Implications of incorectly determining site index on stand-level management activities and financial returns in older generation loblolly pine plantations

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Abstract

Predicting future yields normally requires an estimate of site quality. A commonly used measure is site index (SI). SI is often incorrectly quantified operationally due to the ambiguity associated with selecting "site" trees. Plus, error in the measurement of height itself occurs. This study quantifies the impacts on the number and timing of thinnings, and the final harvest ages, as well as financial returns when incorrectly determining SI. Three values of SI (base age 25 years) were examined using two older generation loblolly pine plantation growth and yield simulation models from the Western Gulf, USA; 16.76 m, 21.34 m, and 25.91 m. Firstly, a particular SI was assumed to be the "true" value, growth and yield estimates were obtained, and financial assessments were conducted. The same process was then conducted again, but assuming that the SI was incorrectly determined by varying positively and negatively the SI by up to 1.22 m from the assumed "true" value.

For these older generation plantations, incorrectly determining SI did impact the age of the first thinning by as much as 5 years. In some cases, errors of +/- 1.22 m in SI estimation had little impact on the estimated timing of the first thinning. Errors in SI of up to +/- 1.22 m had little impact on the number of thinnings across economic rotation ages. For both unthinned and twice-thinned stands, final harvest (clearcut) ages differed by as much as 4 years for SI errors up to +/- 1.22 m. These errors led to differences in Land Expectation Value (LEV) up to \$406.50 ha^{-1}. Across the three SI (16.76, 21.34, and 25.91 m), differences in LEV ranged from \$237.49 to \$406.50 ha^{-1}. These differences in LEV could be enough to incorrectly not conduct, or incorrectly conduct, a silvicultural operation such as an herbicide treatment or a fertilization treatment across a rotation, among other treatments.

Keywords

Pinus taeda; Land expectation value; Economics; Growth and yield

Contents

1 Introduction

The inclusion of a site quality measure into growth and yield models is essential for prediction of future yields (Borders et al. 2008). Beyond that, management thresholds are often based on site quality measures (Kangas et al. 2011) and site quality estimates are regularly used to help determine optimum operational management actions and regimes (Borders et al. 2008). A commonly used measure of site quality is site index (SI). Conceptually, for a particular species, SI is a collective influence of soil factors and climatic conditions and when excluding extremes, SI is thought to be independent of stand density (Burkhart and Tennent 1977; Ritchie et al. 2012; Burkhart et al. 2019, pg. 303). Hence, SI is both advantageous and non-advantageous because it is a function of the existing trees – hence the existing genetics and management practices of the current rotation and even residual effects of previous rotations. However, it is often non-advantageous because it doesn’t provide a direct explanation of site growing conditions. Beyond that, unless accounted for, factors such as genetics (Boyer 1983; McKeand et al. 2006; Zhai et al. 2015), fertilization (Tiarks and Haywood 1996; Subedi et al. 2014), site preparation (Haywood and Tiarks 2002), stand density (Boyer 1983), thinning (Ritchie et al. 2012), and planting density (MacFarlane et al. 2000; Antoń-Fernańdez et al. 2011; Akers et al. 2013) can all contribute to reducing the effectiveness of SI to differentiate sites as to their ability to produce yields of a particular species. These issues associated with SI are widely known.

However, often measurement error is as important in nullifying SI to determine relative productivity levels among sites as the previously mentioned factors. Measurement errors include not only the inability to truly identify trees that should be used to quantify SI, or “site” trees (e.g. Figure 1), but also errors in the height measurements of site trees. Another error is not selecting site trees consistent with the SI definition being used. For instance, using a SI calculated as the average height of dominants/codominants and entering it as top height into a growth and yield model may lead to erroneous results. Beyond that, although not as common in loblolly pine plantations, particularly those with well-maintained records, are errors in determining the current age of a stand (McRoberts et al. 1994).

There are numerous definitions of “site” trees to be included in the calculation of SI for tree species across the world (Burkhart and Tennent 1977; Lenhart et al. 1986; Cao et al. 1997; Sharma et al. 2002; Antoń-Fernańdez et al. 2011; Ritchie et al. 2012). Different definitions of dominant height have been proposed for southern yellow pines (*Pinus spp.*) in the Southeastern US (Lenhart et al. 1986), including the tallest 50% of trees per acre/ha (Golden et al. 1981; Boyer 1983) and dominants and co-dominants (e.g. Zarnoch and Feduccia 1984; Amateis and Burkhart 1985; Cao et. al. 1997). One of the two former definitions calculates dominant height using a fixed proportion of trees while the other estimates dominant height based on crown classes (often dominants and co-dominants). Some amount of the largest diameter trees has also been used (Sharma et al. 2002).

