DEVELOPMENT OF A PRODUCTIVITY INDEX FOR DOUGLAS-FIR

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ABSTRACT

Site index is a commonly used method for indicating productivity of a range of plantation species throughout the world. For Douglas-fir in New Zealand, basal area 'level' (as represented by site basal area potential, or SBAP) is also a key component in determining volume yield, and therefore also needs to be considered. A productivity index combining SI and SBAP shows promise for comparing yields across a range of sites. The index has been standardised to a specific regime, involving thinning to waste by 15m MTH to 500 stems/ha, and then growing the stand to age 40 yrs. Because of this, it has been named the '500 Index'. Its development is described, and sensitivity of the index to minor variations in the underlying assumptions is presented.

Introduction

Site Index (SI) is a common type of productivity index, and is used for a range of plantation species throughout the world. SI is usually estimated as the mean top height (MTH[1]) of a stand for a given reference age- for Douglas-fir in New Zealand, that reference age is 40 years. SI is traditionally considered independent of stand management, and the conclusion is drawn that SI is strongly correlated with overall volume yield (e.g. Lewis et al, 1976, Bradley et al, 1966, Avery and Burkhart, 1994). In intensively managed stands of both *Pinus radiata* and Douglas-fir in New Zealand, SI alone has been found to be insufficient to predict volume productivity. Two stands with similar silviculture and SI can have widely differing levels of basal area growth, and hence volume production. Analysis of data from permanent sample plots in New Zealand Douglas-fir stands has shown that two measures of productivity are required- SI and basal area growth potential.

The index of basal area growth used for Douglas-fir in New Zealand is Site Basal Area Potential (SBAP), expressed in m^2/ha/yr. SBAP can be approximated as the basal area current annual increment (CAI) of a 30-35 year-old fully-canopied stand of Douglas-fir. It is site, forest or region specific, depending on modelling resolution, and ideally needs to be determined *a priori* from sample plot or inventory data. For practical purposes, it can also be described as the value that when entered into the national Douglas-fir growth model (DF NAT), gives least error in basal area prediction for that particular site, forest or region.

The question therefore arises- how do SI and SBAP contribute to the volume yield of Douglas-fir (as expressed as MAI) in New Zealand? Knowles and Hansen (2004) describe how these terms are used within the national stand-level Douglas-fir growth model (DF NAT). Fight et al (1995) described an earlier version of this model. The goal of this study is to understand the individual contribution of SI and SBAP to yield prediction, with a view to developing one simple volume index that can be applied across a wide range of sites.

The silvicultural regimes commonly practiced in New Zealand also have the potential to affect productivity, with lower stockings and incomplete canopy closure over at least part of the rotation. With radiata pine, an MAI index (termed the 300 Index) was developed initially, and from that a comprehensive growth model - the 300 Index Growth Model- was subsequently derived. The 300 Index is the mean annual increment in volume for a stand of radiata pine that has been pruned to 6m, thinned at the completion of pruning, and grown to a final stocking of 300 stems/ha at age 30 years. The opposite route is being followed with Douglas-fir. We already have the growth model, and from that we can explore the possibility of deriving an MAI index.

Most initial stockings of Douglas-fir are in the range of 1250-1650 stems/ha. It has been common to thin to waste to a stocking of 500-800 stems/ha by MTH of 14-18m. There is clear evidence that for a stocking of 800 stems/ha, mortality will become severe by age 40 years, indicating that for the purposes of developing an index free of mortality complications, a stocking of around 500 stems/ha will be more stable and less prone to influence from excessive mortality.

For these reasons, the suggested definition of the standardised ‘Douglas-fir Productivity Index’ regime is as follows. Planted at 1250-1650 stems/ha, (90%-95% survival), thinned to waste to 500 stems/ha by MTH 15m, and clear-felled at age 40 years.

The 500 Index is then defined as the mean annual volume increment (total standing volume at age 40 years), for the above stand.

