

Comparison of site index and biomass production of spruce-fir stands by soil drainage class in Maine

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ABSTRACT

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Site index and biomass production of natural, even-aged spruce-fir (*Picea rubens* Sarg., *Picea mariana* (Mill.) B.S.P., *Abies balsamea* L.) stands on four soil drainage classes were compared to determine the relationship between site index and biomass production. Biomass yield equations using stand age at breast height and site index as independent variables were developed by soil drainage class. Site index was determined from equations developed for each drainage class and revealed that site index for spruce and fir increased with improved drainage. Site index was found to be a poor predictor of stand biomass production on the soils studied as there was no significant change in the biomass production with increase in site index on the poorer drained soils. However biomass production decreased with increase in site index on the better drained soil suggesting that rates of self-thinning may increase on these soils with increase in site index. Site index, which measures only the height growth of the forest, may not be adequate in classifying sites into productivity classes, as it does not take into account the relation between soil and other stand properties. Stand biomass production was also compared among all soils, revealing that differences in biomass productivity among these soils is not evident at early ages. No significant differences in biomass productivity among stands were found until about stand age 60 years, where production of stands on the better drained soils became greater than those on the poorer drained soils.

INTRODUCTION

Increasing demands for products from a decreasing land base concerns forest managers with the productivity of their present forests. Arising from this concern is a need to refine the understanding and the measurement of this productivity. Site index, the traditional method of measuring productivity, has worked well in some situations but poorly in others.

More complete utilization of the tree has led to an interest in biomass production as a measure of site productivity. Studies have been conducted in

Maine to examine the relationship between soil and spruce-fir forest biomass production (Schiltz and Grisi, 1980; Ferwerda and Young, 1981; Young, 1981; Grisi, 1982). Soil drainage class was shown to be an important influence on biomass productivity, with productivity of even-aged, natural stands being greater on better drained than on the poorer drained soils. However, Ferwerda and Young (1981) concluded from linear analysis of stand biomass over stand age the possibility of greater biomass productivity on the poorer drained soils at younger stand ages.

This latter conclusion is contrary to site index, which assumes from height measurements that growth on a particular site is always greater than the site class below it and always less than the one above, at any given age. Therefore, this study sought to determine the site index of spruce (*Picea rubens* Sarg., *Picea mariana* (Mill.) B.S.P.) and balsam fir (*Abies balsamea* (L.) Mill.) growing on different drainage classes and compare this with the biomass yields of spruce-fir forests growing on those same classes. Soils from the Chesuncook catena were chosen for this study as it is a major catena in north-central Maine upon which much of the spruce-fir forest grows.

METHODS

Sample plot information

A total of 126 sample plots were located in even-aged spruce-fir stands, which: (1) appeared to have developed without cultural treatments; (2) were free from recent insect or disease damage; (3) were not over-mature; and (4) were fully to over-stocked. Ages of the sampled stands ranged from 10 to 80 years (Table 1). The specific soils studied in the Chesuncook catena were Monarda (poorly drained), Telos (somewhat poorly drained), Chesuncook (moderately well to well drained), and Elliottsville (well drained). These soils have developed in a very compact basal till derived from dark-colored slate

TABLE 1

Number of sample plots per age class by soil

Soil	Age class (years)								Total
	10	20	30	40	50	60	70	80	
Elliottsville	–	–	–	–	11	4	–	–	15
Chesuncook	2	–	1	–	14	7	–	–	24
Telos	4	–	1	1	21	13	4	1	45
Monarda	3	–	–	6	20	12	–	1	42
Totals	9	0	2	7	66	36	4	2	126

and phyllite bedrock. Soil texture is typically light loam and silt loam for the solum and gravelly loam and silt loam for the subsoil.

Circular sample plots were 0.01 ha in size, except for plots located in the 10-year-old stands which were 0.002 ha in size owing to the large number of stems. Soils were relatively uniform beyond the boundaries of all plots. A tally of all stems 1.3 m or greater in height by breast height diameter (dbh), crown class, and species was performed on each of the 0.01 ha plots. Total height, basal diameter (at groundline), and dbh of trees 1.3 m or greater in height, and species was recorded for each stem on the 0.002 ha plots.

