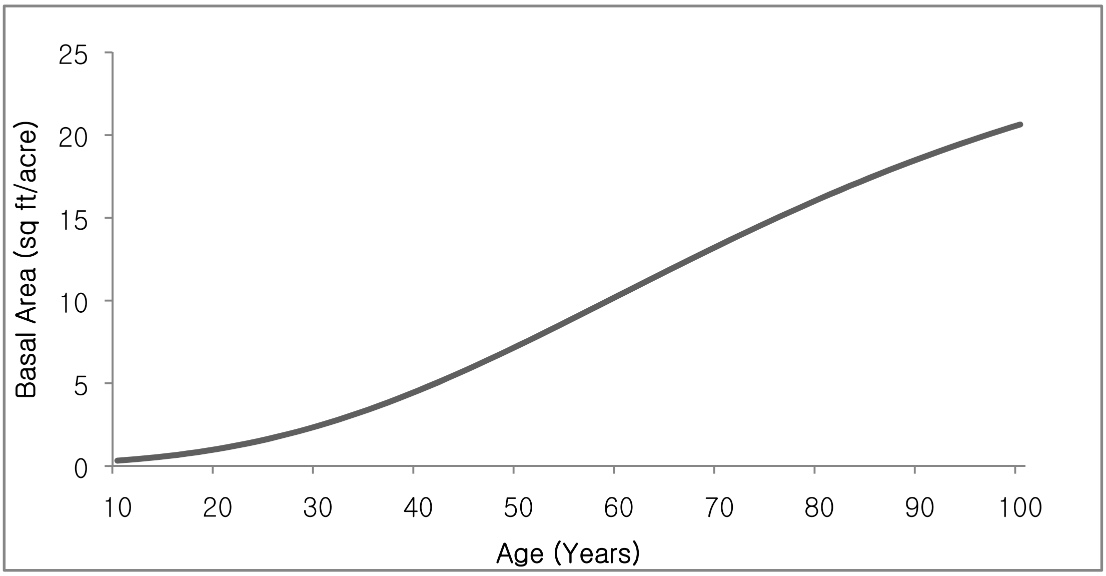


Figure 5.2 The change of basal area by simulation year 90 with no harvest, disturbances, or regeneration.

5.2.2 Single-species even-aged stand with the initial number 100

Based on estimated growth and mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 100 at age 10 year were simulated for 90 years. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand at age 10 with the initial number 100 starts from 1% and increases steadily because of trees growth over time (Fig. 5.3). For simulation year 90, there is no decrease or fluctuation because relative stand density did not reach the threshold where self-thinning works. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. My design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data (Schnur, 1937; Drew et al, 1979).

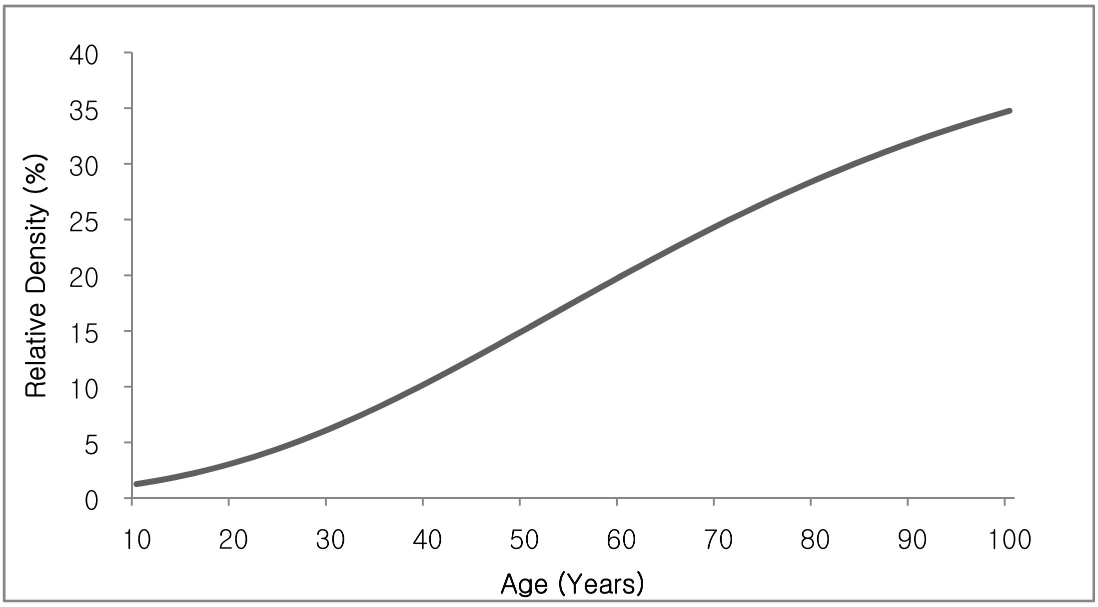


Figure 5.3 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand at age 10 with the initial number 100 starts from 1.0 square feet per acre and increases steadily because of tree growth over time (Fig. 5.4). Its trajectory shows a similar pattern to that of relative density (Fig. 5.3). At age 100, the basal area becomes 41 square feet per acre and it is the maximum basal area for the simulation year 90. For simulation year 90, there is no decrease or fluctuation because relative stand density did not reach the threshold where self-thinning works. The pattern of change of basal area over time also matches the pattern of the basal area in growth and yield table of Schnur (1937).

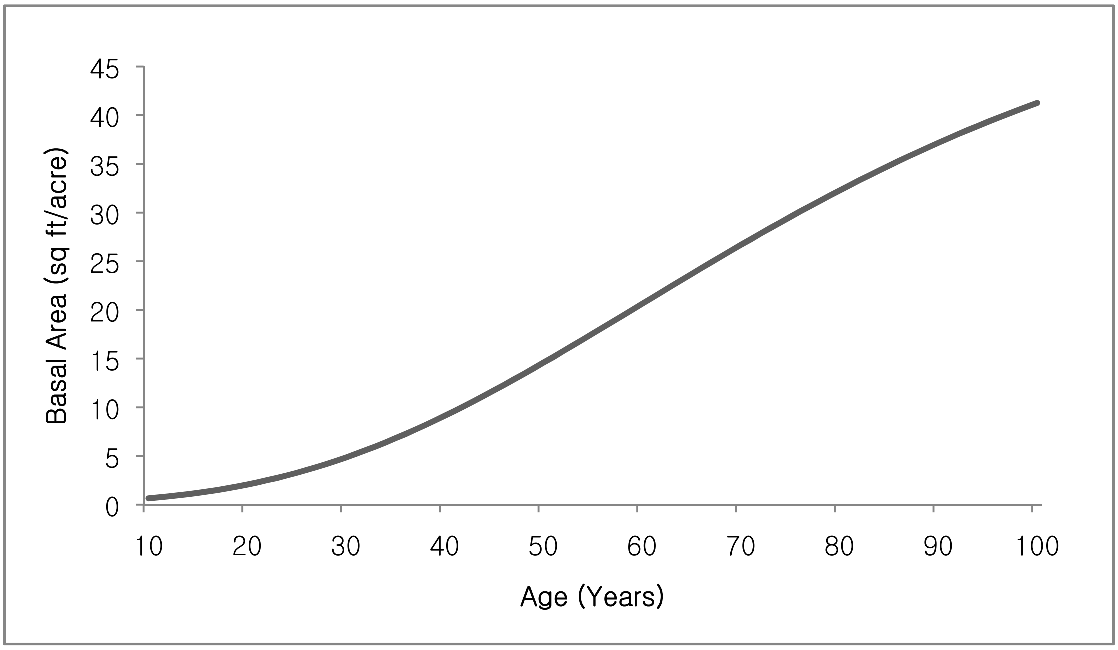


Figure 5.4 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

5.2.3 Single-species even-aged stand with the initial number 200

Based on estimated growth and modified mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 200 at 10 year were simulated for 90 years. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand with the initial number 200 at 10 year starts from 2% and increases steadily because of trees growth over time (Fig. 5.5). At about simulation year 70, relative density reaches 55% at which point tree number begins to decrease because SDI algorithm is designed that self-thinning starts when relative density reaches this value. The trajectory of relative density starts to decrease relatively from this point and it is the range of relative density which self-thinning works in field. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. My design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data (Schnur, 1937; Drew et al, 1979).

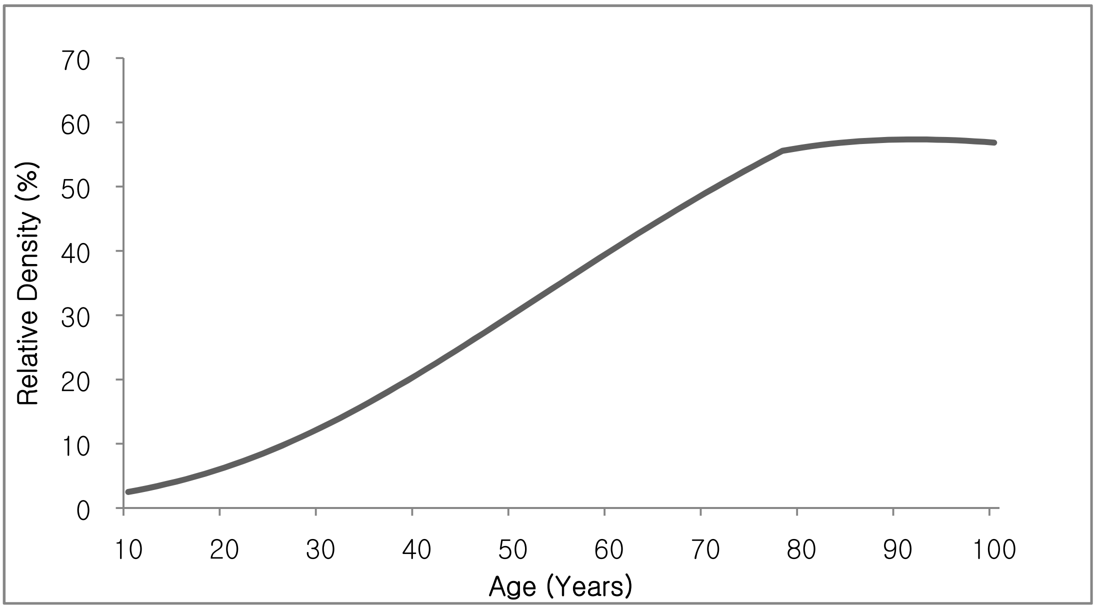


Figure 5.5 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand with the initial number 200 at 10 year starts from 1.5 square feet per acre and increases steadily because of tree growth over time (Fig. 5.6). Its trajectory shows a similar pattern to that of relative density (Fig. 5.5). At about simulation year 70, basal area reaches 75 square feet/acre at which point it begins to decrease because self-thinning starts. The trajectory starts to change from this point. At age 100, the basal area becomes 68 square feet per acre and it is the maximum basal area for the simulation year 90. The pattern of change of basal area over time also matches the pattern of the basal area in growth and yield table of Schnur (1937).

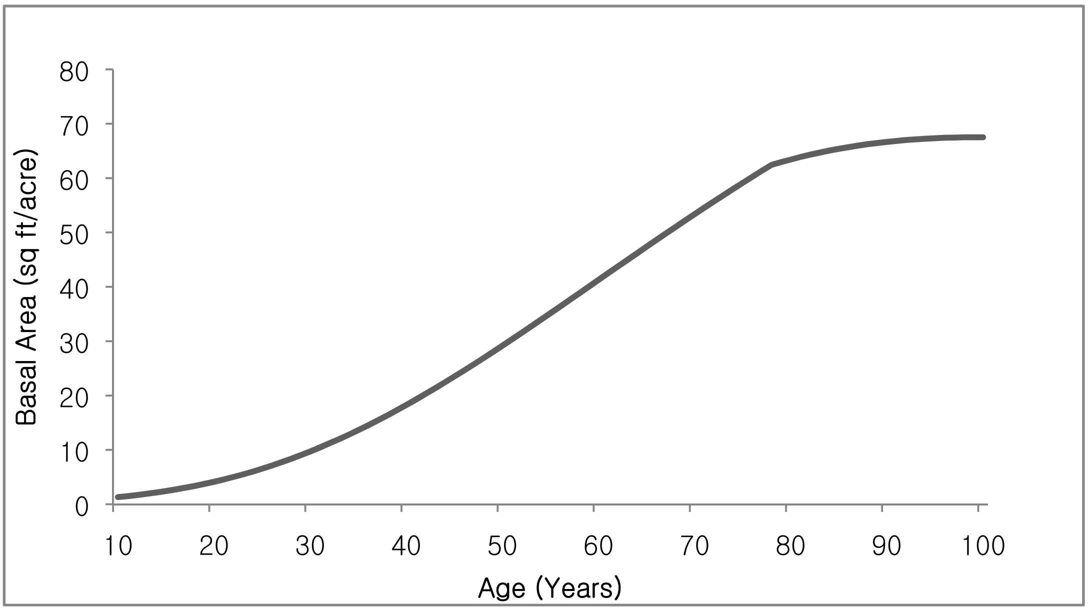


Figure 5.6 The simulation results for basal area by simulation year 90 with no harvest, disturbances or regeneration.

5.2.4 Single-species even-aged stand with the initial number 400

Based on estimated growth and modified mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 400 at 10 year were simulated for simulation year 90. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand with the initial number 400 at 10 year starts from 5% and increases steadily because of trees growth over time. At age 49, relative density reaches 55% at which point tree number begins to decrease because SDI algorithm is designed that self-thinning starts when relative density reaches this value. The trajectory of relative density starts to decrease from this point (Fig. 5.7) and it is the range of relative density which self-thinning works in field. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. My design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data (Schnur, 1937; Drew et al, 1979).