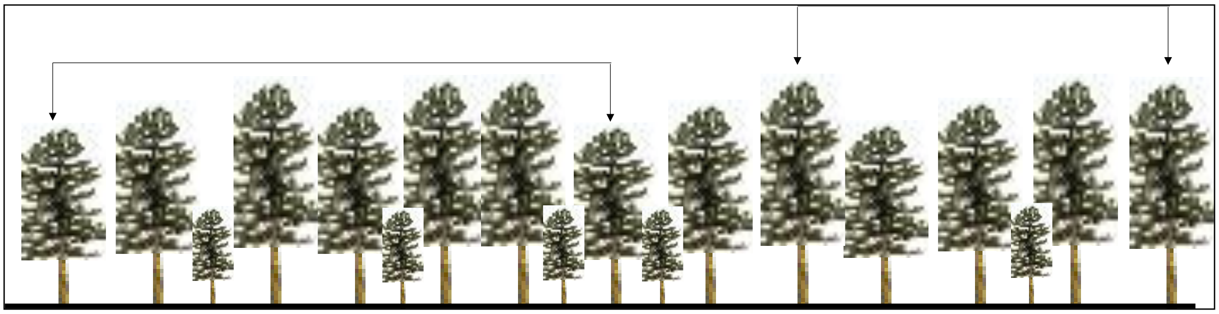

Figure 1. Trees depicted above in the overstory are assumed to be dominant and codominant, and there are a few suppressed trees. If only two trees are used to determine average dominant/codominant height, obviously the average height can differ substantially depending on the two dominant and codominant trees selected. Although easy to differentiate in the figure above, actually selecting appropriate "site" trees in the field is subjective and can be difficult.

When determining SI, some sampling protocols allow for sample sizes as low as one tree to be used. For instance, the USDA Forest Service Forest Inventory and Analysis (FIA) protocol allows for only one tree to be used to quantify SI for a condition class on a plot (USDA Forest Service 2022, pg. 136). Many FIA plots only have one condition class, but some FIA plots have more than one condition class. A condition class, for example, could be a 15-year-old loblolly pine (*Pinus taeda* L.) plantation while a second condition class within the same FIA plot could be an uneven-aged bottomland hardwood stand. For both condition classes of the same FIA plot, only one tree could potentially be used to quantify a condition class specific SI. Obviously, the use of only one, two, three trees, etc., can lead to a fair amount of variability in determining SI within a condition class. FIA plot data are used regularly during regional and national assessments and in developing growth and yield models. Each FIA plot condition class, for instance, generally represents roughly 1,214 to 2,428 ha and hence errors in SI can have a meaningful impact on assessments.

Growth and yield projections are commonly used in financial assessments to determine an optimal silvicultural regime and the timing of various operations, such as thinnings and final harvests. For this purpose, inaccurate projections of growth and yield are certainly not desired. However, since we never know the true growth and yield of plantations when projections are being made, if these errors do not lead to substantial differences in what is considered to be the optimal silvicultural practice, the predictive errors are actually of little consequence (Kangas et al. 2011; Ruotsalainen et al. 2021). Site index, or a measure of site quality, is commonly used as a driver in stand-level growth and yield projection models. Thus, most, if not all, predicted stand-level variables are impacted by the inputted SI. Other studies have demonstrated that errors in SI can have an meaningful impact on projected growth and yield; for instance, Gertner and Dzialowy (1984) for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in Oregon and McRoberts et al. (1994) largely for northern hardwood stands in Michigan. Others have quantified how errors in SI can meaningfully impact not only growth and yield, but also the determined optimal management scenario and its associated economic impact. For instance, Eid (2000) for Norway spruce (*Picea abies* (L.) Karst.) in Norway.

All three studies referenced above found errors in SI to have a large impact on growth and yield and/or management regimes; thus it is of extreme importance to quantify the potential errors for loblolly pine plantations. But little work has addressed how much errors in determining the SI of loblolly pine plantations can impact what is considered to be the optimal management scenario for a particular stand and the impacts of errors on financial assessments.

Borders et al. (2008) demonstrated that poor timber inventory information can lead to losses in revenues for loblolly pine plantations, but never related these losses directly to SI since errors were across several variables simultaneously. Beyond that, they did not present results showing how errors in SI can lead to incorrect timings of thinnings and the number of thinnings across a rotation given there is a true SI. Given errors in determining the true SI of a site, it is important to determine directly how much impact errors in SI estimation can have not only on financial returns, but also its impact on what is determined to be optimal silvicultural regimes within these plantations.

Growth and yield projections are also commonly used in harvest scheduling operations and timber supply assessments (Zhang and Pearse 2012, pg. 229). Thus, potentially unlike when determining optimal silvicultural regimes, errors in stand level growth and yield projections will probably always be of concern for these types of analyses. Impacts to timber supply will likely always be consequential. However, potentially, it could be that even at a landscape level predictive errors in growth and yield projections resulting from errors in SI may not impact what management is considered optimal; but this seems unlikely. Quantifying how errors in SI impact silvicultural regimes will allow us to infer about how any potential differences would impact estimates of what is considered to be the optimal forest management scenario at landscape levels.

