Site Index Conversion Equations for Mixed Trembling Aspen and White Spruce Stands in Northern British Columbia

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White spruce and trembling aspen are two important commercial species in British Columbia. They often grow in association, particularly in the Boreal White and Black Spruce and Sub-Boreal Spruce biogeoclimatic zones. Site index conversion equations are useful for estimating the site index of one species from the site index of another species. This study fills a need for site index conversion equations for mixed spruce/aspen stands. Seventy 0.01 ha study plots were established in mixed spruce/aspen stands. One site tree of each species was selected from each plot. The height and breast height ages of the site trees were measured and the site index was estimated with these data. The correlation between the site index of spruce and aspen was 0.6. Geometric mean regression was used to estimate the parameters of a linear site index conversion equation. The analysis did not reveal any differences in the conversion equations across the three major biogeoclimatic units (BWBSmw1, BWBSmw2, and SBS) that were sampled. Therefore, only one conversion equation is required.

Keywords mixed species, site index, trembling aspen, white spruce
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1 Introduction

Site index is a species-specific measure of the potential productivity of a site (Helms 1998). In British Columbia, site index is defined as the height of a site tree at breast height age 50, where a site tree is the largest diameter tree of the target species in a 0.01 ha plot (Site Productivity Working Group 1998). The site tree must be undamaged and unsuppressed so that its growth reflects the potential productivity of the site. Site index conversion equations provide estimates of the site index of one species from the site index of another species when both species are growing in a mixed-species stand. Most, if not all, conversion equations are simple linear models (Doolittle 1958, Foster 1959, Carmean and Vasilevsky 1971, Carmean 1979, Nigh 1995a, 1995b, 1998, Nigh and Krestov 1999, Nigh and Kayahara 2000).

White spruce (*Picea glauca* (Moench) Voss) and trembling aspen (*Populus tremuloides* Michx.) are two common species in the boreal and sub-boreal regions of British Columbia. Spruce is one of the most importance commercial species in the interior of British Columbia (Coates et al. 1994). It is primarily used for lumber production and pulp, while aspen is used for lumber, reconstituted wood panels, and pulp (Klinka et al. 2000).

Spruce is found in most of the biogeoclimatic zones of British Columbia. Spruce is abundant in the Alpine Tundra, Spruce-Willow-Birch, Boreal White and Black Spruce (BWBS), and Sub-Boreal Pine-Spruce zones, and is common in the Sub-Boreal Spruce (SBS) zone (Coates et al. 1994). Trembling aspen is found throughout the interior of British Columbia, and is a significant component of the Interior Douglas-fir, Interior Cedar-Hemlock, BWBS, and SBS zones (Peterson and Peterson 1995).

Trembling aspen often grows in association with white spruce in both the BWBS and SBS zones. These zones were the target of the study. The BWBS biogeoclimatic zone is dominated by the moist warm (mw) subzone. The elevation of the mw1 variant ranges from 750 to 1050 m whereas the mw2 can also be found down at elevations of 300 m. The mw1 has a drier and cooler growing season than the mw2 but the winters are warmer and moister (DeLong et al. 1990). The SBS zone is found to the west of the BWBS zone and is moister, warmer, and less continental than the BWBS zone (DeLong et al. 1990).

The mixedwood growth model (MGM) is a deterministic, distance-independent growth model capable of summarizing both tree and stand characteristics. MGM is designed specifically for boreal mixedwood stands and is in the process of being adapted for northeastern British Columbia forests (Titus 1998, Harper 1999). The model is to be used in British Columbia primarily for white spruce and trembling aspen stands. MGM is needed for inventory projection, supplying yield tables, to simulate silviculture prescriptions, and to assist in forest level planning (Harper 1999). Many development issues have been identified for a successful adaptation of MGM in British Columbia. Of those issues, site index conversion equations for mixed white spruce and trembling aspen stands has been rated as moderate to high in priority (Harper 2000).

