Growth intercept models for assessing the site potential of young lodgepole pine stands in Alberta

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Executive Summary

Forest management practices related to tree harvesting and regeneration in Alberta have historically attempted to replicate the effects of natural disturbance patterns. In order to maintain a sustained yield, and an ecosystem based sustainable forest management practice that aims at duplicating (or potentially exceeding) natural forest yields, and that emphasizes the maintenance of diversity among forest types, an assessment of the regeneration performance on the harvested areas is required. This assessment includes the quantification of regenerated site potentials, as commonly measured by site index. Growth intercept models were developed in this study to estimate site index based on a few years of juvenile height growth above a conveniently selected base height. In addition to being able to be used to predict site index in juvenile stands, these growth intercept models can also be used as the basis for projecting regenerated yields, evaluating silvicultural alternatives, and establishing site- and subregion-specific height regeneration standards within an ecologically based management framework.

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1.0 Introduction

Growth intercept models are developed to predict site index at a selected reference age based on a few years (e.g., 2, 3, 4, 5, or 10 years) of juvenile height growth above a base height, commonly set at 1.3 metres (m) above the ground. They are used to evaluate the site productivity for stands that are too young to use the conventional site index approach. In a broad growth and yield modelling sense, growth intercept models also provide a critical linkage between yields of natural and regenerated stands.

The growth intercept (GI) models developed in this study apply to lodgepole pine (*Pinus contorta* var. *latifolia*) in Alberta. They possess a number of distinct characteristics that are uncommon among many types of growth intercept models, and can be used for many purposes in addition to predicting site index at young ages. Because of the way they are formulated, application of these growth intercept models is relatively simple and flexible. Height and site index predictions can be made directly from the observed growth intercept in t years above a base height h_0, where both t and h_0 can take any reasonable number.

The usefulness of growth intercept models is reflected in their roles of estimating site productivity in juvenile stands, describing early stand dynamics, developing growth and yield models for regenerated stands, and establishing meaningful height regeneration standards on a site-specific level within an ecologically based management framework.

The main objectives of this study were:

(1). To develop growth intercept models that can be used to predict site index for lodgepole pine at young ages.

(2). To describe the application procedures for using the growth intercept models to predict total tree height and site index, and to explore the possibilities for using these models for other purposes.

(3). To exert some caution in making inferences based on the growth intercept approach, especially when using such an approach as the basis for comparing growth and yield between natural and regenerated stands under a paired-plot sampling scheme.

(4). To discuss the factors (mainly, stand density and age) that may affect the appropriateness of site index predictions (at young ages) from the growth intercept approach, and to provide some suggestions on possible techniques that may be used to correct or compensate for these factors.

(5). To present other existing or potentially useful growth intercept methods that can also be used to predict site index in juvenile stands, and that are worth investigating in future studies.

(6). To identify future research areas related to the growth intercept approach and to the estimation of site index at young ages in general.

The materials presented in this report are probably beyond what one actually needs in practice. They cover a wide range of topics, some of which may not have any concrete solution at the present time, or have any agreed-upon understanding. One of the primary purposes for doing this is to provide some relevant background and a more complete picture, as well as some thought on some of the predicaments and concerns commonly encountered in evaluating site productivity, with the intention that future research may benefit from such discussions. Readers who are more interested in applications may want to skip the contents of Sections 5.0 to 8.0.

2.0 The Data

Data for this study were collected by Weyerhaeuser Canada Ltd. (Grande Prairie) and Simons Reid Collins (1995) on two forest management agreement (FMA) areas in Alberta: the Weyerhaeuser FMA (Grande Prairie) and the Weldwood FMA (Hinton). A circular plot of 363.05 m^2 (10.75 m in radius) was selected prior to field work, and a total of 40 plots were established in 40 undamaged, pure, even-aged, "typical" lodgepole pine stands throughout both FMAs. A detail description on stand selection and sampling procedures is provided in Simons Reid Collins (1995).

Within each sample plot, two to three (mostly three) healthy, undamaged largest diameter trees with a dominant or a co-dominant crown position were selected as the site trees. Each site tree was felled, sectioned into short pieces, and measured. All site trees were older than 50 years breast height age (i.e., ring count at breast height 1.3 m > 50), so a "true" site index value could be determined (through linear interpolation) from the section that encompasses the site index (height at 50 years breast height age). This observed "true" site index value is required for estimating some types of growth intercept models, and for evaluating the accuracy and precision of site index predictions based on different growth intercept approaches.

For each selected site tree, a detailed stem analysis was conducted (Simons Reid Collins 1995), which included felling the tree at stump height (0.3 m above ground), horizontally and longitudinally sectioning the stem close to the base until the 6th or 11th pith node above breast height was located (Figure 1). The portion of the stem above 6th or 11th pith node was sectioned horizontally only. The distances between each pith node were measured, and ring counts at the top of each horizontally cut section along the entire stem were recorded. A small bias at each horizontally cut sectioning point was corrected (see Figure 1). This bias occurs because a horizontal cut usually occurs between the pith nodes rather than at exactly the tip of a pith node (Carmean 1972; Newberry 1991; Fabbio et al. 1994). If uncorrected, this bias will shift the actual height-age curve and affect the computation of breast height age by a half-year margin on average (e.g., a ring count of 100 at 1.3 m above ground indicates that the corrected breast height age is 99.5, rather than 100 years obtained without correcting the bias). Note that this correction does not affect the calculation of the growth intercept, which uses the distance between two pith nodes (see Figure 1).

The stem analysis data allowed the construction of detailed height-age curves, as shown in Figure 2 for the combined data, and for data from the Weyerhaeuser and the Weldwood FMAs, respectively. In order to have a closer look at the early height growth patterns, "enlarged" graphs showing up to 30 years of height growth above breast height are also provided (Figure 2). The bias corrections and the data ranges for total tree height and breast height age, as well as for the site index, are clearly visible in Figure 2. The total number of sample observations (height-age pairs) for the combined data set is 1,924.

The stem analysis data also allowed the construction of height-age curves by natural subregions. These curves are displayed in Figure 3 for the lower foothills, the upper foothills, and the sub-alpine subregions. The differences among the regional height-age curves are obvious as seen from Figure 3.

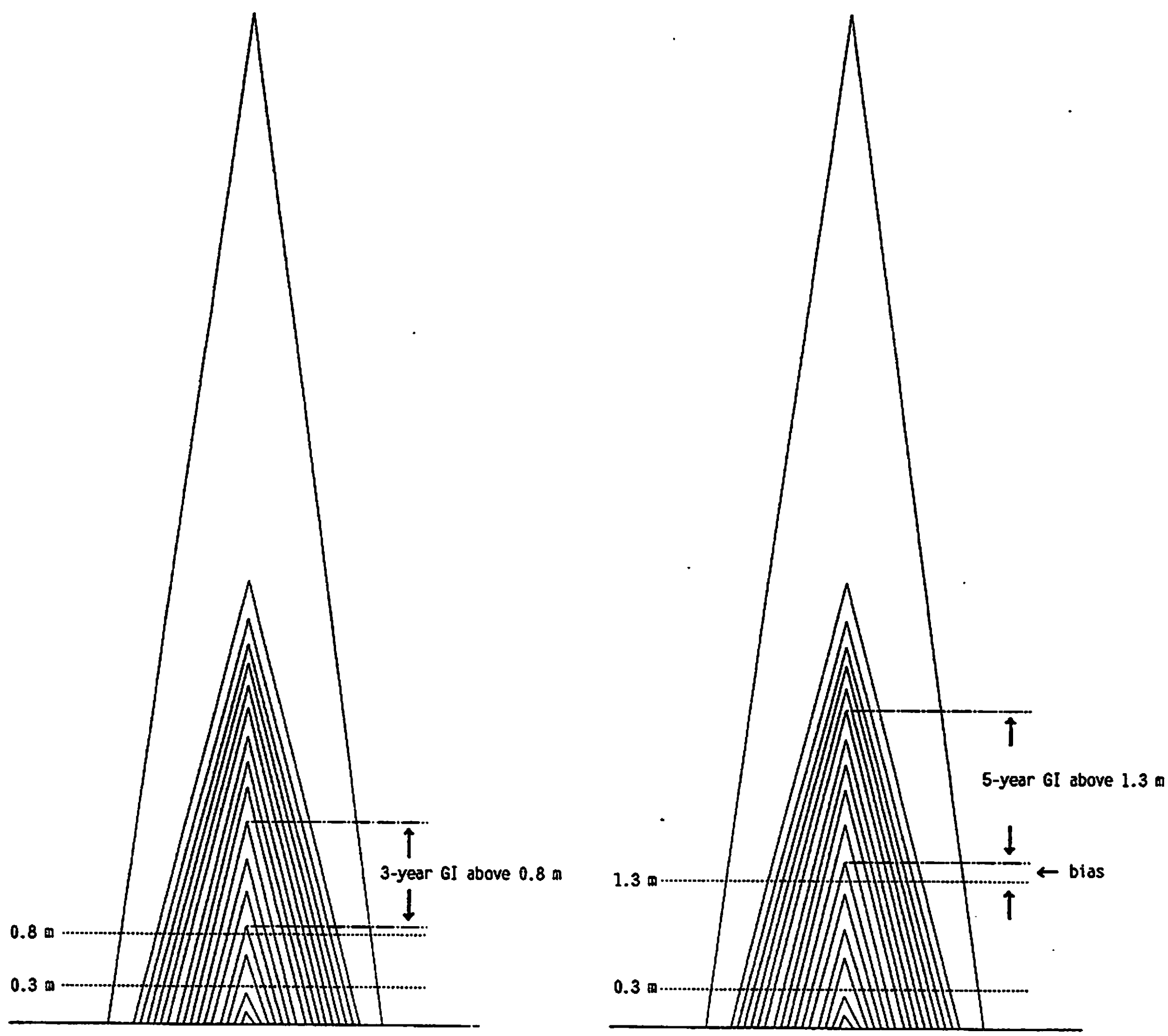


Figure 1. An illustration of a growth intercept sample tree and data collection procedures.

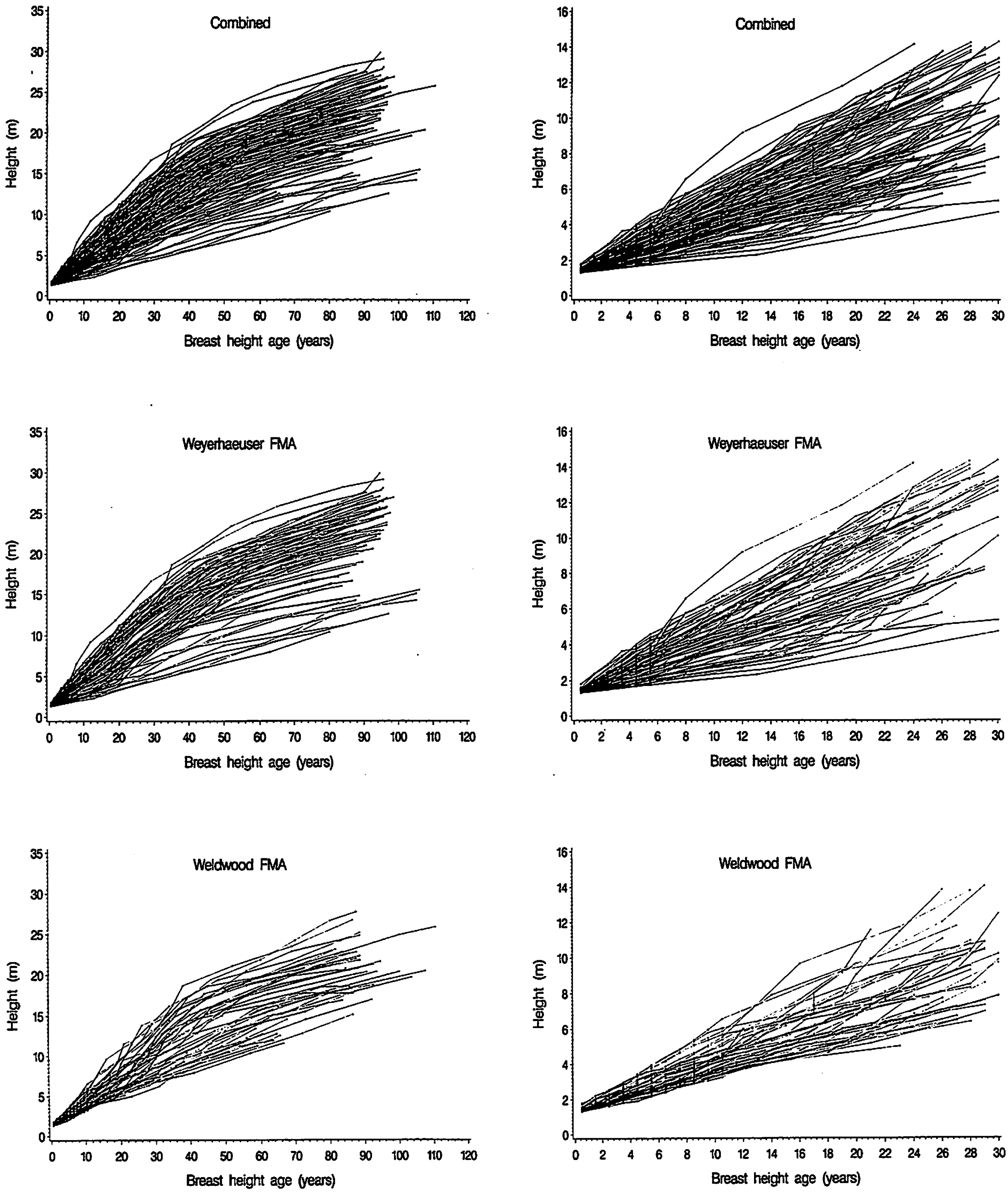


Figure 2. The height-age trajectories for lodgepole pine. The graphs shown on the right-hand side describe the height growth up to 30 years above breast height. They correspond to the lower end of their respective counterparts on the left-hand side.

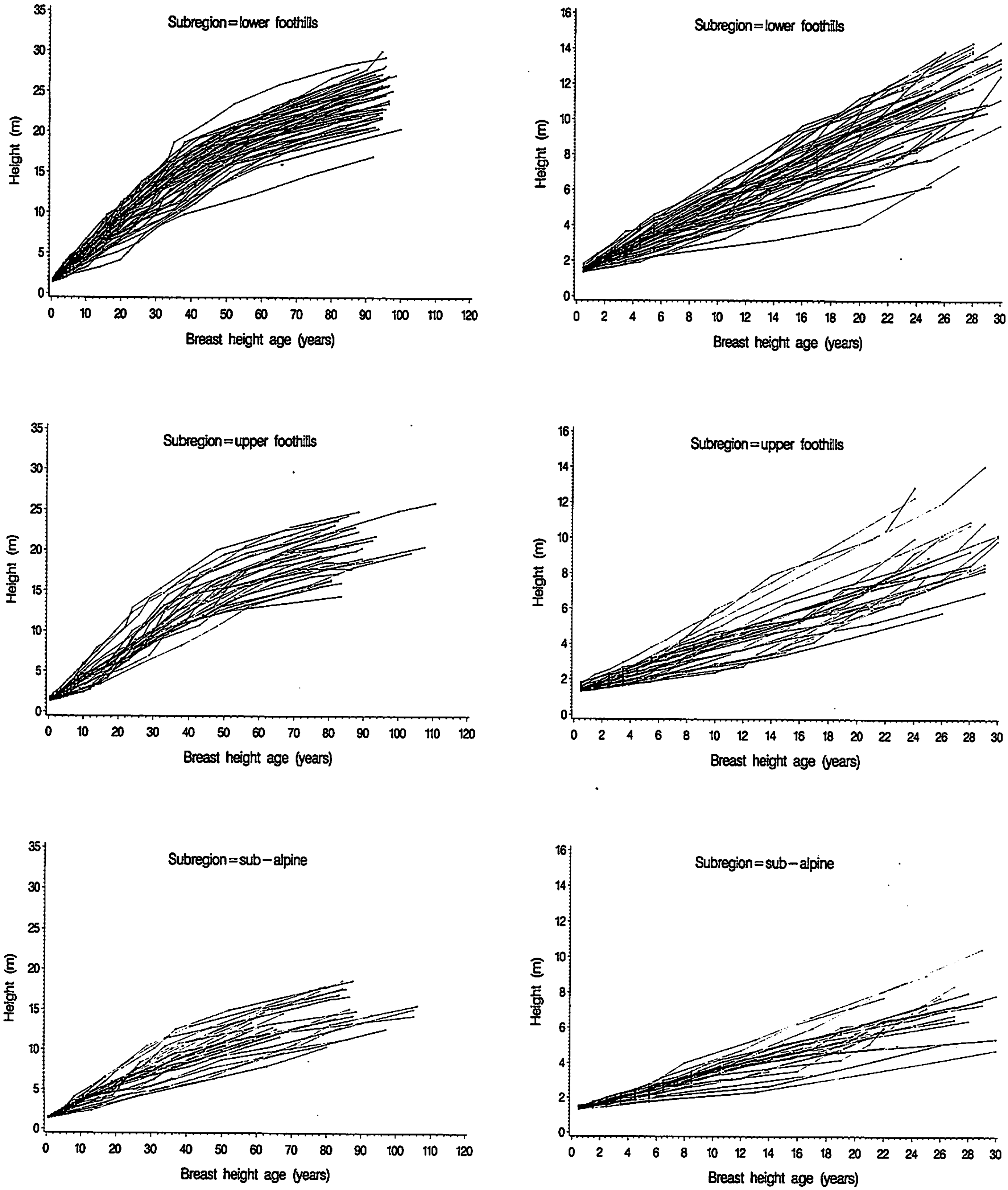


Figure 3. The height-age trajectories for lodgepole pine by natural subregions. The graphs shown on the right-hand side describe the height growth up to 30 years above breast height. They correspond to the lower end of their respective counterparts on the left-hand side.

3.0 The Growth Intercept Models

Method I

The following height growth intercept model based on the height-age-growth intercept relationship was identified for lodgepole pine in Alberta:

$$Ht = 1.3 + b_0 GI^{b_1} Age^{k} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4} \qquad [1]$$

where: Ht = total tree height (m)
Age = breast height age (years)
GI = average annual growth intercept (m/year) in t-years above the base height h_0
k = constant
b_0, b_1, b_2, b_3, and b_4 = parameters to be estimated.

Because the height growth patterns in different subregions and FMAs are different, the following "best" forms (all are variations of model [1]), were identified for each specific data group:

(1). For the combined (provincial) and the sub-alpine subregions, and the Weyerhaeuser FMA (k=1/3):

$$Ht = 1.3 + b_0 GI^{b_1} Age^{1/3} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4} \qquad [1a]$$

(2). For the Weldwood FMA (k=1/2.5):

$$Ht = 1.3 + b_0 GI^{b_1} Age^{1/2.5} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4} \qquad [1b]$$

(3). For the lower and the upper foothills subregions (k=1/3 and b_1=1/10):

$$Ht = 1.3 + b_0 GI^{1/10} Age^{1/3} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4} \qquad [1c]$$

The above equations can all be expressed in the following general form, as initially proposed by Brown and Stires (1981):

$$Ht = f\,(Age, GI)$$

The parameters in [1a]-[1c] were estimated for the following combinations:

(1). Using average annual growth intercepts from 1 year, 2, 3, 4, and 5 years, respectively. For data from the Weldwood FMA, additional growth intercepts from 6, 7, ⋯, 10 years were also used.

(2). For a base height of 0.3, 0.5, 0.75, 0.8, 1.0, and 1.3 m above ground. Base heights of greater than

1.3 m were also examined but were subsequently discarded in this study.

(3). For combined data from the Weyerhaeuser and the Weldwood FMAs.

(4). For each of the three natural subregions: the lower foothills, the upper foothills, and the sub-alpine. Since only eight trees were sampled in the central mixedwood subregion, regionalized growth intercept models for this subregion were not estimated at this time.

(5). For data sets from the Weyerhaeuser FMA and the Weldwood FMA, separately.

It is apparent that [1a]-[1c] can also be fitted for other combinations (e.g., by natural subregions within each FMA). However, the continued partitioning of the limited data set used in this study resulted in unstable parameter estimates, and produced less reliable predictions. A total of more than 200 sets of parameters were estimated corresponding to the above five combinations. Those that are most likely to be used in practice are listed in Table A1 of Appendix 1 (other specific sets of parameters are available upon request).

Many conventional growth intercept models were developed based on a 5-year growth intercept above 1.3 m. The use of a base height lower than 1.3 m and a time interval shorter than 5 years allow height and site index predictions to be made as early in the stand development stage as possible.

Having the estimated coefficients (Table A1), equations [1a]-[1c] can be used directly to predict the site index at any desired reference age. For instance, to predict the site index at a reference breast height age of 50 years, the breast height age in [1a]-[1c] is set at 50 (Age=50), and the GI is replaced by an observed growth intercept (m/year) in t-years above the base height h_0. The predicted total height value at the 50 years breast height age equals the site index at this reference age. In many practical situations, the use of a t value of 3, 4, or 5 years, and an h_0 value of 0.8 or 1.3 m, is recommended to achieve the "best" results.