Five dominant or codominant spruce and/or fir trees were selected from each plot for site index determinations. Stem analysis was performed on these selected trees from 12 of the 0.01 ha plots, and total tree height and breast height age data were collected from trees on the remaining plots. Trees selected for stem analysis were cut from a 0.15 m stump, and disk samples were taken at groundline, at 0.15 m, and every 1.2 m thereafter. These samples were taken to the laboratory and their disk age was determined with a 40 \times microscope.

Data from the Chesuncook and Elliottsville soils were combined to increase the number of sample plots representing the better drained soils of the catena. This was reasonable owing to the similarity in physical properties of the two soils (Schiltz and Grisi, 1980). Analysis of covariance was performed on the stand data using the method of least squares to fit a general linear model, with age class as the covariate and soils as the grouping variable. This analysis demonstrated that the numbers of trees per hectare, basal area per hectare, mean stand diameter, stand density index, and average height of the dominants and codominants were similar between these two soils in any given age class.

Site index

Height/age data for this analysis came from two sources: (1) total tree height/breast height age pairs; and (2) height/age pairs from stem analysis. When trees are sectioned for stem analysis, the section points do not necessarily coincide with the tip of the annual leader (Carmean, 1972; Lenhart, 1972). The procedure described by Carmean (1972) to adjust tree height measurement at the sample point was used in this study.

Vicary (1982) explored 13 linear and nonlinear height–age equations for spruce and fir, and found two basic nonlinear height equations that yielded higher R^2 values and lower standard errors of the regression estimates than the linear equations. The base equation that Vicary chose was proposed by Richards (1959) and later developed for site index by Lundgren and Dolid (1970) of the form

$$\text{Height} = b_1 (1 - e^{b_2(\text{Age})})^{b_3} \quad (1)$$

where e is the base of the Napierian logarithm.

Vicary (1982) and Carmean (1972) successfully used a variation of eqn. (1) in a simpler form

$$H_{bh} = b_1 (1 - e^{b_2 A_{bh}}) \quad (2)$$

where H_{bh} is height above breast height and A_{bh} is the recorded age at breast height. When tested in this study, eqn. (2) underestimated the site indices of stands on the poorer site classes and young stands.

A variation of eqn. (1) in the form

$$H_{bh} = b_1 (1 - e^{b_2 A_{bh}})^{b_3} \quad (3)$$

was also tried and performed much better, apparently because height growth of trees on the poorer drained soils and in younger stands displays a more characteristic sigmoidal pattern. The inclusion of the b_3 coefficient (initial growth pattern) allows the lower concave portion of the pattern to develop, giving better estimates of the b_1 (asymptotic height) and b_2 (growth rate) coefficients. Therefore, eqn. (3) was used in this study and equation coefficients were estimated for spruce and for fir from each soil using the multivariate secant method (Table 2). Height used in eqn. (3) was height above breast height because shade-tolerant species such as balsam fir and the spruces of the northeast may survive extended periods of suppression in their early life before responding to release. Hoar and Young (1965) found that once red and white spruce (*Picea glauca* (Moench) Voss) reached breast height they generally displayed free growth. In addition Husch (1956) found that most

TABLE 2

Equations^a to predict total height from age at breast height

Species	Soil	Coefficients			Sample size ^b	R^2
		b_1	b_2	b_3		
Red/black spruce	Chesuncook-Elliottsville	22.464	-0.032	1.603	151	0.95
	Telos	21.737	-0.030	1.632	311	0.96
	Monarda	16.339	-0.052	2.795	329	0.96
Balsam fir	Chesuncook-Elliottsville	29.843	-0.019	1.159	215	0.92
	Telos	20.572	-0.043	2.134	206	0.90
	Monarda	19.044	-0.034	1.823	67	0.94

^a $H = 1.3 + b_1 (1 - e^{b_2 A})^{b_3}$ where H is total height (m), A is age at breast height.

^bNumber of height/age observations.

species do not display normal height growth until breast height has been reached.