The purpose of this project is to develop site index conversion equations for mixed white spruce and trembling aspen stands. Site index conversion equations essentially have two purposes. They can be used to estimate the site index of one species when only the site index of the other species in a mixed species stand is known. This is often the case in inventory work where only the site index of the leading species is obtained in ground sampling and/or photo interpretation. Knowledge about the site index of one species can also occur if good site trees are not available for a species. This may be the case in spruce/aspen stands, where spruce can grow in the understorey and hence may be suppressed early in its life. The other potential use for the conversion equations is in stand conversion situations, where one species is harvested and replaced by another species. The site index of the replacement species is required for planning purposes. Site index conversion equations are one way of obtaining these site indices. Caution is required when using the equations in stand conversion situations, though, because one or both of the species may grow differently in a mixed stand than in a pure stand. This would lead to biased site index estimates.

2 Materials and Methods

Target study locations were mixed white spruce and trembling aspen stands. These stands were selected from an area ranging just south of Prince George, British Columbia up to the Yukon border, and from Vanderhoof, British Columbia east to the Alberta border. The sample stands were fire-origin and naturally regenerated. Sample plots were located subjectively to cover the range of site index of both species. At each study location, a 0.01 ha (5.64 m radius) plot was established such that one site tree of both species was in the plot. Site trees are the largest diameter trees of the target species that are healthy, undamaged, and have been free-growing since they reached breast height. The need for unsuppressed trees made it difficult to find suitable sampling locations because the spruce is suppressed by the aspen in many stands. The sample sites contained spruce trees that managed to avoid suppression from the aspen, at least above breast height. The total height and breast height age (ring count at breast height) of the site trees were measured. Increment cores were used to get the breast height age of the spruce trees. Ages on the aspen trees were obtained from increment cores and by felling the tree and counting the rings on a disk taken at breast height. A full ecosystem description of the plots was also done (DeLong et al. 1990, DeLong et al. 1993, DeLong, 1996). The site indices of both species were calculated from the heights and ages of the site trees using the recommended site index models (Thrower et al. 1994).

Seventy plots were successfully established. The heights, breast height ages, and site indices are summarized by species and ecosystem in Table 1.

The heights, breast height ages, and site indices were plotted (Fig. 1a, b, and c, respectively) with the data for white spruce on the Y axis and the data for trembling aspen on the X axis. The heights and breast height ages were plotted to get an indication of the site tree height and age structure. In an even-aged and single layer structure, the heights and ages should lie around the 1:1 line (shown on the graphs). The site indices were graphed to provide insight into the relationship between the site index of aspen and spruce.

Fig. 1c indicates that the following linear equation is a reasonable model form to capture the functional relationship between the site index of aspen and spruce:

$$\mathrm{SI}_{\mathrm{Sw}} = b + m \times \mathrm{SI}_{\mathrm{At}} \tag{1}$$

where $\mathrm{SI}_{\mathrm{Sw}}$ is the site index (m) of white spruce, $\mathrm{SI}_{\mathrm{At}}$ is the site index (m) of trembling aspen, and b and m are the intercept and slope parameters. The parameters b and m were estimated with geometric mean regression (GMR). GMR is well-suited for this application because both site index estimates are subject to error making it an errors-in-variable problem, and a trend line is needed. A

Table 1. Data summarized by species and ecosystem.

Ecosystem		Number of plots	Species					
Zone	Subzone/variant		White spruce			Trembling aspen		
			Height	Bha	Site index	Height	Bha	Site index
BWBS	mw1	39	20.39	64	17.61	20.36	74	16.99
	mw2	12	26.79	89	18.27	27.49	99	20.37
	wk1	1	14.10	30	21.84	13.00	42	14.60
BWBS total		52	21.75	69	17.84	21.86	79	17.72
SBS	dk1	4	22.08	56	20.21	20.20	72	16.54
	dw3	4	25.10	71	19.85	25.90	80	20.69
	mc3	1	20.30	62	17.09	19.80	81	15.26
	mk1	5	22.94	75	17.24	24.24	86	18.67
	wk1	4	24.20	57	22.17	24.85	59	22.90
SBS total		18	23.36	65	19.56	23.60	75	19.40
Grand total		70	22.16	68	18.29	22.31	78	18.15

trend line gives consistent conversions, that is, the model is mathematically identical regardless of which species is the predicted or predictor variable (Nigh and Kayahara 2000). There is error in both the SI_{Sw} and SI_{At} variables in the functional relationship (equation 1). This makes linear regression an inappropriate technique for estimating the parameters. Instead, a structural model is more appropriate when both variables have error (Kendall and Stuart 1979, Leduc 1987, Rayner 1985). The GMR model is derived from a structural relationship by assuming that the ratio of the error variances is the same as the ratio of the data variances. If these ratios are unknown, then GMR provides the least-biased estimator of the functional relationship (Kendall and Stuart 1979, Rayner 1985).