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[1] MTH- the average height of the 100 trees/ha with the largest diameters.

Methods and Materials

Volume is a product of height and basal area, and is often shown to be a function of these two stand parameters in the following simple form.

Volume =a*MTH*BA (1)

If a volume index is estimated at a constant rotation age corresponding to the reference age for Site Index (i.e. 40 years) SI can be substituted for MTH in the above equation. As SBAP is a measure of basal area growth potential, it can also be substituted for BA, but as SBAP remains constant across regimes but BA does not, there is a need to standardise the index to a single regime, as indicated above. Also, because SI and SBAP are in different units, it is necessary to provide each with its own coefficient. A power term offers more flexibility than a straight multiplication. The slope of this function is unlikely to be one, so a slope coefficient will also be necessary i.e.

Volume Index=a*SI^c*$SBAP^b$ (2)

where *a* is the slope coefficient, and *b* and *c* are the power coefficients for SI and SBAP respectively.

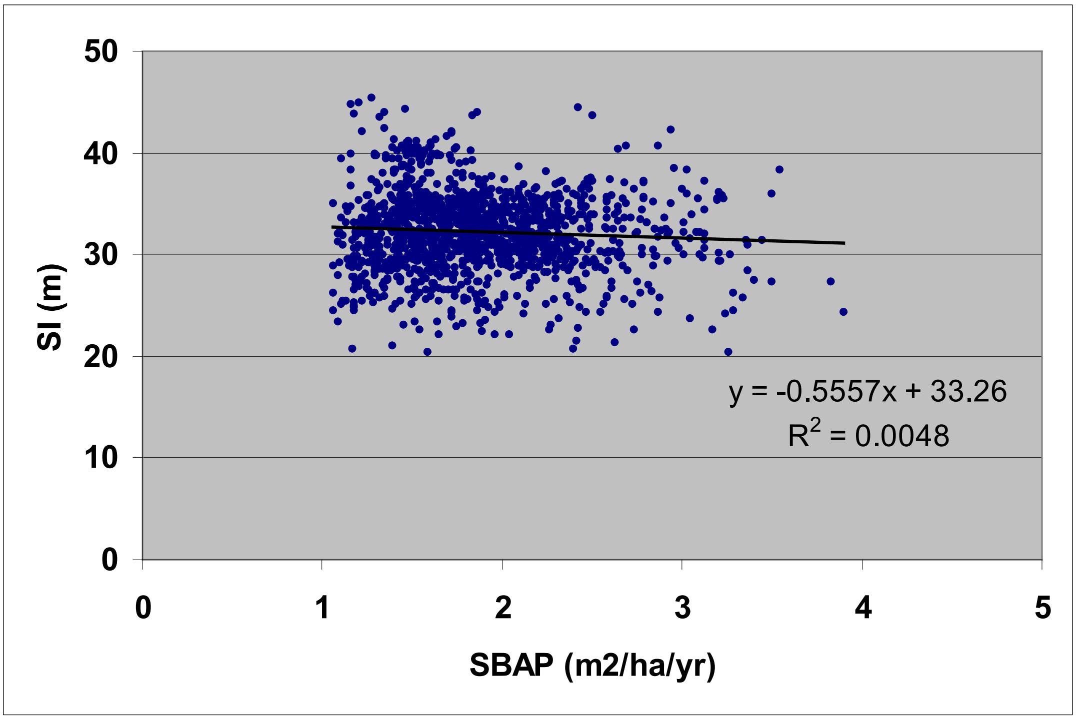
Finally, most New Zealand foresters think of productivity in terms of MAI rather than total yield.

MAI Index=Volume Index/rotation age (3)

The utility of function (2) above can be tested by using DF NAT to predict the total standing volumes (TSV) for a wide range of SI and SBAP combinations at age 40 years for stands grown under the above regime. The TSV can be divided by rotation age to obtain MAI, which can then be regressed against SI and SBAP.