If age in eqn. (3) is the base age at which site index is determined, then height equals site index at the chosen base age

$$SI_{bh} = b_1 (1 - e^{b_2 A_b})^{b_3} \quad (4)$$

where SI_{bh} is the site index above breast height, and A_b is the base age.

With this known relationship in eqn. (4), two courses of logic were pursued in an attempt to rearrange eqn. (3) to predict the site index of the study plots. First, the estimates for b_3 and b_2 appeared to be better than estimates for b_1 , because most of the data probably fell within the b_3 and b_2 portion of the curve. Equation (4) was then rewritten with site index as a function of the b_1 coefficient

$$b_1 = SI_{bh} / (1 - e^{b_2 A_b})^{b_3} \quad (5)$$

The expression for b_1 in eqn. (4) was substituted for b_1 in eqn. (1), then solved for site index

$$SI_{bh} = H_{bh} (1 - e^{b_2 A_b})^{b_3} / (1 - e^{b_2 A_{bh}})^{b_3} \quad (6)$$

Equation (6) worked well for study plots 40 years of age and older, but greatly overestimated the site index of some plots under 40 years of age. Site index, which essentially becomes the b_1 coefficient in eqn. (6), was more than likely overestimated on these plots because the asymptotic height (b_1) was not fixed, and these young trees displayed vigorous growth in the b_3 and b_2 portion of the height growth curve.

The second course of logic was to use site index as a function of the b_2 coefficient (growth rate) with both ends of the height growth curve fixed. Equation (4) was rewritten to solve for b_2 :

$$b_2 = \ln\{1 - (SI_{bh}/b_1)^{(1/b_3)}\} / A_b \quad (7)$$

The expression for b_2 from eqn. (7) was substituted in eqn. (3), and solved for site index

$$SI_{bh} = b_1 \{1 - e^{\ln(1 - (H_{bh}/b_1)^{(1/b_3)}) (A_b/\text{Age})}\} \quad (8)$$

The predictability of eqn. (8) worked very well for plots of all ages and was used in this study. However the measured heights of 13 spruce trees from five plots and three fir trees from two plots were higher than the estimated asymptotic height (b_1 coefficient), hence could not be used to estimate site index for those plots. Since these trees occurred on plots in the older stands, eqn. (6) was used to estimate the site index of these plots.

Stand biomass

Non-linear equations to predict total oven-dry biomass for individual spruce and fir trees growing on the Chesuncook catena (Williams, 1986) were applied to individual trees. Equations by Dyer (1967), Hocker and Earley (1983) and Young et al. (1980) were used to predict individual tree biomass of the few remaining species other than spruce and fir that occurred on the plots. The individual tree biomass was summed on each plot and converted to oven-dry tonnes per hectare.

As the main objective of this study was to test the ability of site index to predict biomass production, an equation to predict total stand biomass from site index and age was developed. A stepwise regression technique which maximizes the R^2 value for each equation was used.

The stand age used in this analysis is the "effective" stand age at breast height, or age since stand release. It was apparent from the stem analysis that some trees had been suppressed above 1.3 m and released after the spruce budworm outbreak of the early 1900s, or had experienced top-kill during the budworm epidemic with subsequent rejuvenation of terminal shoot elongation. The effective stand age was estimated by solving for age in eqn. (3), using the appropriate coefficients estimated for each soil and species, and applied to plots that displayed this problem.

Using actual chronological age instead of effective age on these plots overestimates the time during which these partially suppressed trees would have accumulated their biomass had they grown freely. Also, the sizes of these older dominant and codominant trees were not much different from their unsuppressed counterparts. Therefore, the differences in individual biomass between these trees were considered non-significant.

The first step in developing the stand biomass equation was to perform the stepwise procedure with the data pooled from all soils. The best equation produced was of the form

$$y = b_0 + b_1(A) + b_2(S)(A)^2 + b_3(S)(A)^3 \quad (9)$$

where y is stand biomass (oven-dry tonnes per hectare); A is stand age at breast height; S is spruce site index; and b values are the coefficients to be estimated.