Quantifying the impacts of incorrect SI estimates on the number and timings of thinnings, and the final harvest age are minimal in general, but especially for loblolly pine plantations. Kangas et al. (2011) did examine how errors in stand-level variables impacted the timings of thinnings and clearcuts for spruce forests in Finland, but errors in SI were not addressed directly. Rather, errors in dominant height, or SI, occurred indirectly because of its relationship in their analysis with both mean diameter and mean height and the specified measurement errors of those variables. Plus, the assessments were only for the upcoming 10 years, not across an entire rotation.

In this paper, stand conditions were examined for loblolly pine plantations in the Western Gulf of the southeastern US. The primary objective of this study was to determine how using incorrect SI values in growth and yield projection models can impact the estimated number and timing of thinnings, returns on investment, and optimum economic rotation ages. Observations from loblolly pine plantation research trials show that SI can vary around at least 3.05 m depending on what trees are selected as “site” trees, particularly when sample sizes of site trees are low (e.g. one or two trees). The primary objectives was accomplished by assuming a particular SI is the true value, obtaining growth and economic projections for that assumed true value, and then conservatively reducing or increasing the SI by up to 1.22 m and comparing growth and economic projections from these “incorrect” SIs to those from the true value.

2 Methods

Projections were obtained using two different growth and yield projection systems.

2.1 Forest vegetation simulator (FVS)

The Southern variant (SN, version 1860) of FVS covers forest areas in the southern United States including Louisiana, East Texas, and Mississippi (Dixon 2002; Keyser 2018). SN model relationships were fit in the early 2000s using FIA periodic inventory data from all southern states. For loblolly pine enough data existed to modify the growth of plantations (MANAGED keyword in FVS). This is a distance-independent individual tree model.

Within SN, the "Bareground" option was used to generate plantations of 1,075 seedlings ha^{-1}. Survival at age one was assumed to be 100 percent and the "Sprouting" option was turned off to eliminate natural regeneration. The "MANAGED" keyword was used to reflect that in general plantations have greater diameter growth rates relative to natural, or "unmanaged" stands. Discounted regeneration costs of \$666.74 ha^{-1} were assumed and consists of \$345.95 ha^{-1} for site preparation, \$70 per thousand seedlings, \$0.12 to plant each seedling, and a \$123.55 ha^{-1} first year herbaceous weed control treatment. Costs are based on Maggard (2021) but adjusted based on recent experience of local foresters.

Minimum merchantability limits were consistent with standard FVS SN protocol and stump height was set to 0.15 m. Minimum merchantable pulpwood diameter at breast height (1.37 m about ground level, DBH) was 15.24 cm, and upper stem diameter outside-bark (DOB) was 10.16 cm. Chip-n-saw specifications were minimum DBH of 20.32 cm to 27.94 cm, and a DOB of 10.16 cm. Sawtimber specifications were minimum DBH of 27.94 cm and a DOB of 17.78 cm. Volumes were calculated using the "SpMcDBH" keyword within FVS. Topwood, or upper-stem pulpwood on chip-n-saw and sawtimber merchandized trees, was included in the pulpwood class. The default FVS max Stand Density Index (SDI) of 505 was used.

Site index equations within FVS use a base age of 50 years. However, projections were desired based on SIs using a more operationally common base age of 25 years. Hence, for a desired SI at a base age of 25 years, SIs at a base age of 50 years were iteratively entered until they produced the desired SI at a base age of 25 years.

Within FVS, thinnings were conducted whenever a stand basal area ha^{-1} trajectory reached 25.25 m^2 ha^{-1} leaving a residual basal area of 16.07 m^2 ha^{-1}. Within FVS a "Thin from Below" operation was selected for all thinnings.

2.2 LOBeatx

Data used in developing equations (Lee and Coble 2006; Coble 2009) were obtained from long-term measurements of operationally established unthinned plantations across the growing conditions of East Texas as part of the East Texas Pine Plantation Research Project – ETPPRP (https://scholarworks.sfasu.edu/etpprp/). A total of 187 plots were originally established ranging in planting density from 865 to 3,336 seedlings ha^{-1}. Plantations represented by these plots ranged in total age from 2 to 35 years, 198 to 2,471 trees ha^{-1}, and 12.19 to 27.43 m SI (base age 25 years). Site preparation was minimal with the most intensive consisting of raking, piling, and burning. The plantations were established using bareroot seedlings and woods-run genetic stock, and since they were established prior to 1980, regeneration practices and seedling quality (through improved nursery practices) are not necessarily indicative of more recent regeneration practices (e.g. intensive management, and Elite or Mass Control Pollinated seedlings [MCP]).