Examination of the NZ permanent sample plot (PSP) data base (Ellis and Hayes, 1997) shows that for Douglas-fir sample plots, SBAP ranges between 1.0 and 3.8, and SI ranges between 20m and 45m. Very few *stands* exceed a SI of 40m, and an SBAP of 2.6. Fig 1 clearly illustrates the lack of correlation between SI and SBAP, and confirms that both need to be included in a productivity index.

Fig 1. Relationship between SI and SBAP for 1365 NZ Douglas-fir sample plots



DF NAT is contained in version 2 of the Douglas-fir Calculator (Halliday and Knowles, 2003) which is an EXCEL implementation. The 'Explorer' facility within the calculator was used to estimate total standing volumes at 40 years for the '500 Index' regime, covering this matrix, with steps of 4m for SI and $0.2m^2$/ha/yr for SBAP. This involved setting up a single run of the model to predict total standing volume at age 40 years for 48 stands. Because the ht/age curve for NZ Douglas-fir includes a latitude term, latitude was also held constant at 42^0 South, which is the average for the Douglas-fir range in NZ. The initial BA at the starting age of 10 years is the default value as predicted by the calculator. The output is shown in table 1.

Table 1. Output from the Calculator

Run	SBAP	SI	Rot age	Start age	Stocking	Initial BA	Thin	MTH	Stems/ha	Final stocking	TSV	MAI
1	1	20	40	10	1500	3.4	W	15	500	486	208	5.19
2	1.2	20	40	10	1500	3.6	W	15	500	484	249.3	6.23
3	1.4	20	40	10	1500	3.9	W	15	500	483	291.2	7.28
4	1.6	20	40	10	1500	4.2	W	15	500	482	333.4	8.33
5	1.8	20	40	10	1500	4.5	W	15	500	480	375.8	9.39
6	2	20	40	10	1500	4.8	W	15	500	479	418.5	10.46
7	2.2	20	40	10	1500	5.2	W	15	500	478	461.4	11.53
8	2.4	20	40	10	1500	5.5	W	15	500	477	504.5	12.61
9	1	24	40	10	1500	5.1	W	15	500	476	275.1	6.88
10	1.2	24	40	10	1500	5.5	W	15	500	474	329.1	8.23
11	1.4	24	40	10	1500	6.0	W	15	500	472	383.2	9.58
12	1.6	24	40	10	1500	6.4	W	15	500	470	437.6	10.94
13	1.8	24	40	10	1500	6.9	W	15	500	468	492.1	12.30
14	2	24	40	10	1500	7.4	W	15	500	466	546.8	13.67
15	2.2	24	40	10	1500	7.9	W	15	500	465	601.7	15.04
16	2.4	24	40	10	1500	8.4	W	15	500	463	656.8	16.42
17	1	28	40	10	1500	7.1	W	15	500	468	343.9	8.60
18	1.2	28	40	10	1500	7.7	W	15	500	465	410.3	10.26
19	1.4	28	40	10	1500	8.3	W	15	500	462	476.8	11.92
20	1.6	28	40	10	1500	8.9	W	15	500	460	543.4	13.58
21	1.8	28	40	10	1500	9.5	W	15	500	457	610.1	15.25
22	2	28	40	10	1500	10.2	W	15	500	455	677.0	16.93
23	2.2	28	40	10	1500	10.9	W	15	500	453	744.1	18.60
24	2.4	28	40	10	1500	11.6	W	15	500	451	811.3	20.28
25	1	32	40	10	1500	9.3	W	15	500	461	413.4	10.33
26	1.2	32	40	10	1500	10.0	W	15	500	457	492.2	12.30
27	1.4	32	40	10	1500	10.8	W	15	500	454	571.0	14.28
28	1.6	32	40	10	1500	11.6	W	15	500	451	650.0	16.25
29	1.8	32	40	10	1500	12.5	W	15	500	448	729.1	18.23
30	2	32	40	10	1500	13.3	W	15	500	445	808.2	20.21
31	2.2	32	40	10	1500	14.3	W	15	500	443	887.5	22.19
32	2.4	32	40	10	1500	15.2	W	15	500	440	966.9	24.17
33	1	36	40	10	1500	11.6	W	15	500	454	483.7	12.09
34	1.2	36	40	10	1500	12.6	W	15	500	450	575.1	14.38
35	1.4	36	40	10	1500	13.6	W	15	500	446	666.4	16.66
36	1.6	36	40	10	1500	14.6	W	15	500	443	757.8	18.95
37	1.8	36	40	10	1500	15.6	W	15	500	439	849.3	21.23
38	2	36	40	10	1500	16.7	W	15	500	436	940.9	23.52
39	2.2	36	40	10	1500	17.9	W	15	500	434	1032.6	25.81
40	2.4	36	40	10	1500	19.1	W	15	500	431	1124.4	28.11
41	1	40	40	10	1500	14.1	W	15	500	447	555.7	13.89
42	1.2	40	40	10	1500	15.3	W	15	500	443	659.8	16.50
43	1.4	40	40	10	1500	16.5	W	15	500	439	763.9	19.10
44	1.6	40	40	10	1500	17.8	W	15	500	435	868.0	21.70
45	1.8	40	40	10	1500	19.1	W	15	500	431	972.1	24.30
46	2	40	40	10	1500	20.4	W	15	500	428	1076.4	26.91
47	2.2	40	40	10	1500	21.8	W	15	500	425	1180.8	29.52
48	2.4	40	40	10	1500	23.2	W	15	500	422	1285.2	32.13