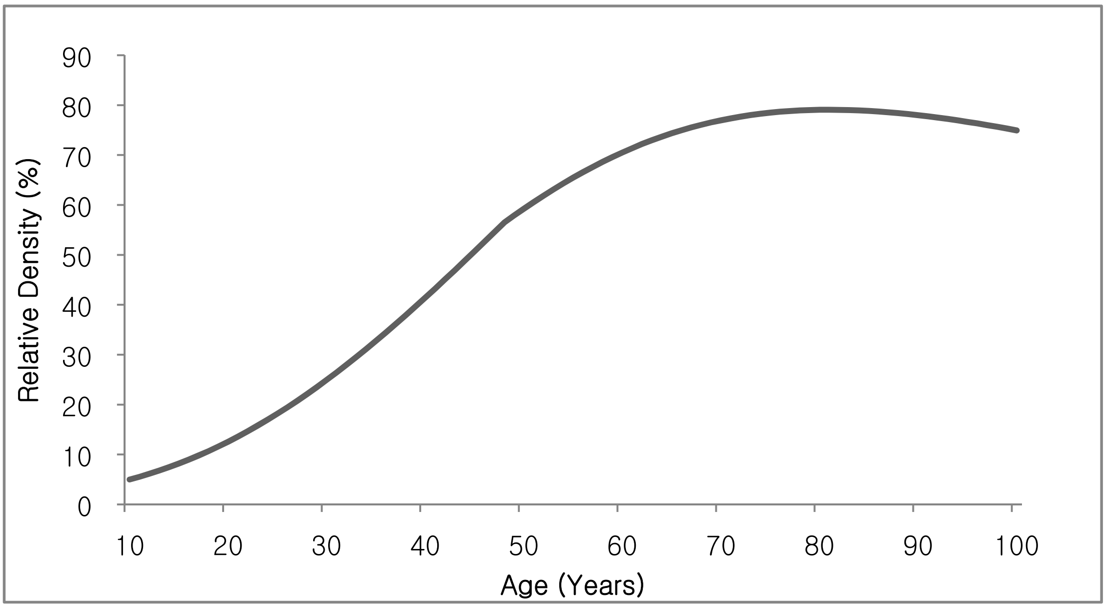


Figure 5.7 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand with the initial number 400 at 10 year starts from 3.0 square feet per acre and increases steadily because of tree growth over time. Its trajectory shows a similar pattern to that of relative density (Fig. 5.7). At about age 49, basal area reaches 56 square feet/acre at which point, number of trees begins to decrease because self-thinning starts. The trajectory starts to change from this point (Fig. 5.8). After year 90, the basal area start to decrease and at age 89, the basal area becomes its maximum value, 90.7 sq ft/acre and at age 100. The pattern of change in basal area over time also reasonably matches the pattern of the basal area in growth and yield table of Schnur (1937).

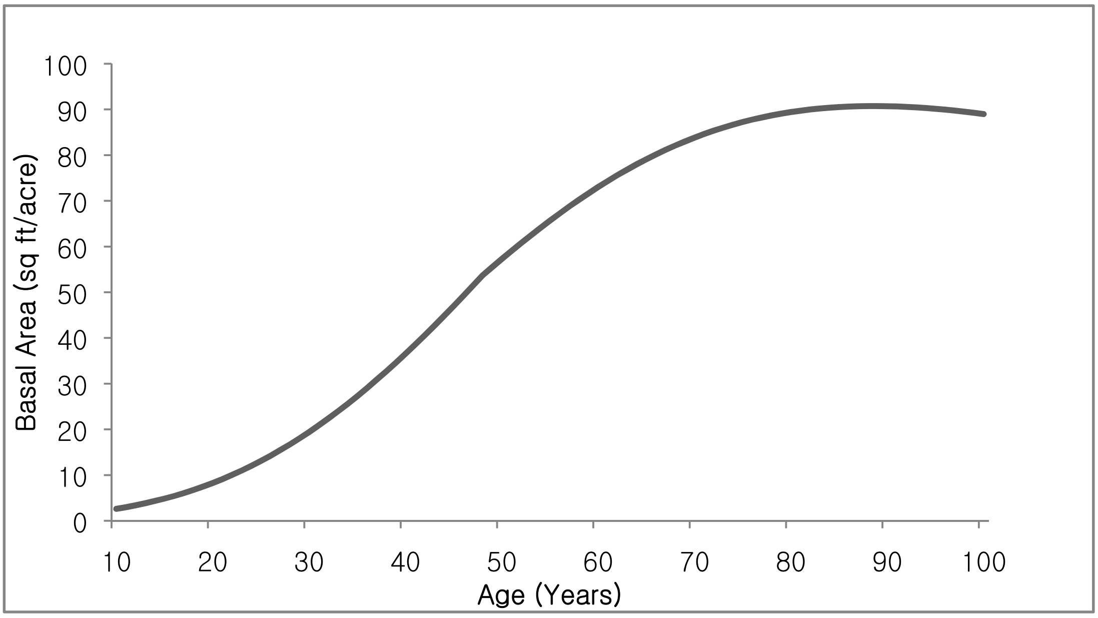


Figure 5.8 The simulation results for basal area by simulation year 90 with no harvest, disturbances or regeneration

5.2.5 Single-species even-aged stand with the initial number 800

Based on estimated growth and modified mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 800 at 10 year were simulated for 90 years. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand with the initial number 800 at 10 year starts from 10% and increases steadily because of trees growth over time. At age 33, relative density reaches 55% at which point tree number begins to decrease because SDI algorithm is designed that self-thinning starts when relative density reaches this value. The trajectory of relative density starts to decrease from this point (Fig. 5.9) and it is the range of relative density which self-thinning works in field. At age 52, the relative density reach 100% and it starts to fluctuate by random number of mortality to make relative density ranges from 95% to 100%. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. Thus, my design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data (Schnur, 1937; Drew et al, 1979).

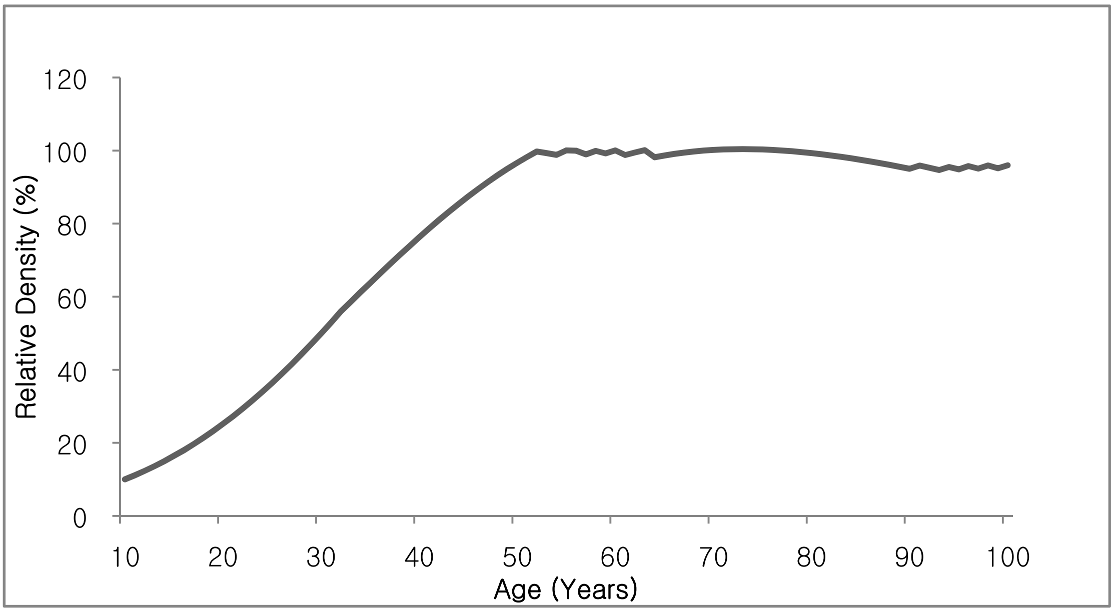


Figure 5.9 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand with the initial number 800 at 10 year starts from 3.0 square feet per acre and increases steadily because of tree growth over time. Its trajectory shows a similar pattern to that of relative density (Fig. 5.9). At about age 49, basal area reaches 56 square feet/acre at which point, number of trees begins to decrease because self-thinning starts. At age 100, the basal area becomes 114 square feet per acre and it is the maximum basal area for simulation year 90. The trajectory starts to change from this point (Fig. 5.10). The pattern of change in basal area over time also generally matches the pattern of the basal area in growth and yield table of Schnur (1937).

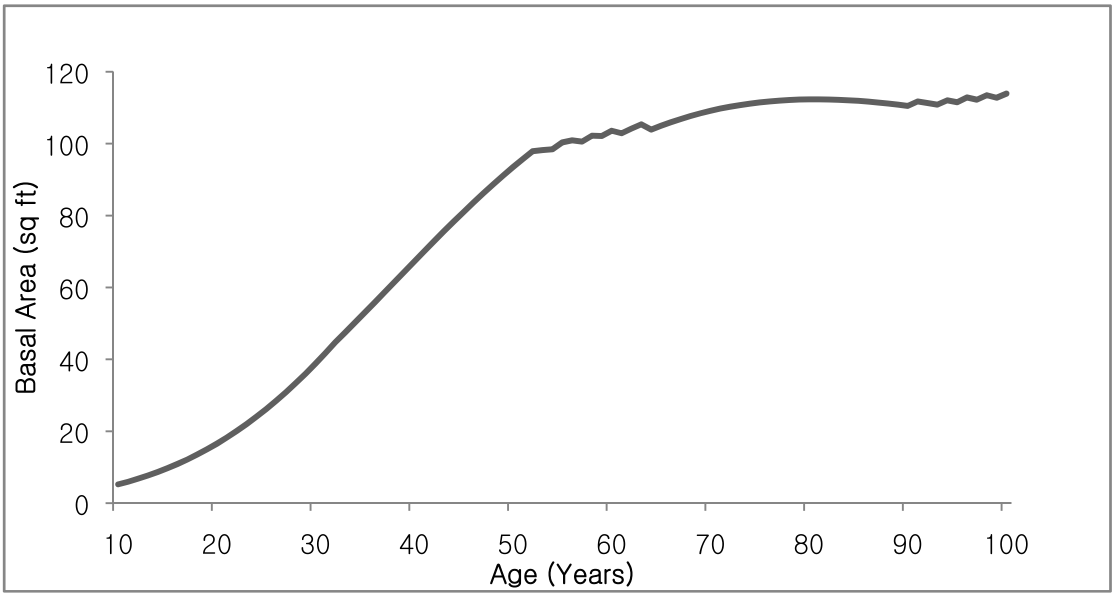


Figure 5.10 The simulation results for basal area by simulation year 90 with no harvest, disturbances or regeneration.

5.2.6 Single-species even-aged stand with the initial number 1600

Based on estimated growth and modified mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 1600 at 10 year were simulated for 90 years. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand with the initial number 1600 at 10 year starts from 20 and increases steadily because of trees growth over time. At age 23, relative density reaches 55% at which point tree number begins to decrease because SDI algorithm is designed that self-thinning starts when relative density reaches this value. The trajectory of relative density starts to change from this point (Fig. 5. 11) and it is the range of relative density which self-thinning works in field. At age 34, the relative density reach 100% and it starts to fluctuate by random number of mortality to make relative density ranges from 95% to 100%. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. Thus, my design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data (Schnur, 1937; Drew et al, 1979).

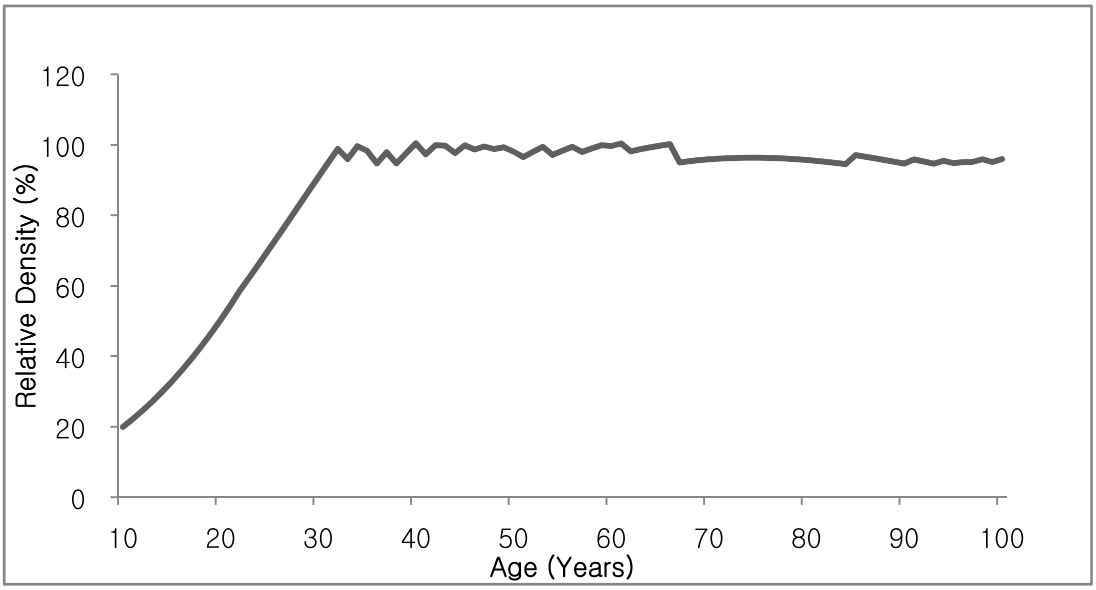


Figure 5.11 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand with the initial number 1600 at 10 year starts from 3.0 square feet per acre and increases steadily because of tree growth over time. Its trajectory shows a similar pattern to that of relative density (Fig. 5.11). At about age 49, basal area reaches 95 square feet/acre at which point, number of trees begins to decrease because self-thinning starts. The trajectory starts to change from this point (Fig. 5.12). Even though fluctuations happen, the basal area generally keeps growing as time goes. At age 100, the basal area becomes 114 square feet per acre and it is the maximum basal area for the simulation year 90. The pattern of change in basal area over time also generally matches the pattern of the basal area in growth and yield table of Schnur (1937).

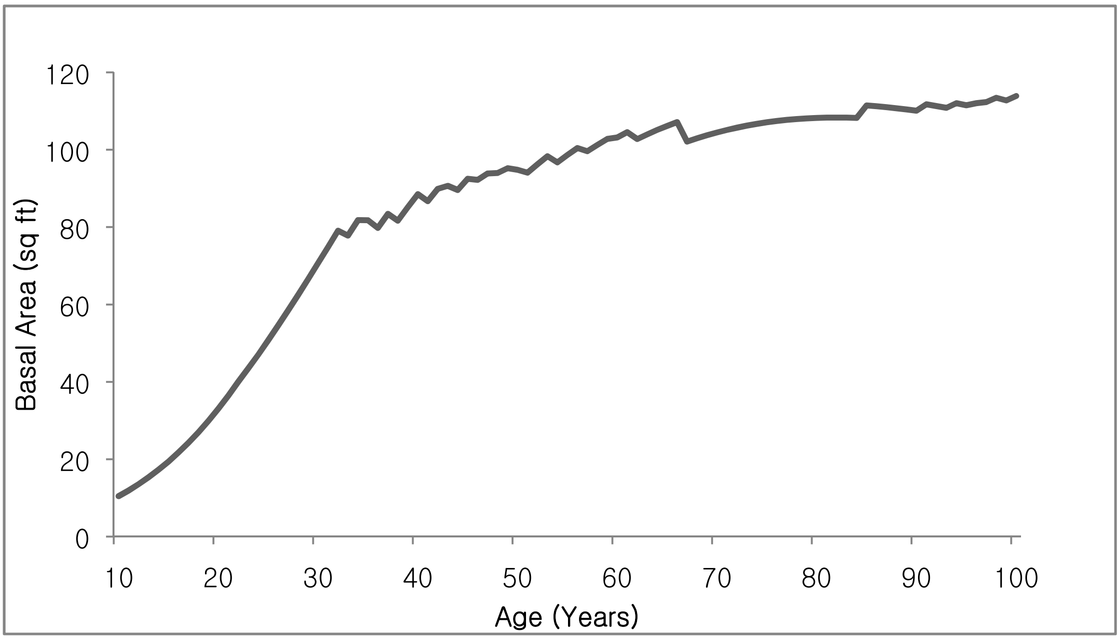


Figure 5.12 The simulation results for basal area by simulation year 90 with no harvest, disturbances or regeneration.