Spruce site index was chosen over fir because spruce trees from which the site index was determined occurred on 100 of the 126 sample plots, whereas fir occurred on only 84 plots. Regression equations were developed for each soil to predict the mean site index for plots with no spruce by using mean plot site index for fir as the independent variable.

After performing the stepwise procedure for separate soils, eqn. (9) remained the best common equation for each of the three soil groups, but with coefficients now estimated for each soil group rather than for the overall data.

TABLE 3

Stand biomass prediction equations

Soil group	Model ^a	<i>F</i> value	<i>P</i> value	Sample size	<i>R</i> ²
Chesuncook- Elliottsville	$Y = -12.138$	-0.373	0.7117	39	0.69
	$+5.261(A)$	2.820	0.0079		
	$-5.94(10)^{-3}(S)(A)^2$	-1.952	0.0589		
	$+7.91(10)^{-5}(S)(A)^3$	2.378	0.0230		
Telos-Monarda	$Y = 21.537$	2.234	0.0281	87	0.78
	$+2.487(A)$	5.652	0.0001		
	$+1.37(10)^{-3}(S)(A)^2$	2.010	0.0477		
	$-2.01(10)^{-5}(S)(A)^3$	-2.958	0.0040		

^a*Y* is oven-dry biomass (tonnes per hectare), *A* is stand age at breast height (years), *S* is spruce site index (m).

The *F*-test at *P*=0.05 about the sum of square error for all three biomass equations indicated that differences existed among these equations. Visual comparison of the plotted equations, using the mean plot spruce site index for each soil, suggested that equations for the Telos and Monarda soils were similar but different from the Chesuncook-Elliottsville equation. This was verified by the *F*-test and precipitated two final equations, an equation for the Chesuncook-Elliottsville soils and one for the Telos-Monarda soils (Table 3).

RESULTS AND DISCUSSION

The site index values for each soil grouping as determined from the height/age equations (Table 2) and the mean site index values determined for the study plots from eqns. (6) and (8) are listed in Table 4. Since the site index values from eqns. (6) and (8) were height above breast height, 1.3 m was added to each equation so the results would be expressed in terms of total tree height. As expected, site index for both spruce and fir increased with improved soil drainage.

The two biomass yield equations were plotted using the mean spruce site index from the study plots for each soil grouping. The 95% confidence bounds for individual predictions about each observation (Fig. 1) reveal that there is no significant difference in the biomass production among soils at younger ages. However, beyond about 60 years of age, biomass production on the better drained Chesuncook-Elliottsville soils surpasses that of the poorer drained Telos-Monarda soils.

The equations were then plotted as a function of site index at successive ages (Fig. 2). Within the Telos-Monarda soil grouping, the total predicted

TABLE 4

Site index values (m) for spruce and fir by soil drainage

Species	Soil	Site index ^a	Mean site index ^b	Plot minimum value	Plot maximum value
Red/black spruce	Chesuncook–Elliottsville	17.1	17.4	14.8	20.8
	Telos	15.6	16.2	13.3	17.9
	Monarda	14.6	15.1	9.8	18.6
Balsam fir	Chesuncook–Elliottsville	18.2	18.0	14.1	21.2
	Telos	17.0	17.4	13.2	20.8
	Monarda	14.6	14.6	11.2	18.3

^aDetermined by using base age of 50 years in the height/age equations (Table 2) with the appropriate coefficients for species and soil.

^bMean value of the study plots, using appropriate coefficients for species and soil (Table 2) in eqn. (8) to determine plot values.