The ‘solve’ facility in EXCEL was then used to predict the three coefficients in equation (2) above, so that the root mean square residual was minimised.

Results

Equation 4 shows the coefficients, and figure 2 shows the values for MAI predicted using function 4, compared to the values estimated using DF NAT.

$$500\ \text{Index}=a*\text{SI}^{b}*\text{SBAP}^{c} \qquad (4)$$

where a=0.097, b=1.344, and c=0.973.

In the event that 500 Index and SI are known, for example from sample plot or inventory data, then SBAP can be solved as

$$\text{SBAP}=(500\ \text{Index}/(a*\text{SI}^{b}))^{1/c} \qquad (5)$$

This can be simplified as

$$\text{SBAP}=(500\ \text{Index}/(a*\text{SI}^{b}))^{d} \qquad (6)$$

where d=1.028

Figure 2. MAI predicted using DF NAT, compared to MAI using the 500 Index

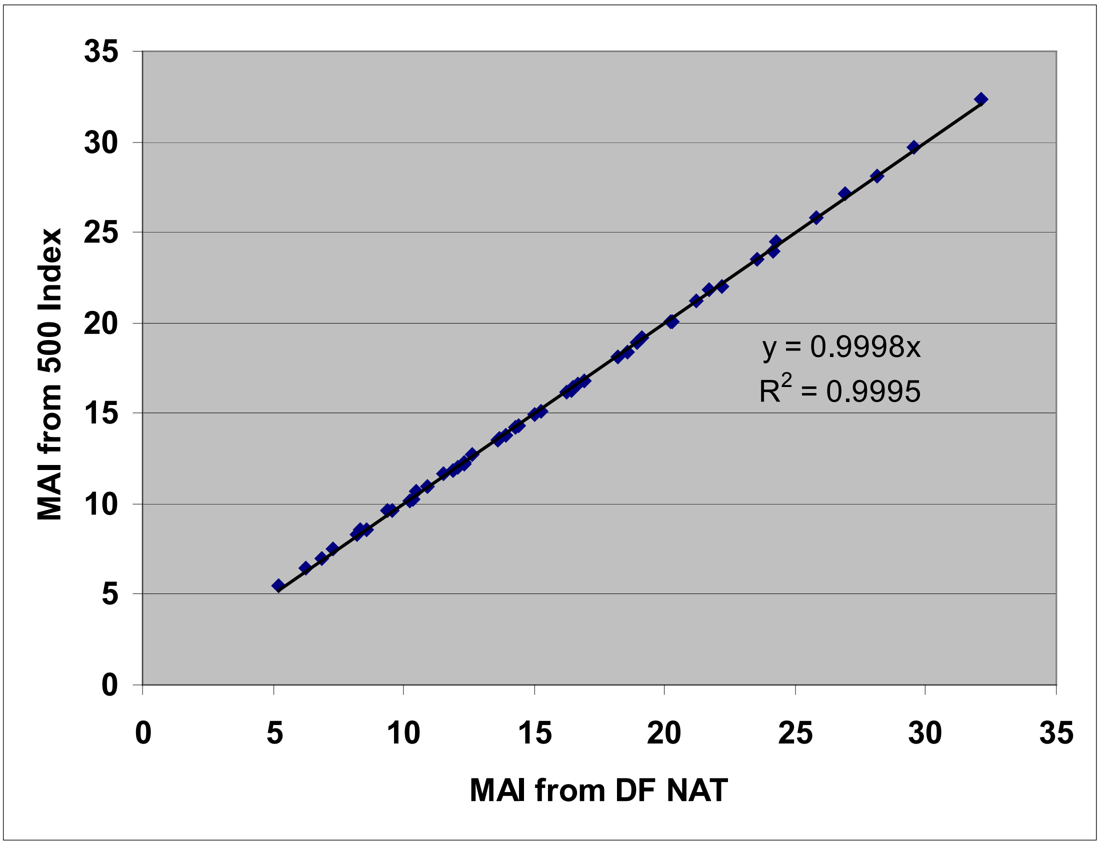


Table 2 provides a simple look-up table (based on equation 4) showing how various combinations of SBAP and SI contribute to the MAI for the 500 Index regime.

Table 2. Look-up table for 500 Index (numbers are MAI m^3/ha/yr)

SBAP	Site Index (m)										
(m^2/ha/yr)	20	22	24	26	28	30	32	34	36	38	40
1.0	5.4	6.2	7.0	7.7	8.6	9.4	10.2	11.1	12.0	12.9	13.8
1.1	6.0	6.8	7.6	8.5	9.4	10.3	11.2	12.2	13.2	14.1	15.2