5.2.7 Single-species even-aged stand with initial number 3200

Based on estimated growth and modified mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 3200 at 10 year were simulated for 90 years. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand with the initial number 3200 at 10 year starts from 40 and increases steadily because of trees growth over time. At age about 14, relative density reaches 55% at which point tree number begins to decrease because SDI algorithm is designed that self-thinning starts when relative density reaches this value. The trajectory of relative density starts to change from this point (Fig. 5.13) and it is the range of relative density which self-thinning works in field. At age 21, the relative density reach 100% and it starts to fluctuate by random number of mortality to make relative density ranges from 95% to 100%. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. Thus, my design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data (Schnur, 1937; Drew et al, 1979).

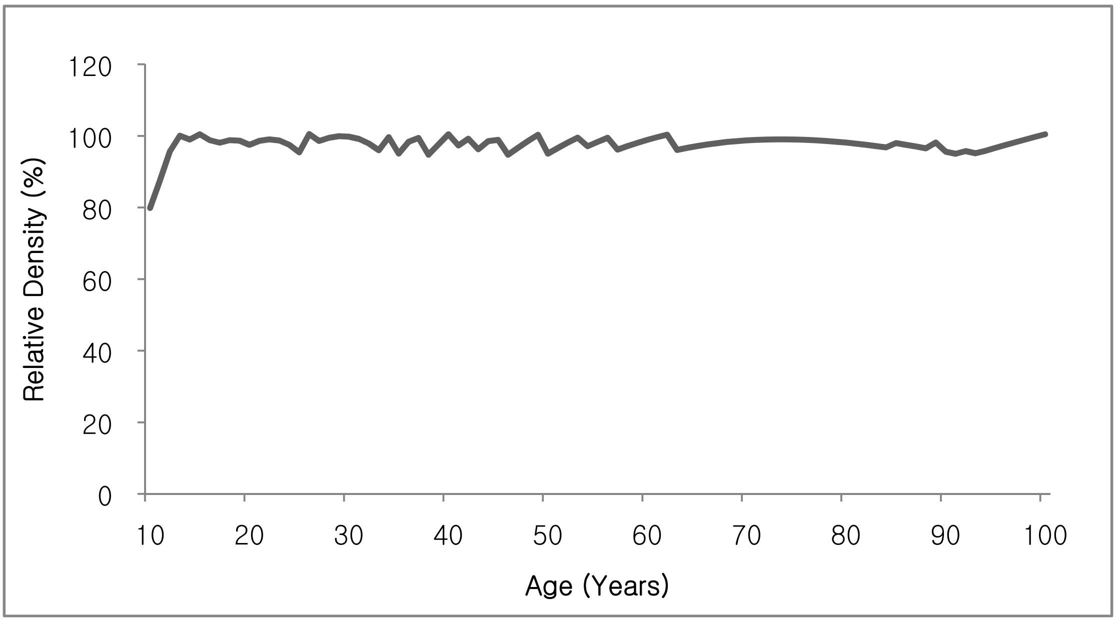


Figure 5.13 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand with the initial number 3200 at 10 year starts from 20 square feet per acre and increases steadily because of tree growth over time. Its trajectory shows a similar pattern to that of relative density (Fig. 5.13). At about age 15, basal area reaches 38 square feet/acre at which point, number of trees begins to decrease because self-thinning starts. The trajectory starts to change from this point (Fig. 5.14). Even though fluctuations happen, the basal area generally keeps growing as time goes. At age 100, the basal area becomes 119 square feet per acre and it is the maximum basal area for the simulation year 90. The pattern of change in basal area over time also generally matches the pattern of the basal area in growth and yield table of Schnur (1937).

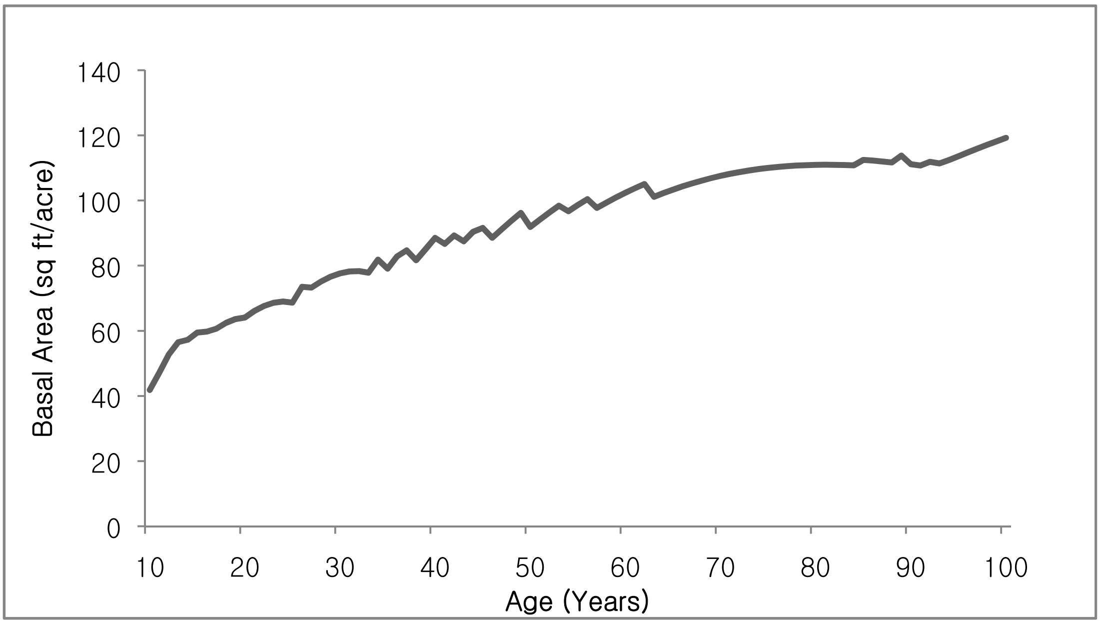


Figure 5.14 The simulation results for basal area by simulation year 90 with no harvest, disturbances or regeneration.

5.2.8 Single-species even-aged stand with initial number 6400

Based on estimated growth and modified mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 6400 at 10 year were simulated for 90 years. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand with the initial number 6400 at 10 year starts from 80 and increases steadily because of trees growth over time. Because the relative stand density starts from 80% that SDI algorithm is designed that self-thinning works when relative density are among this value, self-thinning starts to work from the simulation year 1 and it is the range of relative density which self-thinning works in field (Fig. 5.15). At age 13, the relative density reach 100% and it starts to fluctuate by random number of mortality to make relative density ranges from 95% to 100%. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. Thus, my design of relative density in SDI module correctly modeled the dynamics of relative density illustrated by field data (Schnur, 1937; Drew et al, 1979).

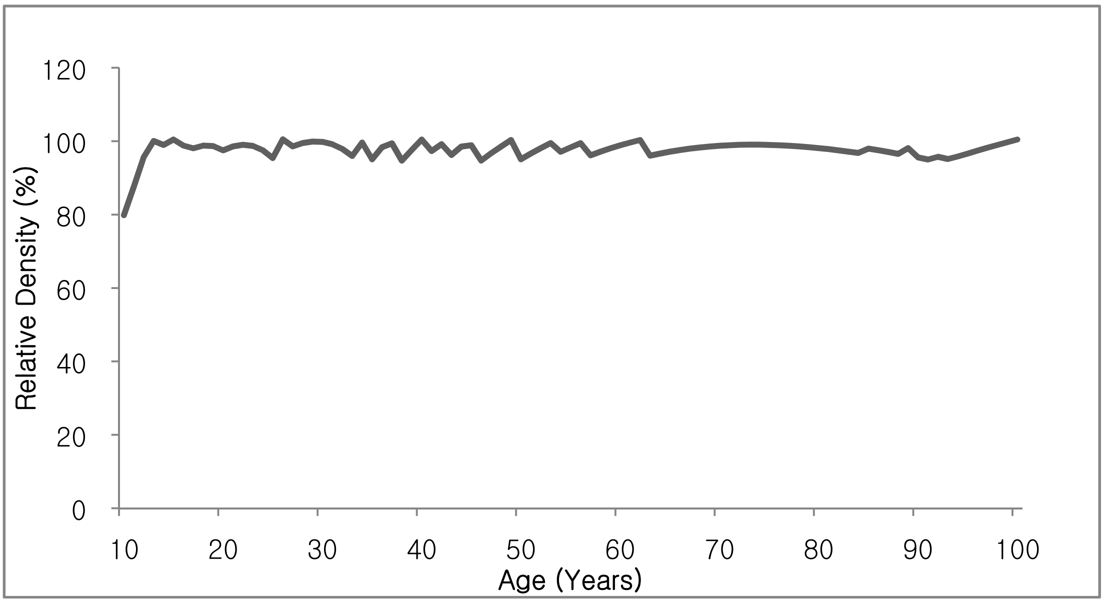


Figure 5.15 The change of relative density by simulation year 90 with no harvest, disturbances, or regeneration.

Basal area of the upland white oak of even-aged stand with the initial number 6400 at 10 year starts from 42 square feet per acre and increases steadily because of tree growth over time. Its trajectory shows a similar pattern to that of relative density (Fig. 5.15). At age 13, the trajectory starts to fluctuate from this point where the relative stand density reaches 100 % (Fig. 5.16). Even though fluctuations happen, the basal area generally keeps growing as time goes. At age 100, the basal area becomes 119 square feet per acre and it is the maximum basal area for the simulation year 100. The pattern of change in basal area over time also generally matches the pattern of the basal area in growth and yield table of Schnur (1937).

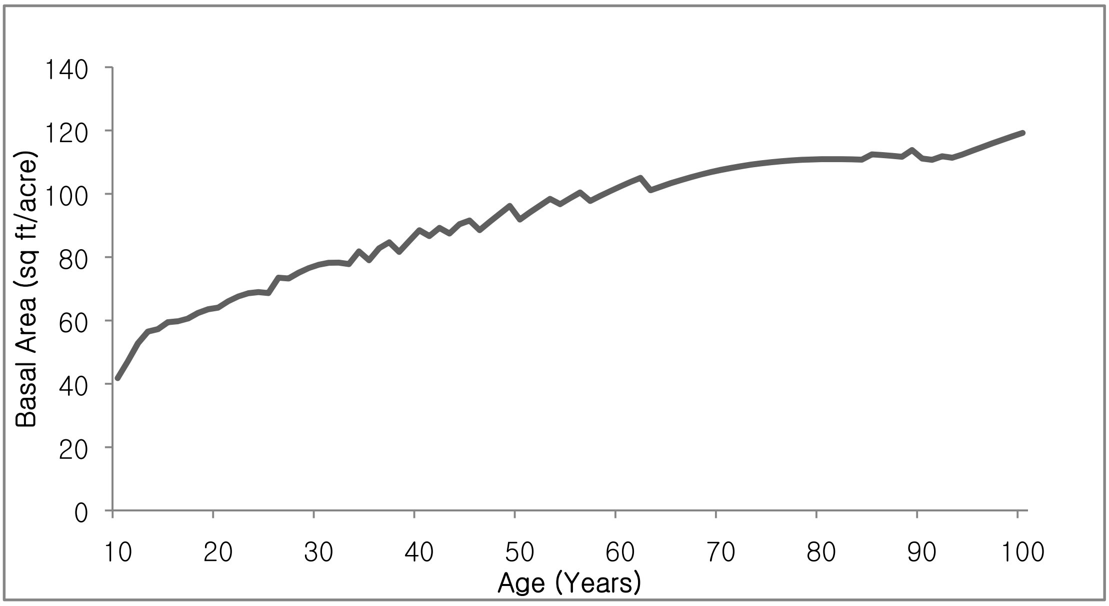


Figure 5.16 The simulation results for basal area by simulation year 90 with no harvest, disturbances or regeneration.

5.2.8 Comparisons on the change in relative density with variable initial numbers of trees.

The change in relative stand density with various initial numbers of trees at age 10 was compared for simulation year 90. The trajectories of relative density based on different scenarios in initial number of tree clearly show the relationship that high initial number of trees corresponds to faster growth and higher value in relative density (Fig. 5.17). The stands with the initial number ranging from 50 to 400 at age 10 do not reach relative stand density 100, which implicate that those initial numbers of trees are not enough to reach the maximum stand density index. The stand with the initial number of trees over 800 at age 10 reached the stand relative density 100.

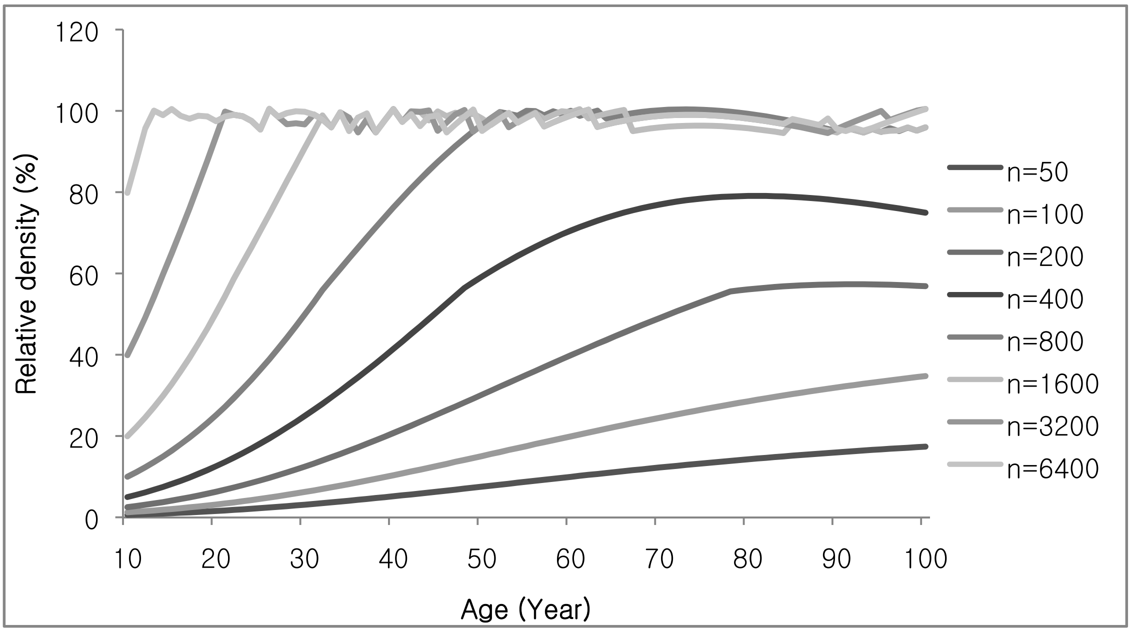


Figure 5.17 Change of relative density with various initial numbers of trees. n is initial number of tree of oak at age 10 in one acre.