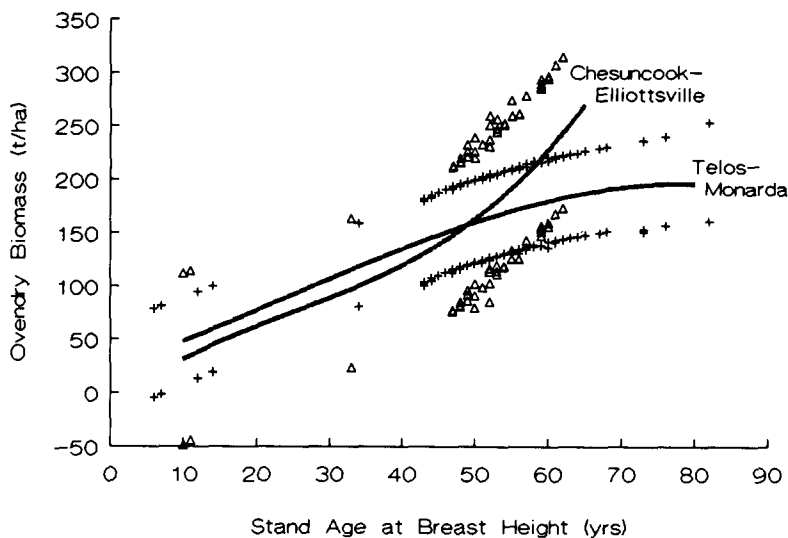


Fig. 1. Biomass prediction equations plotted with the 95% confidence bounds for individual predictions about each observation (Δ = Chesuncook–Elliottsville soils, + = Telos–Monarda soils).

stand biomass remains nearly constant with an increase in site index at a given age. However, within the Chesuncook–Elliottsville soil grouping, the total predicted stand biomass decreases with increase in site index.

Since the amount of biomass in a given area is influenced by the numbers of plants, their size, species, etc., analysis of covariance was performed on the

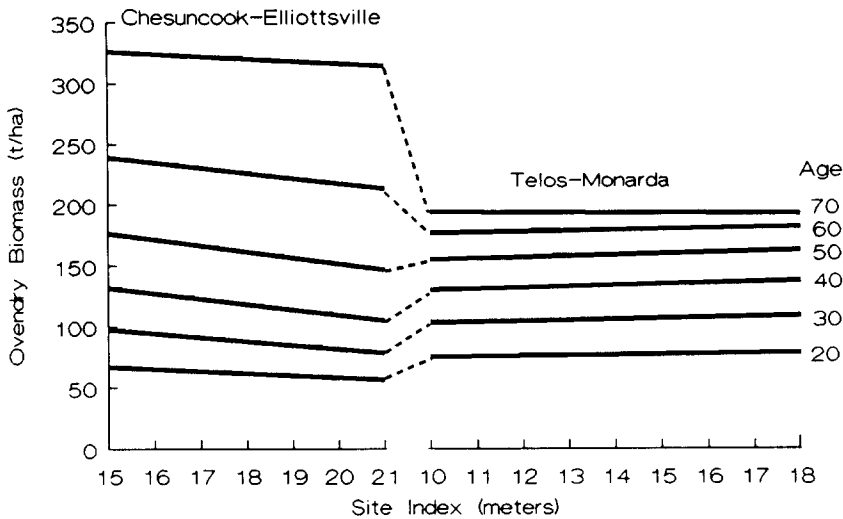


Fig. 2. Biomass prediction equations plotted as a function of site index at selected stand ages at breast height by soil grouping.

data for number of trees and basal area per hectare, mean stand diameter (based on tree of average basal area), and the average height of the dominant and codominant trees. A method of least squares to fit a general linear model with age class as the covariate and soils as the grouping variable was used and tested at the $P=0.05$ level. The analysis revealed that all soils had similar basal area, but mean stand diameter and average stand height increased with improved drainage, and the number of trees per hectare decreased with improved drainage.

Apparently individual trees on the better drained Chesuncook-Elliottsville soils were able to express dominance earlier on the sites with the higher site index (within the soil group) than on the poorer sites owing to more rapid height growth. As a result, more individual trees drop out of the stands on the better sites, thus producing fewer trees per hectare with subsequent decreases in total biomass. The number of trees per hectare shows an insignificant but negative correlation (-0.11) with site index within this soil group. This self-thinning directly results from an increase in tree size, which apparently increases more rapidly as site index increases. The biomass that is lost through mortality of individual stems apparently is not totally recovered in the remaining dominants and codominants. The increases in the negative slopes of these lines with age in Fig. 2 for the Chesuncook-Elliottsville soils indicate that this dominance factor becomes more important as the stands age.

Individual trees on the poorer drained Telos and Monarda soils do not display the rapid growth and dominance seen in those on the better drained soils. Hence, the individual shade-tolerant spruce and fir trees on these poorer

drained soils display slower growth and subsequent change in tree size while continually competing for growth resources.