A total of 1,112 seedlings were planted ha^{-1}. Discounted regeneration costs of \$673.78 ha^{-1} were assumed and consists of \$345.95 for site preparation, \$70 per thousand seedlings, \$0.12 to plant each seedling, and a \$123.55 first year herbaceous weed control treatment.

Pulpwood was defined as all trees with a DBH of 11.43 cm and greater to a 5.08-cm DOB, chip-n-saw was defined as all trees with a DBH from 20.32 cm to 27.94 cm up to a 10.16-cm DOB, and sawtimber was defined as all trees with DBH's greater than 27.94 cm up to a 20.32-cm DOB. Topwood, or upper-stem pulpwood on chip-n-saw and sawtimber merchandized trees, was included in the pulpwood class. Since LOBeatx only projects growth and yield of unthinned stands, and at least one thinning is commonly conducted in loblolly pine plantations in this region throughout a rotation, results from LOBeatx are probably most useful in helping to determine the timing of the first thinning.

2.2.1 Timing of a first thinning using LOBeatx

Three density management tools were used to determine the timing of the first thinning. The first was a "rule-of-thumb" to thin when the stand basal area reaches 25.25 m^2 ha^{-1}. The second and third were based on two separate Density Management Diagrams. The first DMD was developed by Dean and Baldwin (1993) which uses a maximum Reineke (Reineke 1933) Stand Density Index (SDI) of 1,112 (metric) and it is assumed the first thinning should occur at a relative density of 30%, or a SDI of 334 (metric). The second is a planting density specific DMD developed by VanderSchaaf and Burkhart (2012). Maximum SDI was set at 1,240 (metric), and based on equations presented in their work, when planting at 1,112 seedlings ha^{-1}, the lower limit of self-thinning should be a SDI of 437 (metric), or 35% of maximum SDI.

For both FVS and LOBeatx conceptual SIs of 16.76, 21.34, and 25.91 m (base age 25 years) were examined. Cubic ft volumes were converted to green tons assuming 63 lbs per cubic ft. Stumpage values per green ton for pine pulpwood, chip-n-saw, and sawtimber were \$10, \$19, and \$25, respectively, and were based on the 4th quarter, 2021 Louisiana Stumpage Report (Guo 2022).

The implications of errors when determining site index on financial returns and final harvest rotation ages were quantified by examining the differences in land expectation value (LEV) between site indexes. An interest rate of 6% was used. Land expectation value, or LEV, is thus calculated as (Gregory 1987, pg. 322; Zhang and Pearse 2012, pg. 198):

$$\text{LEV} = \frac{\mathrm{R} - [\mathrm{DC} * 1.06^{t}]}{1.06^{t} - 1}$$

Where: LEV – land expectation value, DC – discounted costs at year 0, \$666.74 ha^{-1} for FVS analyses and \$673.78 ha^{-1} for LOBeatx analyses, *t* – a potential final harvest rotation age, and R – total stumpage revenues of pulpwood, chip-n-saw, and sawlog product classes at the potential rotation age (t).

3 Results and discussion

3.1 Unthinned loblolly pine plantations (LOBeatx)

For unthinned loblolly pine (Figure 2), this analysis showed that errors in determining SI can impact the final rotation age by up to 3 years. For loblolly pine, this is biologically and economically meaningful. In terms of forest level planning such as harvest scheduling, these errors could have a meaningful impact on even-flow volume constraints across time and long-term sustainability estimates. Kangas et al. (2011), for example, specified that errors in excess of +/- 3 years in estimated final harvest ages were significant for spruce forests in Finland that grow slower than loblolly pine plantations in the southeastern US. On lower quality sites (e.g. 16.76 m), LEV differed by nearly as much as \$247.11 ha^{-1}, and on medium sites (e.g. 21.34 m) LEV differed by nearly as much as \$321.24 ha^{-1}. Depending on stumpage values and reforestation costs, on lower quality sites, errors in SI determination could result in erroneously concluding that a particular management regime is economically feasible. For example, on the erroneous SI 17.98 m site, LEV was \$-21.84 (close to being positive) but the correct SI of 16.76 m had a LEV of \$-147.52.