Method I has a number of distinct characteristics, which include:

(1). It is very flexible in terms of predicting site index at any reference age. Using equation [1], site indices can be estimated at any reasonable reference age that is consistent with the "current" management practice (i.e., at 50 years breast height age), or that may be used for a particular application or future applications (e.g., age at the maximum mean annual increment or rotation age, at 30, 80, or 100 years breast height age, etc.). Site index predictions are a subset of the height predictions from equation [1] when age equals the selected reference age. They are used for labelling purposes.

(2). It does not require height and age measurements when predicting site index from the fitted model. This characteristic has been regarded by many as one of the most important advantages for using the growth intercept approach. It eliminates the need for measuring height and age entirely, saving considerable time in the process and removing the errors associated with height and age measurements.

(3). It does not require a known site index when estimating the parameters of the model. This characteristic is very similar to a class of so-called difference equation site index models. It removes the need (and the practical difficulties) for knowing the "true" site index value, and eliminates the errors incurred in measuring or interpolating the "true" site index.

(4). It provides an "automatic" connection between different sets of curves (e.g., natural and regenerated growth curves). How and where to make an appropriate connection between natural and regenerated growth curves is a "black box" in many ways. Using the growth intercept models developed in Method

I, the contents of this black box are revealed, and the techniques for "smoothing" the curves to make them better connected simply become less relevant (as this will become clear later in Section 5.0 and Figures A1-A6, Appendix 1). This may be considered as a notable advantage when one tries to make long-range forest management plans and conduct preliminary timber supply analysis for regenerated stands.

Method I has some other characteristics that may also be worth-noting. These will be discussed later in Section 5.0. The implication of the growth intercept models developed in Method I is that the entire height growth trajectory of a tree can be assessed directly based on a few years of early height growth in the juvenile phase. While this assumption may still be considered as speculation and may not be entirely satisfactory or acceptable to some, it is probably one of the only ways that the regenerated stand data can be bridged with the natural stand projections without "disrupting" or "switching" otherwise continuous and "smooth" growth and yield curves.

In order to facilitate the practical use of the fitted growth intercept models, a site index prediction table is formulated (see Table A2, Appendix 1), based on the estimated coefficients listed in Table A1 of Appendix 1 and a reference breast height age of 50 years. A number of typical graphs showing the projected height-age-GI curves are also provided in Figures A1-A6 of Appendix 1. Other curves and tables can be constructed in a similar manner.

Alternative functional forms for Method I:

In addition to the growth intercept models shown above, numerous other functional forms (including those with the constant 1.3 m replaced by other appropriate base heights or a parameter) were also examined. The following functional form was also found to give some of the best fits:

$$Ht = 1.3 + b_0 GI^{b_1}[1-\exp(-b_2 Age)]^{b_3 GI^{b_4}}$$

where the variables in the above equation are the same as those defined earlier. Estimated coefficients and fit statistics, along with the fitted curves and formulated tables, from this alternative functional form for Method I, were shown in an earlier version of this report, which is available upon request. In terms of the fit statistics, this alternative functional form was even marginally better than the recommended growth intercept models. However, it behaved slightly poorer than the recommended models at very young ages based on the results obtained from the available data.

Another alternative functional form for Method I was identified as:

$$Ht = (1.3+b_0 GI) + b_1 GI^{b_2} Age^{k}[1-\exp(-b_3 GI^{b_4} Age)]^{b_5}$$

The above function is more flexible. It was shown to fit the data well, especially at young ages. However, it produced a number of insignificant coefficients when estimated on smaller, regionalized data sets.

It is not difficult to imagine that other "best" functional forms also exist for a given data set, but the fundamental relationship symbolized in the expression Ht=*f*(Age, GI) remains the same, as long as Method I is implemented.

Method II

Note that Method I was estimated by different h_0 (m) values, and different t (years) values, producing a large number of equations (see Table A1). To reduce the total number of equations required to make site index predictions, the following growth intercept model was also fitted by incorporating the time component t as an independent variable:

$$Ht = 1.3 + b_0 GI^{b_1} Age^{k} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4 t^{b_5}} \qquad [2]$$

where: Ht = total tree height (m)
Age = breast height age (years)
GI = average annual growth intercept (m/year) in t-years above the base height h_0
t = number of years in which the growth intercept is observed
k=constant
b_0, b_1, b_2, b_3, and b_4 = parameters to be estimated.

The following variations of model [2] were identified and fitted for each of the following specific data groups:

(1). For the combined (provincial) and the sub-alpine subregions, and the Weyerhaeuser FMA (k=1/3):

$$Ht = 1.3 + b_0 GI^{b_1} Age^{1/3} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4 t^{b_5}} \qquad [2a]$$

(2). For the Weldwood FMA (k=1/2.5):

$$Ht = 1.3 + b_0 GI^{b_1} Age^{1/2.5} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4 t^{b_5}} \qquad [2b]$$

(3). For the lower and the upper foothills subregions (k=1/3 and b_1=1/10):

$$Ht = 1.3 + b_0 GI^{1/10} Age^{1/3} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4 t^{b_5}} \qquad [2c]$$

In a more general form, the above equations can all be expressed by:

$$Ht = f(Age, GI, t)$$

The parameters in [2a]-[2c] were estimated by natural subregions, base heights (i.e., 0.3, 0.5, 0.75, 0.8, 1.0, and 1.3 m), and FMAs. The estimation process was implemented based on the stacked data sets that have different t values. Some selected sets of the estimates are shown in Table A3, Appendix 2 (other specific sets of the estimates are available upon request).

Method II could be considered as a compacted version of Method I, with the time component t treated as an independent variable rather than fitting the Method I equations by each and every different t value. In addition to having the main characteristics of Method I, the inclusion of the time component t in Method II also allows the investigator to:

(1). Use the average annual growth intercept (m/year) in t-years to predict height and site index, where t is not fixed and can take any reasonable number. This increased flexibility is sometimes desirable in applications. Note that all predictions for varying t values are made from a single equation written in the form of Ht=*f*(Age, GI, t).

(2). Evaluate the impact and the significance of using different t values. For example, if t is statistically insignificant, or the growth intercept models fitted using different t values are identical (as judged from the indicator variable approach), one may want to use a 1-year, instead of a 3-, 5-, or 10-year, growth intercept to predict height and site index. The basic motivation in this situation appears to be parsimony and convenience: if a 1-year growth intercept can "explain" or "satisfactorily predict" the height and site index, why use a 2-year growth intercept? For some, the use of a shorter growth intercept enable them to get a site index estimate that may otherwise cannot get or have to wait. It may also save some time and money in estimating site productivity.

As seen from Table A3 of Appendix 2, for the lodgepole pine data, equations [2a]-[2c] provided fits that were almost as good as those from equations [1a]-[1c], but [2a]-[2c] was found to be slightly poorer than [1a]-[1c] in terms of its prediction performance when compared on independent testing data sets (see an example in Section 6.0).

Using the estimated coefficients shown in Table A3, equations [2a]-[2c] can be used directly to predict the site index at any desired reference age. For instance, to predict the site index at a reference breast height age of 50 years, the breast height age in [2a]-[2c] is set at 50 (Age=50 years), and the GI is replaced by an observed growth intercept (m/year) in t-years above the base height h_0. In practice, the use of a t value of 3, 4, or 5 years, and an h_0 value of 0.8 or 1.3 m, is recommended to achieve the "best" results.

A site index prediction table similar to that shown in Method I (Table A2 in Appendix 1) can also be formulated for Method II. A number of typical graphs describing the projected height-age-GI curves from the fitted growth intercept models [2a]-[2c], are displayed in Figures A7-A12 of Appendix 2. They are fairly close to those derived from Method I.

Alternative functional forms for Method II:

In addition to the growth intercept models shown above, numerous other functional forms (including those with the constant 1.3 replaced by other base heights or a parameter) were also examined. The following functional form, which corresponds to [2], was also found to provide some of the best fits:

$$Ht = 1.3 + (b_0 t^2 + b_1 GI^{b_2}) Age^k [1 - \exp(-b_3 GI^{b_4} Age)]^{b_5}$$

where the variables in the above function are the same as those defined earlier. Several "best" variations of the above function, corresponding to equations [2a], [2b], and [2c], respectively, were also identified for each of the following specific data groups:

(1). For the combined (provincial) and the sub-alpine subregions, and the Weyerhaeuser FMA (k=1/3):

$$Ht = 1.3 + (b_0 t^2 + b_1 GI^{b_2}) Age^{1/3} [1 - \exp(-b_3 GI^{b_4} Age)]^{b_5}$$

(2). For the Weldwood FMA (k=1/2.5):

$$Ht = 1.3 + (b_0 t^2 + b_1 GI^{b_2}) Age^{1/2.5} [1 - \exp(-b_3 GI^{b_4} Age)]^{b_5}$$

(3). For the lower and the upper foothills subregions (k=1/3 and b_1=1/10):

$$Ht = 1.3 + (b_0 t^2 + b_1 GI^{1/10}) Age^{1/3} [1 - \exp(-b_3 GI^{b_4} Age)]^{b_5}$$

Estimated coefficients, together with the fitted curves and formulated site index prediction tables, from the above alternative functional forms for Method II, were presented in an earlier version of this report, which is available upon request. Other "best" functional forms also exist. All are embodied in the expression given by: Ht=*f*(Age, GI, t). The origin of the curves can also be estimated based on the given data set, rather than fixed at 1.3 m above ground.

Method III

This conventional growth intercept method provides the simplest and sometimes the most effective way for estimating site index in young stands. It expresses site index as a function of average annual (or cumulative) growth intercept in t-years above the base height h_0:

$$SI = f(GI)$$

where SI=site index (m), which is the tree height at 50 years breast height age and GI=average annual growth intercept (m/year) in t-years above the base height h_0. A large number of explicit functional forms for this method were evaluated, they include:

$$SI = b_0 GI^{b_1}$$
$$SI = b_0 e^{b_1/GI}$$
$$SI = b_0 + b_1 GI$$
$$SI = b_0 e^{b_1 e^{b_2 GI}}$$
$$SI = b_0 e^{b_1/(GI+b_2)}$$
$$SI = e^{b_0 + b_1 GI + b_2 GI^2}$$
$$SI = b_0 GI^{b_1} e^{-b_2 GI}$$
$$SI = b_0 (1 - e^{-b_1 GI})$$
$$SI = b_0 (1 - e^{-b_1 GI})^{b_2}$$
$$SI = b_0 GI/(b_1 + GI)$$
$$SI = b_0 + b_1 GI + b_2 GI^2$$
$$SI = b_0/(1 + b_1^{-1} GI^{-b_2})$$
$$SI = b_0 GI/(b_1 + GI + b_2 GI^2)$$

where b_0, b_1, and b_2 are parameters to be estimated. The selected model takes the following form:

$$SI = \frac{b_0 GI}{(b_1 + GI)} \qquad [3]$$

Estimated coefficients for [3] by various combinations are listed in Table A4, Appendix 3. The graphs showing the fitted site index-GI curves are also provided in Appendix 3 (see Figures A13 to A20), along with the actual site index-growth intercept data from the stem analysis trees. This method was also fitted for major tree species in Alberta as a quick way of predicting site index in juvenile stands (Huang 1996). One of the earliest examples of this approach, using the quadratic function with the cumulative 5- or 10-year growth intercept above a base height of 1.3 m as the independent variable, was demonstrated by Udell and Dempster (1986) for lodgepole pine in the Weldwood FMA area. In the past, various t and h_0 values had been used by different researchers to define the growth intercept concept and to compute the growth intercept values.

Other Methods

Several other growth intercept methods were also examined. They include:

(1). The inverse approach (e.g., Beck 1971), which expresses the growth intercept GI as a function of site index (SI):

$$GI = f(SI)$$

This method differs from Method III in that it uses the growth intercept, rather than site index, as the dependent variable. Site index is solved algebraically or numerically after the above function has been estimated. Note that the growth intercept models presented in this study can all be estimated using the growth intercept GI as the dependent variable, but this approach has several statistical and practical drawbacks in terms of predicting site index (i.e., the site index predictions are usually inefficient and biased, see Section 5.0).

(2). The site index-height-age approach (e.g., Wang and Armstrong 1996), which expresses the site index as a function of height and age:

$$SI = f(Ht, Age)$$

Numerous such SI-Ht-Age equations have been developed for mature stands. In order to accomplish the "best" site index predictions in juvenile stands, Wang and Armstrong (1996) used the height and age data up to 30 years breast height age to reduce the possible under- or over-estimations caused by estimating the function over the entire range of stand development (i.e., from very young to old age). This approach requires height and age measurements for site index predictions, but it is particularly useful for species such as aspen, whose annual height increments may not be readily discernable and the internode counts may be inaccurate.

Nigh (1995) fitted the following single-equation growth intercept model for lodgepole pine in British Columbia:

$$SI = b_1 \cdot e^{b_2 \cdot A} GI_A^{b_3 \cdot e^{b_4 \cdot A}} = b_1 \cdot e^{b_2 \cdot A} [100(H_A - 1.3)/A]^{b_3 \cdot e^{b_4 \cdot A}}$$

A selected range of the data ($1 \leq Age \leq 30$) was used to estimate the parameters in the above function to achieve better site index predictions at young ages. A total of 30 sub-models for breast height ages 1 to 30 (A=1, 2, ⋯, 30), respectively, each in the form shown as follows, were also estimated:

$$SI = b_{A,1} \cdot GI_A^{b_{A,2}} = b_{A,1} \cdot [100(H_A - 1.3)/A]^{b_{A,2}}$$

where H_A is the total tree height at breast height age A (A=1, 2, ⋯, 30), $b_{A,1}$ and $b_{A,2}$ are age-specific model parameters. Note that in Nigh's single-equation approach, the age is not fixed and the height has undergone a conversion; In the sub-model approach, the age is fixed and the height has undergone a conversion (Nigh 1995, pp.12-13). Since both approaches express site index as a function of height and age, both may also be classified into the site index approach symbolized by SI=*f*(Ht, Age).

(3). Site index prediction based on the following SI-GI-t relationship:

$$SI = f(GI, t)$$

where the site index is expressed as a function of the growth intercept in t-years above the base height h_0. A more explicit expression for the above function could be: $SI = a \cdot GI^b t^c$ (see Lakusta and Huang 1996), where a, b, and c are model parameters to be estimated. A transformed version of this function was estimated by Wang and Armstrong (1996). Note that either the cumulative, or the average annual, growth intercept in t-years above h_0 may be used as an independent variable. The time component t (in years) is also an independent variable, and can take any reasonable number. If the main purpose is to look at site-specific early height growth patterns, a function such as GI=*f*(SI, t), Ht =*f*(SI, age), or Ht =*f*(GI, age) may also be fitted using data from the first 20 or 30 years of height growth above the base height.

(4). Site index prediction based on the following SI-GI-t-h_0 relationship:

$$SI = f(GI, t, h_0)$$

where the base height component h_0 is included as an independent variable, so site index predictions can be made from the t-year growth intercept above any reasonable base height (e.g., 0.3-1.3 m). This method is a more generalized form of the above method shown in (3). Numerous explicit functional forms for this method exist.

(5). Site index prediction based on the following Ht-Age-GI-t-h_0 relationship:

$$Ht = f(Age, GI, t, h_0)$$

This method is an extension of Method II, with the base height component h_0 included as an additional independent variable. To predict the site index at a reference breast height age of 50 years, the breast height age is set at 50 (Age=50 years), and the growth intercept in t-years above the base height h_0 is observed, where both t and h_0 can take any reasonable numbers. Note that this formulation possesses the main characteristics of Method I and Method II. It can be classified into the "base-height invariant variable-length growth intercept models" referred to by Huang (1994, p.44) in a review of the growth intercept approach. Most of the other growth intercept approaches described earlier can be considered as special cases of this method.

To evaluate the growth intercept methods, equations estimated based on the Weyerhaeuser data were used to make site index predictions for the Weldwood data, and the predicted site index values were compared to the actual values. The mean and the standard deviation of the prediction bias, as well as the mean squared error of prediction, were calculated according to Rawlings (1988, pp.187-188). In general, Method I achieved the smallest bias and the smallest mean squared error of prediction, whereas Method III produced the worst predictions in many cases even though site index is used directly as the dependent variable in its formulation and the sum of the squared "prediction errors" (i.e., residuals) on the model fitting data set is minimized for the site index (a direct consequence of the least squares method). Similar results were also obtained when the Weldwood data were used as the model fitting data and the Weyerhaeuser data were used as the model testing data, although the direction of the biases was changed and the variation increased.

The growth intercept methods were also evaluated by splitting the combined (provincial) data into two random halves of equal size. One half was used for model fitting and the other half was used for model testing and comparison. The results (see Section 6.0) indicated once again that, in general, Method I gave the smallest bias and the lowest mean squared error of prediction.

There are many other procedures that could be used to examine different methods. It is expected that the "best method" is likely to vary depending on the natural subregions, species, and the particular data sets or sampling schemes involved. It is also worthwhile to note that an evaluation of competing growth intercept methods simply based on a few statistical considerations may not be enough, practical concerns (cost, speed, and convenience), logical interpretations and "desirable features" of the models, and sometimes even personal preferences or different modelling philosophies, play an important role. This is especially true when evaluating methods with different characteristics and different focuses, such as those presented in this study. Some of the relevant topics related to this will be discussed in Sections 5.0 and 6.0.

For this particular study, Method I was recommended based on the results shown. However, because the data set used in this study is limited, this recommendation will be evaluated further and should not be used to exclude Methods II and III, or any other previously discussed growth intercept methods. In fact, when the combined (provincial) data set were split into two random halves repeatedly, and the model fitting and testing procedures were conducted many times (which equates to a practical simulation process), the rankings among Methods I, II, and III were not always consistent.

Although the formulation and the fitting of the growth intercept models presented in this study appear relatively simple and straightforward, it involves a number of rather intricate statistical concepts and problems, which include (1) the choice of the "best" functional form; (2) the usefulness and the inferences concerning the inverse regression; (3) the timewise and the spatially correlated nature of the stem analysis data (timewise correlation arises from the height-age growth series, spatial correlation arises from measurements taken from the same tree at various heights above ground); (4) the inter-correlation among the models fitted from different but "close" t and h_0 values (all models can be regarded as a set of "seemingly unrelated regression equations", or SURE as termed in econometrics); (5) the use of the indicator variable approach to test the similarities and differences among the growth intercept models fitted for different subregions and FMAs, using different t and h_0 values; and (6) the procedures for comparing and validating different models. All these are either omitted or discussed briefly in the present report.

4.0 Applications and Discussion

Examples illustrating the main use of the growth intercept models are provided in this Section. All are based on Method I (equations [1a]-[1c]) estimated on the combined (provincial) data (applications based on other methods can be illustrated accordingly). An illustration of the growth intercept measurements required for the computations is provided in Figure 4, which is adapted from Figure 3 of Hägglund (1981). Relevant topics associated with the practical use of the growth intercept models are also discussed.

1. Predicting Site Index

(1). If the average annual growth intercept in 5 years above 1.3 m is 0.45 (m/year), the predicted site index (height at breast height age 50 years) is 18.5 m (from Table A2), which is calculated using equation [1a] with Age=50 (years), GI=0.45 (m/year), b_0=6.431852, b_1=0.227735, b_2=0.059855, b_3=0.526582, and b_4=0.919781. The coefficients are shown in Table A1.

(2). If the average annual growth intercept in 3 years above 0.8 m is 0.25 (m/year), the predicted site index (height at breast height age 50 years) is 15.2 m (from Table A2), which is calculated using equation [1a] with Age=50 (years), GI=0.25 (m/year), b_0=6.376533, b_1=0.205812, b_2=0.062451, b_3=0.549108, and b_4=0.906160. The coefficients are shown in Table A1.

(3). Note that based on the coefficients shown in Table A1, t can be 1 year, 2, 3, 4 or 5 years, and h_0 can be 0.3, 0.5, 0.8 or 1.3 m. Judging from the fit and testing statistics, larger t and h_0 values will generally give better site index predictions. In practice, a base height $h_0 \geq 0.8$ m and a $t \geq 3$ years are recommended to be used. The use of an h_0 lower than 0.8 and a t less than 3 years is possible, but should probably be restricted, or at least used with great caution, because it frequently produces less reliable site index predictions.

(4). For any particular application, if possible, it is almost always best to apply the same t value and the same h_0 value throughout the application to achieve consistency and to avoid confusion among the surveyors, even through the possibilities for using different t and h_0 values in the same survey do exist.