The findings also suggest that trees become established at higher densities on the poorer drained soils than on the better drained. This is a function of species and site, the latter being related to available moisture, organic layer depths and total rooting depth.

The thickness of the O1 horizon decreases significantly with increasingly better drainage, while the thickness of the O2 horizon decreases to a lesser extent on those soils (Schiltz and Grisi, 1980). The mean total organic matter thickness decreases significantly with increasingly better drainage, ranging from 11.4 cm for the Monarda soil to 7.9 cm for the Chesuncook–Elliottsville group (Schiltz and Grisi, 1980). The total rooting depth (including thickness of the organic matter), mineral soil rooting depth, depth to mottling, and depth to hardpan also increases with better drainage.

Apparently the available moisture and seedbed conditions are important factors that influence the differences in establishment densities on these soils. The wetter Monarda soils seemingly provide a better moisture supply for the germinating seeds than do the drier Telos and Chesuncook–Elliottsville soils. The forest floor of these wetter soils has deeper organic layers with a heavier sphagnum moss cover. Black spruce, which characterize these soils, germinate and become established readily on the sphagnum moss, perhaps because it is almost constantly moist (Fowells, 1965). Adequate moisture is the chief factor controlling red spruce regeneration, with germination occurring on almost any type of seedbed, but reproduction success depends more on factors determining seedling survival than on requirements for germination (Fowells, 1965). Almost any type of seedbed is also satisfactory for balsam fir if enough moisture is present, but thick duff layers may delay or prohibit germination. Balsam-fir seedlings may be able to compensate for this by the fact that they develop longer taproots than spruce seedlings.

After germination, the rooting depth of the soil becomes crucial. Plant root systems develop poorly in wet soils. This poor growth is related to the oxygen diffusion rate, which is about 10 000 times more rapid in air than in water (Foth and Turk, 1972). In unsaturated soils, thin films of water around the root surfaces produce a short diffusion path that enables roots to obtain sufficient oxygen. The enormously longer diffusion paths in water-saturated soils, coupled with the very low diffusion rate of oxygen in water, produce oxygen deficiencies. Root tips are regions of rapid cell division and elongation and have a high oxygen requirement. Typically, roots do not penetrate the water-saturated soils because of oxygen deficiencies. As a result, tree growth is slower on the poorly drained Monarda soil, and is aggravated by the fact that more root systems are competing for the same soil resources as a result of the higher stand densities.

Full site occupancy by the stand probably occurs at some point shortly after

the onset of competitive interaction. This presumably occurs at later ages as the soil drainage improves. The individual stems within the spruce-fir stands developing on the better drained soils are able to express dominance at an earlier age compared with those on poorer drained soils.

CONCLUSIONS

Differences in biomass production among these soils are not evident at early ages. Even though the poorer drained soils support more trees per hectare, the biomass is distributed on smaller, shorter trees as compared with the better drained soils. However, as the result of continued better height growth of the fewer, larger individuals on the better drained soils, the total stand biomass accumulation eventually surpasses that of the poorer drained soils at later ages.

Site index is a poor predictor of biomass yield of spruce-fir stands on the soils studied as the relationship between site index and biomass was found to be inconsistent. There was no significant change in the biomass yield with a change in site index within the Telos-Monarda soil grouping. Moreover, total biomass yield decreased as site index increased within the Chesuncook-Elliottsville soil grouping.

With all of the complexities and interactions of stand properties, site index may not be adequate to classify sites into biomass productivity classes, as height alone does not account for differences in biomass between site classes. Site index measures only the height dimension of the forest and does not take into account the relation between soil and the resulting stand properties. The site rated at the higher site index may have more potential for height growth, but not necessarily for total productivity.

However, in order to measure the total biomass production potential of a site, the stocking levels of the stand must be considered fully to over-stocked, and not all stands exist in this condition for reasons either natural or otherwise. Secondly, species composition, growth rates, tolerances, specific gravities, ages of individual trees, and form factors can create differences in biomass for stands of similar densities.

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