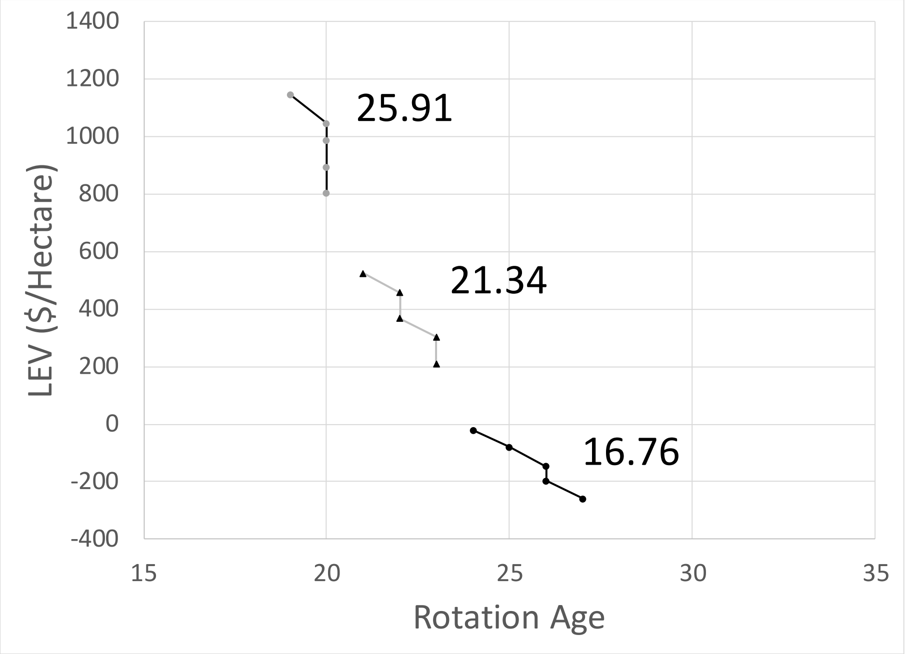

Figure 2. Financially optimal rotation ages and amounts (Land Expectation Value – LEV) for unthinned loblolly pine plantations in East Texas using LOBeatx. True site indexes are assumed to be 16.76 m (15.54, 16.15, 17.37, 17.98), 21.34 m (20.12, 20.73, 21.95, 22.56), and 25.91 m (24.69, 25.30, 26.52, 27.13) at a base age of 25 years. Values in parentheses for a particular site index are incorrectly measured site indexes.

Although errors in SI had little impact on rotation age for high quality sites (e.g. 25.91 m), it could lead to drastically different optimum management regimes. A difference of \$345.95 ha^{-1} (e.g. estimating SI to be 24.69 m rather than 27.13 m) could lead a manager to conduct a reduced amount of management activity or, conversely, an increased amount of management activity across a rotation such as fertilization or second-year herbaceous weed control treatments. In 2020, fertilization treatments, for example, averaged around \$217.45 ha^{-1} across the southeastern US (Maggard 2021) while in Arkansas during 2022 a very similar price was reported of \$214.98 ha^{-1} (Chhetri and Pelkki 2022).

3.1.1 Timing of first thinning

When using LOBeatx, the three approaches to determining when an initial thinning should be conducted produced drastically different timings for the same SI (Table 1). For high quality sites there was little difference within an approach, however, for lower quality sites there was a five-year difference between a SI of 15.54 m and a SI of 17.98 m when using a basal area ha^{-1} of 25.25 m^2 as the thinning “trigger”. From the correct SI of 16.76 m, there was up to a three-year difference. When placed into regional harvest schedule analyses, these errors in the timing of the first thinning could have a meaningful impact on estimated workloads and budgets. Kangas et al. (2011), for example, specified that errors in excess of +/- 2 years in estimated ages of when a thinning should be conducted were significant for spruce forests in Finland that grow slower than loblolly pine plantations in the southeastern US. Beyond that, a 3-year delay in the timing of the first thinning could lead to issues with southern pine beetle (SPB) (*Dendroctonus frontalis* Zimmermann) and will likely result in a delay of chip-n-saw and sawlog production, and a delay in the timing of the second thinning and final harvest. When using VB there was a three-year difference for the lower quality site (SI 16.76 m) between the low and high SIs; these differences can be meaningful.

Table 1. Age of first thinnings by site index for loblolly pine plantations when using LOBeatx. True site indexes are assumed to be 16.76 m (15.54, 16.15, 17.37, 17.98), 21.34 m (20.12, 20.73, 21.95, 22.56), and 25.91 m (24.69, 25.30, 26.52, 27.13) at a base age of 25 years; values in parentheses for a particular site index are incorrectly measured site indexes. Where: Basal Area – thin when standing basal area ha^{-1} equals 25.25 m^2, DB – management based on DMD from Dean and Baldwin (1993), and VB – management based on DMD from VanderSchaaf and Burkhart (2012).