5.2.9 Comparisons on the change in basal area with variable initial numbers of trees.

The change in basal area with various initial numbers of trees of upland oak at age 10 was compared for simulation year 90. The trajectories of basal area based on different scenarios in initial number of tree clearly show the relationship that high initial number of trees corresponds to faster growth and higher value in basal area (Fig. 5.18). The stands with the initial number ranges from 50 to 400 do not reach the estimated maximum basal area (120 sq ft/acre), which implicate that those initial numbers of trees are not enough to reach the maximum basal area per acre. The stands with the initial number of trees over 800 reach the estimated maximum basal area. Considering the change in relative density, the change of basal area is more slowly increased than that of relative density in the condition that the initial number is same. Thus, even though the relative density of each stand reaches maximum stand density, the basal area did not always reach the estimated maximum basal area.

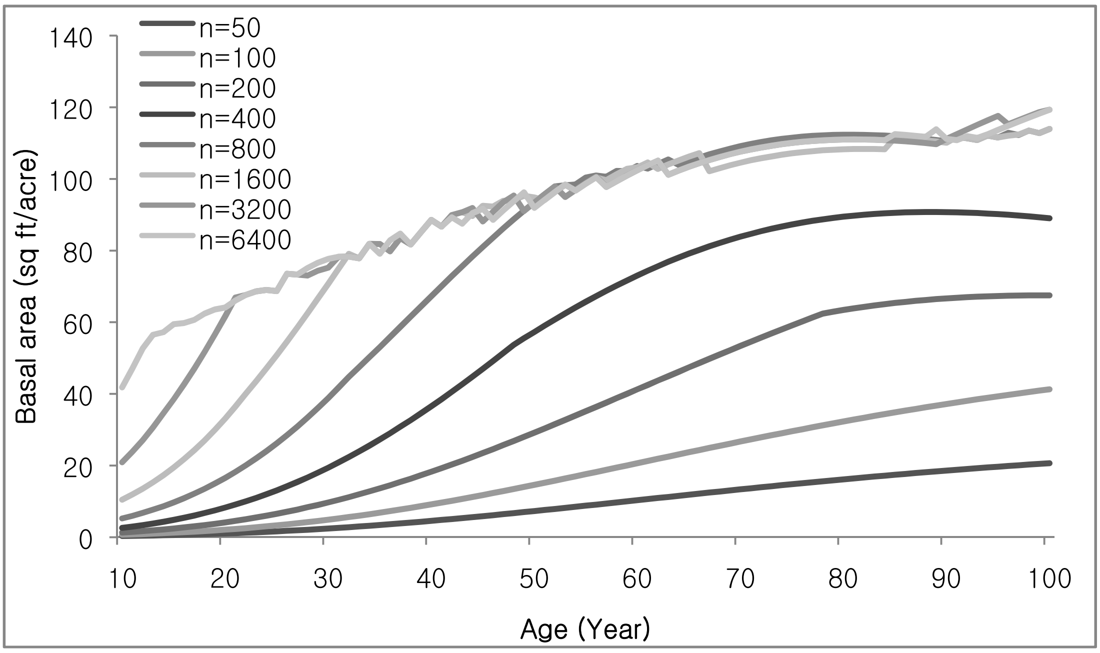
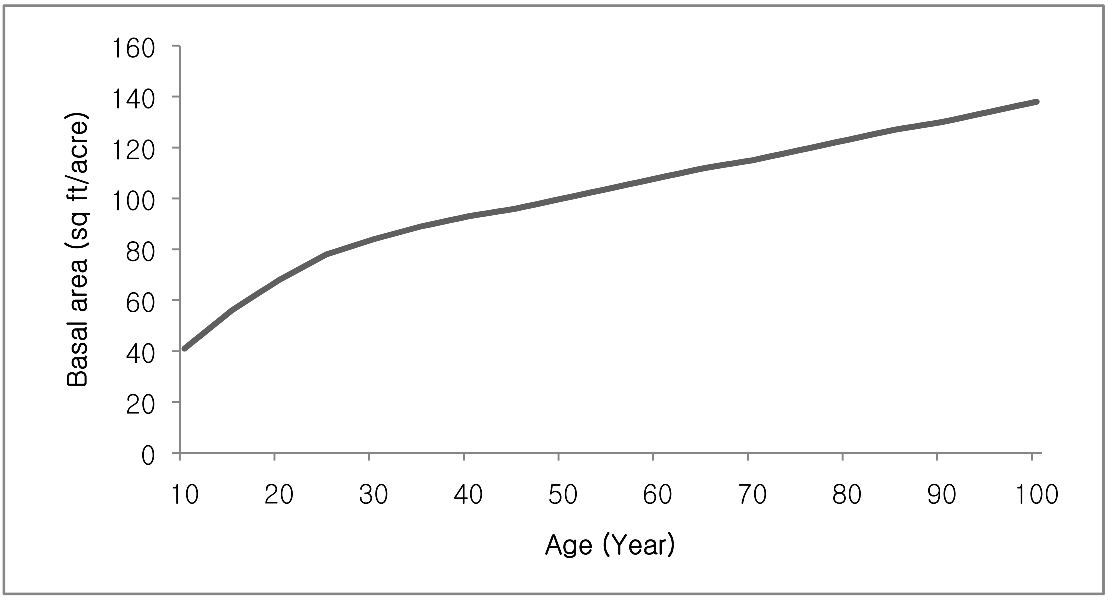


Figure 5.18 Changes of basal area with various initial numbers of trees. n is initial number of tree of oak at age 10 in one acre.

5.3 Sensitivity analyses on the estimation of basal area in even-age stand with the Stand Density Module with self-thinning mortality model.

Sensitivity analysis is used to describe how sensitive a model is to changes in the value of the parameters of the model and to changes in the structure of the model. I conducted the sensitivity analysis on parameters as a series of tests to see how a change in the parameter bring a change in the dynamics of the stand and to determine what level of accuracy is required for a parameter to make the model useful and valid. For the purpose, I conducted the sensitivity analysis on the parameters of maximum stand density index, slope of maximum stand density index, and the average of mortality rate against relative stand density with reasonable parameters and will make the outcomes based on the parameters changes.

As the base of a field data to compare the simulation results, the basal area of upland oak at age 10 in site index 60 for simulation year 90 was selected (Schuner, 1937). Every simulation runs with changing parameters for the sensitivity analysis were conducted based on the same initial conditions. (Number of tree =4020, age =10, and area = one acre) to detect the effects on changing parameters.



5.19 The change in basal area of upland oak with initial number 4020 at age 10 in site index 60 (Schnur, 1937)

5.3.1 The effect of change in the maximum stand density index

The stand density maximum number was explored for the sensitivity analysis as one of crucial parameter to decide the relative stand density and the maximum basal area in a stand (Fig. 5.20). The models starts off in almost equilibrium, but after about simulation year 18 each line of different SDImax show the distinctive trajectories slightly. As the SDImax is higher, the simulation results of basal area become higher because higher SDImax enhanced the stand capacity of having more number of trees at a standard condition.

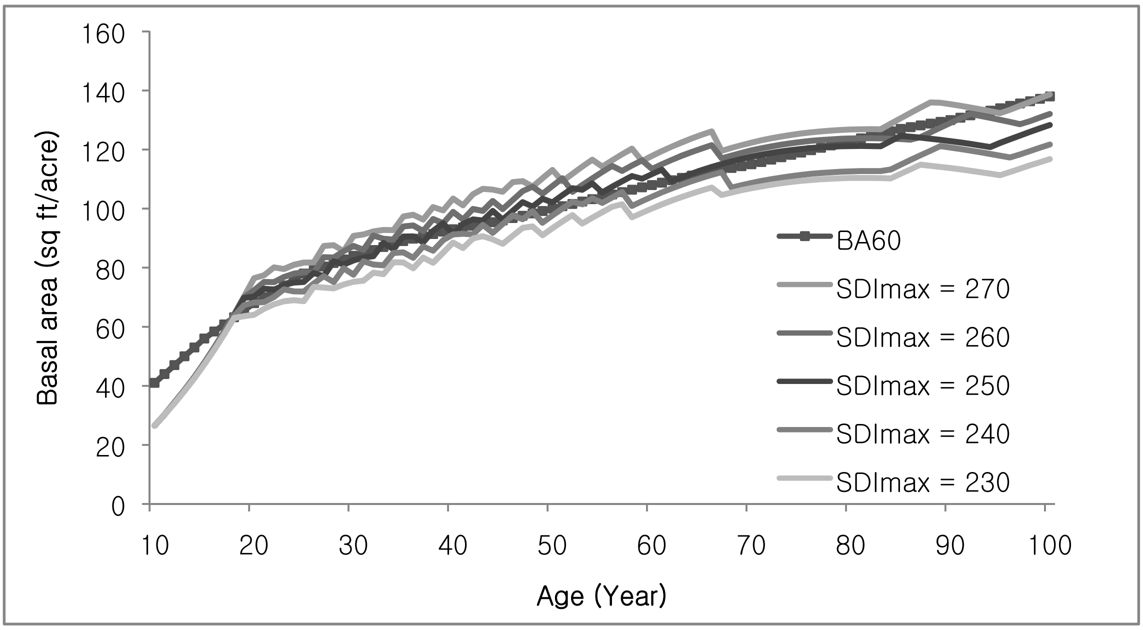


Figure 5.20 The effects on changes in the maximum stand density. BA60 is the change of basal area from the real field data (Schnur, 1937).

Based on the simulation results with various maximum stand density indexes, correlation analyses with the change in basal area of field data (Schnur, 1937) were conducted to analyze the fitness with the changes in basal area with various maximum stand densities (Table 5.1).

Table 5.1 Pearson's product-moment correlation with the change of basal area in the field data (BA60, Schnur, 1937) and the change of basal area in various maximum stand density.

	BA60
SDImax = 230	0.9804854
SDImax = 240	0.9795688
SDImax = 250	0.9785062
SDImax = 260	0.9780899
SDImax = 270	0.97742

Note) All correlation coefficients are highly significant (p < 0.0001).

5.3.2 The effect of change in the slope of maximum stand density index

The slope of maximum stand density index was explored for the sensitivity analysis to investigate how sensitive changes in the value of the slope of maximum stand density on the change of basal area in a stand (Fig. 5.21). The models start off in equilibrium, but after about simulation year 18 each line of different slopes of SDImax showed the distinctive trajectories slightly. However, for simulation year 90, their trajectories with different slopes of SDImax showed almost similar patterns of basal area change.

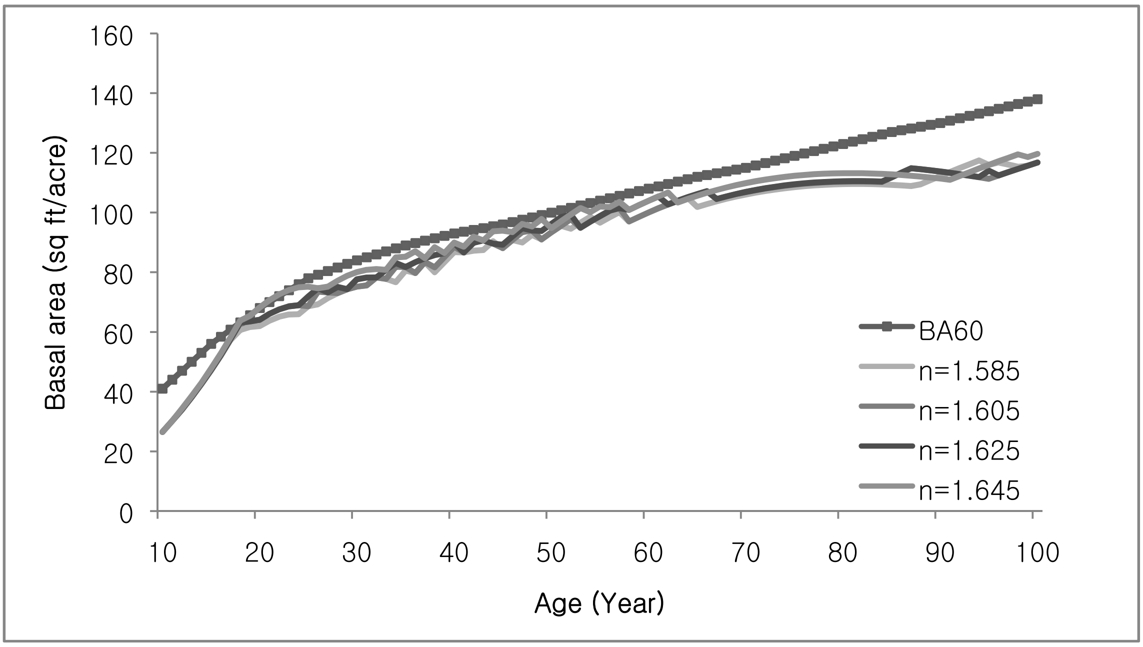


Figure 5.21 The effects on changes in the slope of maximum stand density. BA60 is the real field data (Schnur, 1937) and n means the parameters that decide the slope of maximum stand density index.

Based on the simulation results with various parameters that decide the slope of maximum stand density indexes, correlation analyses were conducted with the change in basal area of field data (Schnur, 1937) to analyze their fitness (Table 5.2).

Table 5.2 Pearson's product-moment correlation with the change of basal area in the field data (BA60, Schnur, 1937) and the change of basal area in various slopes of maximum stand density. n means the parameters that decide the slope of maximum stand density index.

	BA60
n=1.585	0.985405
n=1.605	0.980485
n=1.625	0.977985
n=1.645	0.974483

Note) All correlation coefficients are highly significant ($p < 0.0001$).