1.2	6.5	7.4	8.3	9.2	10.2	11.2	12.2	13.3	14.3	15.4	16.5
1.3	7.0	8.0	9.0	10.0	11.0	12.1	13.2	14.3	15.5	16.6	17.8
1.4	7.6	8.6	9.6	10.7	11.9	13.0	14.2	15.4	16.6	17.9	19.2
1.5	8.1	9.2	10.3	11.5	12.7	13.9	15.2	16.5	17.8	19.1	20.5
1.6	8.6	9.8	11.0	12.2	13.5	14.8	16.2	17.5	18.9	20.4	21.8
1.7	9.1	10.4	11.7	13.0	14.3	15.7	17.2	18.6	20.1	21.6	23.2
1.8	9.6	11.0	12.3	13.7	15.2	16.6	18.1	19.7	21.2	22.8	24.5
1.9	10.2	11.6	13.0	14.5	16.0	17.5	19.1	20.7	22.4	24.1	25.8
2.0	10.7	12.1	13.6	15.2	16.8	18.4	20.1	21.8	23.5	25.3	27.1
2.1	11.2	12.7	14.3	15.9	17.6	19.3	21.1	22.9	24.7	26.5	28.4
2.2	11.7	13.3	15.0	16.7	18.4	20.2	22.0	23.9	25.8	27.8	29.8
2.3	12.2	13.9	15.6	17.4	19.2	21.1	23.0	25.0	27.0	29.0	31.1
2.4	12.8	14.5	16.3	18.2	20.1	22.0	24.0	26.0	28.1	30.2	32.4
2.5	13.3	15.1	17.0	18.9	20.9	22.9	25.0	27.1	29.2	31.5	33.7
2.6	13.8	15.7	17.6	19.6	21.7	23.8	25.9	28.1	30.4	32.7	35.0

Sensitivity to Input Values

In many examples, a user may have a stand against which they wish to validate the 500 Index, but for which the regime differs slightly from the 500 Index definition. For example, the stand may have been thinned at 17m MTH rather than the 15m MTH used in the 500 Index definition. The question therefore arises- how sensitive is the volume MAI to such relatively small changes in the definition?