The estimators of b and m, denoted $\hat{b}$ and $\hat{m}$, are calculated from the following formulae:

$$\hat{m} = \operatorname{sgn}(r) \times \frac{S_Y}{S_X} \tag{2}$$

$$\hat{b} = \overline{Y} - \hat{m} \times \overline{X} \tag{3}$$

where r is the correlation coefficient for the site index pairs, sgn(r) is: +1 if r is positive, –1 if r is negative, and 0 if r is 0, S_Y and S_X are the standard deviations of the dependent and independent variables, respectively, and $\overline{Y}$ and $\overline{X}$ are the means of the dependent and independent variables, respectively ($Y = SI_{Sw}$, $X = SI_{At}$). The correlation coefficient indicates the strength of the relationship. Formulae for the 95% confidence intervals for the geometric mean regression parameters, $\hat{m}$ and $\hat{b}$, are given in Eqs. 4, 5, and 6 (Kermack and Haldane 1950, Rayner 1985), respectively,

$$\left[\hat{m} \times \sqrt{\frac{1-Q}{1+Q}}, \hat{m} \times \sqrt{\frac{1+Q}{1-Q}}\right] \tag{4}$$

$$\begin{aligned}\Bigg[&\hat{b} - t_{n-2,0.975} \times \sqrt{\frac{S_Y^2}{n} \times (1-r) \times \left(2 + \overline{X}^2 \times \frac{1+r}{S_X^2}\right)},\\ &\hat{b} + t_{n-2,0.975} \times \sqrt{\frac{S_Y^2}{n} \times (1-r) \times \left(2 + \overline{X}^2 \times \frac{1+r}{S_X^2}\right)}\Bigg]\end{aligned} \tag{5}$$

where $t_{n-2,0.975}$ is the 0.975th quantile of the Student's t distribution with $n-2$ degrees of freedom, n is the number of observations, and

$$Q = t_{n-2,0.975} \sqrt{\frac{1-r^2}{r^2 \times (n-2)}} \tag{6}$$

In Eqs. 1–3 above, the dependent and independent variables can be reversed so that the site index of aspen is predicted from the site index of spruce. This will result in a model that is mathematically identical to the one presented above.

Since validation data were not available, the fitted model was tested using the PRESS statistic (Myers 1986, p. 106–7). Each observation was removed from the data set sequentially and model 1 was refit. The error in the estimated site index for both aspen and spruce was determined, and the mean and standard deviation of the errors for both species were calculated.

The data were divided into three groups based on ecological unit: BWBSmw1, BWBSmw2, and SBS zone. The mw1 and mw2 are the Peace moist warm (mw) and Fort Nelson moist warm variants, respectively, of the BWBS zone. The structural model was fit to all the data, and to the data from each of the three ecological units (the one plot in the BWBSwk1 – Murray wet cool variant – was not included in this analysis) to see if there was any difference in the relationship between the units.

3 Results

Fig. 1a indicates that the trembling aspen trees were in general older than the white spruce trees. The heights of the two species were about the same (Fig. 1b). The average age difference was only 10 years (Table 1) so the plots were, generally, in even-aged single layer stands. Fig. 1c shows that there is quite a bit of variability in the relationship between the site indices of the two species. No clear stratification in height, age, or site index between the sub-populations is apparent.

Table 2 presents the results of the analysis of model 1 for the complete dataset, and the three