5.3.3 The effect of change in the mortality rate against relative stand density.

The mortality rate against relative stand density was explored for the sensitivity analysis to investigate how sensitive changes in the value of the mortality rate against relative stand density on the change of basal area in a stand (Fig. 5.22). The models start off in almost equilibrium, but after about simulation year 18 each line of different mortality rate against relative stand density showed the distinctive trajectories slightly. However, for simulation year 90, their trajectories with different mortality rate against relative stand density showed almost similar patterns of basal area change.

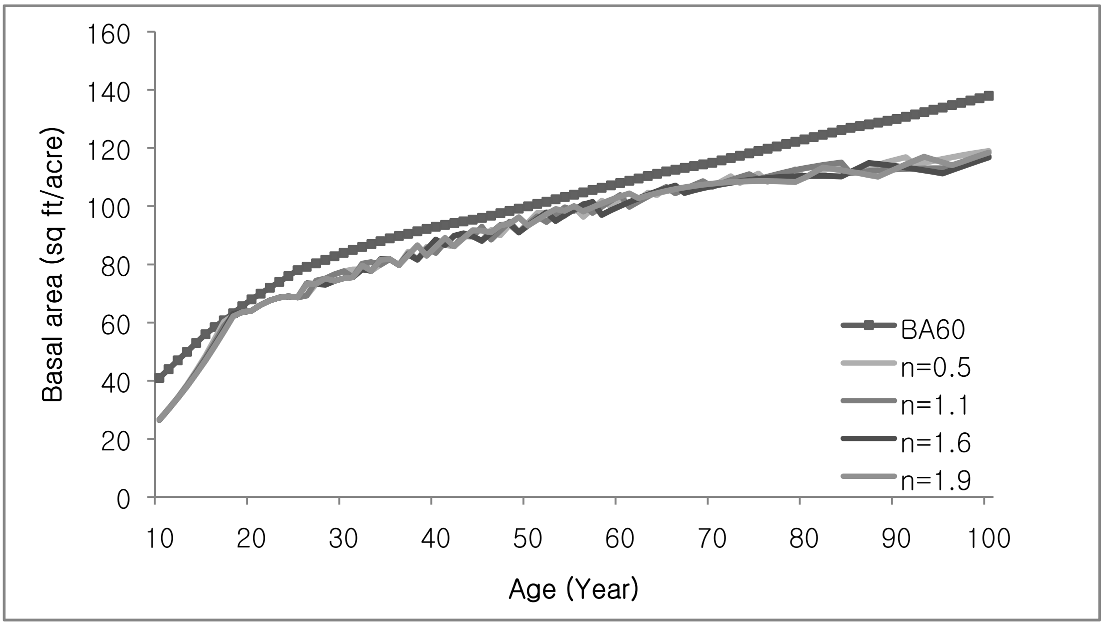


Figure 5.22 The effects on changes in the mortality rate against relative stand density. BA60 is the real field data (Schnur, 1937) and n means the parameters of the mortality rate against relative stand density.

Based on the simulation results with various parameters of the mortality rate against relative stand density, correlation analyses were conducted with the change in basal area of field data (Schnur, 1937) to analyze their fitness (Table 5.3).

Table. 5.3 Pearson's product-moment correlation with the change of basal area in the field data (BA60, Schnur, 1937) and the change of basal area in various mortality rates against relative density. n means the parameters of mortality rates against relative density.

	BA60
n= 0.5	0.985921
n=1.1	0.980499
n=1.6	0.980485
n=1.9	0.98174

Note) All correlation coefficients are highly significant ($p < 0.0001$).

5.4 Verification of the Stand Density Module in the quantification of stand basal area

Verification of the stand density module was conducted in the quantification in basal area with self-thinning model (Eq.3.7). Using the stand density module with mortality model (Eq. 3.1, Eq. 3.3, Eq. 3.6, Eq. 3.7, and Table 3.1), I simulated the change in the basal area with the same conditions of initial number, age, DBHqmax and SDImax in three stands having different site indexes from yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937). Finally, I compared the simulation results using the stand density module with mortality model to the trajectory of basal area in the field data (Schnur, 1937).

5.4.1 Verification of the stand density module with comparison of the simulation results of basal area with the trajectory of basal area in field data of site index 40.

Using the stand density module with the self-thinning mortality model (Eq. 3.1, Eq. 3.3, Eq. 3.6, Eq. 3.7, and Table 3.1), the basal area was simulated with the same initial conditions of number of tree, age, DBHqmax and maximum SDI in site index 40 from yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937). The simulation results of basal area generally fit very well the field data for simulation year 90 based on the correlation analysis using R (Figure. 5.23, Table 5.4).

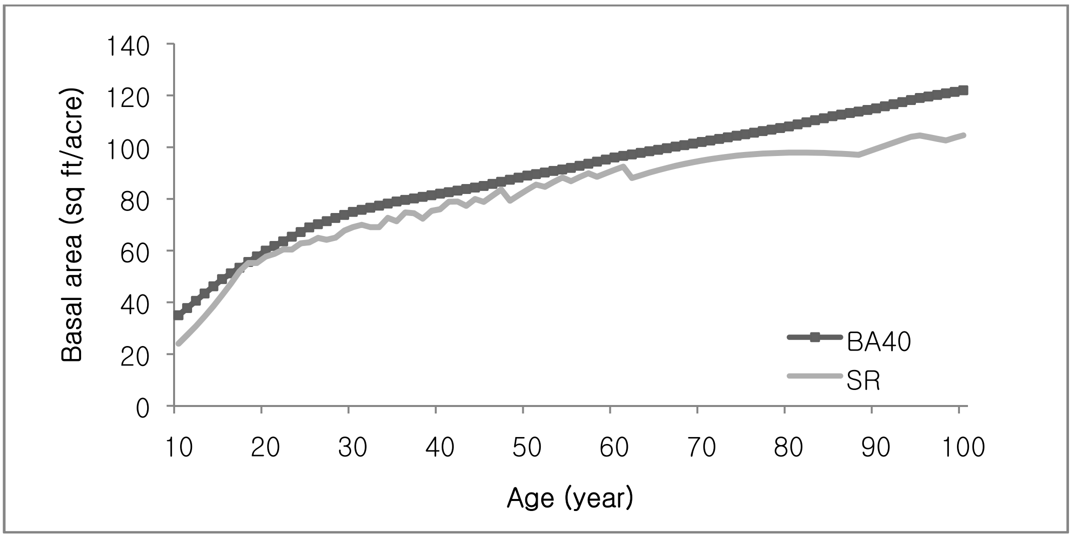


Figure 5.23 Comparison of the simulation results with the changes of basal in site index 40 from yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937). BA40 is the trajectory of basal area in site index 40 from the field data (Schnur, 1937) and SR is the simulation results with the same initial conditions (number of tree = 6850, age = 10, DBHqmax = 7.4 inch, SDImax =230).

Table. 5.4 Pearson's product-moment correlation between the change of basal area in the field data in site index 40 and the simulation results using the stand density module with self-thinning mortality model

Pearson's product-moment correlation
t = 54.0194, df = 89, p-value < 2.2e-16
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
0.9774439 0.9901578
sample estimates:
cor
0.9850905

5.4.2 Verification of the stand density module with comparison of the simulation results of basal area with the trajectory of basal area in field data of site index 60.

Using the stand density module with the self-thinning mortality model (Eq. 3.1, Eq. 3.3, Eq. 3.6, Eq. 3.7, and Table 3.1), the basal area was simulated with the same initial conditions of number of tree, age, DBHqmax and maximum SDI in site index 60 from yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937). The simulation results of basal area generally fit very well the field data for simulation year 90 based on the correlation analysis using R (Figure. 5.24, Table 5.5).

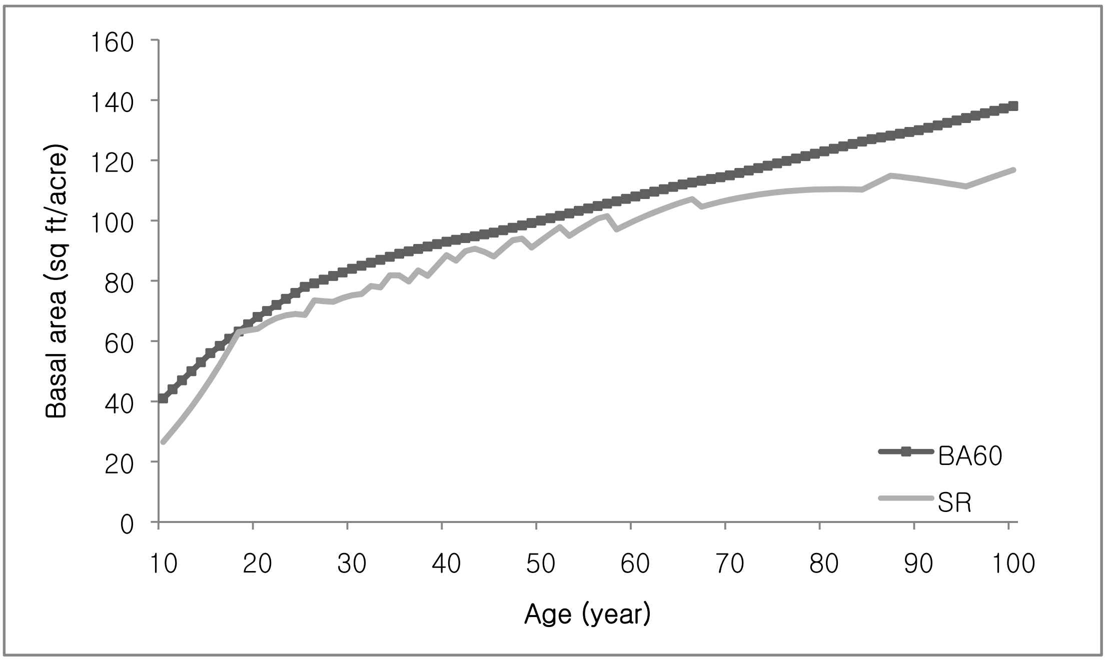


Figure 5.24 Comparison of the simulation results with the changes of basal in site index 60 from yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937). BA60 is the trajectory of basal area in site index 60 from the field data (Schnur, 1937) and SR is the simulation results with the same initial conditions (number of tree = 4060, age = 10, DBHqmax = 10.1 inch, SDImax =230).

Table. 5.5 Pearson's product-moment correlation between the change of basal area in the field data in site index 60 and the simulation results using the stand density module with self-thinning mortality model

Pearson's product-moment correlation
t = 54.0194, df = 89, p-value < 2.2e-16
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
0.9774439 0.9901578
sample estimates:
cor
0.9850905

5.4.3 Verification of the stand density module with comparison of the simulation results of basal area with the trajectory of basal area in field data of site index 80.

Using the stand density module with the self-thinning mortality model (Eq. 3.1, Eq. 3.3, Eq. 3.6, Eq. 3.7, and Table 3.1), the basal area was simulated with the same initial conditions of number of tree, age, DBHqmax and maximum SDI in site index 80 from yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937). The simulation results of basal area generally fit very well the field data for simulation year 90 based on the correlation analysis using R (Figure. 5.25, Table 5.6).

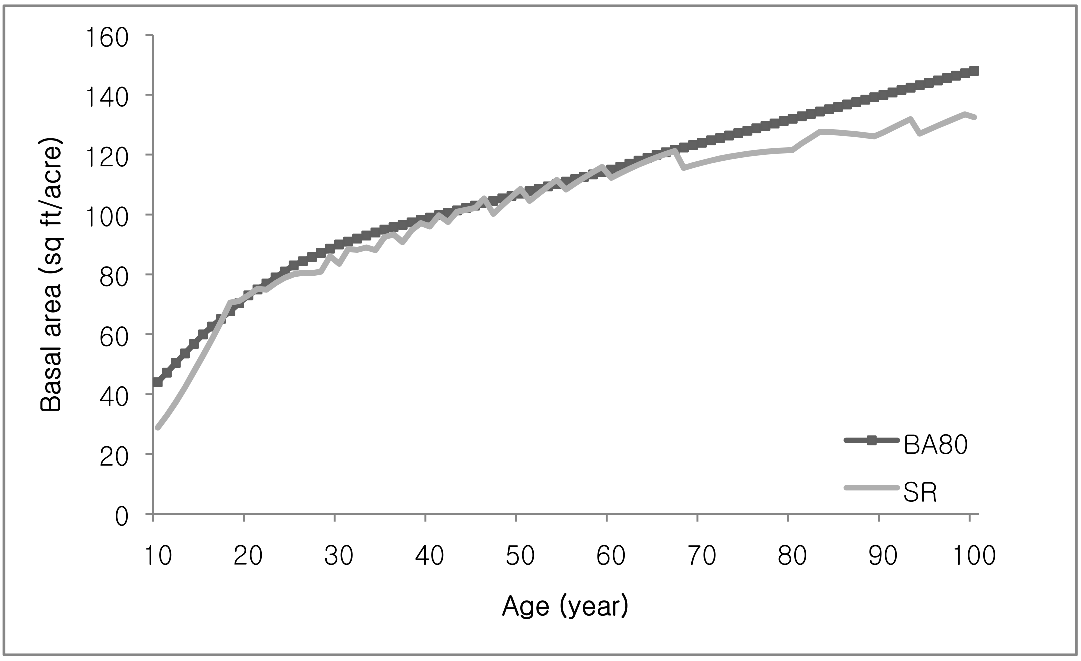


Figure 5.25 Comparison of the simulation results with the changes of basal in site index 80 from yield, stand and volume tables for even-aged upland oak forests (Schnur, 1937). BA80 is the trajectory of basal area in site index 80 from the field data (Schnur, 1937) and SR is the simulation results with the same initial conditions (number of tree = 2435, age = 10, DBHqmax = 13.6 inch, SDImax =230).

Table. 5.6 Pearson's product-moment correlation between the change of basal area in the field data in site index 80 and the simulation results using the stand density module with self-thinning mortality model

Pearson's product-moment correlation

t = 54.0194, df = 89, p-value < 2.2e-16

alternative hypothesis: true correlation is not equal to 0

95 percent confidence interval:

0.9774439 0.9901578

sample estimates:

cor

0.9850905

5.5 Scenarios with regeneration, fire disturbances and harvest.

The relative stand density and basal area were simulated based on the stand density module with self-thinning mortality model (Eq. 3.5, Eq. 3.6, Eq. 3.7) in the various scenarios of disturbances, harvest and regeneration. It is assumed that the physical site conditions are same in all stands and the simulation time-step was 1 year and the duration of simulation is 90 years

5.5.1 Scenario of regeneration

Based on estimated growth and mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 100 at age 10 year were simulated for 90 years. At simulation year 20, regeneration was simulated in a scenario that five hundred new seedlings of white oak were established. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand at age 10 with the initial number 100 (cohort 1) starts from 1% and increases steadily because of trees growth over time (Fig. 5.26). At simulation year 20, regeneration was simulated in a scenario that five hundred new seedlings of white oak and from the point of simulation year 20, the stand relative density become higher urgently. At simulation year 70, there happened to decrease or fluctuation in relative density because relative stand density reached the threshold of stand relative density where self-thinning starts to work. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 on table 3.1. My design of relative density in SDI module reasonably modeled the dynamics of relative density in a scenario of regeneration illustrated by field data (Schnur 1937, Drew et al, 1979).