SI	Basal Area	DB	VB	SI	Basal Area	DB	VB	SI	Basal Area	DB	VB
15.54	27	13	19	20.12	20	11	14	24.69	16	9	12
16.15	25	13	18	20.73	19	11	14	25.30	16	9	12
16.76	24	13	17	21.34	18	10	14	25.91	16	9	12
17.37	23	12	17	21.95	18	10	13	26.52	15	9	12
17.98	22	12	16	22.56	18	10	13	27.13	15	9	11

Delaying thinnings often increases SPB hazard ratings (Mason et al. 1985), and thus errors in anticipated thinning ages can have serious implications. Based on an equation found in Mason et al. (1985, pg. 21) that has been widely used in the Western Gulf region, for the SI 25.91 m site when using LOBeatx and a thinning “trigger” of 25.25 m^2 ha^{-1}, for example, a one-year delay in the first thinning increases the SPB score from 154.39 at the original thinning age of 16 years to 165.40 at age 17. Both scores are in the Medium hazard class rating (scores of 62-167), just on the cusp of the High hazard class rating (scores of 168-219). However, a two-year delay in the first thinning to age 18 increases the SPB score to 175.26 which is now in the High hazard class rating. Of course, the 1,112 seedling ha^{-1} planting density was in part designed to address potential issues with SPB. Thus, delayed first thinnings of higher planting densities will likely have greater negative impacts and more serious consequences.

3.2 Thinned loblolly pine plantations (FVS)

When including thinnings into projections (Figure 3), this analysis showed that incorrectly determining SI can impact the final rotation age by up to 3 years. On lower quality sites (SI 16.76 m), for FVS projections, rotation ages differed by as much as 3 years and LEV differed by as much as \$331 ha^{-1}, on medium sites (SI 21.34 m) rotation ages differed by as much as 2 years and LEV differed by nearly as much as \$368 ha^{-1}, and on high sites (SI 25.91 m) differences up to \$401 ha^{-1} were observed and rotation ages differed by as much as 2 years. In all cases, LEV was positive and hence establishing loblolly pine plantations on all three sites is estimated to be financially viable. Kangas et al. (2011) specified that errors in excess of +/- 3 years in estimated final harvest ages were significant for spruce forests in Finland that grow slower than loblolly pine plantations in the southeastern US.

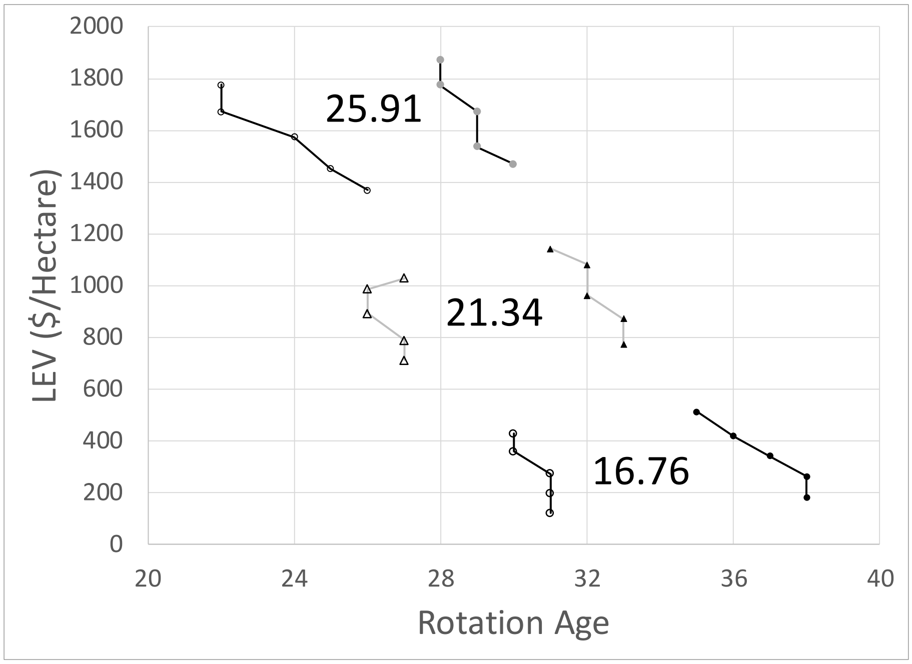

Figure 3. Financially optimal rotation ages and amounts (Land Expectation Value – LEV) for unthinned and thinned loblolly pine plantations in the Western Gulf region using FVS. True site indexes are assumed to be 16.76 m (15.54, 16.15, 17.37, 17.98), 21.34 m (20.12, 20.73, 21.95, 22.56), and 25.91 m (24.69, 25.30, 26.52, 27.13) at a base age of 25 years. Values in parentheses for a particular site index are incorrectly measured site indexes. For a particular site index, unfilled values are unthinned LEVs (left) and filled values are thinned LEVs (right).

Although errors in SI did not substantially impact rotation age for high quality sites, it could lead to drastically different optimum management regimes. Differences of \$321 to \$395 ha^{-1}, resulting from variation in growth and yield projections due to erroneous SI estimates, could lead a manager to conduct a reduced amount of management activity or, conversely, an increased amount of activity across a rotation such as fertilization or second-year herbaceous weed control treatments.