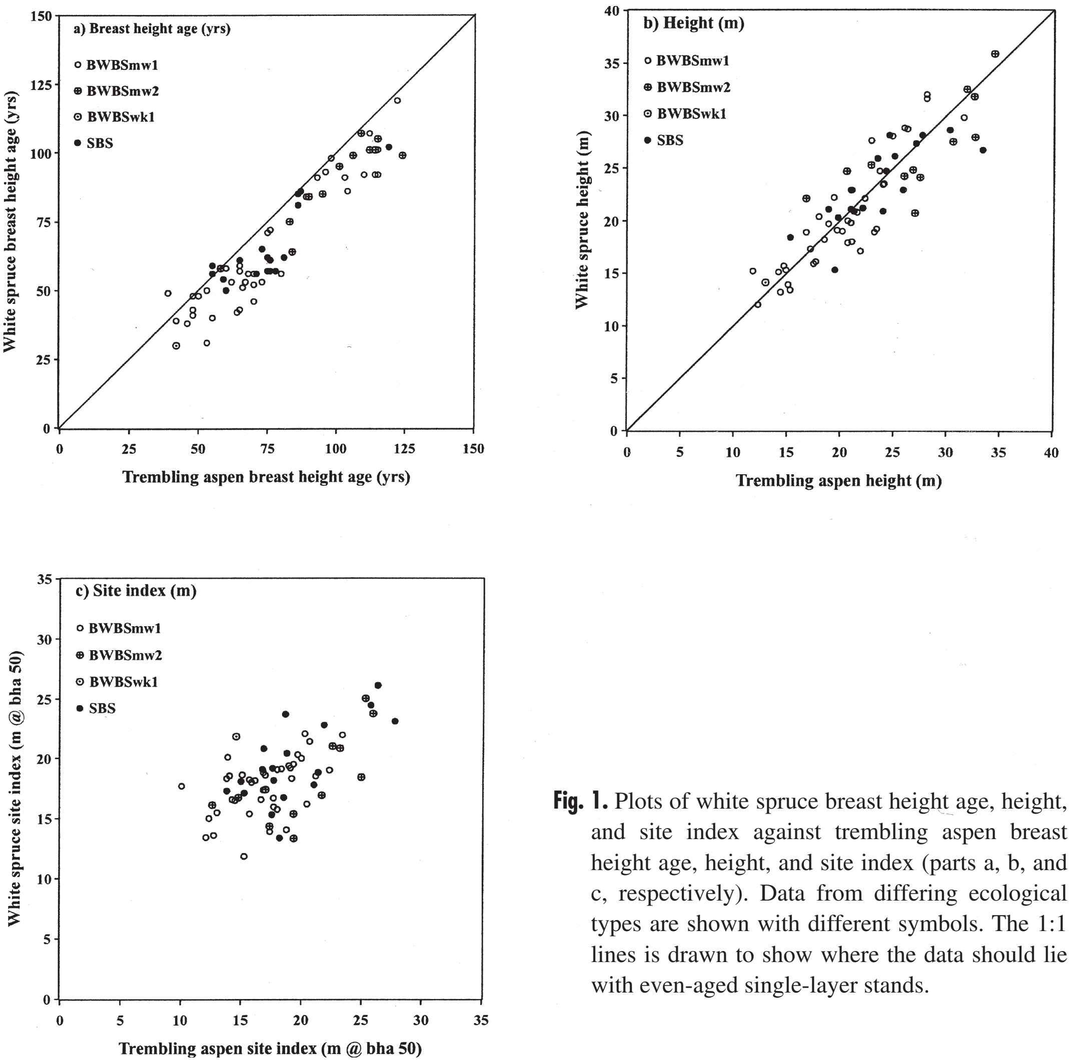

Fig. 1. Plots of white spruce breast height age, height, and site index against trembling aspen breast height age, height, and site index (parts a, b, and c, respectively). Data from differing ecological types are shown with different symbols. The 1:1 lines is drawn to show where the data should lie with even-aged single-layer stands.

sub-populations. This table includes the means and standard deviations of the two site indices and the correlation between them, the parameter estimates $\hat{b}$ and $\hat{m}$, and their 95% confidence intervals. The slope estimate for the complete dataset and the three sub-populations are approximately the same. The intercept for the complete dataset and the BWBSmw1 and the SBS sub-populations are also approximately the same. The intercept for the BWBSmw2 sub-population is about 3 m lower than for the others, but its confidence interval is very wide due to the small number of samples (12) in that unit.

The correlation coefficient indicates the strength of the relationship. The correlations range from about 0.5 to 0.7. The correlation for the complete dataset is about 0.6. This is lower than for other species pairs, for example, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn ex D. Don) (r = 0.82, Nigh and Kayahara 2000), western hemlock and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (r = 0.94, Nigh 1995a), lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) and white spruce (r = 0.83, Nigh 1995a), and others (Carmean 1979, Carmean and Vasilevsky 1971,

Table 2. Results of the analysis of model 1.