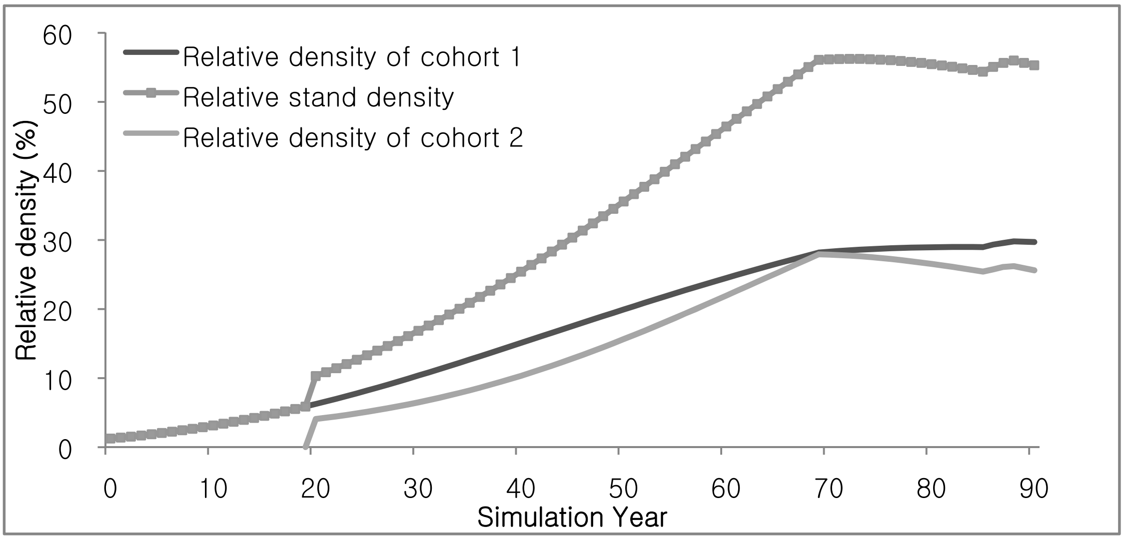


Figure 5.26 The change of relative density by simulation year 90 with regeneration at simulation year 20. Cohort 1 is old cohort of white oak and cohort 2 is regenerated cohort white oak.

Basal area of the upland white oak of even-aged stand at age 10 with the initial number 100 starts from 1.0 square feet per acre and increases steadily because of tree growth over time (Fig. 5.27). At simulation year 20, the stand basal area starts to increase urgently due to regeneration. At simulation year 70, the stand basal area begins to decrease because the stand relative density reached the threshold at which self-thinning starts to work. The pattern of change of basal area over time in a scenario of regeneration reasonably matches the pattern of the basal area in growth and yield table of Schnur (1937).

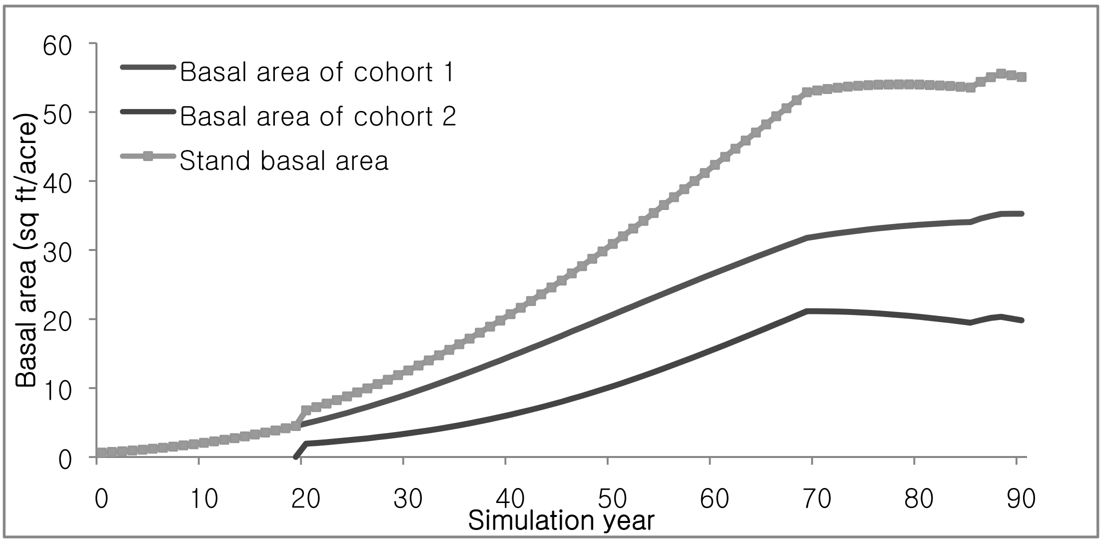


Figure 5.27 The change of relative density by simulation year 90 with regeneration. Cohort 1 is old cohort of white oak and cohort 2 is a regenerated cohort.

5.5.2 Scenario of regeneration and harvest

Based on estimated growth and mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 100 at age 10 year were simulated for 90 years. At simulation year 20, regeneration was simulated with a scenario that five hundred new seedlings of white oak were established. At simulation year 50, a scenario that harvests all trees of old cohort of white oak (cohort 1) was simulated. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand at simulation year 0 with the initial number 100 (cohort 1) starts from 1% and increases steadily because of trees growth over time (Fig. 5.28). At simulation year 20, regeneration was simulated in a scenario that five hundred new seedlings of white oak and from the simulation year 20, the stand relative density become higher urgently. At simulation year 50, a harvest on old cohort (cohort 1) are conducted and the stand relative density decreased dramatically by the scenario of harvest. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. My design of relative density in SDI module reasonably modeled the dynamics of relative density in a scenario of regeneration and harvest illustrated by field data (Schnur 1937, Drew et al, 1979).

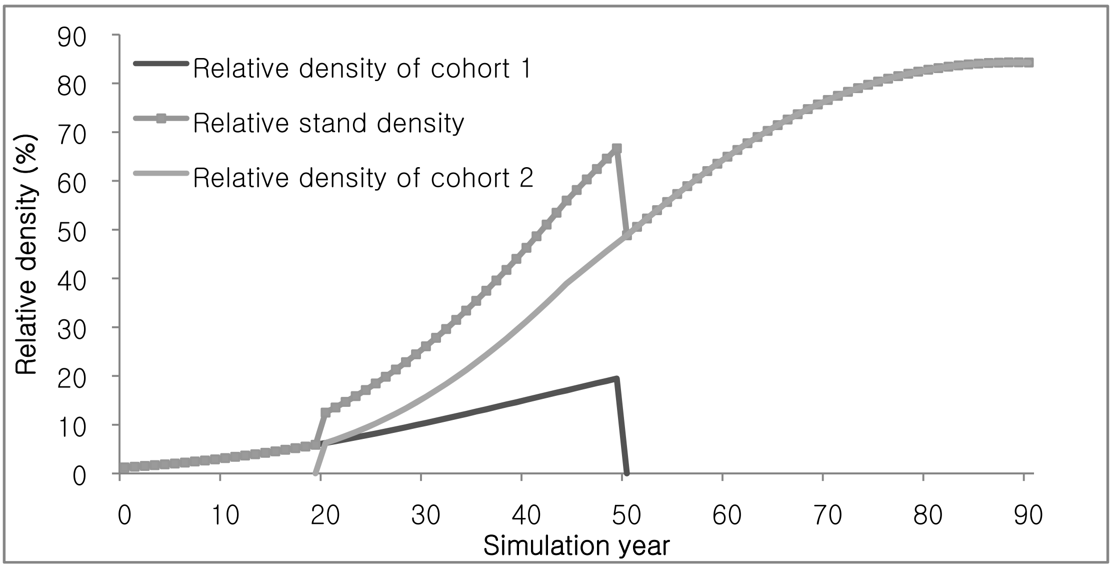


Figure 5.28 The change of relative density by simulation year 90 with regeneration at simulation year 20 and harvest at simulation year 50 on old cohort. Cohort 1 is old cohort of white oak and cohort 2 is regenerated cohort.

Basal area of the upland white oak of even-aged stand at simulation year 0 with the initial number 100 starts from 1.0 square feet per acre and increases steadily because of tree growth over time (Fig. 5.29). At simulation year 20, the stand basal area starts to increase urgently due to regeneration. At simulation year 50, the stand basal area decreases dramatically because the old cohort was removed by harvest. The pattern of change of basal area in a scenario of regeneration and harvest over time also reasonably simulated the pattern of the basal area in growth and yield table of Schnur (1937).

5.5.3 Scenario of regeneration, harvest, and fire disturbance

Based on estimated growth and mortality coefficients (Table 4.2, Table 4.5), relative density and basal area of white oak with the initial number 100 at age 10 year (cohort 1) were simulated for 90 years. At simulation year 20, regeneration was simulated with a scenario that five hundred new seedlings of white oak were established (cohort 2). At simulation year 50, a scenario that harvests all trees of old cohort of white oak (cohort 1) was simulated. At simulation year 80, a scenario of fire disturbance was operated, which resulted in removing all tree in the stand. At simulation year 81, regeneration of three hundred white oaks (cohort 3) was simulated. The trajectories of relative density, and basal area were calculated using equations 3.3, 3.6 and 3.7.

Relative density of upland white oak of even-aged stand at age 10 with the initial number 100 (cohort 1) starts from 1% and increases steadily because of trees growth over time (Fig. 5.29). At simulation year 20, regeneration was simulated with a scenario that five hundred new seedlings of white oak and from the year the stand relative density become higher urgently. At simulation year 50, a harvest on old cohort (cohort 1) are conducted and the stand relative density decreased dramatically by harvest. At simulation year 80, fire disturbance occurred, thus the entire tree in the stand are removed. At simulation year 81, regeneration of three-hundred white oaks was simulated (cohort 3) and the regeneration increased the stand relative density. The calculation of relative density is done using equation 3.3 and the current SDI is calculated using equation 3.1 and the maximum SDI is 230 based on table 3.1. My design of relative density in SDI module reasonably modeled the dynamics of relative density with a scenario of regeneration, harvest, and fire disturbance illustrated by field data (Schnur 1937, Drew et al, 1979).

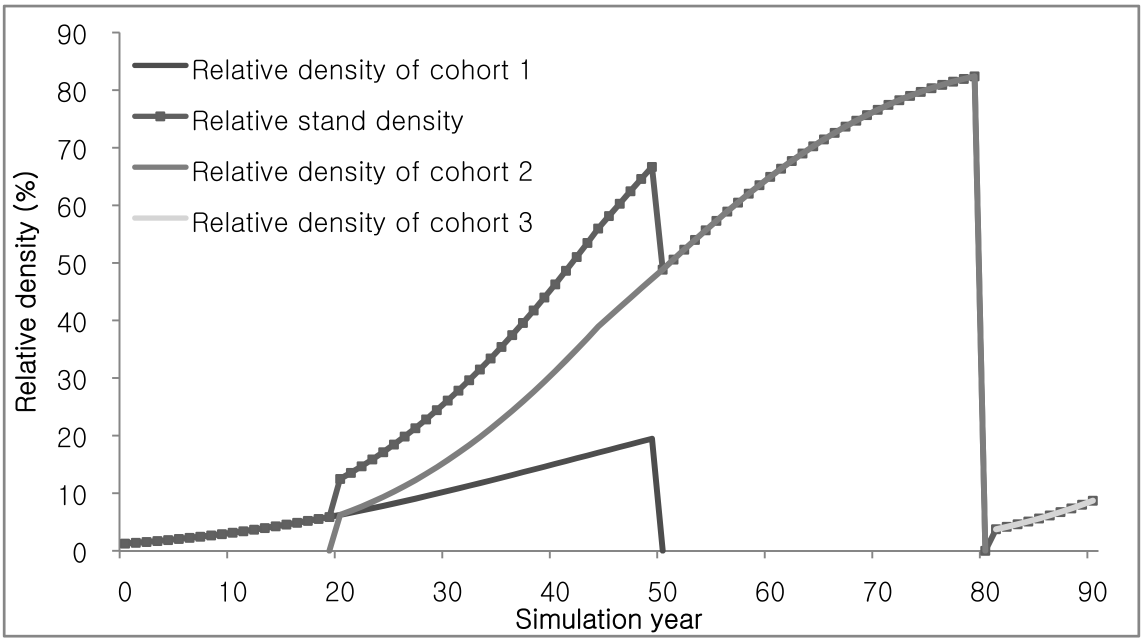


Figure 5.29 The change of relative density by simulation year 90 with regeneration at simulation year 20 and harvest at simulation year 50 on old cohort. Cohort 1 is old cohort of white oak, cohort 2 is regenerated cohort at simulation year 20, and cohort 3 is regenerated at simulation year 81.

Basal area of the upland white oak of even-aged stand at age 10 with the initial number 100 starts from 1.0 square feet per acre and increases steadily because of tree growth over time (Fig. 5.30). At simulation year 20, the stand basal area starts to increase urgently due to regeneration of five-hundred white oaks. At simulation year 50, the stand basal area decreases dramatically because the old cohort was removed by harvest. The stand basal area and basal area of cohort 2 keep increasing after harvest and at simulation year 80, fire disturbance occurred and it removed the entire trees in the stand, thus the basal area of the stand become zero. At simulation year 81, regeneration of three-hundred white oaks (cohort 3) was simulated and the stand basal area starts to increase again. The pattern of change of basal area over time are reasonably simulated based on the pattern of the basal area in growth and yield table of Schnur (1937) with a scenario of regeneration, harvest, and fire disturbance.