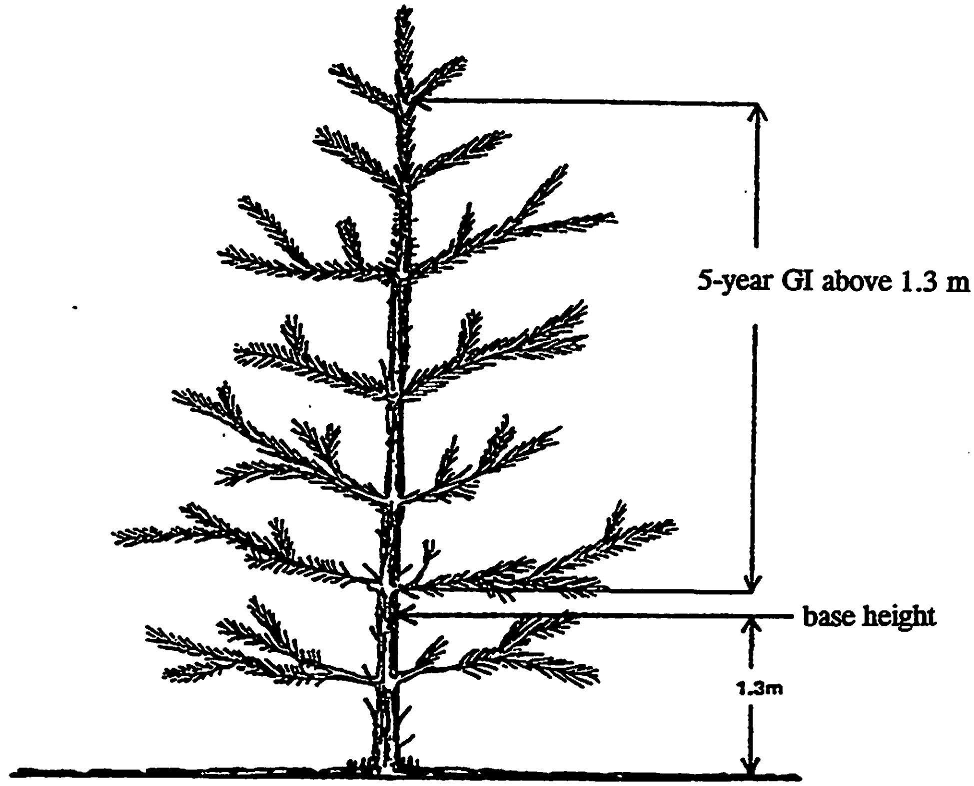
(5). Because the growth intercept models were developed from the tree data (i.e., tree height-age trajectories) rather than stand data, they are used to predict the site index for each individual site tree from measured growth intercept. An average site index value for the stand is obtained by averaging the site index values from all site trees (or top height trees) selected in the stand.

(6). In counting the annual height increments for GI calculations, one should be very careful about lammas shoots and avoid double counting or missing the years (internodes). This is easier to say than to do it. The key to good data collection is training and experience.

2. Estimating Expected Height At Any Age, on Any Site, Directly From Method I

(1). If the average annual growth intercept in 5 years above 1.3 m is 0.35 (m/year), the predicted site index (height at breast height age 50 years) is 16.9 m (from Table A2), which is calculated using equation [1a] with Age=50 (years), GI=0.35 (m/year), b_0=6.431852, b_1=0.227735, b_2=0.059855, b_3=0.526582, and b_4=0.919781. The coefficients are shown in Table A1.

(2). On a 16.9 m site, the projected height-age trajectory is described by the line having GI=0.35,



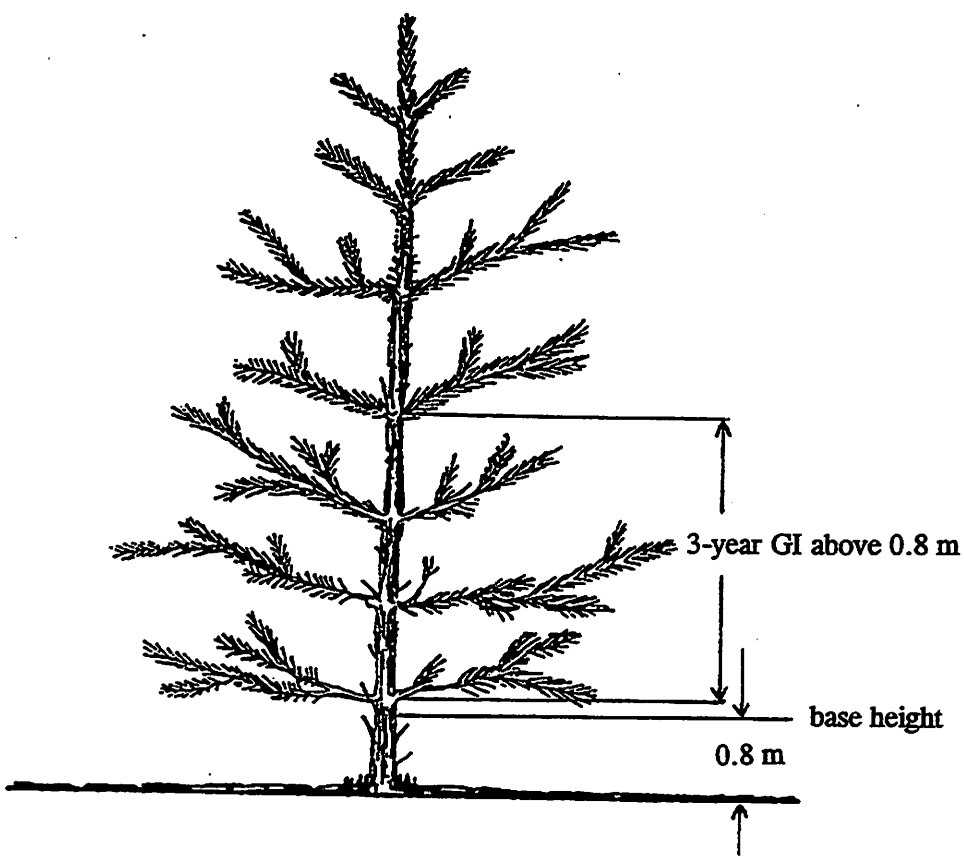


Figure 4. An illustration of the use of a 5-year growth intercept (m/year) above 1.3 m, or a 3-year growth intercept (m/year) above 0.8 m, to predict the site index.

shown in the third graph on the lower left-hand side corner of Figure A1. It was drawn using equation [1a] with Age=1 to 120 (years) and GI=0.35 (m/year).

(3). Essentially, based on the observed t-year growth intercept above h_0 on any given site, both the site index and the expected height at any age on that site can be predicted. Note that all predictions are made directly from the equations estimated in Method I without rearranging, inversing, constraining, or "smoothing" them to make better connections between different sets of curves (e.g., natural and regenerated height growth curves). The knowledge of the expected height and height growth at any age, on any site, is particularly useful in establishing the regeneration standards from which the height growth performance of regenerated stands can be judged and compared with.

3. Evaluating Stand Density and Treatment Effects

(1). If the regenerated stands came from a range of different starting densities and different levels of interspecific competition, the predicted site index values from the growth intercept models can be plotted against the stand densities. If the data points in the plot show an approximately horizontal band across the full range of the stand densities, then it is very likely that there is no relationship between the predicted site index and stand density. Any other no-horizontal pattern may indicate the existence of a relationship between site index and stand density. One may want to model this relationship, or to simply compare the average site index predictions grouped by assorted stand density classes to determine, for example, the "optimum" stand density that results in the biggest increase in site productivity.

(2). If the regenerated stands came from different silvicultural treatments, the predicted site index values can be grouped and compared by the treatments. This will allow the investigator to see whether or not the predicted site index values are different among different treatments. For a volume production purpose, the "optimum" treatment is the one that produces the biggest increase in predicted site index values.

(3). Site index predictions can also be grouped by other relevant factors (or variables), to examine whether or not these factors may have any significant impact on the potential capability of the site. Various statistical models or analysis of variance techniques may also be used to quantify the impact of each individual factor and the interactions among the factors.

4. Comparing Height Growth Patterns Between Natural and Regenerated Stands on Matching Sites

The height growth trajectories of the natural stands at the juvenile phases are assumed to follow those described by the fitted growth intercept models. If the height growth trajectories of the regenerated stands are observed, they can be compared to their counterparts from natural stands. Examination of the differences among the trajectories from different stand types will reveal how well the regenerated stands grow compared to natural stands. Regression equations may also be established to quantify the differences, and to investigate what kinds of factors (stand density? age? treatment? or others?) may have contributed to such differences.

5. Comparing Growth and Yield Between Natural and Regenerated Stands on Matching Sites

(1). Assume that a fire-origin natural stand and a regenerated stand are growing on the same site with similar physiographic site conditions. If the site index value of the natural stand is known and the site index value of the regenerated stand adjacent to the natural stand is also known, then the site index values can be compared in many different ways. A regression relationship between the site index values of natural and regenerated stands can also be established. Such a relationship may be postulated in the following general form, which takes into account the age and density factors:

$$SI_R = f(SI_N, Age_N, Density_N, Age_R, Density_R)$$

where: SI_R = site index for regenerated stands, predicted from the growth intercept model, SI_N = site index for natural stands, predicted from either the conventional site index equation based on the given height and age values, or the growth intercept model if the annual increments close to the base height can be accurately determined, Age= stand age, and Density=stand density. The subscripts N and R represent natural and regenerated stands, respectively.

Obviously, many simplified versions of the above general form exist if one or more variables on the right-hand side of the equation are found to be insignificant and can be dropped. More complicated forms also exist if additional factors are included.

Many functional forms presented in Method III may be used as the base models to portray the above relationship, with SI and GI in those formulas replaced by SI_R and SI_N, respectively. Note that the above functional relationship can be used as one of the most effective ways for demonstrating that the regenerated stands have enhanced, maintained, or reduced the potential site productivity. It may also be used to uncover the sources as to why the site productivity behaves that way (caused by age? density? treatment? or others?).

(2). Having the height and site index predictions from the fitted growth intercept models, volume projections for regenerated stands can be approximated from an existing volume equation such as Volume=*f*(Ht), developed as a part of the Alberta Phase 3 forest inventory (Alberta Forest Service 1985). Since such a volume equation generally applies to fully-stocked natural stands only, due to the fact that it was estimated from fully-stocked fire-origin natural stands and the stand density factor was not included in its formulation, it could over- or under-estimate the volumes for regenerated stands, depending on whether or not these stands are under- or over-stocked. This problem may be solved by using a volume function with the stand density factor accounted for, such as Volume=*f*(Ht, density).

Regenerated yield curves that account for the stand density factor are currently being built for major Alberta tree species (pine, white spruce and aspen). An interim regenerated growth and yield system for lodgepole pine is expected to be completed by December 1996. It will consist of the following principle equations (other equations such as diameter and basal area growth equations will be added on later):

(a). Site index prediction equation: SI = *f*(GI) or Ht=*f*(GI, age).
(b). Height projection equation: Ht=*f*(SI, age) or Ht=*f*(GI, age).
(c). Mortality equation: N=*f*(Ht, $N_{initial}$ or $N_{planting}$, age), where N=trees/ha
(d). Volume equation: Volume=*f*(Ht, N, age) or Volume=*f*(Ht, N), where Volume can

be total or merchantable at any specified utilization standard.

The possibilities of including certain additional variables are being examined. Since a variable appearing on the right-hand side of an equation can also appear on the left-hand side of another equation in the same system, simultaneous equation methods may give a better understanding of the correlation structure and feedback mechanism among the variables used to describe the system of compatible, integrated, interdependent, and analytically related equations.

6. Conducting Preliminary Timber Supply Analysis for Regenerated Stands

(1). The growth intercept models developed in Method I allow height and site index to be predicted from a few years of early height growth above a conveniently selected base height. Using the predicted height and site index, volume projections can be made (as previously illustrated) by assuming regenerated yield is equal to natural stand yield when the initial conditions are the same. All these, combined with other necessary constraints, allow *preliminary* timber supply analysis to be conducted and annual allowable cuts (AACs) calculated for regenerated stands. This can be very important for long-term forest management planning purposes.

(2). Practically speaking, however, whether or not the regenerated stands will actually conform to the results derived from the timber supply analysis will not be known until these stands have grown to rotation age. Prior to reaching the rotation age, any result generated from the timber supply analysis should be considered *preliminary*. The AAC calculation for regenerated stands should almost always be made on the more "conservative" side to ensure that any inaccuracy or uncertainty will favour the timber left in the forests, but not the timber to be harvested and delivered to a mill. It should also be constantly monitored or even recalculated to ensure that the AAC calculation is kept up to date, and is more or less consistent with the regeneration performance observed so far.

(3) The assumption of a constant site index value, predicted from the growth intercept model at young ages for regenerated stands, over the entire timber supply analysis rotation may also be questionable. Site index developers have always warned of large errors at young ages, and recommended against the use of the conventional site index equations for young stands (i.e., for stands <20 or 30 years), in which the site index values are frequently over-estimated and the height values under-estimated (see a review on this in Huang 1994, pp.38-43 and p.90). A valid concern about the growth intercept method is that whether or not a few years of early height growth is indeed reflecting subsequent height development patterns and the potential productivity of the site.

For many species, the early height development of the trees can be affected in many different ways and may not provide any useful information in estimating site quality since many "non-site" factors mask and confound the effects of site quality. These factors include severe brush competition and suppression, surface soil characteristics, initial stocking levels, planting stock quality, site preparation methods, planting techniques, animal bruising, short-term climatic fluctuations and small micro-site differences (see Huang 1994, pp.42-43). It is possible that the early stand growth patterns may not accurately reflect the growth that follows because of the changing impacts from these factors.

In many cases, the early height development pattern of the trees may be more closely related to various silvicultural systems, rather than to the potential capability of the site. It can be used to reflect and measure the effectiveness of silvicultural systems under different management scenarios, such as controlling micro-site differences, reducing initial stand densities (i.e., to prevent possible stagnation in pine stands) and removing brush competition and suppression. Each one of these may exert a more significant effect on early height growth than the potential capability of the site as the growth intercept model implies. For instance, the increased site productivity for regenerated lodgepole pine stands in Alberta, reported by Udell and Dempster (1986), might be a result of an appropriate stand density management practice that removed density-related suppression commonly occurred in natural pine stands.

(4). If there is no reason to believe that the site index value predicted for a 150-year-old natural stand applies to the same stand when it was 20 years old, then there is very little reason to believe that the site index value predicted for a 20-year-old regenerated stand should apply to the same stand when it eventually reaches 150 years old. One could use such an argument to invalidate the whole effort for predicting site index at young ages, and to cast some serious doubts upon the assumption that the predicted site index will remain unchanged over the entire rotation. On the other hand, one could argue that the over- or under-estimations were typically associated with the conventional site index equations, but not with the growth intercept models since the growth intercept models are specifically designed for young stands and should have corrected the over- or under-estimations originated from using trees at young ages (e.g., as judged from site index-age plot in which the data points display a horizontal band over a wide range of ages).

(5). The practice of estimating growth intercept models from data collected in natural stands, and then applying the estimated models to regenerated stands constitutes a situation in which the models were estimated from one population (natural stands) and then applied to a different population (regenerated stands). Statisticians may have difficulty in accepting such a practice. But with the option of fitting the growth intercept models from data collected in regenerated stands not feasible at this time, the "switching" of the models between the populations should be permissible for practical purposes, if due precautions are taken. In fact, many did caution the use of the growth intercept approach and recommend that it should be used only as an "interim" site measure (see a review on this in Huang 1994, pp.37-44). This, to some degree, might explain why the growth intercept approach was developed early enough but had rarely received any widespread applications as enjoyed by other site classification techniques. Only in recent years, has the growth intercept approach received increasing attention as a planning and an operational tool.

(6). It is worthwhile to emphasize that, while recognizing that there are limitations to the growth intercept method, one should still realize that the merits for using such an approach outweigh its shortcomings until a more reasonable approach is developed. Caution, however, must be exerted in interpreting and applying the results obtained from the growth intercept approach. Many factors are influencing the height growth of regenerated trees in the juvenile phase. The results (such as site index) derived at such young ages may easily deviate from the expected norms described by the fitted models.

Comparing the growth and yield relationships between natural and regenerated stands and conducting the *preliminary* timber supply analysis for regenerated stands, could be much more complicated than previously discussed. There are many additional factors affecting the calculation of AAC. Other relevant topics, including the impact of stand density, the possible problems of overestimation and related difficulties associated with the growth intercept approach, are discussed in Sections 7.0 and 8.0.

5.0 A Comparison to Phase 3 Site Curves

The growth intercept-based site index curves derived from Method I fitted on the combined provincial data set were compared to the Phase 3 site index curves (Alberta Forest Service 1985), developed by W.R. Dempster and Associates (1983). For lodgepole pine, the Phase 3 site index equation takes the following form:

$$Ht = 1.3+(SI-1.3)\,\frac{1+\exp[7.4871-1.2036\ln(50)-0.9576\ln(SI-1.3)]}{1+\exp[7.4871-1.2036\ln(Age)-0.9576\ln(SI-1.3)]}$$

where: Ht = total tree height (m)
SI = site index (m), which is the tree height at 50 years breast height age
Age = breast height age of the tree (years).

Site index values of 5, 10, 15, 20, and 25 m at 50 years breast height age (SI=5, 10, 15, 20, 25) were used in the above equation to generate a set of height and site index curves for breast height ages 1 to 120 (Age=1 to 120). These curves are shown in Figures 5 and 6.

To generate a set of growth intercept-based site index curves based on the given site index values of 5, 10, 15, 20, and 25 m at 50 years breast height age, equation [1] is rearranged into the following form:

$$GI = \left(\frac{1}{b_0}\cdot\frac{Ht-1.3}{Age^{k}[1-\exp(-b_2 GI^{b_3}Age)]^{b_4}}\right)^{1/b_1}$$

An iterative routine is needed to solve the GI for each given site index value. For instance, given the site index value of 20.0 m at 50 years breast height age, the Ht and the Age variables in the above equation are known (Ht=20.0 and Age=50). An initial value for GI on the right-hand side of the equation, termed GI_0, is guessed. A good initial value for GI_0 is 0.20 (m/year). Once the Ht, Age, and GI_0 are available, the first estimation of GI on the left-hand side of the equation, termed GI_1, is calculated. Having the calculated GI_1, the next initial value for GI, termed GI_2, is estimated by: $GI_2=(GI_1+GI_0)/2$, which is then substituted into the right-hand side of the above equation to predict the next GI value on the left-hand side of the equation. This process is repeated until a desired precision level set by the user is achieved, for example:

$$|GI_i - GI_{i-1}| < \Delta = 0.00000001$$

where i is the number of iterations performed (those who may not want such a high convergence precision can establish the stopping rule with a larger **Δ** value, e.g., **Δ**=0.001 or **Δ**=0.01).

The programing logic of the above iterations is almost identical to that used for iteratively solving the site index from the Ht=*f*(site index, age) equation based on given height and age values. An example of this type of program in a SAS format is available (Huang 1994, p.117), which is used to predict the site index from the Phase 3 site index equation developed by W.R. Dempster and Associates (1983).

Note that the prediction of the x-variable from the fitted function y=*f*(x; **β**) constitutes the so-called "inverse regression", "inverse prediction", or "discrimination", which predicts the value of the independent

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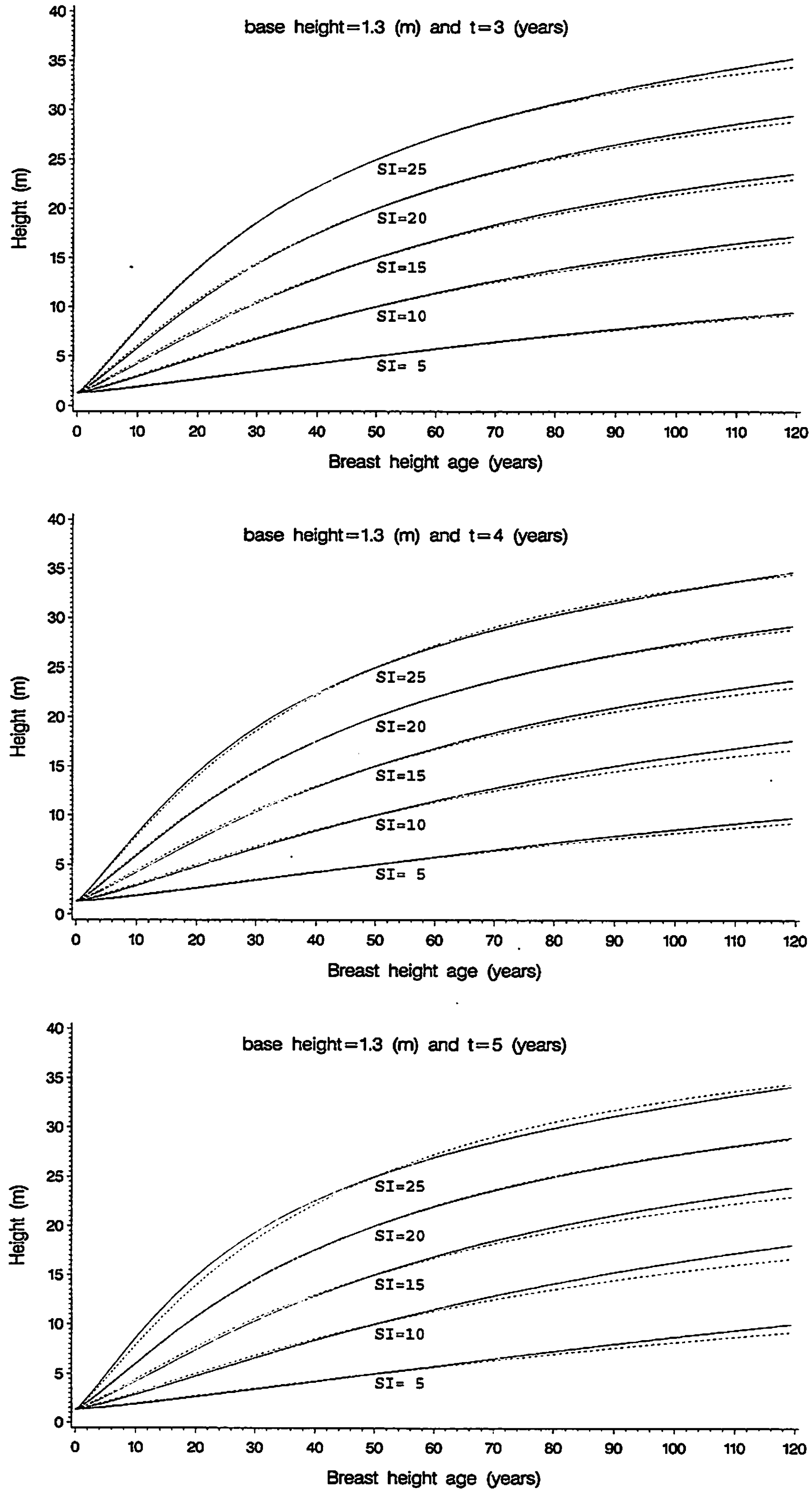

Figure 5. Comparison between the growth intercept-based site curves (solid lines) and Phase 3 site curves (dashed lines). The growth intercept-based site curves were generated using equation [1] with a base height of 1.3 m.