Dataset	Species	Mean	Standard deviation	Correlation coefficient	Parameter $\hat{b}$			Parameter $\hat{m}$		
					Estimate	Lower CI	Upper CI	Estimate	Lower CI	Upper CI
All	Sw	18.29	2.995	0.6042	3.804	0.9799	6.628	0.7978	0.5732	1.110
	At	18.15	3.754							
BWBSmw1	Sw	17.61	2.391	0.5178	4.221	0.4282	8.015	0.7881	0.4244	1.463
	At	16.99	3.034							
BWBSmw2	Sw	18.27	3.671	0.7143	0.9720	–7.017	8.961	0.8494	0.3636	1.984
	At	20.37	4.321							
SBS	Sw	19.56	3.376	0.6844	2.986	–3.201	9.173	0.8547	0.4509	1.620
	At	19.40	3.950							

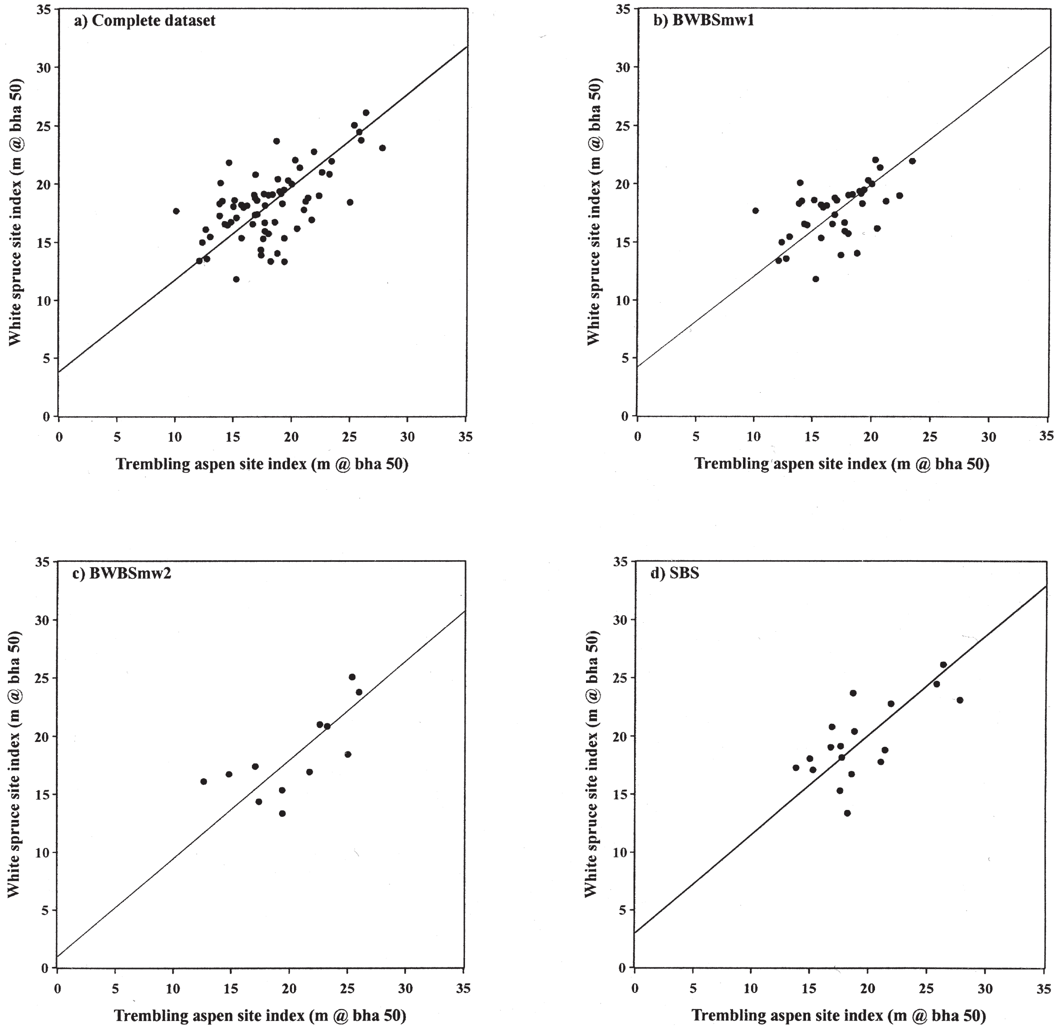

Fig. 2. Fitted lines overlaid on the data points for the complete dataset (part a), and the BWBSmw1 (part b), BWBSmw2 (part c), and SBS (part d) sub-populations.