Projections from FVS were also obtained for unthinned plantations. For all SI, LEV was positive (Figure 3). For lower (SI 16.76 m) and medium (SI 21.34 m) quality sites, errors in SI had little impact on rotation ages, differing only by one year. However, for high (SI 25.91 m) quality sites rotation ages differed by as much as 4 years. For the same site quality, in terms of absolute values, errors in SI produced a similar range in responses for LEV in unthinned and thinned plantations.

However, for the same site quality, since unthinned LEVs were always lower relative to thinned LEVs, but the magnitude in errors were similar, errors in SI generally produced slightly greater percent LEV errors for unthinned stands. The exception being the lower quality site (SI 16.76 m), where percent LEV errors were meaningfully greater in unthinned stands. On the lower quality site (SI 16.76 m), when compared to a SI of 15.54 m, percent errors in LEV for unthinned stands ranged from 63% to 255% as compared to the thinned stands where the range was from 46% to 184%. On lower quality sites, thinnings may help to reduce the impacts on LEV when incorrectly determining SI. For the high site (SI 25.91 m), when comparing all LEVs to a SI of 24.69 m, percent errors ranged from 5% to 27% for thinned sites and from 6% to 30% for the unthinned sites. On the medium site (SI 21.34 m), when comparing all LEVs to a SI of 20.12 m, percent errors ranged from 13% to 48% for thinned sites and from 11% to 45% for the unthinned sites.

The impacts of errors when determining SI on LEVs and financially optimal rotation ages may become greater as the number of product classes increase, particularly if these product classes are narrowly defined in terms of DBH, upper stem diameters, or log lengths. Impacts will likely be exacerbated when there are greater disparities in stumpage values among product classes, particularly when product classes are narrowly defined as previously described. Slight errors in SI may not necessarily produce substantially different total yields or diameter distributions, but associated changes may be enough to produce significantly greater yields of more valuable, but narrowly defined, product classes. Further yet, these issues will likely be exacerbated even more as site quality increases since these sites will tend to cover the range of product classes to a greater extent throughout rotations relative to lower quality sites. For example, for unthinned stands, the higher site qualities (SI 25.91 m) often had some sawlog production at the optimal financial rotation age, unlike the medium (SI 21.34 m) and lower (SI 16.76 m) quality sites which had no sawlog production at their optimal financial rotation ages.

3.2.1 Timing of first thinning

When using a basal area ha^{-1} of 25.25 m^2 as the thinning “trigger”, there was a three-year difference between the first thinning on poor sites (SI 16.76 m) and a two-year difference on medium-quality sites (SI 21.34 m) between the erroneous low and high SIs for a particular “true” SI (Table 2). A difference of three years can be meaningful. A three-year difference between the timing of the first thinning can impact loblolly pine growth and yield enough to lengthen rotation ages and subsequently impact estimated financial returns and harvest scheduling and regionwide assessments. Kangas et al. (2011), for example, specified that errors in excess of +/- 2 years in estimated ages of when a thinning should be conducted were significant for spruce forests in Finland that grow slower than loblolly pine plantations in the southeastern US.

3.2.2 Number of thinnings across a 40-year rotation

Across a 40-year rotation, for the most part errors in SI had little impact on the number of thinnings except for the poor site (SI of 16.76 m) where if the correct SI was 16.76 m, but determined in the field to be an SI of 15.54 m or 16.15 m, only two thinnings would be conducted rather than three thinnings. Of course, different planting densities may produce varying results than the 1,075 seedlings ha^{-1} used for this analysis.

Table 2. Number and age of thinnings by site index for loblolly pine plantations across a 40-year rotation when using Forest Vegetation Simulator (FVS). The second number under SI is the optimum economic rotation age. True site indexes are assumed to be 16.76 m (15.54, 16.15, 17.37, 17.98), 21.34 m (20.12, 20.73, 21.95, 22.56), and 25.91 m (24.69, 25.30, 26.52, 27.13) at a base age of 25 years; values in parentheses for a particular site index are incorrectly measured site indexes. Timings of the Third thinning are based on projections, while the optimum economic rotation age is based on projections but also financial considerations and thus is younger in age than the age of the projected Third thinning.

SI	First	Second	Third	SI	First	Second	Third	SI	First	Second	Third
15.54 - 38	22	31	-	20.12 – 33	18	26	37	24.69 - 30	15	22	32
16.15 - 38	21	30	-	20.73 – 33	17	25	36	25.30 - 29	15	22	32
16.76 - 37	20	28	39	21.34 – 32	17	25	36	25.91 - 29	14	21	30
17.37 – 36	20	28	39	21.95 – 32	16	23	33	26.52 - 28	14	21	30
17.98 - 35	19	27	38	22.56 - 31	16	23	33	27.13 - 28	14	21	30

3.2.3 Number of thinnings across an economically optimum rotation

Errors in SI had little impact on the number of thinnings when using financial criteria (LEV) to determine rotation age. Every site quality resulted in two thinnings. The final harvest ages for the low quality site in particular (SI 16.76 m), but also for the medium quality site (SI 21.34 m), are likely longer than what is commonly observed today given newer generation silvicultural practices. This is likely observed because FVS predicts slower stand development relative to newer generation plantations (Fox et. al 2007, Jokela et al. 2010, Burkhart and Yang 2022). Different results may be observed when using planting densities other than the 1,075 seedlings ha^{-1} as used for this analysis.