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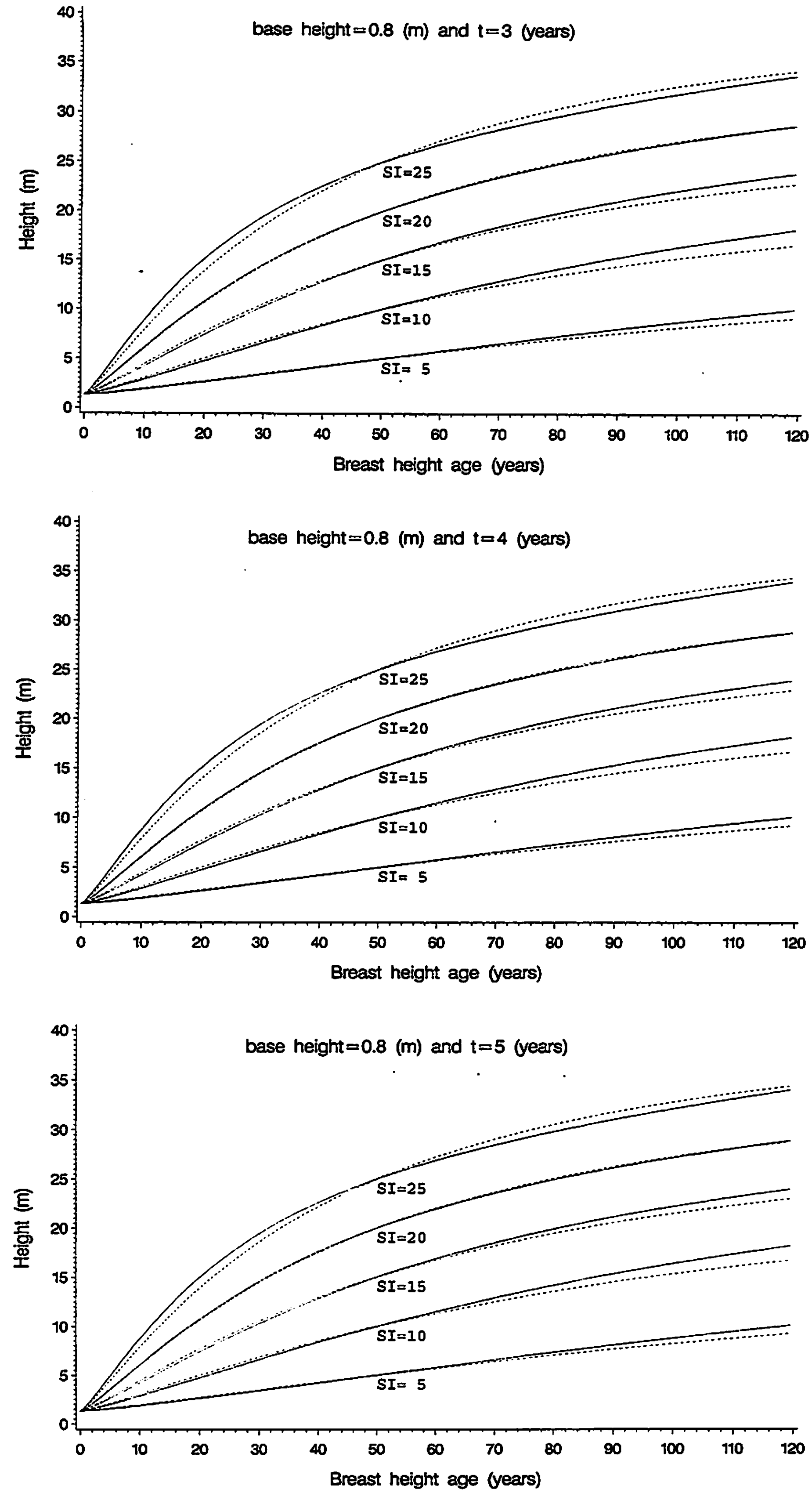

Figure 6. Comparison between the growth intercept-based site curves (solid lines) and Phase 3 site curves (dashed lines). The growth intercept-based site curves were generated using equation [1] with a base height of 0.8 m.

variable x given the value of the dependent variable y. The x-value predicted in this manner is usually biased and inefficient (i.e., does not have a minimum variance), regardless of whether the iterative or the algebraical procedures are used. Statistical inferences (interval estimation and hypothesis testing) for the inverse regression differ from those conventional ones for the dependent variable y. Those who are interested in the technical details of the inverse regression, especially with regard to its roles and inferences in a nonlinear regression setting, are referred to Seber and Wild (1989, pp.245-50). In practice, inverse regression must be used with caution. Indiscriminant use of this technique can cause severe statistical and practical problems (i.e., a biased and inefficient x estimate and a "no-solution"). Practitioners should restrict its use to some limited classes of models (e.g., simple linear models, quadratic models, and some types of simple nonlinear models), but not to more complicated nonlinear models, sigmoidal shape growth models with a fixed asymptote, and many types of transformed models.

Having the calculated GI values that correspond to given site index values (SI=5, 10, 15, 20, 25), the projected heights at breast height ages 1 to 120 were computed by:

$$Ht = 1.3 + b_0 GI^{b_1} Age^{k} [1 - \exp(-b_2 GI^{b_3} Age)]^{b_4}$$

where the above equation is identical to [1]. Different sets of coefficients that correspond to different t and base height h_0 values (as shown in Table A1 of Appendix 1) were used to generate the growth intercept-based site index curves. These curves are also displayed in Figures 5 and 6, overlaid on the corresponding Phase 3 site index curves. The difference (or the closeness) among the site index curves is readily discernable from Figures 5 and 6. In general, it is not very substantial. This is probably somewhat expected since both sets of site index curves were developed from trees grown in natural stands.

The Phase 3 site index curves were also compared to the following alternative functional form shown in Method I of this study (see Figures 7 and 8):

$$Ht = (1.3 + b_0 GI) + b_1 GI^{b_2} Age^{k} [1 - \exp(-b_3 GI^{b_4} Age)]^{b_5} \qquad [4]$$

The coefficients for the above function are:

Base height (m)	t (years)	b_1	b_2	b_3	b_4	b_5	b_0	RMSE	R^2
1.3	3	6.503758	0.268762	0.052533	0.279662	1.119561	1.193838	1.652	0.947
1.3	4	6.415395	0.253316	0.056053	0.357307	1.083736	1.000717	1.610	0.950
1.3	5	6.339899	0.235998	0.060289	0.456536	1.047332	0.862597	1.588	0.951
0.8	3	6.352451	0.212738	0.062124	0.507231	0.963498	0.420309*	1.636	0.948
0.8	4	6.431670	0.231574	0.064095	0.502801	1.008926	0.657947	1.567	0.952
0.8	5	6.426145	0.235668	0.063520	0.498558	1.017009	0.694269	1.542	0.954

Note: * indicates an insignificant estimate at α=0.05.

Apparently, the difference between this function and the Phase 3 curves occurs at very young ages. Future studies based an expanded data collection effort currently ongoing may reveal whether this alternative functional form behaves better than the recommended form.

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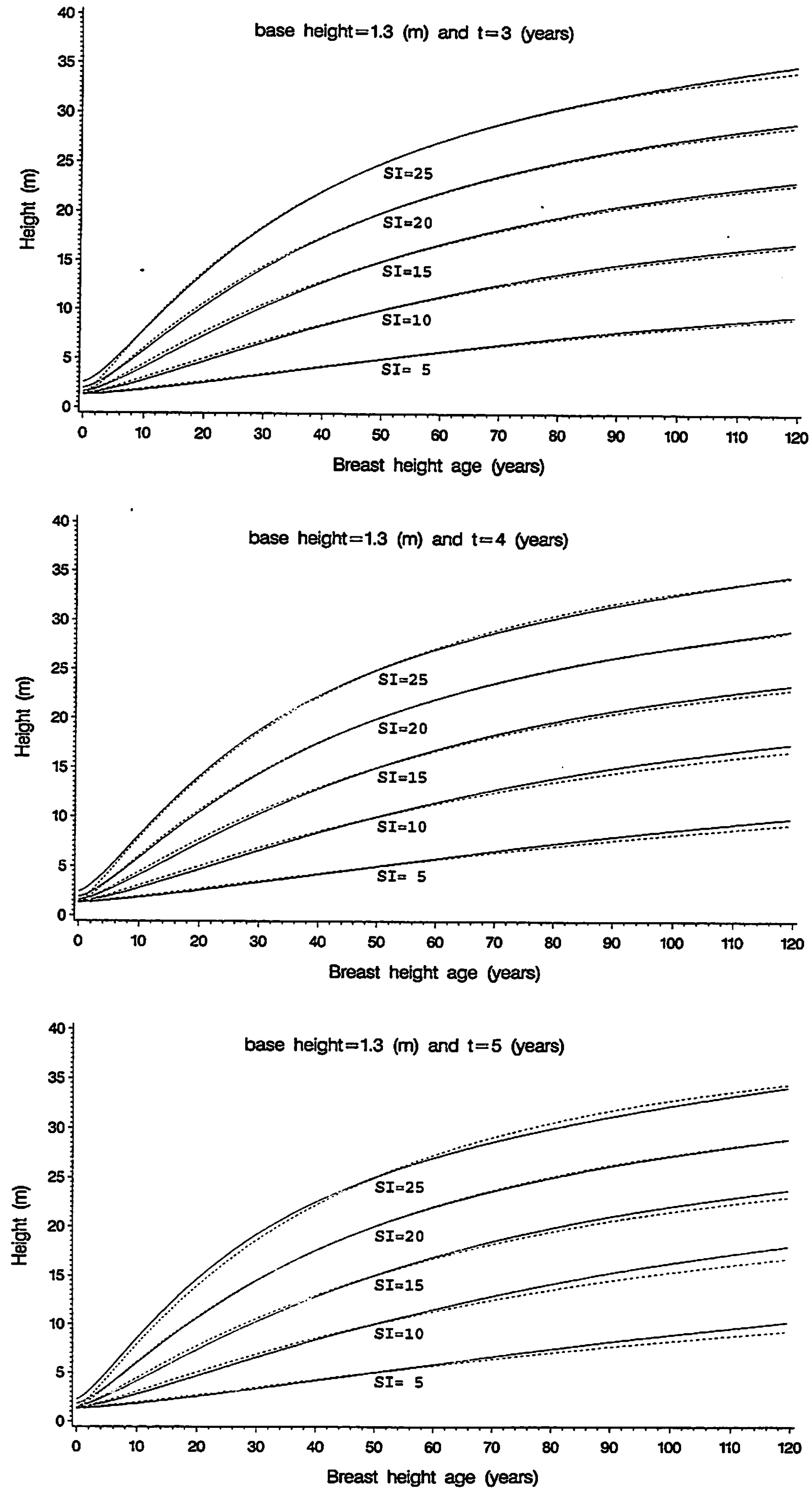

Figure 7. Comparison between the growth intercept-based site curves (solid lines) and Phase 3 site curves (dashed lines). The growth intercept-based site curves were generated using equation [4] with a base height of 1.3 m.

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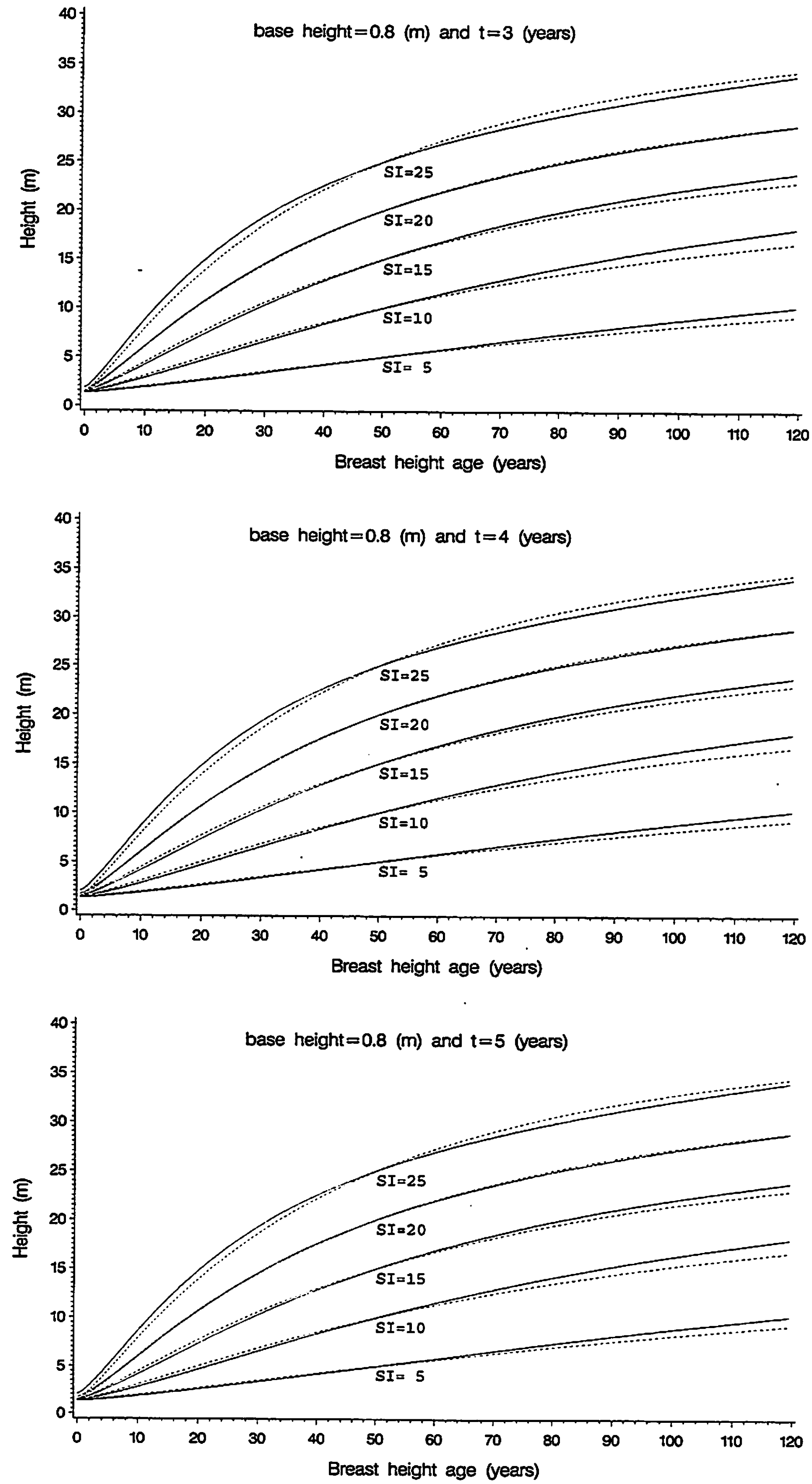

Figure 8. Comparison between the growth intercept-based site curves (solid lines) and Phase 3 site curves (dashed lines). The growth intercept-based site curves were generated using equation [4] with a base height of 0.8 m.

In modelling growth and yield for regenerated stands, one of the simplest approaches involves a two-step procedure: (1) predict the site index from a conventional growth intercept model such as SI=f(GI) from Method III, and (2) substitute the predicted site index into an existing Ht=f(SI, age) model, usually estimated from natural stands, to make height and volume projections (in Alberta, volume projections are made through Volume=f(Ht), see Alberta Forest Service 1985). If the growth intercept equation [1] developed in Method I of this study is used, this two-step procedure is reduced to a one-step procedure, because the height can be predicted directly from the growth intercept equation and the "intermediate" site index model Ht=f(SI, age) is not required.

Regardless of the type of growth intercept model used, the implication of the growth intercept method is that the entire height growth trajectory can be assessed (directly or indirectly) based on a few years of height growth in the juvenile phase. Whether or not a few years of juvenile height growth is reflecting the subsequent height development patterns and the potential capability of the site is still open for discussion, at least until the regenerated stands have reached the maturity, and are growing in a relatively "stable" fashion. This and other related topics will be discussed in Sections 7.0 and 8.0.

Many growth intercept models are developed to predict site index only. Sometimes, they may also be used to project the height development pattern at the juvenile phase up to a certain arbitrarily selected age point (a "joint"), commonly chosen at 20 or 30 years breast height age. For the latter, when projecting the height after that age point, the height growth pattern is "switched" to an existing set of height-site index-age curves. The problem with such an approach is that the "joint" may not always be "smooth", although different splining techniques and a purposely selected (e.g., constrained) regression function can be used to make the connection or transition look smooth.

As noted in Section 3.0, the growth intercept models developed in Method I (or Method II) provide an "automatic", smooth connection between different sets of curves (e.g., natural and regenerated growth curves). In the past, one was frequently confronted with the problem of how and where to make a reasonable connection between natural and regenerated curves, which was considered a "black box" in many ways. Using the growth intercept models developed in this study, the contents of this black box are revealed, and the height-age growth trajectories on different sites with varying capacities can be projected in a continuous, rather than segmented, manner. The techniques for "splining" or "smoothing" different sets of growth curves to make them better connected become less important, and the complications involved in finding a model that gives a more or less smooth connection, simply disappear.

Perhaps more importantly, the growth intercept models developed in Method I allow the height to be projected directly from the fitted models, over a wide range of ages (e.g., 1 to 120 years). Extrapolation of the fitted models beyond the data range used to estimate the models did not demonstrate any "erratic" pattern. Site index predictions are also made directly from the fitted models. They are a subset of the height predictions when the age in the models equals the selected reference age (e.g., 50 years or any other reasonable number), and are used for labelling purposes. The implication of these can be interpreted in three ways, which may be considered non-trivial depending on how the investigator looks at them:

(1). Many conventional growth intercept models are used to predict site index. The predicted site index is substituted into existing growth and yield models (usually fitted from natural stands), to make, for example, height projections through Ht=f(SI, age), and volume projections through Volume=f(Ht) (as done in Alberta). If, for some reason, the "existing" height projection model Ht=f(SI, age) is not applicable or is simply not available, the best one can do about these growth intercept models is to use them to predict site index. But the prediction of site index alone may not provide enough information for volume projections. This limitation may seriously undermine the usefulness of the growth intercept models.

The growth intercept models developed in Method I are more flexible. They can be used to predict height and site index. The predicted site index may be inputted into an existing Ht=f(SI, age) equation to make height projections. If one does not want to use the Ht=f(SI, age) equation (because of its poor performance), or it is simply not available, height projections and consequently, volume projections can still be made. In fact, the growth intercept models developed in Method I can always be used to make height projections without requiring the intermediate equation Ht =f(SI, age). In practice, it is usually more convenient to use a single growth intercept model in the form of Ht=f(GI, age) to predict height and site index at the same time.

(2). For a volume projection system with three equations: SI=f(GI) → Ht=f(SI, age) → Volume=f(Ht), where a measure of growth intercept GI is used to predict site index and the predicted site index is used to drive the height-site index-age curves, when the height-site index-age equation Ht=f(SI, age) is changed, the outcome of the volume projections will also be changed, even through the GI from the regenerated stand remains the same.

Volume projections based on the growth intercept models developed in Method I are not affected by the choice or the changes of the site index system. Sometimes this can be advantageous, considering the fact that there are so many different kinds of site index systems available, and that these systems are being constantly re-evaluated, re-fitted, and changed.

(3). Growth intercept models fitted in the form of SI=f(Ht, age) (to some degree, SI=f(GI) and SI=f(GI, t) as well) may be used to inversely predict height. However, as previously noted, inverse predictions are the sources of biased and inefficient predictions for the independent variable height. Further, the use of inverse regression to predict an independent variable from a fitted y=f(x; β) equation is itself a thorny issue. Those who emphasize the importance of "compatibility" between predictions routinely use the inverse regression, regardless of its "imperfectness" in terms of bias and inefficiency. Those who emphasize the importance of achieving the "best" predictions for each individual variable in the model fitting data set always prefer the fitting of separate equations with different dependent variables, regardless of the "incompatibility" between the predictions. Such different attitudes are rampant in formulating height-site index-age equations, where examples of a single height-site index-age equation for both height and site index predictions, and separate height-site index-age and site index-height-age equations for separate height and site index predictions, are too abundant to mention. The choice of any particular approach appears to have become a matter of "personal preference": both approaches are widespread, and one can almost always find some reason to adopt, to question, or to rebuke either approach, depending on the situations involved.