Analysis using DF NAT indicates the following:

1) **Initial stocking**

The 500 Index definition assumes an initial stocking of 1650 stems/ha, with a 90%-95% survival, giving a surviving stocking at age 10 years of approximately 1500 stems/ha. Reduced initial stockings increase the MAI, and increased initial stockings reduces MAI. The effect of varying the age 10 stocking by 100 stems/ha results in a change in MAI of 0.5%. If the stocking at age 10 yrs is 1300 stems/ha, MAI values increased by 1%.

2) **Height at thinning**

For each one-metre change in MTH at thinning, the MAI changes by 1.15%, with earlier thinning increasing the MAI, and delayed thinning reducing MAI. Example: *Thinning to 500 stems/ha at 17m. The reduction in MAI compared to the standard regime defined above, where thinning is at 15m MTH, is 2.3%. If thinning takes place at 13m, the increase in the MAI is 2.3%.*

3) **Stocking following thinning to waste**

The MAI value changes by approximately 3.2-3.4% for a difference of 50 stems/ha from the standard of 500 stems/ha. As an example, if a stand is thinned at 15m MTH to 450 stems/ha, the MAI reduced by 3.2%. If the stand is thinned at 15m MTH to 550 stems/ha, the MAI increased by 3.4%.

4) **Latitude**

Because the ht/age curve used in DF NAT contains a latitude effect, the initial 500 Index model was derived using a mid-range latitude of 42^0 South. Table 3 shows that using latitudes of 38^0S to 46^0S changes the *a* coefficient in the 500 Index, but the *b* and *c* coefficients remain the same. As the *a* coefficient determines the slope of the regression, the difference compared to the standard value of 0.0971 causes a direct proportional change in the MAI. Whether such sensitivities are real or merely an artifact of the form of the ht/age curve has yet to be determined.

Table 3. Coefficients for 500 Index as affected by latitude

Latitude	*a*	*b*	*C*
38^0S	1.000	1.344	0.973
42^0S	0.097	1.344	0.973
46^0S	0.094	1.344	0.973

The recently developed Calculator for Douglas-fir (version 2) contains the following function that includes latitude as a variable, to predict 500 Index:

$$500\ \text{Index} = ((\text{latitude}*e)+f)*\text{SI}^{b}*\text{SBAP}^{c} \qquad (7)$$

where b=1.344, c=0.973, e=-0.00081, f=0.131

Discussion and Conclusions

The importance of adding SBAP to the productivity index can be readily seen in table 2 by examining a column of figures for a given site index. For example, for a site index of 32m, MAI for the same regime can be expected to vary between 10.2 m^3/ha/yr for an SBAP of 1.0, and 25.9 m^3/ha/yr for an SBAP of 2.6.

The coefficients shown in equation (4) differ from those shown by Knowles and Hansen (2004) due to changes in the underlying functions, particularly the function that predicts volume at the stand-level.

For a standard regime, the national growth model DF NAT indicates that SBAP and SI combine in a simple fashion to depict yield, as illustrated by mean annual volume increment (MAI). The derived index (termed the '500 Index') should have widespread field application in predicting yields for a standard regime, and thus for directly comparing site productivities throughout the country. It provides a robust index of productivity that may lead towards development of a new generation of predictive growth functions using environmental variables. The latest version of the Douglas-fir Calculator includes the estimation of 500 Index, using equations (7).

Clearly, the development of such a simple index should greatly assist estimation and comparison of yield for Douglas-fir on all sites throughout NZ.

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