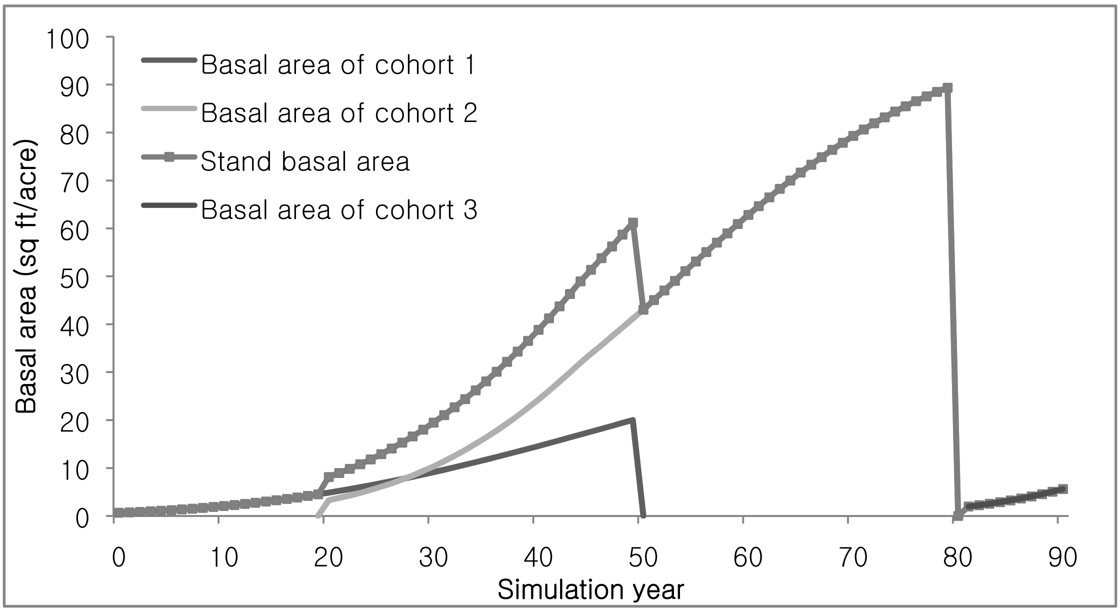


Figure 5.30 The change of relative density by simulation year 90 with regeneration. Cohort 1 is old cohort of white oak and cohort 2 is a regenerated cohort at simulation year 20 and cohort 3 is regenerated at simulation year 81.

6. Discussion

6.1 Growth of a cohort

Simplification is required with reasonable assumptions for growth model for a cohort in large-scaled landscape modeling. The growth assumption that DBHq of a cohort reaches the average of maximum DBHq at the average longevity of cohort using the Gompertz model (Eq. 3.6) is matched well with field data (Schnur, 1937). However, since the changes in DBHq of a cohort are strongly affected by site conditions in real stand dynamics and it is not easy process to track all site conditions influenced by physical and biological environments during simulation year, the growth assumption can be interpreted as trade-off between stand-level quantitative details and large-scale landscape modeling. Considering the simplicity of growth model, the simulation results of relative density and basal area were very accurate and the accuracy proves that the growth model is adjustable to LANDIS. Based on enough tests in various stand structure over large landscapes, if it is concluded that the growth assumption is not sufficient to describe various stand dynamics, classified *DBHqmax* of a cohort and different growth rate based on stand structure and an ecoregion will be alternative options.

The Gompertz curve was fitted with the change of DBHq in field data very well (Fig. 4.1) and the good fitness verified that the Gompertz curve illustrates the DBHq trajectory correctly. It is quite likely that the Gompertz equation is flexible enough to model DBHq to describe tree growth over time. Comparisons with other growth equations such as the logistic equation and Chapman-Richard equation (1959) were not made herein but it is required to compare advantages and disadvantages of various equations to describe quadratic mean diameter change more accurately and decide which is more suitable for describing tree growth in terms of DBHq in the stand density module. The estimation of coefficients k in equation 3.6 will be a crucial process to make the growth assumption describe the growth of a cohort more accurately and efficiently. If an average growth rate for overall species is considered sufficient to describe the change of DBHq over time, just one coefficient for overall species can be adopted as a default. Otherwise, classification for species with similar growth patterns as function of longevity (e.g., hardwood and softwood) will be required and based on the classification the differentiated coefficients can be adopted to distinguish the different growth pattern. Further parameterization works with more empirical data and comparisons with the output of stand-level models such as FVS are needed for confirming that growth assumption is reasonably working in multiple stands including various species composition and age structures.

6.2 Mortality model

Simple and efficient mortality model by self-thinning (Equation 3.7) is designed to be suitable for calibration and parameterization with empirical stand development data based on relative stand density and annual mortality rate (percent of number of trees dead in a stand per one year). For the estimation in coefficients of equation 3.7, empirical data of upland oak and black spruce (Schnur, 1937; Lussier et al., 2002) were utilized with the relationship between relative stand density and mortality rate. The field data of black spruce (Lussier et al., 2002) provide various ranges of relative stand density and clearly resulted in the linear relationship between relative stand density and mortality rate. However, the field data of upland oak (Schnur, 1937) did not bring various ranges of relative density but provide the limited ranges in relative stand density and the variation of mortality on relative stand density was relatively high. Producing random mortality numbers in the case that stand density become over the maximum stand density will cover the variation of self-thinning mortality. Although the coefficient in equation 3.7 (Table 4.5) can be used as a default for overall species based on the statistical significance, more field data of various tree species in diverse site conditions are required to enhance the accuracy in the coefficients which are adoptable to overall species even in multiple stands. The classification of hardwood and softwood for the coefficient in equation 3.7 is recommended to distinguish the self-thinning mortality rate against relative stand density in further step.

6.3 Relative density

Even though SDI was developed for even-age stands, I used SDI in two ways for measuring stand density of various tree species and size distributions. The first is estimation of relative density based on current stand density index calculated by the number of trees and DBHq of a cohort comparison to maximum stand density index (Woodall et al, 2005) and the second way is estimation of relative density using the space that average-sized trees occupy per unit area. In the estimation of relative density based on the number of trees, Woodall et al. (2005) estimated maximum stand density index in mixed species stand based on the mean specific gravity of all trees. This model suggested that the mean specific gravity of individual trees in a stand may serve as a predictor of a stand’s maximum stocking potential, regardless of the stand’s diameter distribution and species composition (Woodall et al, 2005). However, even though they reasonably estimate maximum stand density index with the mean specific gravity of all trees, the concept of changing maximum SDI based on tree component in a stand can be debatable. To estimate relative stand density, an important factor is that the definition of maximum stand density index should be clear.

Therefore, my proposed approach is estimation of relative density using the percentage of the space occupied by average-sized trees per unit area. In this approach, maximum value is a unit area which is defined by user. Based on the maximum unit area, the space where average-sized trees occupy in a unit area is calculated. The ratio of occupied area by average-sized tree per unit area is the relative density which is space based. In this approach, the maximum value is clear thus the definition of relative density is more reasonable than the calculation of relative density using flexible maximum stand density index with the mean specific gravity of all trees tree (Woodall et al, 2005) in that maximum value is fixed. However, to adopt space-based relative density, the assumption that all trees are an average size is required. One other disadvantage of this approach is that we do not know all maximum SDI by species. Thus, unknown maximum SDI value should be estimated with field data (Poage et al., 2007) and specific gravity which is the way that Woodal et al. (2005) proposed.

6.4 Basal area simulation experiments

Through the evaluation of the stand density module with self-thinning mortality based on various initial numbers of trees, the stand density module validated the flexibility of model with relation to initial input. Considering the distinct simulation results of relative density and basal area with the separate initial numbers per unit area (Fig. 5.17, Fig 5.18) , the stand density module which can detect the differences by various initial inputs is regarded as an advance in accuracy to simulate stand quantitative attributes in landscape modeling.

Although the stand relative density which is defined by the relationship of DBHq and number of trees reached the maximum, the basal area kept growing with the scenario of various initial numbers of trees (Fig. 5.17, 5.18). The reason is inferred that at relatively young stands which reached the maximum stand density, the ratio of area where tree branches occupy to area where tree stems occupy is higher than that of old stand. Therefore, it suggests that the maximum stand relative density based on DBHq and tree number did not always mean that the stand reached the maximum stand basal area or maximum biomass. Based on the relationship between the change of relative density and the trajectories of basal area, it is analyzed that the maximum stand density based on DBHq and tree number represents no more space for tree growth at the species composition and age structure of the stand.

The sensitivity analysis on the parameters of maximum stand density index, the slope of maximum stand density index, and the average of mortality rate against relative stand density with the change of basal area provided considerable insights into stand dynamics. The sensitivity analysis in the maximum stand density index showed that the higher values in SDImax resulted in the increased simulation results of basal area through simulation year and reached higher maximum basal area (Fig. 5.20). All coefficients are statistically significant (Table 5.1), and it implicate SDImax 230 (Schnur, 1937) will be enough maximum stand index for upland oak although the simulated maximum basal area is lower than the field data. The slope of maximum stand density did not illustrate sensitive response in the change of basal area in single-species even-aged stand (Fig. 5.21, Table 5.2). The effect of change in the mortality rate against relative stand density was also trivial, which indicate the average coefficient in equation 3.8 can be utilized as a default in single-species even-aged stand (Fig. 5.22, Table 5.3).

Comparisons on the simulation results driven by the stand density module with the trajectory of basal area in the field data (Schnur, 1937) clearly verified that the stand density module quantify the basal area correctly in various site conditions by the proof of high statistical significance (Fig. 5.23, 5.24. 5.25, Table 5.4, 5.5., 5.6). Based on the comparisons, the stand density module with relative density, growth model and self-thinning mortality model validated the accuracy in simulation results of basal area even if the model algorithm is simple.

Under several scenarios within limited condition of stands, the stand density module were tested with regeneration, wildfire and harvest and it verified the flexibility of stand density module to link wide-scale landscape process with stand dynamics (Fig.5.26, Fig. 5.27, Fig. 5.28). Although the simulation results under the confined scenarios were not compared with historic regeneration, disturbance or harvest, the stand density module produced the relatively reasonable outcomes within proper ranges of basal area from field data (Schnur, 1937). This linkage provide crucial information in stand development stages which is used for making lone-term management schemes based on the feedbacks between disturbance and succession and present insight into the stand-scale effects induced by landscape processes in the extended LANDIS version.

7. Conclusions

The stand density module was designed for LANDIS to simulate quantitative stand details in relative density and basal area, which will better represent the effects of landscape processes in combination with stand-level processes. The stand density module design is built based on reasonable assumptions which are derived from natural ecosystem processes (e.g., growth and mortality) and relevant equations which are suitable for large-scale landscape modeling. The same operating unit of a cohort in LANDIS enhance the modeling efficiency in producing the combined results with landscape processes. The stand density module was invented as a module that requires minimal parameterization and can be calibrated with empirical stand data.

The stand density module simulated stand basal area accurately even though the model framework is simple and the accuracy in simulation results validated that the stand density module worked properly using growth model of a cohort, self-thinning mortality model and relative stand density. The evaluation with various initial numbers of trees demonstrated the correctness and the flexibility in model behaviors with relation to the initial input. The sensitivity analysis on major parameters in self-thinning mortality model and maximum stand density index verified that the parameters are reasonably estimated and working properly with model frameworks. The stand density module can interact with other modules (e.g., disturbances and harvest) in LANDIS reciprocally, thus we can investigate the effects of various management regimes and other disturbances on stand-level ecological processes.

Using the stand density module, we can simulate succession in interactions with disturbances and land management. The simulation results enhance our understanding in the effects of landscape processes on stand-level forest land. The stand density module can provide a crucial feedback between succession and large-scale landscape phenomena. Thus, the new invented model can be used as tools which are served for decision-making in long-term forest management. More parameterization works with various empirical data and analysis of the output over large-scale landscapes will raise the suitability of stand density module for LANDIS. With a newly designed stand density module, we can expect to acquire great insight into stand development patterns influenced by various management schemes and disturbance regimes and analyze the interactions between stand dynamics and large-scale ecological processes.

References

Arevalo, C. B. M., T. A. Volk, E. Bevilacqua & L. Abrahamson (2007) Development and validation of aboveground biomass estimations for four Salix clones in central New York. *Biomass & Bioenergy,* 31**,** 1-12.

Baker, W. (1989) A review of models of landscape change. Landscape Ecol. 2, 111–133.

Bechtold, W. A. (2003) Crown-diameter prediction models for 87 species of stand-grown trees in the eastern United States. *Southern Journal of Applied Forestry,* 27**,** 269-278.

Bi, H. Q., G. G. Wan & N. D. Turvey (2000) Estimating the self-thinning boundary line as a density-dependent stochastic biomass frontier. *Ecology,* 81**,** 1477-1483.

Bigler, C. & H. Bugmann (2003) Growth-dependent tree mortality models based on tree rings. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* 33**,** 210-221.

Boncina, A., A. Kadunc & D. Robic (2007) Effects of selective thinning on growth and development of beech (Fagus sylvatica L.) forest stands in south-eastern Slovenia. *Annals of Forest Science,* 64**,** 47-57.

Bortolot, Z. J. & R. H. Wynne (2005) Estimating forest biomass using small footprint LiDAR data: An individual tree-based approach that incorporates training data. *Isprs Journal of Photogrammetry and Remote Sensing,* 59**,** 342-360.

Briegleb, P.A. (1952) An approach to density measurement in Douglas-fir. J. For. **50**: 529–536.

Bullock, J. M. & R. T. Clarke (2000) Long distance seed dispersal by wind: measuring and modelling the tail of the curve. *Oecologia,* 124**,** 506-521.

Caswell, H. (1976) Community structure: a neutral model analysis. Ecol. Monogr. 46: 327-354

Cabaco, S., R. Machas & R. Santos (2007) Biomass-density relationships of the seagrass Zostera noltii: A tool for monitoring anthropogenic nutrient disturbance. *Estuarine Coastal and Shelf Science,* 74**,** 557-564.

Chumachenko, S. I., V. N. Korotkov, M. M. Palenova & D. Politov (2003) Simulation modelling of long-term stand dynamics at different scenarios of forest management for coniferous-broad-leaved forests. *Ecological Modelling,* 170**,** 345-361.

Clark, J.S. (1991) Disturbance and tree life history on the shifting mosaic landscape. Ecology 72, no. 3: 1102-18.

Clark, J. S., M. Silman, R. Kern, E. Macklin & J. HilleRisLambers (1999) Seed dispersal near and far: Patterns across temperate and tropical forests. *Ecology,* 80**,** 1475-1494.

Coomes, D. A. & R. B. Allen (2007) Mortality and tree-size distributions in natural mixed-age forests. *Journal of Ecology,* 95**,** 27-40.

Dean and Baldwin, 1996 T.J. Dean and V.C. Baldwin Jr., The relationship between Reineke's stand-density index and physical stem mechanics, For. Ecol. Manage. 81 (1996), pp. 25–34.