The growth intercept models developed in Method I (or Method II) can be used to estimate height and site index directly without requiring the use of inverse regression. Furthermore, the height and site index predictions are made at the same time. Essentially, site index predictions are a subset of height predictions from the fitted growth intercept models, each expressed by Ht=f(GI, age). If preferred, any height prediction model expressed in the form of Ht=f(GI, age) can also be referred to as a site index prediction model.

A point worth emphasizing is that, a growth intercept model expressed by Ht=f(GI, age) concentrates on height modelling. Site index is a "by-product" directly outputted from this model. It is the predicted height when the age equals an reference age (which can be 50 years or any other number). Site index is treated as an integrated part of the height predictions, and is used for the purposes of labelling and comparison. Site index predictions are intrinsically height predictions, so a height prediction model is itself a site index prediction model.

To see how well the growth intercept-based site index curves developed in this study accommodate the actual height growth trajectories, site index curves generated using different t and base height h_0 values are overlaid on the actual height growth trajectories from natural stands (Figures 9 to 16). As is obvious from these Figures, the fits of the site index curves to observed height growth trajectories are reasonably good, especially for those beyond a breast height age of 2 years. This is a strong indication that the growth intercept-based site index curves agree well with the actual height-age trajectories from natural stands.

Figures 9-16 also suggest that in general, the fits of the curves for the regionalized data are not as good as those for the combined data. This is somewhat expected because the ranges and the sample sizes for the regionalized data sets are limited compared to those for the combined data set. At this time, it is probably best to postpone the use of the regionalized and FMA-based curves until more subregion-specific data are collected and the models re-estimated.

A simple procedure to regionalize the fitted provincial models (or any other regression model) is to use these models to predict the variable in interest, and then compare the predicted values to observed values. A relationship between predicted (x-variable) and observed (y-variable) values can be established, if such a relationship exists. Localized predictions are made based on this new relationship, with the x-variable predicted from the original models that are kept intact.

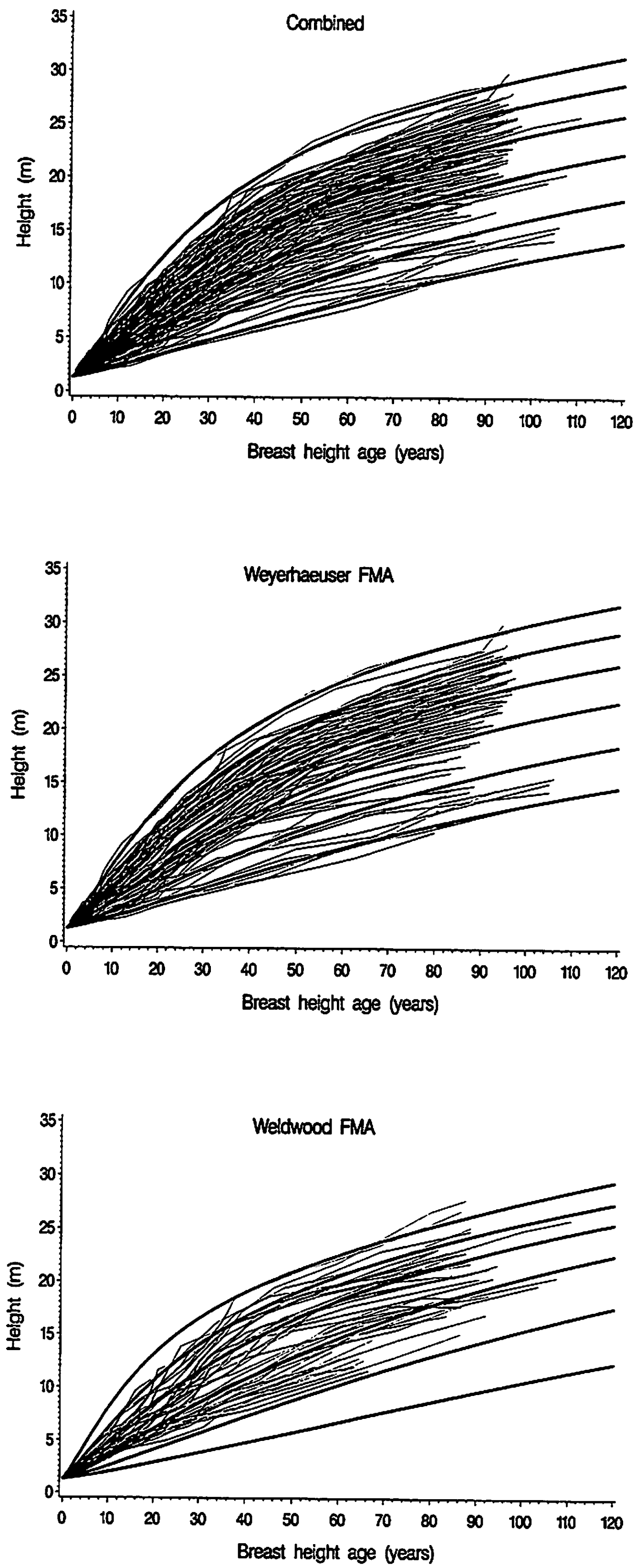

Figure 9. The growth intercept-based site index curves overlaid on observed height growth trajectories. The growth intercept-based site curves were generated using equation [1] with a base height of 1.3 m and a t value of 5-years.

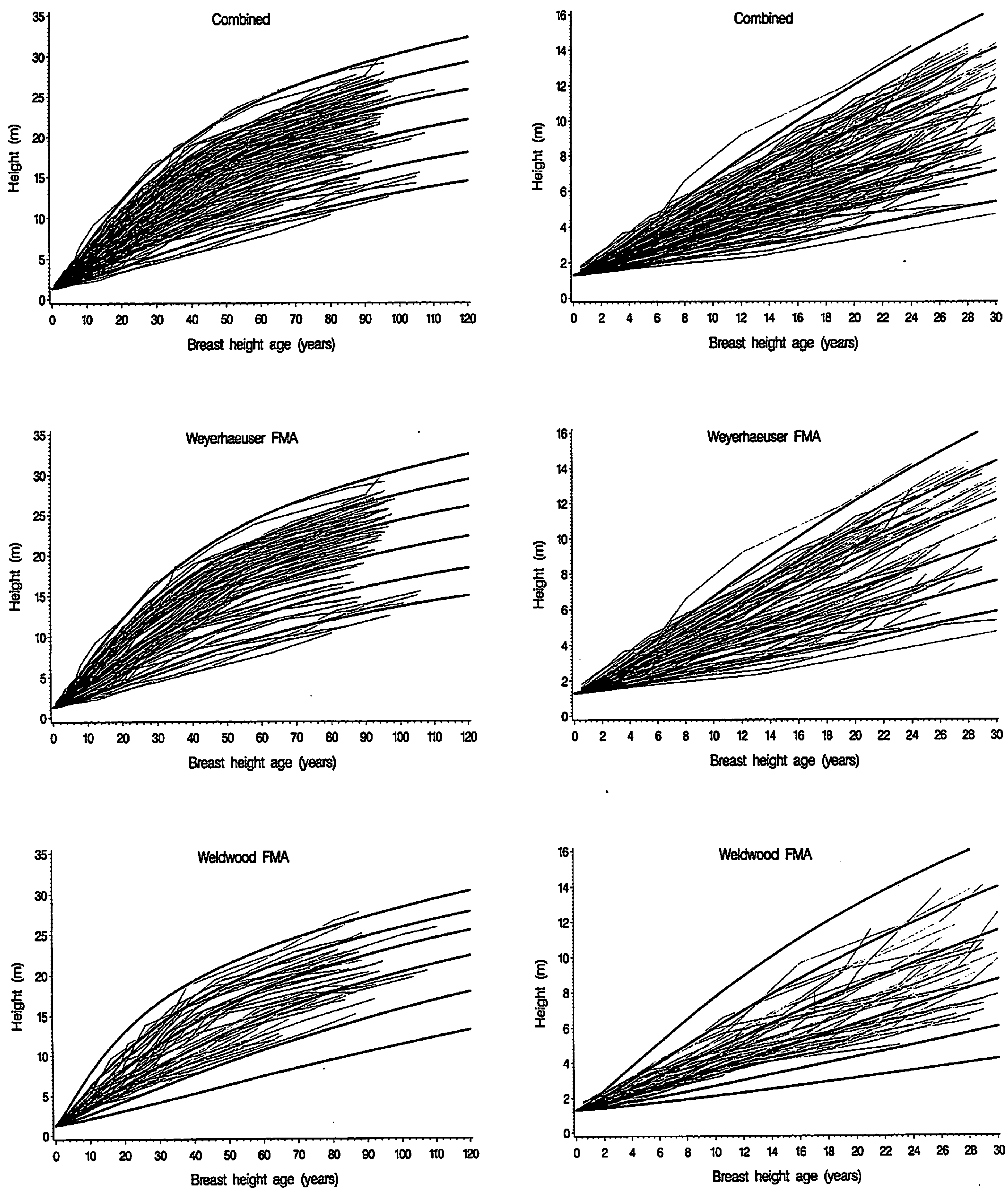

Figure 10. The growth intercept-based site index curves overlaid on observed height growth trajectories. The growth intercept-based site curves were generated using equation [1] with a base height of 1.3 m and a t value of 3-years.

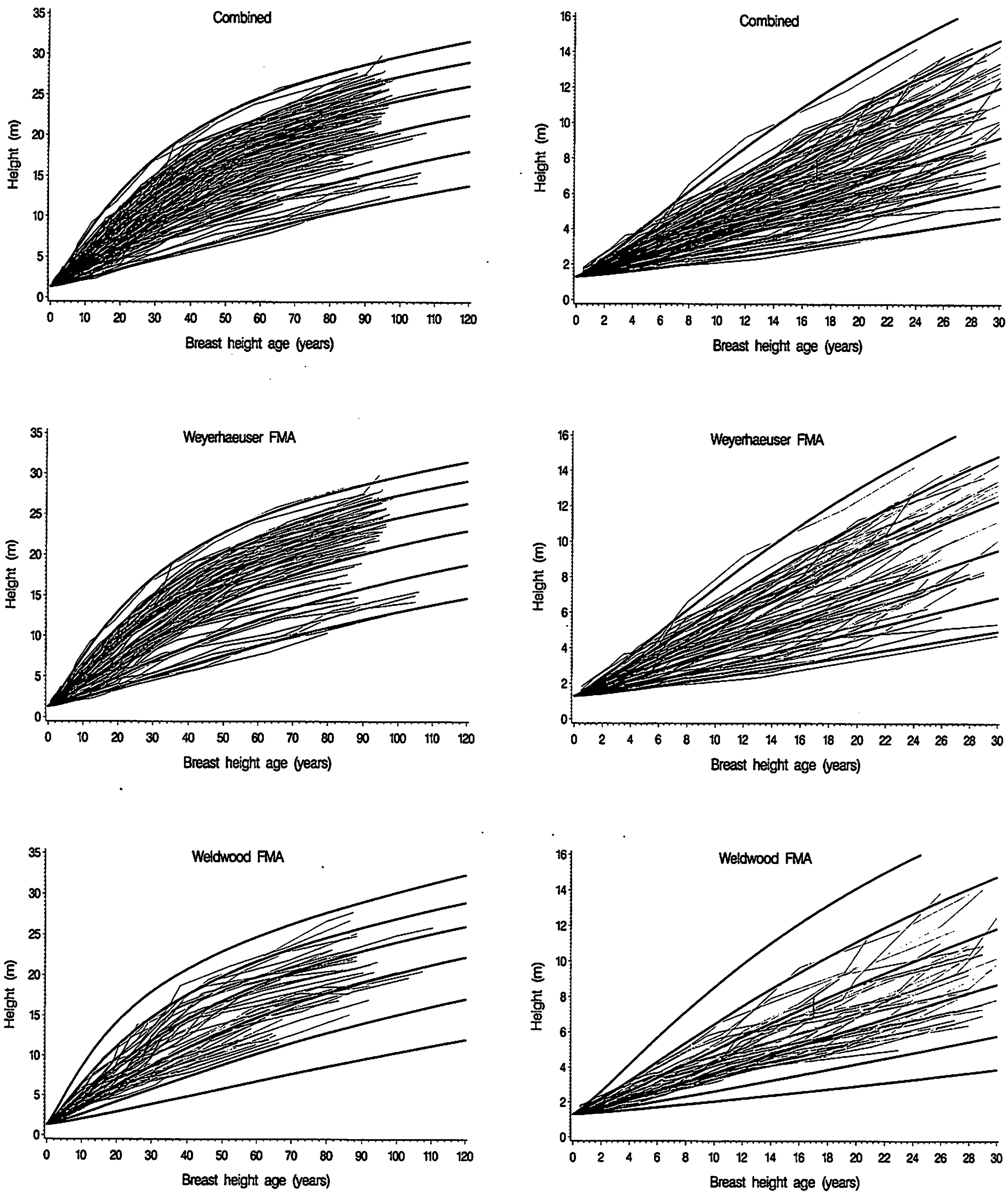

Figure 11. The growth intercept-based site index curves overlaid on observed height growth trajectories. The growth intercept-based site curves were generated using equation [1] with a base height of 0.8 m and a t value of 5-years.

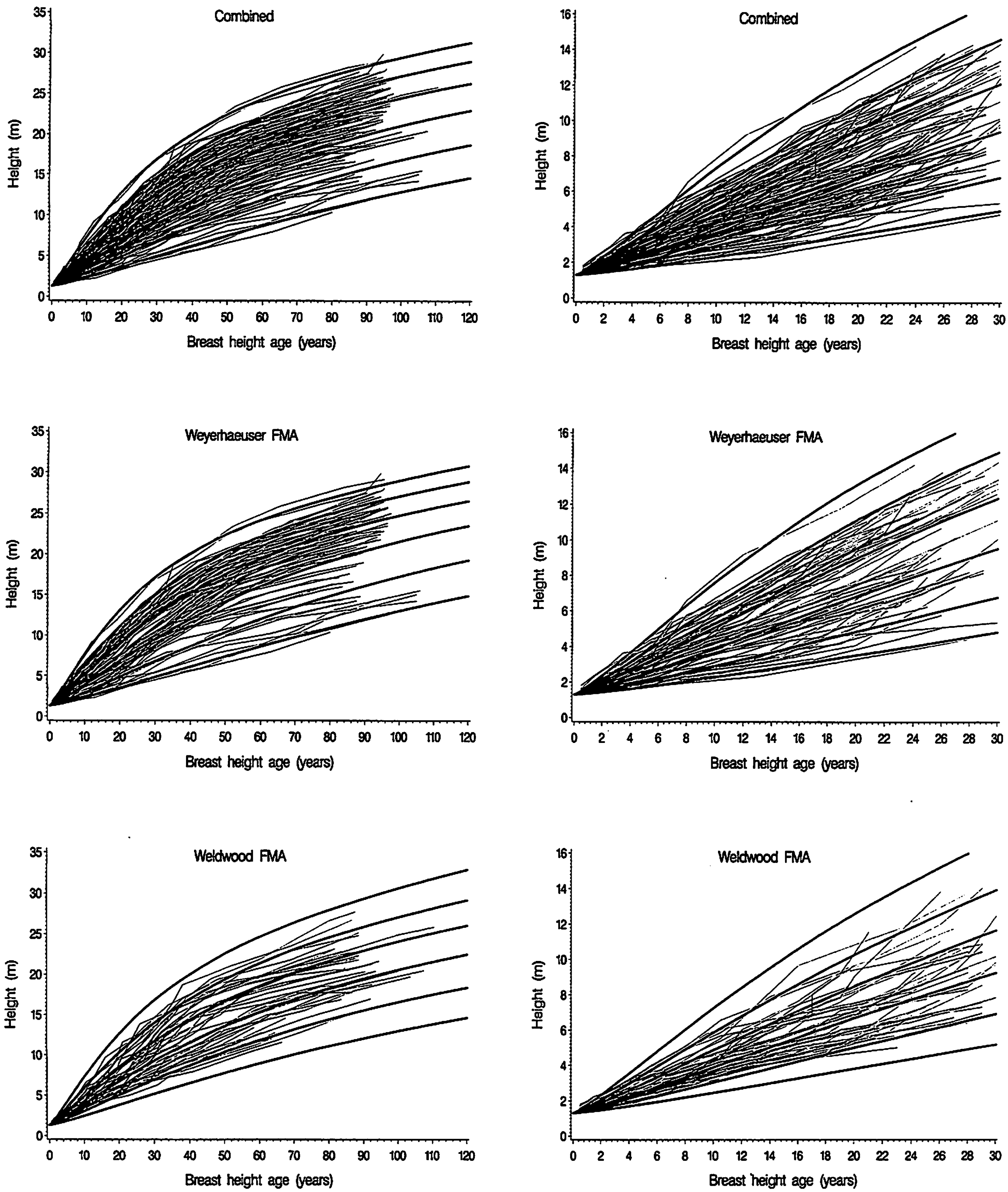

Figure 12. The growth intercept-based site index curves overlaid on observed height growth trajectories. The growth intercept-based site curves were generated using equation [1] with a base height of 0.8 m and a t value of 3-years.

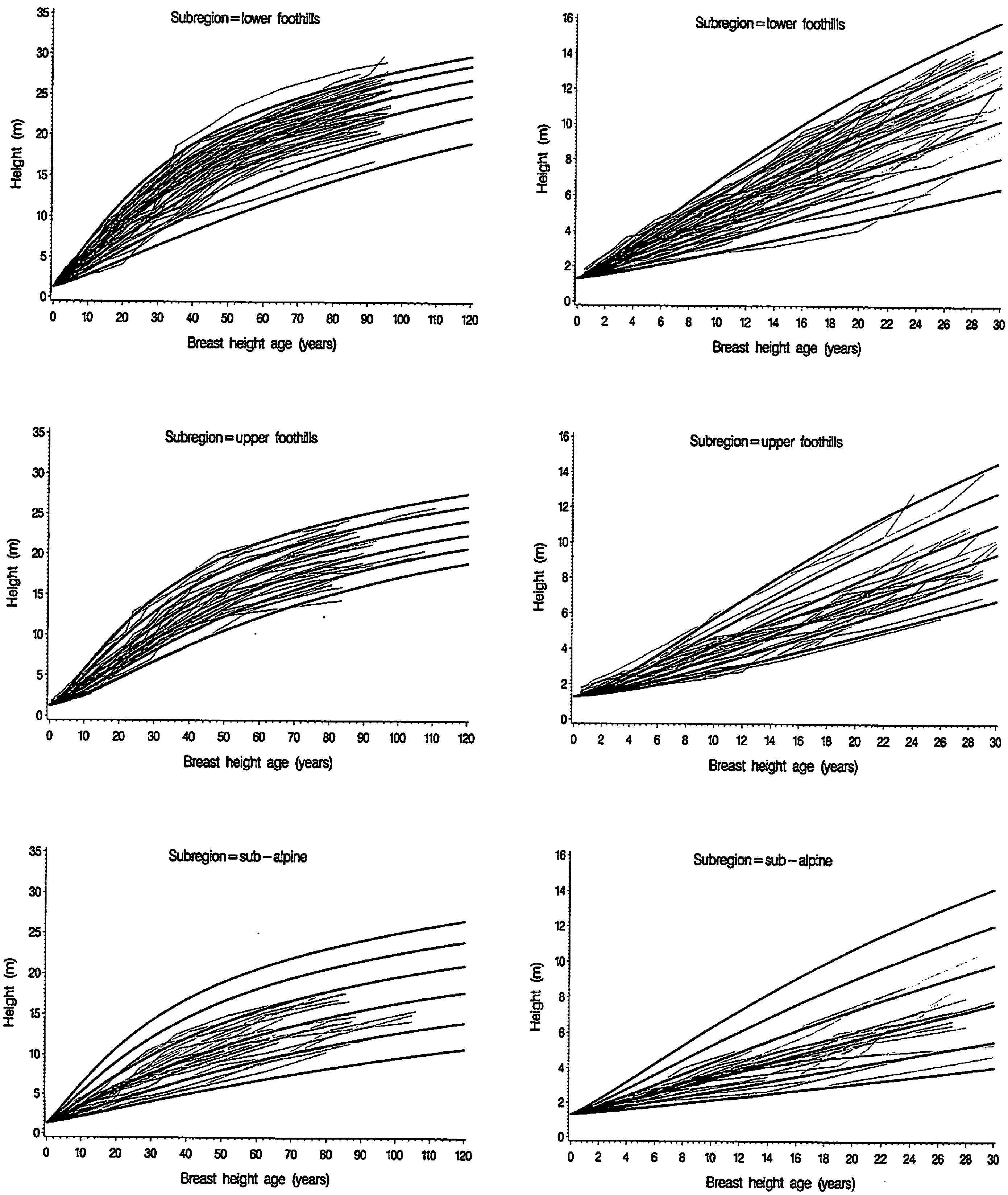

Figure 13. The growth intercept-based site index curves overlaid on observed height growth trajectories by subregions. The growth intercept-based site curves were generated using equation [1] with a base height of 1.3 m and a t value of 5-years.