Doolittle 1958). For comparison, model 1 was also fitted using linear least squares regressions. These models are $SI_{Sw} = 9.536 + 0.4821 \times SI_{At}$ and $SI_{At} = 4.303 + 0.7574 \times SI_{Sw}$. Both of these models had an R^2 of 0.365, which corresponds roughly to $r = 0.6$.

The mean and standard deviation of the errors in the estimated site index for spruce were 0.003 and 2.73 m and for aspen they were 0.005 and 3.42 m. Both mean errors were not significantly different from 0 at $p = 0.05$, and there was no evidence that the errors were not normally distributed.

The fit of the models are shown in Fig. 2, parts a, b, c, and d, for the complete data set and the BWBSmw1, BWBSmw2, and SBS sub-populations, respectively. The fitted model is overlaid on the data points in these graphs.

4 Discussion

One set of site index conversion equations are adequate for predicting the site index of white spruce from the site index of trembling aspen, and vice versa, in mixed spruce/aspen stands. These equations are:

$$SI_{Sw} = 3.804 + 0.7978 \times SI_{At} \tag{7}$$

$$SI_{At} = -4.768 + 1.253 \times SI_{Sw} \tag{8}$$

These two equations were derived using the same data but with the *X* and *Y* variates reversed (the results shown in the previous section are only for model 7). Equation 8 could be derived algebraically from equation 7 and the same parameter values would be obtained, except for rounding errors. Different models for the three sub-populations are not required as the models for all three sub-populations are practically the same as model 7/8.

It was not unexpected that the trembling aspen would be older than the white spruce (Fig. 1a). If the two species were established at about the same time, then the aspen would likely have reached breast height first (Peterson and Peterson 1995). This would make the aspen older when comparing breast height ages, although they would have about the same total age. Most study locations were fire origin, and provided the fires were severe enough, the stands would be even-aged (Lieffers et al. 1996). It was not expected that the spruce would be able to maintain a similar height growth rate as the fast-growing aspen. The similar height growth rate is evident from the single layer nature of the study plots (Fig. 1b) and the higher (on average) site index for spruce (18.28 m for spruce vs 18.08 m for aspen, Table 1). Spruce does not require full sunlight to reach the photosynthetic saturation point (Man and Lieffers 1997) and height growth at 40% transmitted light is approximately the same as height growth at full light (Lieffers and Stadt 1994). Light transmittance is higher in aspen stands than in spruce stands and increases in mixed aspen/spruce stands as the basal area of aspen increases (Constabel and Lieffers 1996, Lieffers and Stadt 1994, Ross et al. 1986). Therefore, the aspen may not be impacting the height growth of spruce in the study sites since many of them were dominated by aspen. In the older stands, the similar heights could also be a result of the aspen trees topping out in height growth, allowing the spruce to catch up in height.

The site index of spruce is higher than the site index of aspen on medium and poor sites (site index of spruce or aspen $<\approx$ 19 m) and the site index of aspen is higher on better sites. This could be because spruce has a greater tolerance to water deficits than aspen (Klinka et al. 2000). A similar phenomenon occurs with biomass, where spruce biomass accumulation can be higher than that of aspen on poor sites (Peterson and Peterson 1995).

The data were split into three sub-populations based on biogeoclimatic unit (BWBSmw1, BWBSmw2, and SBS) to test for differences between the units. The average site indices for the three units were similar, and ranged from 17.61/16.99 m for spruce and aspen, respectively, in the mw1 (with the driest and coolest growing season) to 19.56 m for spruce in the SBS (with the warmest and moistest growing season) and 20.37 m for aspen in the mw2. However, the relationship between the site indices of the two species was the same across the three regions. This similarity across units is good because only one equation needs to be implemented and managed. There is some climatic variation in the SBS zone but a lack of samples prevented testing for differences in the site index relationship between the SBS subzones/variants.

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