Dillen, S. Y., N. Marron, C. Bastien, L. Ricciotti, F. Salani, M. Sabatti, M. P. C. Pinel, A. M. Rae, G. Taylor & R. Ceulemans (2007) Effects of environment and progeny on biomass estimations of five hybrid poplar families grown at three contrasting sites across Europe. *Forest Ecology and Management,* 252**,** 12-23.

Drew, T., John; Flewelling, James W. (1979) Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science. 25(3): 518-532.

Fang, J. Y., A. P. Chen, C. H. Peng, S. Q. Zhao & L. Ci (2001) Changes in forest biomass carbon storage in China between 1949 and 1998. *Science,* 292**,** 2320-2322.

Fang, S., J. Xue & L. Tang (2007) Biomass production and carbon sequestration potential in poplar plantations with different management patterns. *Journal of Environmental Management,* 85**,** 672-679.

Feldpausch, T. R., A. J. McDonald, C. A. M. Passos, J. Lehmann & S. J. Riha (2006) Biomass, harvestable area, and forest structure estimated from commercial timber inventories and remotely sensed imagery in southern Amazonia. *Forest Ecology and Management,* 233**,** 121-132.

Fenneman, N.M. (1938) Physical divisions of Eastern United States: New York, McGraw-Hill, 714 p.

Fraser, E. C., V. J. Lieffers & S. M. Landhausser (2005) Age, stand density, and tree size as factors in root and basal grafting of lodgepole pine. *Canadian Journal of Botany-Revue Canadienne De Botanique,* 83**,** 983-988.

Gompertz, B. (1825) On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Phil. Transac. Roy. Soci. London 115:513-585.

Graney, D.L. (1977) Site index predictions for red oaks and white oaks in the Boston Mountains of Arkansas. USDA For. Serv. Res. Pap. SO-139. 9 p.

Graney, D.L., and T.L Rogerson. (1985) Growth of oak, ash and cherry reproduction following overstory thinning of upland hardwood stands in the Boston Mountains of Arkansas. P. 4–10 in Proc. of the 5th Central Hardwood Forest Conference, Dawson, J. O., and K. A. Majerus (eds.). Dep. of For., University of Illinois, Urbana-Champaign.

Graney, D.L., and P.A. Murphy. (1997) An evaluation of uneven-aged cutting methods in even-aged hickory stands in the Boston Mountains of Arkansas. P. 130–146 in Proc. of the 11th Central Hardwood Forest Conference,Pallardy, S.G., et al. (eds.). USDA For. Serv. Gen Tech. Rep. ND-188.

Jack, S.B., and J.N. Long. (1996) Linkages between silviculture and ecology: An analysis of density management diagrams. For. Ecol. Manage.86:205–220.

Johnson, D.W. (1992) Effects of forest management on soil carbon storage. Water, Air, Soil Pollut. 64, 83±120.

Green, C., B. Tobin, M. O'Shea, E. P. Farrell & K. A. Byrne (2007) Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (Picea sitchensis (Bong) Carr.). *European Journal of Forest Research,* 126**,** 179-188.

Greene, D. F. & E. A. Johnson (1994) Estimating the mean annual seed production of trees. *Ecology,* 75**,** 642-647.

Hall, R. J., R. S. Skakun, E. J. Arsenault & B. S. Case (2006) Modeling forest stand structure attributes using Landsat ETM+ data: Application to mapping of aboveground biomass and stand volume. *Forest Ecology and Management,* 225**,** 378-390.

Hara, T. (1984) Modeling the time course of self-thinning in crowded plant populations. Ann. Bot. (London), **53**: 181–88.

He, H. S., Shang Z. B., Crow, T. R., Gustafson, E. J., Shifley, R. S. (2004) Simulating forest fuel and fire risk dynamics across landscapes—LANDIS fuel module design. Ecological Modelling 180: 135-151.

He, H. S., Li, W., Sturtevant, B. R., Yang, J., Shang, Z. B., Gustafson, E. J., and Mladenoff, D. J. (2005) LANDIS, a spatially explicit model of forest landscape disturbance, management, and succession—LANDIS 4.0 User's guide. USDA Forest Service North Central Research Station General Technical Report. NC-263.

Hyde, P., R. Nelson, D. Kimes & E. Levine (2007) Exploring LIDAR-RaDAR synergy - predicting aboveground biomass in a southwestern ponderosa pine forest using LiDAR, SAR and InSAR. *Remote Sensing of Environment,* 106**,** 28-38.

Jones, R. H., R. R. Sharitz, S. M. James & P. M. Dixon (1994) Tree population-dynamics in 7 south-carolina mixed-species forests. *Bulletin of the Torrey Botanical Club,* 121**,** 360-368.

Katul, G. G., A. Porporato, R. Nathan, M. Siqueira, M. B. Soons, D. Poggi, H. S. Horn & S. A. Levin (2005) Mechanistic analytical models for long-distance seed dispersal by wind. *American Naturalist,* 166**,** 368-381.

Kurinobu, S., D. Prehatin, N. Mohanmad, K. Matsune & O. Chigira (2007) A provisional growth model with a size-density relationship for a plantation of Paraserianthes falcataria derived from measurements taken over 2 years in Pare, Indonesia. *Journal of Forest Research,* 12**,** 230-236.

Laird, D, A.K., S.A. Tyler, and A.D. Barton (1965) Dynamics of normal growth. Growth 29:233-248.

Long, 1995 Long, J.N. (1995) Using Stand Density Index to regulate stocking in uneven-aged stands. In: O'Hara, K. (Ed), Uneven-Aged Management—Opportunities, Constraints, and Methodologies, vol. 56. Montana Forest and Conservation Experiment Station, pp. 110–122, Misc. Pub.

Long and Daniel (1990) J.N. Long and T.W. Daniel, Assessment of growing stock in uneven-aged stands, West. J. Appl. For. 5 (1990), pp. 93–96.

Lundqvist, L., D. Chrimes, B. Elfving, T. Morling & E. Valinger (2007) Stand development after different thinnings in two uneven-aged Picea abies forests in Sweden. *Forest Ecology and Management,* 238**,** 141-146.

Lussier JM, Morin H, Gagnon R (2002) Mortality in black spruce stands of fire or clear-cut origin. *Can J For Res* 32:539-547

Mack, T. J. & T. E. Burk (2005) A model-based approach to developing density management diagrams illustrated with lake states red pine. *Northern Journal of Applied Forestry,* 22**,** 117-123

Makeham, W. M. (1860) "On the law of mortality and the construction of annuity Tables". *J. Inst. Actuaries and Assur. Mag.* **8**: 301–310.

Martinez, D. (1998) Neural tree density estimation for novelty detection. *Ieee Transactions on Neural Networks,* 9**,** 330-338.

McNeill, S. & D. Pairman (2005) Stand age retrieval in production forest stands in New Zealand using C- and L-band polarimetric radar. *Ieee Transactions on Geoscience and Remote Sensing,* 43**,** 2503-2515.

Mladenoff, D.J., Host, G.E., Boeder, J., Crow, T.R. (1996) LANDIS: a spatial model of forest landscape disturbance, succession, and management. In: Goodchild, M.F., Steyaert, L.T., Parks, B.O., Johnston, C., Maidment, D., Crane, M., Glendinning, S. (Eds.), GIS and Environmental Modeling: Progress and Research Issues. GIS World Books, Fort Collins, CO, USA, pp. 175–179.

Mladenoff, D.J., Baker, W.L. (1999) Development of forest and landscape modeling approaches. In: Mladenoff, D.J., Baker, W.L. (Eds.), Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge, UK, pp. 1–13.

Moore, M. M. & D. A. Deiter (1992) Stand Density Index As a Predictor Of Forage Production In Northern Arizona Pine Forest. *Journal of Range Management,* 45**,** 267-271.

Muukkonen, P. & J. Heiskanen (2007) Biomass estimation over a large area based on standwise forest inventory data and ASTER and MODIS satellite data: A possibility to verify carbon inventories. *Remote Sensing of Environment,* 107**,** 617-624.

Nathan, R. & Muller-Landau, H.C. (2000) Spatial patterns of seed dispersal, their determinants and consequences for recruitment. *Trends in Ecology and Evolution*, **15**, 278–285.

Nokoe, S. (1978) Demonstrating the flexibility of the Gompertz function as a yield model using mature species data. Commonw. For. Rev. 57:35-42.

Peltola, H., A. Kilpelainen, K. Sauvala, T. Raisanen & V. P. Ikonen (2007) Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. *Silva Fennica,* 41**,** 489-505.

Pennanen, J., D. F. Greene, M. J. Fortin & C. Messier (2004) Spatially explicit simulation of long-term boreal forest landscape dynamics: incorporating quantitative stand attributes. *Ecological Modelling,* 180**,** 195-209.

Poage, N. J., D. D. Marshall & M. H. McClellan (2007) Maximum stand-density index of 40 western hemlock-sitka spruce stands in southeast Alaska. *Western Journal of Applied Forestry,* 22**,** 99-

104.

Popescu, S. C. (2007) Estimating biomass of individual pine trees using airborne lidar. *Biomass & Bioenergy,* 31**,** 646-655.

Porte, A. & H. H. Bartelink (2002) Modelling mixed forest growth: a review of models for forest management. *Ecological Modelling,* 150**,** 141-188.

Puettmann, K. J., D. E. Hibbs & D. W. Hann (1992) The dynamics Of mixed stands of alnus-rubra and pseudotsuga-menziesii – Extension of size density analysis to species mixture. *Journal of Ecology,* 80**,** 449-458.

Reineke, 1933 L.H. Reineke, Perfecting a stand-density index for even-aged stands, *J. Agric. Res.* **46** (1933), pp. 627–638.

Reid, R. (2006) Diameter-basal area ratio as a practical stand density measure for pruned plantations. *Forest Ecology and Management,* 233**,** 375-382.

Robledo-Arnuncio, J. J. & C. Garcia (2007) Estimation of the seed dispersal kernel from exact identification of source plants. *Molecular Ecology,* 16**,** 5098-5109.

Sander, I.L., and D.L. Graney. (1993) Regenerating oaks in the central states. P. 174–183 in Proc. Oak regeneration: Serious problems, practical recommendations. USDA For. Serv. Gen. Tech. Rep. SE-84.

Scheller, R. M. & D. J. Mladenoff (2004) A forest growth and biomass module for a landscape simulation model, LANDIS: design, validation, and application. *Ecological Modelling,* 180**,** 211-229.

Scheller, R. M.; Mladenoff, D. J. (2005) A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. *Global Change Biology,* 11**,** 307-321.

Scheller, R. M., J. B. Domingo, B. R. Sturtevant, J. S. Williams, A. Rudy, E. J. Gustafson & D. J. Mladenoff (2007) Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. *Ecological Modelling,* 201**,** 409-419

Schnur, 1937 G.L. Schnur, Yield, stand and volume tables for even-aged upland oak forests, U.S.D.A. Tech. Bull. (1937), p. 560.

Schumacher, S., H. Bugmann & D. J. Mladenoff (2004) Improving the formulation of tree growth and succession in a spatially explicit landscape model. *Ecological Modelling,* 180**,** 175-194.

Seymour, R. S. (2007) Low-density management of white pine crop trees: A primer and early research results. *Northern Journal of Applied Forestry,* 24**,** 301-306.

Shaw, J. D. & J. N. Long (2007) A density management diagram for longleaf pine stands with application to red-cockaded woodpecker habitat. *Southern Journal of Applied Forestry,* 31**,** 28-38.

Soons, M. B., G. W. Heil, R. Nathan & G. G. Katul (2004) Determinants of long-distance seed dispersal by wind in grasslands. *Ecology,* 85**,** 3056-3068.

Stankova, T. V. & M. Shibuya (2007) Stand density control diagrams for scots pine and austrian black pine plantations in bulgaria. *New Forests,* 34**,** 123-141.

Tadaki, 1963 Y. Tadaki, The pre-estimating of stem yield based on the competition density effect, Bull. For. For. Prod. Res. Inst. 154 (1963), pp. 1–19.

Tewari, V. P. (2007) Stand density and basal area prediction of unthinned irrigated plantations of Eucalyptus camaldulensis in the hot desert of India. *Bioresource Technology,* 98**,** 1106-1114.

Tews, J., K. Moloney & F. Jeltsch (2004) Modeling seed dispersal in a variable environment: a case study of the fleshy-fruited savanna shrub Grewia flava. *Ecological Modelling,* 175**,** 65-76.

Turnblom, E. C. & T. E. Burk (2000) Modeling self-thinning of unthinned Lake States red pine stands using nonlinear simultaneous differential equations. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* 30**,** 1410-1418.

Turner, M. G., G. J. Arthaud, R. T. Engstrom, S. J. Hejl, J.Liu, S. Loeb, and K. McKelvey. (1995) Usefulness of spatially explicit population models in land management. Ecological Applications 5:12-16.

VanderSchaaf, C. L. & H. E. Burkhart (2007) Comparison of methods to estimate Reineke's maximum size-density relationship species boundary line slope. *Forest Science,* 53**,** 435-442.

Wallace, H. M., M. G. Howell & D. J. Lee (2008) Standard yet unusual mechanisms of long-distance dispersal: seed dispersal of Corymbia torelliana by bees. *Diversity and Distributions,* 14**,** 87-94.

Waterworth, R. M., G. P. Richards, C. L. Brack & D. M. W. Evans (2007) A generalised hybrid process-empirical model for predicting plantation forest growth. *Forest Ecology and Management,* 238**,** 231-243.

Willson, M.F. (1993) Dispersal mode, seed shadows, and colonization patterns. Vegetatio, 107/108, 261–280.

Wimberly, W.C. (2004) Fire and forest landscapes in the Georgia Piedmont: an assessment of alternative spatial modeling assumptions. Ecol. Model. 180, 41–56.

Winsor, C.P. (1932) The Gompertz curve as a growth curve. Proc. Nat. Acad. Sci. 18:1-8.

Woodall, C. W., C. E. Fiedler & K. S. Milner (2003) Stand density index in uneven-aged ponderosa pine stands. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* 33**,** 96-100.

Woodall, C. W., P. D. Miles & J. S. Vissage (2005) Determining maximum stand density index in mixed species stands for strategic-scale stocking assessments. *Forest Ecology and Management,* 216**,** 367-377.

Woodall, C. W., C. H. Perry & P. D. Miles (2006) The relative density of forests in the United States. *Forest Ecology and Management,* 226**,** 368-372.

Yang, J., He, H. S., Gustafson, J. E. (2004) A hierarchical statistical approach to simulate the temporal patterns of forest fire disturbance in LANDIS model. Ecological Modelling 180: 119-133

Zeide, B. (1993) Analysis of growth equations. For. Sci. **39**: 594–616.

Zeide, B. (2004) Optimal stand density: a solution. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, 34**,** 846-854.