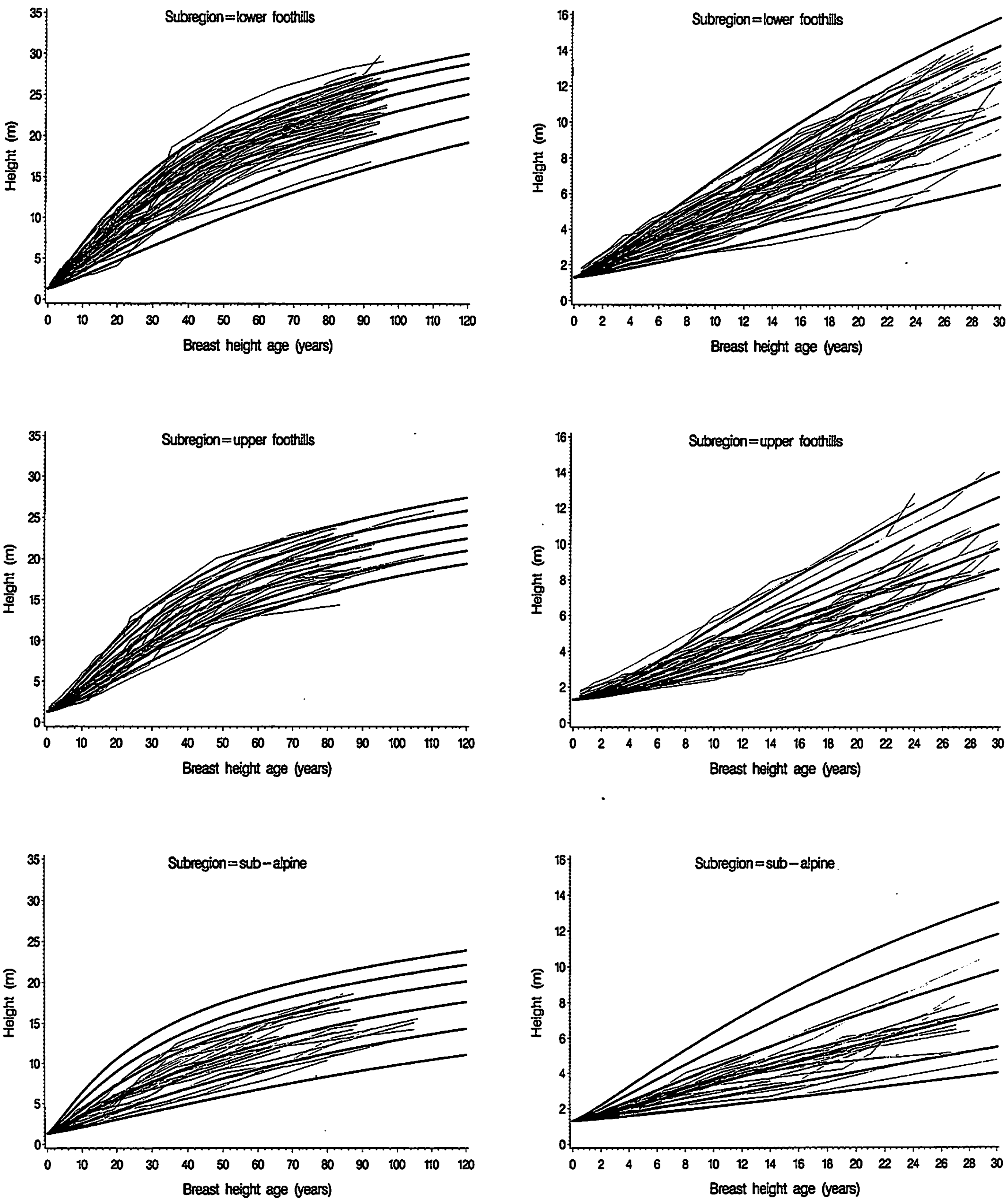

Figure 14. The growth intercept-based site index curves overlaid on observed height growth trajectories by subregions. The growth intercept-based site curves were generated using equation [1] with a base height of 1.3 m and a t value of 3-years.

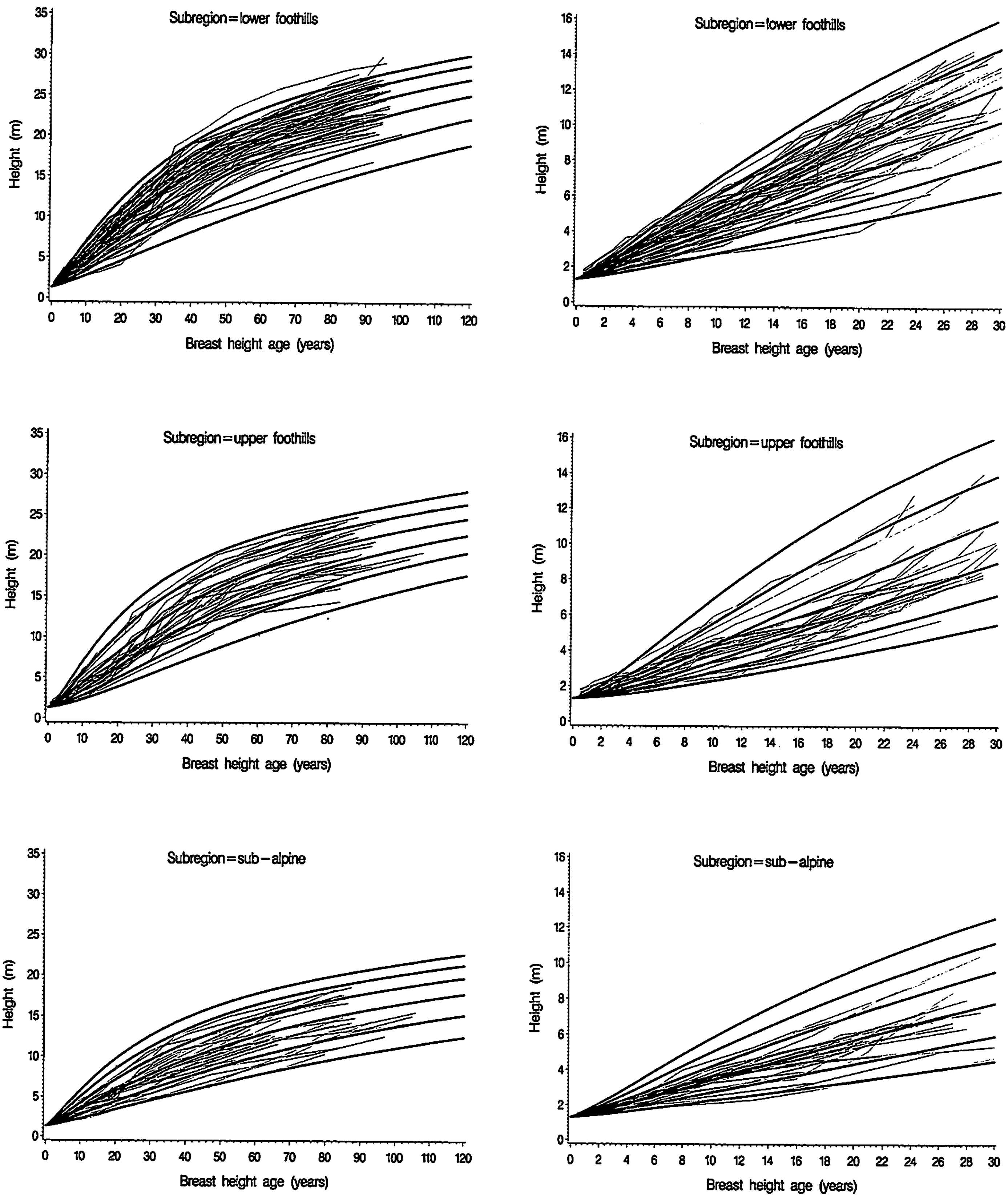

Figure 15. The growth intercept-based site index curves overlaid on observed height growth trajectories by subregions. The growth intercept-based site curves were generated using equation [1] with a base height of 0.8 m and a t value of 5-years.

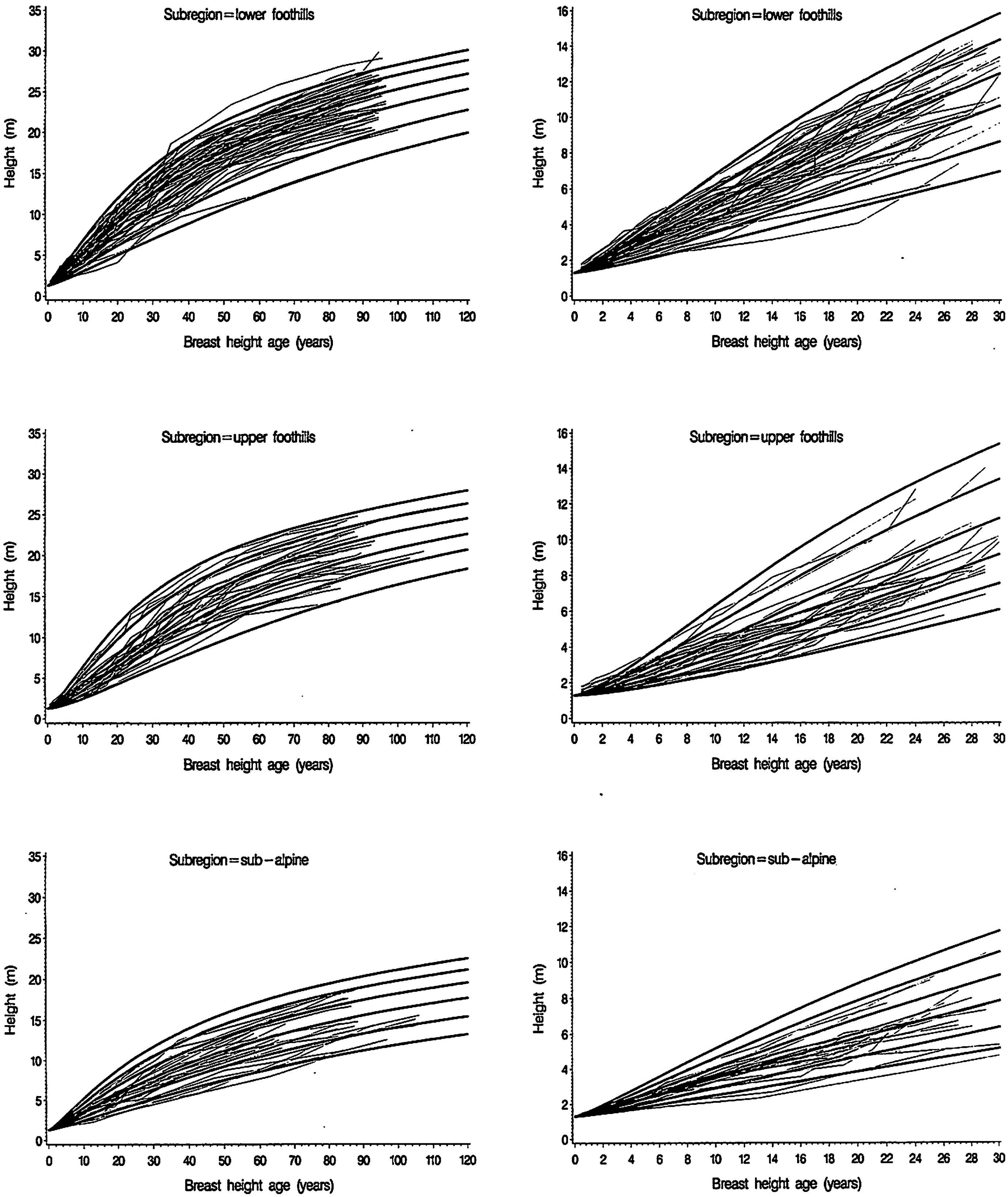

Figure 16. The growth intercept-based site index curves overlaid on observed height growth trajectories by subregions. The growth intercept-based site curves were generated using equation [1] with a base height of 0.8 m and a t value of 3-years.

6.0 Model Comparison and Accuracy of the Site Index Predictions

The combined provincial data set (110 trees) is used here to illustrate the procedures involved in model comparison and evaluating the accuracy of site index predictions. These procedures are equally applicable to data sets from individual subregions or FMAs. Readers who are more interested in applications may want to skip the content of this or any subsequent section.

The combined data set was divided into two random halves of equal size. Each has 55 trees. One half was used for model fitting and the other half for model testing and comparison. Both the fitting and testing data sets are graphically depicted in Figure 17, with the enlarged graphs showing the first 30 years of height growth above breast height (1.3 m) attached in respective cases. Equations [1], [2], and [3], corresponding to Methods I, II, and III, respectively, were estimated on the model fitting data set. Estimated coefficients, together with the root mean squared error (RMSE) and the coefficient of determination (R^2), for the selected t and h_0 values, are shown in Table 1.

Table 1. Fit statistics for Methods I, II, and III on the model fitting data set.

Method	Equation	h_0 (m)	t (years)	Estimate b_0	b_1	b_2	b_3	b_4	b_5	RMSE	R^2
Method I	[1]	1.3	3	6.644473	0.239376	0.056712	0.486774	0.903256		1.625	0.953
			4	6.423625	0.208035	0.063249	0.594496	0.899392		1.548	0.957
			5	6.162746	0.162222	0.069953	0.731092	0.878572		1.525	0.958
		0.8	3	5.876454	0.098224	0.080063	0.840785	0.853146		1.591	0.954
			4	6.287405	0.167438	0.077296	0.776707	0.877860		1.487	0.960
			5	6.246512	0.160618	0.077220	0.802057	0.869542		1.458	0.962
		0.5	3	5.638708	0.051926*	0.094916	0.950838	0.838115		1.805	0.941
			4	5.395200	0.006895*	0.117639	1.166076	0.822640		1.677	0.949
			5	5.533382	0.030148*	0.122582	1.200822	0.831907		1.522	0.958
		0.3	3	6.309768	0.145006	0.061438	0.527246	0.863579		1.881	0.936
			4	6.064944	0.110524	0.081981	0.802343	0.840017		1.773	0.943
			5	5.679666	0.049802*	0.106556	1.062428	0.819502		1.669	0.950
Method II	[2]	1.3	1 to 5	6.124297	0.156804	0.060741	0.584110	0.835225	0.058241	1.664	0.950
		0.8	1 to 5	5.823761	0.089840	0.077384	0.806590	0.791128	0.083425	1.616	0.953
		0.5	1 to 5	6.141977	0.130486	0.069317	0.659273	0.766614	0.119578	1.854	0.938
		0.3	1 to 5	6.284059	0.140224	0.057242	0.490699	0.751084	0.131105	1.904	0.935
Method III	[3]	1.3	3	26.280392	0.176564					2.438	0.540
			4	26.516797	0.182175					2.285	0.596
			5	26.790307	0.190726					2.230	0.619
		0.8	3	26.430058	0.168285					2.362	0.568
			4	27.821925	0.195352					2.211	0.622
			5	27.983061	0.201500					2.154	0.641
		0.5	3	26.614475	0.160112					2.706	0.434
			4	28.133025	0.188373					2.493	0.519
			5	29.502487	0.214603					2.250	0.608
		0.3	3	24.019601	0.107159					2.907	0.347
			4	26.484534	0.151326					2.695	0.438
			5	28.069859	0.182019					2.521	0.508

Note: * indicates an insignificant estimate at $\alpha=0.05$.

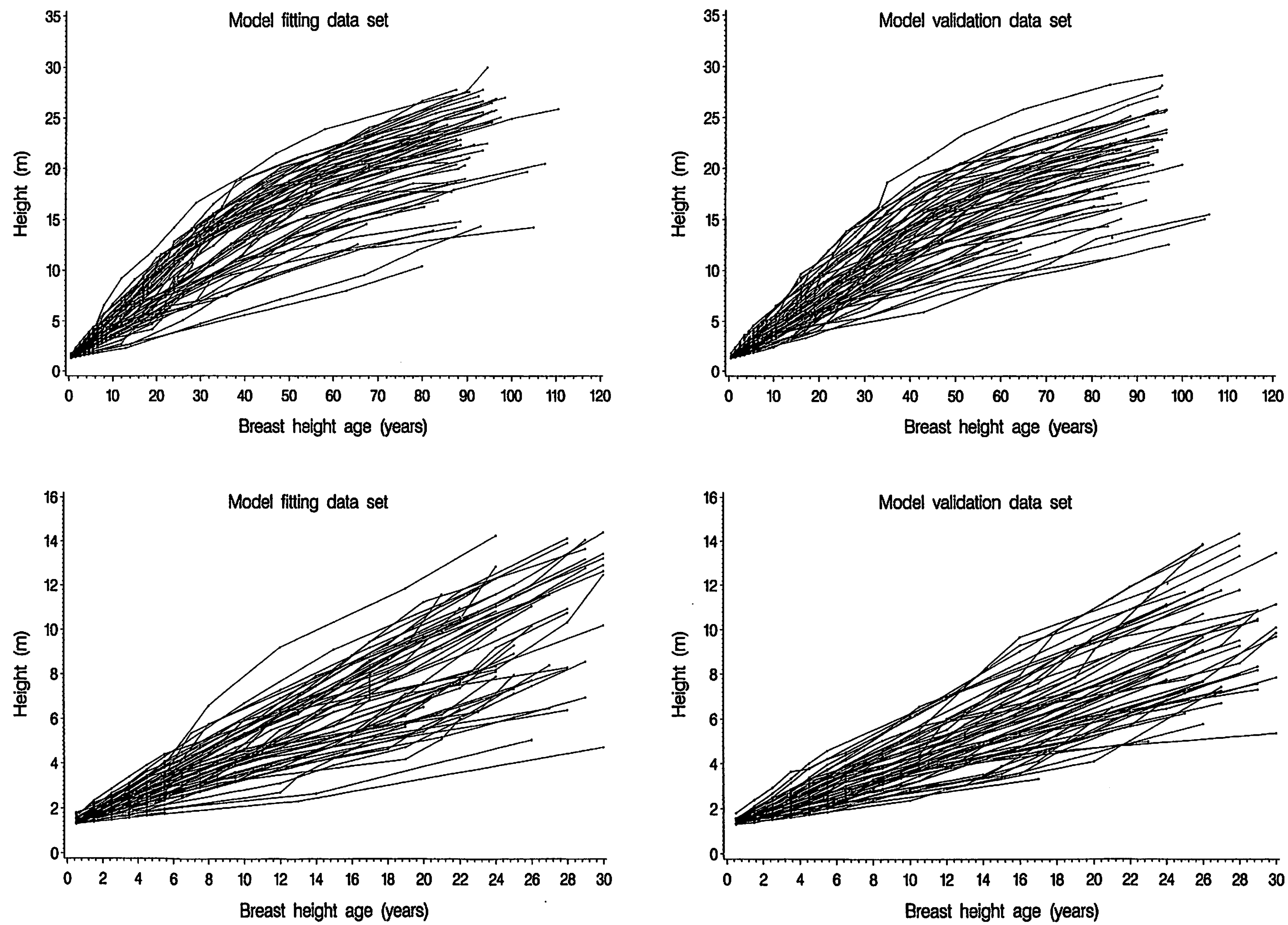

Figure 17. Graphic descriptions of the model fitting and testing data sets.

Once the coefficients were estimated, the testing data set was used to compare the models and evaluate the accuracy of site index predictions. The error of the prediction for the *i*th observation of the testing data set was obtained by subtracting the predicted site index from the observed site index. The mean and the standard deviation of the prediction biases were calculated by [5] and [6], respectively:

$$\bar{e} = \frac{\Sigma_{i=1}^{n}(y_i - \hat{y}_i)}{n} = \frac{\Sigma e_i}{n} \quad [5]$$

$$s_e = \sqrt{\frac{\Sigma_{i=1}^{n}(e_i - \bar{e})^2}{n-1}} = \sqrt{\frac{\Sigma e_i^2 - (\Sigma e_i)^2/n}{n-1}} \quad [6]$$

where $\bar{e}$ is the mean prediction bias, s_e is the standard deviation of the prediction errors, *n* is the total number of observations in the validation data set (*n*=55), e_i is the *i*th prediction error ($e_i = y_i - \hat{y}_i$), y_i is the *i*th observed "true" site index and $\hat{y}_i$ is its prediction from the fitted model (*i*=1, 2, ..., *n*). The mean prediction bias $\bar{e}$ can be more intuitively expressed as the percent bias (bias%) calculated by:

$$bias\% = \frac{\bar{e}}{\bar{y}} \times 100 = \frac{\bar{e}}{\Sigma y_i / n} \times 100 \quad [7]$$

where $\bar{y}$ is the average of the observed site index values ($\bar{y} = \Sigma y_i/n$). The root mean squared error of prediction (RMSEP) on the testing data set (Rawlings 1988, p.187), was also calculated:

$$RMSEP = \sqrt{\frac{\Sigma_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad [8]$$

Calculated statistics for model comparison (and validation) are listed in Table 2. Figure 18 shows the observed versus predicted site index values based on Method I with h_0 values of 0.8 m and 1.3 m.