For projections from both LOBeatx and FVS, errors when quantifying SI can substantially impact estimated financial returns (Figures 2 and 3). Depending on stumpage revenues and reforestation costs, capital investments in plantations that were found to be negative when using the correct SI could potentially be found to be positive if SI is overestimated.

Within individual stands errors in SI can lead to meaningfully different optimal management scenarios. Beyond that, these errors will also have substantial impacts on regional or national level assessments and in harvest scheduling analyses. Across a landscape, it would be hoped that errors among stands would cancel out to where SI in some stands would be underpredicted while in other stands SI would be overpredicted. However, in some cases errors in SI are likely not normally distributed around the “true” SI. Thus, the SIs will be somewhat skewed and hence errors may not cancel each other out as compared to if indeed the “true” SI was actually known for every stand. Plus, underpredicting of the same magnitude in SI may impact projected growth and yield differently than overpredicting of the same magnitude (Tables 1 and 2), thus errors in predicted growth and yield may not cancel each other out.

Error levels of SI, and in a sense dominant height, as used in this study are likely conservative. For instance, for the SI 25.91 m site, errors in dominant height only ranged up +/- 1.22 m. Other studies have used errors in determining height of up to 20% (Eid 2000), 25% (Borders et al. 2008), 30% (Kangas et al. 2011), and 50% (Gertner and Dzialowy 1984). Among different field crews, McRoberts et al. (1994) found that SI estimates varied from 15.24 to 23.16 m (base age 50) on one site, with a coefficient of variation of 13%, and from 14.02 to 23.16 m (base age 50) on another site, with a coefficient of variation of 16%. Both sites were dominated by sugar maple (*Acer saccharum* Marsh.). Thus, the impacts on LEV and the timing and number of thinnings found in this study are likely conservative as to what may be observed operationally. However, these relatively lower levels of error were selected to show that even small errors in SI can be important. Measurement error will likely never be eliminated during forest inventories, and thus indirectly when conducting harvest scheduling or management regime simulations. However, it is still vitally important that logistical and economically feasible efforts are made to minimize errors in determining SI and ultimately within the analytical system.

To gain some idea of how much impact larger errors can have when quantifying SI, we can assume the true SI is 20.12 m but that errors vary from an SI of 17.98 m to an SI of 22.56 m. For LOBeatx, in this case, LEV can differ by as much as \$546.37 ha^{-1} (Figure 2) and the timing of the first thinning (Table 1) and final rotation age (Figure 2) can differ by as much as 4 years and 3 years, respectively. When using FVS projections, LEVs of thinned stands can differ by as much as \$630.44 ha^{-1} (Figure 3) and the timing of the first thinning (Table 2), second thinning, and final rotation age can differ by as much as 3 years, 4 years, and 4 years, respectively. Due to improved loblolly pine plantation silvicultural practices over the past 30 or so years (Fox et al. 2007; Jokela et al. 2010; McKeand et al. 2021; Burkhart and Yang 2022), particularly with regards to genetics (Fox et al. 2007; McKeand et al. 2021; Burkhart and Yang 2022), perhaps more uniformity in height (Yáñez et al. 2017) may reduce measurement errors in SI.

4 Conclusions

Predicting future yields normally requires an estimate of site quality, for loblolly pine plantations, this is commonly some definition of SI. Although the use of SI within growth and yield models is conceptually easy, the actual practice of determining SI within the field is often difficult and subjective.

Errors in SI often occur because of the ambiguity associated with selecting “site” trees. Plus, errors in “site” tree height measurements themselves. Additionally, errors in SI occur because the user is not determining “site” trees correctly in the field given the definition of SI used within the growth and yield model. Although not as common in loblolly pine plantations, particularly those with well-maintained records, the estimated current age of a stand may be incorrect. The use of advanced hypsometers (e.g. lasers) should help to reduce measurement errors. To further reduce errors in determining SI, foresters should take care to select "site" trees consistent with the definition of SI that is being used and to more accurately determine stand age.

This analysis does not produce definitive impacts on management scenarios and financial assessments when errors in SI are made. Firstly, the "true" SI is never known. Plus, different stumpage values, different interest rates, different growth and yield models, etc., would produce different results. However, this analysis does likely show the relative impacts on financial analyses, the number and timing of thinnings, and final rotation ages, when errors in SI are made. It demonstrates that growth and yield projections are only tools. Some type of actual quantitative sensitivity analysis should always be associated with growth and yield results and outputs.

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