It is relatively clear from Table 2 that in general, equation [1] of Method I produced the smallest mean prediction bias and the lowest bias%. The difference between the values of RMSEP from Methods I and II is marginal. All are smaller that those obtained from Method III. This suggests that on average, Method I gave the most accurate and precise site index predictions for this particular testing data set. If the recommended t value of 3, 4, or 5 years, and an base height (h_0) value of 0.8 m or 1.3 m are used, an average prediction bias of less than 3% is most likely to be expected (see bias% in Table 2). Because the variation of the site index predictions is quite large (in terms of RMSEP), a small *average* prediction bias does not suggest that the site index prediction for a particular sample observation will always be accurate. In fact, a deviation of six or more metres away from an observed "true" site index value of the tree is still possible, as is evident from Table 2 and Figure 18, where the maximum site index prediction errors can exceed six or more metres.

The validation statistics shown in Table 2 also indicate that, for the recommended Method I:

(1). When the base height h_0 is fixed, a larger t (years) value is associated with a smaller bias and bias%, as well as a smaller mean squared error of prediction.

Table 2. Validation statistics for Methods I, II, and III on the testing data set.

Method	Equation	h_0 (m)	t (years)	Bias (m) Mean	Min.	Max.	Std. dev.	RMSEP (m)	Bias %
Method I	[1]	1.3	3	-0.183	-6.439	6.268	2.731	2.713	-1.216
Method II	[2]	1.3	3	-0.221	-6.600	6.036	2.740	2.724	-1.469
Method III	[3]	1.3	3	-0.247	-6.723	7.396	2.859	2.844	-1.642
Method I	[1]	1.3	4	-0.135	-5.935	5.984	2.706	2.685	-0.897
Method II	[2]	1.3	4	-0.221	-6.168	5.462	2.694	2.678	-1.469
Method III	[3]	1.3	4	-0.264	-6.217	6.625	2.785	2.772	-1.755
Method I	[1]	1.3	5	-0.081	-5.485	6.053	2.652	2.629	-0.538
Method II	[2]	1.3	5	-0.268	-5.878	5.169	2.648	2.637	-1.781
Method III	[3]	1.3	5	-0.269	-5.771	6.333	2.694	2.683	-1.788
Method I	[1]	0.8	3	-0.266	-6.596	4.100	2.692	2.681	-1.768
Method II	[2]	0.8	3	-0.318	-6.680	3.948	2.686	2.680	-2.114
Method III	[3]	0.8	3	-0.527	-6.946	3.792	2.708	2.735	-3.503
Method I	[1]	0.8	4	-0.157	-6.709	4.668	2.644	2.625	-1.044
Method II	[2]	0.8	4	-0.230	-6.892	4.413	2.626	2.612	-1.529
Method III	[3]	0.8	4	-0.387	-7.064	4.329	2.659	2.663	-2.572
Method I	[1]	0.8	5	-0.155	-6.601	4.962	2.616	2.597	-1.030
Method II	[2]	0.8	5	-0.274	-6.841	4.569	2.597	2.588	-1.821
Method III	[3]	0.8	5	-0.402	-6.970	4.662	2.633	2.640	-2.672
Method I	[1]	0.5	3	-0.501	-6.261	3.294	2.631	2.654	-3.330
Method II	[2]	0.5	3	-0.683	-6.502	3.001	2.604	2.669	-4.540
Method III	[3]	0.5	3	-0.753	-6.564	3.051	2.649	2.731	-5.005
Method I	[1]	0.5	4	-0.227	-6.678	4.035	2.615	2.601	-1.509
Method II	[2]	0.5	4	-0.557	-6.976	3.306	2.551	2.589	-3.702
Method III	[3]	0.5	4	-0.591	-7.009	3.558	2.598	2.641	-3.928
Method I	[1]	0.5	5	-0.138	-6.094	4.400	2.540	2.521	-0.917
Method II	[2]	0.5	5	-0.545	-6.635	3.782	2.481	2.518	-3.623
Method III	[3]	0.5	5	-0.548	-6.499	3.915	2.517	2.554	-3.643
Method I	[1]	0.3	3	-1.076	-6.756	3.693	2.679	2.865	-7.152
Method II	[2]	0.3	3	-1.007	-6.659	3.910	2.695	2.854	-6.694
Method III	[3]	0.3	3	-1.201	-7.058	3.845	2.687	2.920	-7.983
Method I	[1]	0.3	4	-0.571	-6.277	3.086	2.562	2.602	-3.796
Method II	[2]	0.3	4	-0.834	-6.644	3.576	2.604	2.712	-5.544
Method III	[3]	0.3	4	-0.790	-6.589	3.050	2.584	2.680	-5.251
Method I	[1]	0.3	5	-0.296	-6.368	3.931	2.567	2.561	-1.968
Method II	[2]	0.3	5	-0.796	-7.041	3.510	2.580	2.678	-5.291
Method III	[3]	0.3	5	-0.620	-6.727	3.507	2.568	2.619	-4.121

Note: * indicates an insignificant estimate at $\alpha=0.05$.

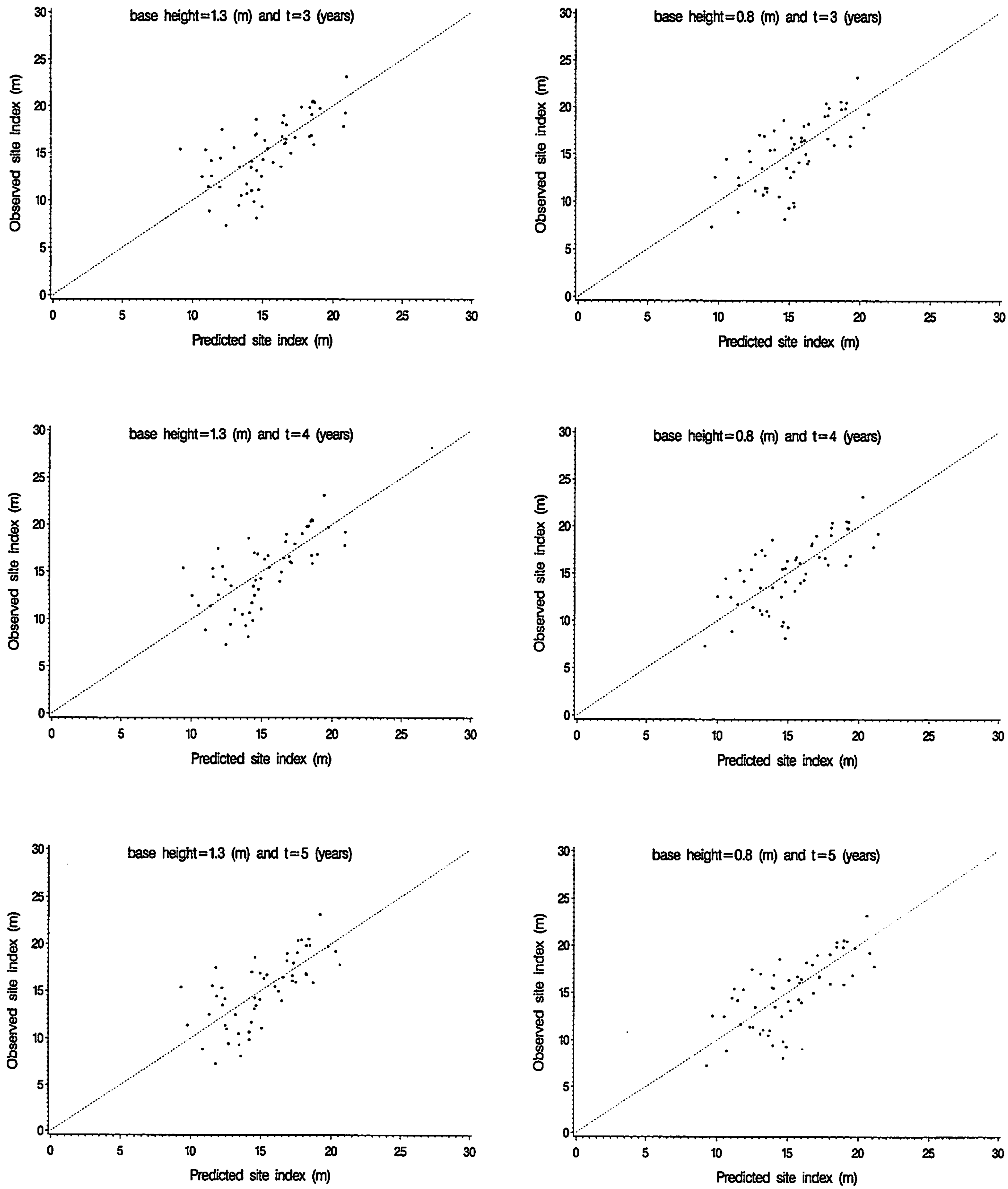

Figure 18. Observed versus predicted site index values for the testing data set. Predicted site index values were obtained from equation [1] using different h_0 and t values.

(2). When the t value is fixed, a larger base height (m) value is associated with a smaller bias and bias%, as well as a smaller mean squared error of prediction.

The above results suggest that, a higher base height (h_0) and a longer growth interval (t) will generally produce better site index predictions. This is intuitively reasonable because a higher base height and a longer growth interval are expected to have a closer tie to the true site index value. Note that the values for the bias% are all negative, suggesting that in these cases the site index predictions from the fitted growth intercept models are overestimated. Since the growth intercept models fitted on one half of the data using t values of 1 year and 2 years resulted in many insignificant coefficients, they were not considered in model evaluation.

The computations and the graphs demonstrated in this section are used to illustrate some of the most basic procedures for model comparison and validation. There are many other procedures that can also be used. These procedures can be diverse and sometimes appear to be incoherent. It is often sufficient for practitioners to take a "practical" look at the differences between the observed and predicted values by simply plotting these values (as done in Figures 18), calculating the bias percent (bias%), and then determining whether or not such differences are acceptable (speaking in terms of model validation). Obviously, in comparing different models on the same testing data set, the model that gives the smallest mean prediction bias and bias%, as well as the lowest RMSEP, is the "best" for that data set, even though some researchers may contest that the differences among the biases and the bias percents, as well as the RMSEPs, may not be statistically significant enough to warrant a distinct separation among the alternative models unless a statistical test is conducted. This and other related topics are probably beyond the scope of this study, and will not be addressed here.

Note that the growth intercept models fitted in Method I (and Method II) can also be used to evaluate the accuracy of height predictions along the entire range of ages (e.g., 1 to 120 years, respectively), or by a 5- or 10-year age class. This feature is not available from Method III, where the accuracy of height predictions (i.e., the site index predictions) can only be evaluated at a single age point (50 years breast height age). The example results listed in Table 3 were obtained when the fitted models from Method I with varying h_0 and t values were used to make height predictions for the validation data set.

Table 3. Mean height prediction biases from Method I on the testing data set.

Age class (years)	Number of observations	Height prediction biases from Method I with selected h_0 (m) and t (years) values							
		$h_0=1.3$ & t=3		$h_0=1.3$ & t=5		$h_0=0.8$ & t=3		$h_0=0.8$ & t=5	
		Bias (m)	Bias%	Bias (m)	Bias%	Bias (m)	Bias%	Bias(m)	Bias%
age<5	275	0.0315	1.60	0.0241	1.22	-0.0160	-0.81	0.0025	0.13
5≤age<15	218	-0.1229	-3.39	-0.1248	-3.44	-0.1493	-4.12	-0.1274	-3.52
15≤age<25	94	-0.3818	-5.44	-0.2848	-4.05	-0.4535	-6.46	-0.4036	-5.75
25≤age<35	71	-0.3180	-3.06	-0.2979	-2.86	-0.2240	-2.16	-0.2444	-2.36
35≤age<45	59	-0.1561	-1.21	-0.0049	-0.04	-0.1695	-1.31	-0.1312	-1.02
45≤age<55	41	0.1509	0.99	0.2320	1.51	-0.2378	-1.56	-0.0580	-0.38
55≤age<65	40	-0.8788	-5.56	-0.7847	-4.96	-0.8984	-5.68	-0.7881	-4.98
65≤age<75	27	0.2475	1.33	0.2148	1.15	-0.4792	-2.57	-0.0862	-0.46
75≤age<85	37	-0.6698	-3.46	-0.4966	-2.55	-1.0577	-5.47	-0.8702	-4.50
85≤age<95	32	-0.2565	-1.17	-0.5004	-2.28	-0.6633	-3.02	-0.5024	-2.29
age≥95	13	-1.5908	-6.99	-1.3937	-6.13	-1.6575	-7.28	-1.8022	-7.92
Total	907	-0.1783	-2.32	-0.1520	-1.97	-0.2712	-3.53	-0.2184	-2.84

Notes: bias and bias% were calculated according to [5] and [7], respectively, with the y-variable replaced by height.

The growth intercept models presented in Section 3.0 are based on the data set combined from the two halves. This will produce models that are generally better than those fitted on either half alone (Rawlings 1988, p. 189), assuming that the biases and the root mean squared error of predictions are all within the "acceptable" levels established by the investigator.

It may be worthwhile to note that, if site index is used directly as the dependent variable in the growth intercept formulation, as was done in Method III, the sum of the squared "prediction errors" (i.e., residuals) on the model fitting data set is minimized for site index (a direct consequence of the least squares principle). This will give the smallest possible mean site index prediction error on the model fitting data set. According to one of the least squares properties, such a mean error is always equal to zero for linear models, and very-very close to zero for correctly fitted nonlinear models if the sample size is large enough. However, this does not imply that the minimized error on the model fitting data set will still be a minimum on the independent testing data set. A preferred model is the one that demonstrates the best or close to the best statistical behaviour on the independent testing data set (plus other considerations such as cost, speed, and convenience, as well as logical interpretations and "desirable features" of the model).

For any growth intercept model expressed in the form of Ht=*f*(GI, age), the predicted site index is a height prediction at a user-defined reference age that is consistent with the current practice (e.g., 50 years). In theory, this "index" can be set at any age that is chosen and agreed-upon by the users. It does not have any feedback mechanism on the height projections, but merely "an index" or a subset of height predictions used for labelling or comparison purposes. The impact of the site on height growth is embodied in the observed GI values, because the growth intercept approach assumes that after reaching the base height h_0, trees will grow at comparable rates for the next few years on comparable sites, whereas on contrasting sites they will grow at consistently contrasting rates. Note that the predominant purpose of "indexing" is to provide a common base for comparing otherwise incomparable (or not directly comparable) attributes. In the case of Ht=*f*(GI, age), the GI values from comparable or contrasting sites are "grow" to a common base (reference age) so that they can be compared and good, medium, or poor sites determined.

7.0 The Density Factor and Future Studies

It was mentioned in Section 4.0 that the growth intercept models developed in this study can be used to evaluate stand density and treatment effects, even though density is not explicitly included in the formulation of the growth intercept models. It is possible to include the stand density component as an independent variable in the models, if it is shown that there is some value in doing so (e.g., the stand density factor is statistically significant).

To illustrate how the stand density factor may impact juvenile height growth, first the average annual height growth intercept in t years above the base height h_0 was plotted against stand density, measured by the number of trees per hectare. Various t and h_0 values were used. Several typical plots generated from a t value of 3 or 5 years, and an h_0 value of 0.8 or 1.3 m, are displayed in Figure 19.

Next, the site index value for each stand was plotted against the number of trees per hectare. This plot is demonstrated in Figure 20.

The data points shown in Figures 19 and 20 exhibit a loose but obvious downward trend, suggesting that high densities result in a reduction in both the height growth and the site index. This trend is statistically significant in every instance since the significance probabilities for the F values of the fitted models, each with growth intercept or site index as the dependent variable, and stand density as the independent variable, are all smaller than 0.05, that is, $(Prob>F)<0.05$.

Apparently, the above observation made from Figures 19 and 20 conforms to the common belief about the "height reduction" (with an increasing stand density) in lodgepole pine stands. But such a conclusion, and probably other similar or different conclusions based on such figures with the stand density factor represented by the number of trees per hectare, should be made very carefully. This is because number of trees per hectare may not be an adequate reflection of stand density in mature stands.

Since the number of trees per hectare does not account for different tree sizes (i.e., diameters at breast height, DBH), the number of trees per hectare alone is usually not considered a good measure of stand density for mature stands, even though it is generally regarded as the simplest and the most reasonable one for young stands. Because all growth intercept trees used in this study were sampled from mature stands, the use of basal area per ha, stand density index, crown competition factor, or some other measure that combines the number of trees with the sizes they represent, would be preferred.

Several typical graphs showing the average annual height growth intercept against basal area per ha are displayed in Figure 21. A plot of site index against basal area per ha is shown in Figure 22. The data points exhibited in both Figures 21 and 22 indicate no obvious trend (except some slight upward tendency in Figure 21). Subsequent analyses of the data points using simple linear regression techniques produced the following significance probabilities for the F value:

(1). In Figure 21 (y-variable=average annual growth intercept, x-variable=basal area per ha):

when h_0 = 1.3 m and t = 3 years, $(Prob>F)=0.0189$.
when h_0 = 1.3 m and t = 5 years, $(Prob>F)=0.0561$.
when h_0 = 0.8 m and t = 3 years, $(Prob>F)=0.0671$.
when h_0 = 0.8 m and t = 5 years, $(Prob>F)=0.0508$.

(2). In Figure 22 (y-variable=site index, x-variable=basal area per ha), $(Prob>F)=0.1951$.

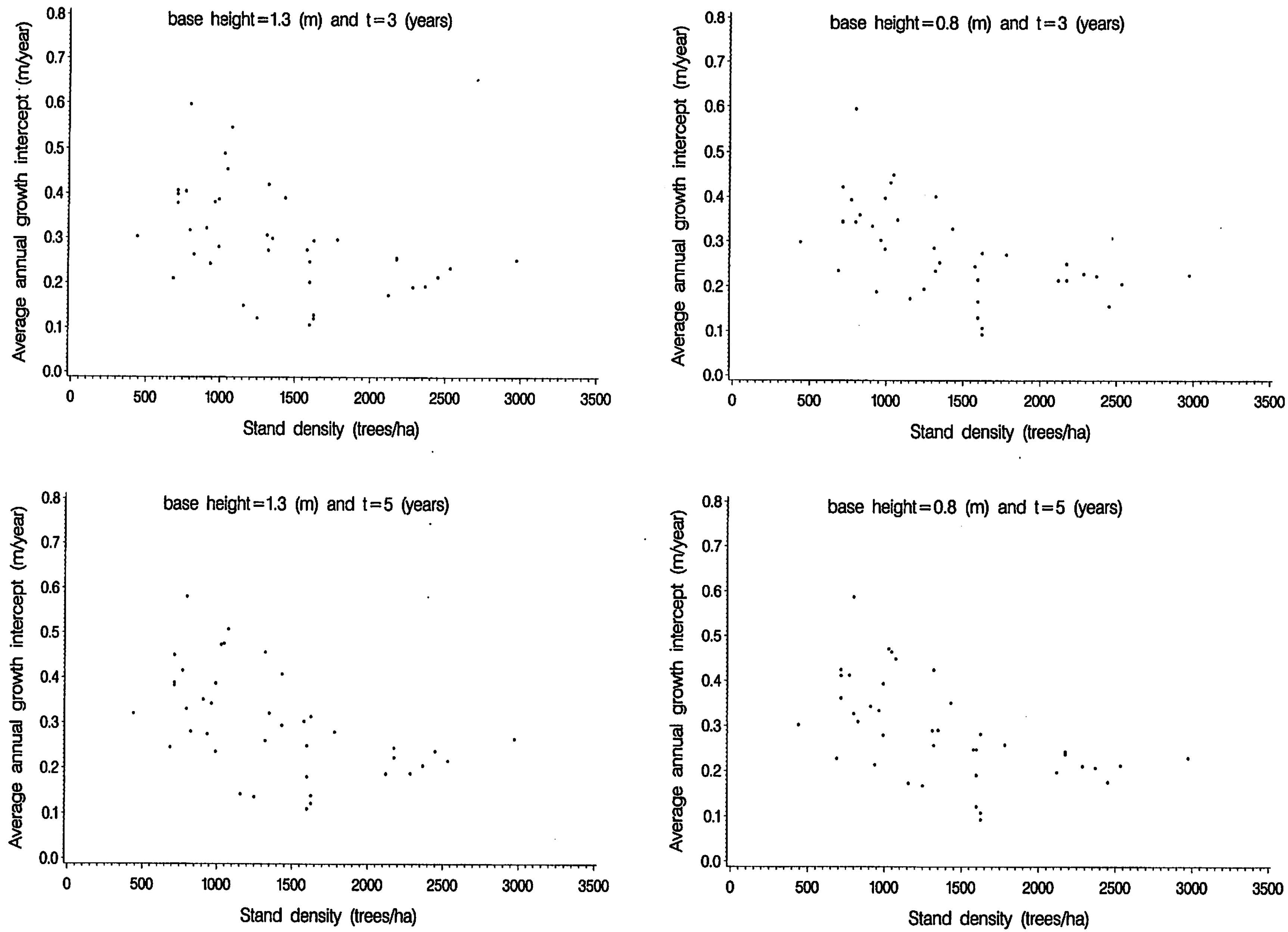

Figure 19. Average annual growth intercept versus number of trees per ha.

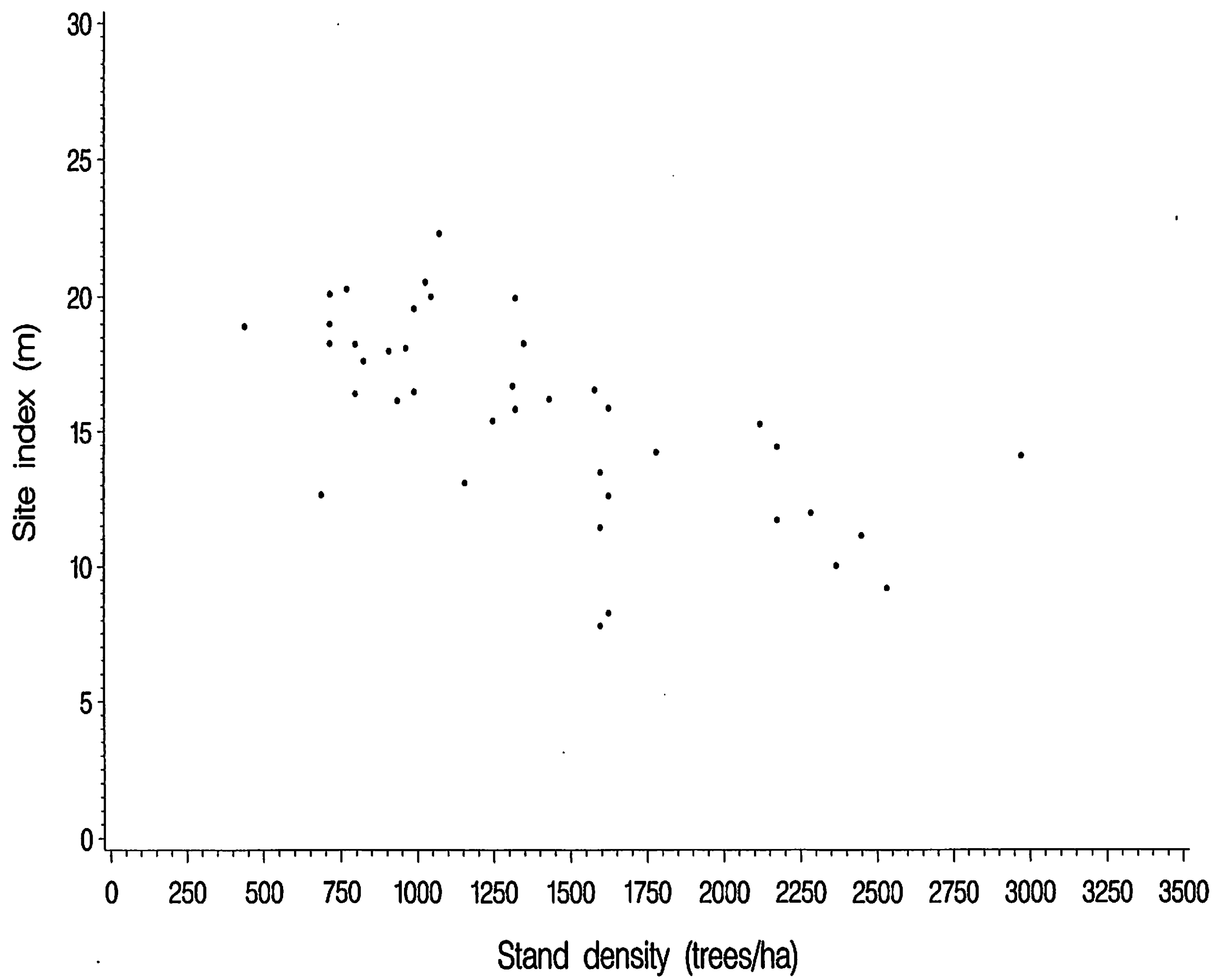

Figure 20. Site index versus number of trees per ha.

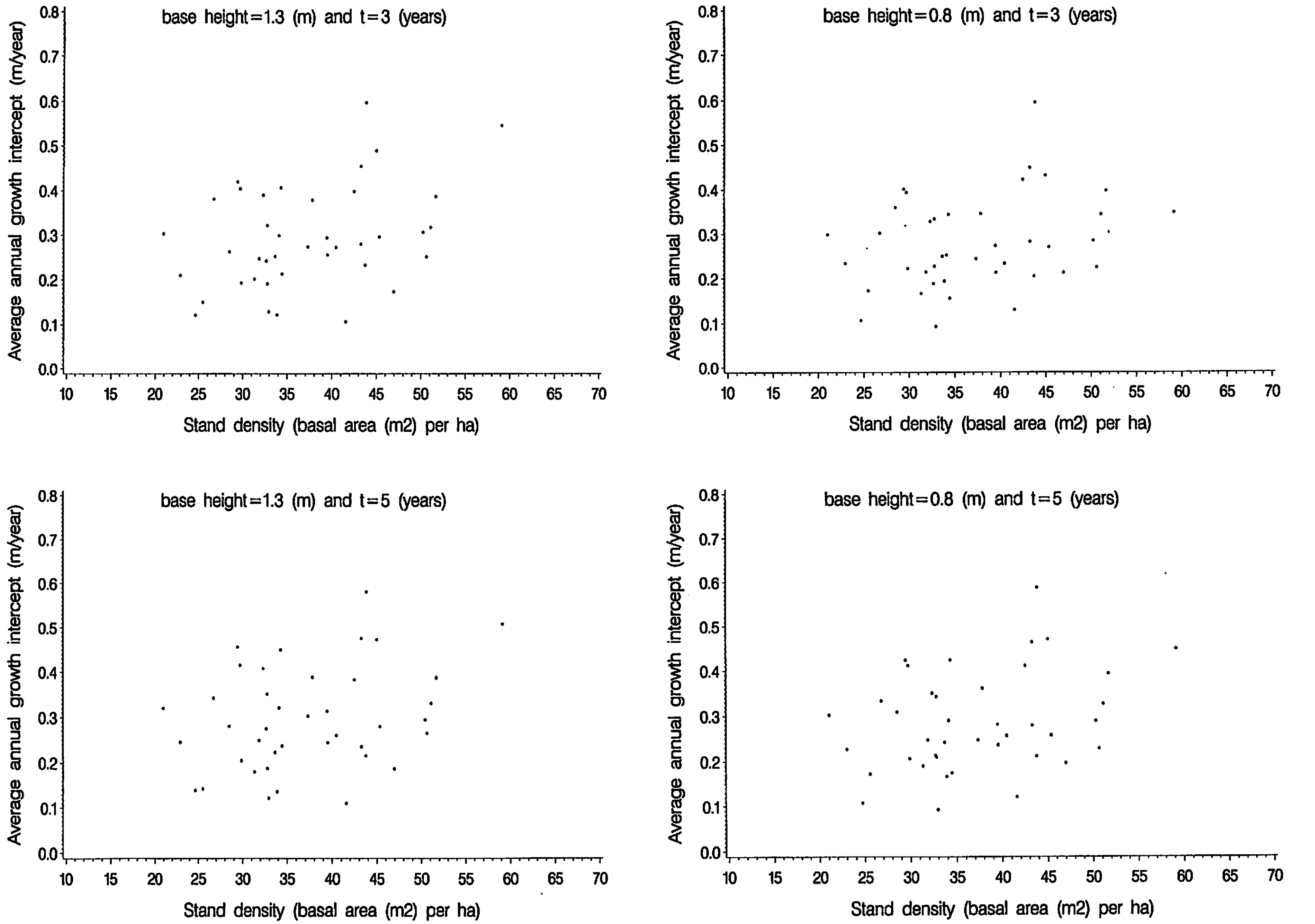

Figure 21. Average annual growth intercept versus basal area (m^2) per ha.

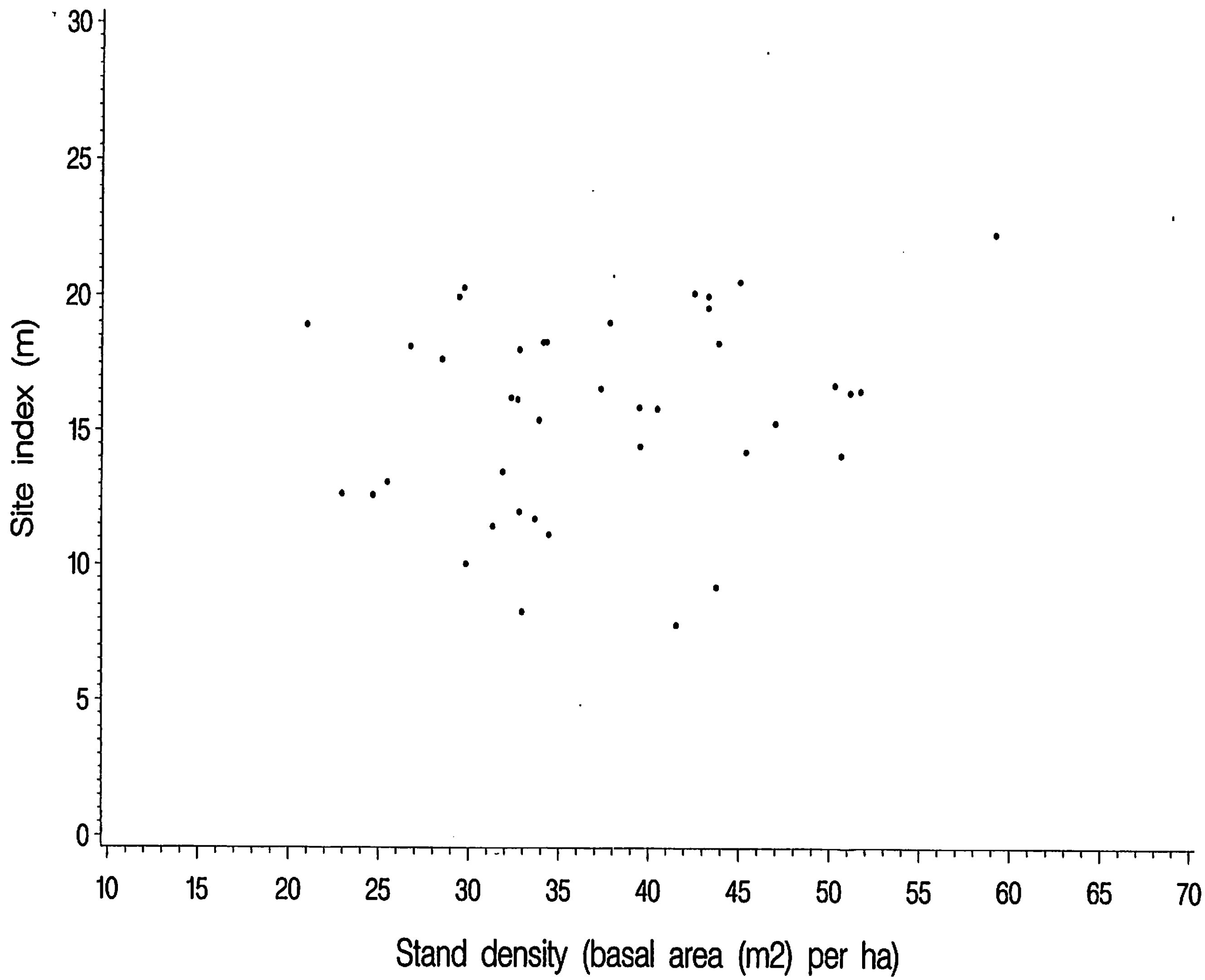

Figure 22. Site index versus basal area (m^2) per ha.

Except in Figure 21, with a base height $h_0=1.3$ m and a time interval $t=3$ years, where the trend is significant at $\alpha=0.05$ and insignificant at $\alpha=0.01$, the trends exhibited in all other plots are insignificant at $\alpha=0.05$ since $(Prob>F)>0.05$. This result suggests that, in general, stand density as measured by total basal area per ha does not have any significant impact on either the height growth or the site index predictions, and that high densities will not cause a "height reduction" in lodgepole pine stands. Such a conclusion apparently contradicts the commonly held belief about the "height reduction" in lodgepole pine stands.

The stand density effect on height growth and site index could be more "formally" evaluated by adding a measure of stand density into the growth intercept models, expressed in either one of the following general forms:

$$Ht = f(Age, GI, t, h_0, density)$$

$$SI = f(GI, t, h_0, density)$$

where the density variable can be, number of trees per ha, total basal area per ha, stand density index, spacing index, crown competition factor, or any point density (see Clutter et al. 1983, pp.70-83). It is also relatively straightforward to suggest that other variables of interest may also be incorporated into the above formulations. Various simplified versions of the above formulations, derived by dropping one or more variables, also exist. For example:

$$Ht = f(Age, GI, density)$$

$$SI = f(GI, density)$$

The implication of a significant density component in an equation such as $Ht=f(Age, GI, density)$ is that, for any given combination of height, age and growth intercept, there will be a different expected future height development trajectory for every possible value of stand density. The combination of height, age and growth intercept alone is not sufficient to define the expected future height growth pattern. This definition is established only when the stand density component is accounted for, and is used in combination with height, age and growth intercept.

In practice, incorporating stand density into growth intercept models also enables silviculturalists to seek and to "manipulate" the "optimum" stand densities that may enhance otherwise "fixed" site productivity (as measured by the site index). For lodgepole pine, this can be particularly important because it has been well documented that lodgepole pine height growth is markedly influenced by the starting densities and different levels of interspecific competition. Many natural pine stands are generally overstocked or "brushed-in" during their juvenile phase, which tends to slow the height growth rates for this period, causing a reduction effect in the juvenile height development.

Having illustrated and discussed the above density related phenomena, it is time to address a practical difficulty in finding a density measure that is reasonable for both natural and regenerated stands. Earlier it was demonstrated that the conclusions reached about the "height reduction" in lodgepole stands were different, depending on whether the number of trees per hectare or basal area per ha (m^2/ha) was used. It is not difficult to imagine that a different conclusion could have been reached if a different stand density measure were used instead.

Ideally, if the density of natural stands could be readily traced back to the juvenile phase in which the height growth intercept corresponds, the results illustrated in Figures 19-22 could have been more meaningful. The problem, however, is that there is almost no way that the density of the natural stands can be easily traced back to an earlier date (e.g., to the juvenile phase).

Clearly, the existing data set used in this study covers only a very limited range of stand density (see Figures 19-22). Therefore, at the present time, it is probably best to defer any concrete quantitative conclusion about the impact of stand density on height growth and site index, until a stand density measure that is based on the two-dimensional number-size relationship (or the three-dimensional number-size-stand age relationship) is established from permanent sample plot data. Such a stand density measure should apply to both the natural and regenerated stands, and could be used to trace back the density of natural stands. Given the available data and resources, the stand density index (SDI) approach to be briefly discussed in Section 8.0 provides one of the most promising procedures for "harmonizing" the stand density measures between natural and regenerated stands, in which the number of trees may be the same but the tree sizes (in terms of diameters) and stand ages can be drastically different.

Several hypothesized scenarios regarding the stand density impact on height growth are presented in Figure 23. These are being tested on the permanent sample plot (PSP) data from fire-origin natural stands and on several data sets collected from regenerated stands: the Stand Dynamics System (SDS), the Monitor Plot System (MPS), the Juvenile Stand Survey (JSS), the Paired-plot System (PPS), and the Regenerated Yield and Standards Initiative (RYSI). Future studies based on these data sets, and on expanded data collection efforts currently ongoing should answer some of the questions and concerns associated with the stand density factor. Such questions and concerns may include "which is the 'best' stand density measure that is applicable for both natural and regenerated stands?", "what should be incorporated into growth intercept models to represent stand density effect?", "which hypothesis illustrated in Figure 23 appears to be most reasonable as judged from the specific data set given?", and "what are the practical implications if the stand density component is significant and is included in (or excluded from) the models?".

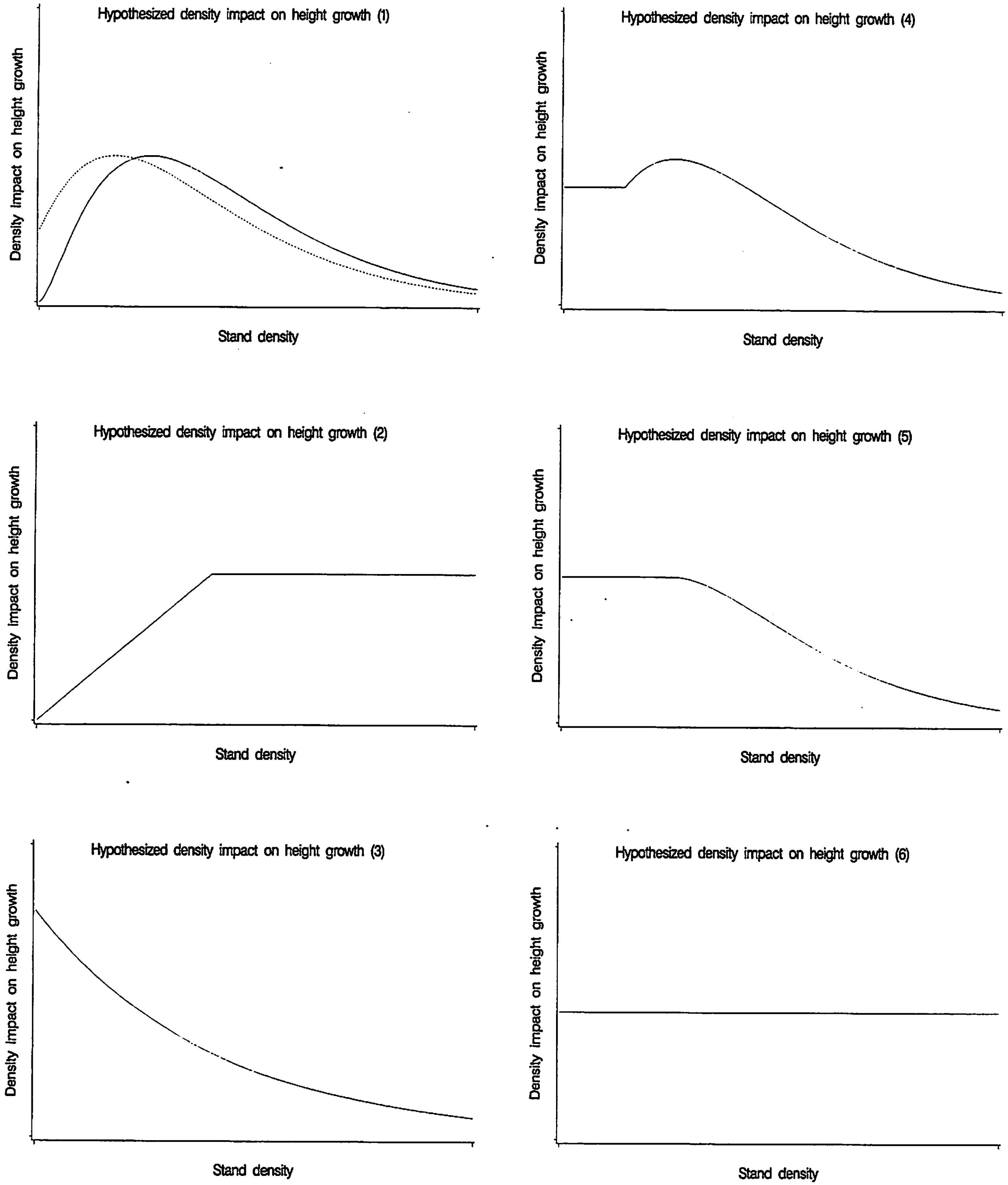

Figure 23. Hypothesized stand density impact on height growth: the possibilities.

8.0 Other Topics and Cautions

Several additional topics related to the growth intercept approach are discussed here. At the present time, "definite" agreed-upon answers to these topics may not exist. These are described in this study for three purposes: to stimulate discussions, to exert some serious cautions in applying the growth intercept approach, especially when using it as the foundation for comparing the growth and yield between natural and regenerated stands, and to present some potentially useful techniques that may be used to deal with some of the problems commonly encountered in the growth intercept approach and in estimating site index in general.

A Note of Caution on the Tendency of Over-estimation

Like most growth intercept models, the growth intercept models developed in this study were estimated based on sectioned trees from natural stands. They represent the expected height growth pattern under natural conditions. When such growth intercept models are used to predict height and site index in regenerated juvenile stands, which may have been planted at a density well below that in natural stands, or which may have been tended by various silvicultural means to improve tree growth, the predicted site index is likely to be a larger value compared to that obtained from overstocked and untended fire-origin natural stands. This often leads to the following conclusion: the site productivity of regenerated stands has been increased. In fact, almost every reported study dealing with regenerated growth has showed that on average, trees in regenerated stands are growing better than their counterparts in natural stands at comparable ages, the only difference appears to be the magnitude of the increases.

While the conclusion of increased site productivity, originated from increased regeneration endeavours and improved silvicultural and management techniques, may be correct in general, caution must be taken in interpreting the magnitude of the increases, and in extending this increase to volume projections and timber supply analysis. Since the stem analysis data from natural stands were used in the construction of the growth intercept models, matching the growth intercept observations from regenerated stands (a different population) that have been well-tended or planted at a density well below that in natural stands at the juvenile phase, will likely indicate an increased height growth when compared to the generally over-stocked and untended natural stands. Clearly one can accomplish some very rapid juvenile height growth in well-tended regenerated stands (via scarifications, spacing controls, fertilizations, or removal of competitors, etc.). However, one should not expect that this is going to be sustained or can be extrapolated over the entire rotation. Tending of regenerated stands by various silvicultural methods simply reduces the time that the regenerated stands takes to reach crown closure. But it should have very limited impact on the height growth of the stands once the stands have reached crown closure. In fact, preliminary examination of several data sets in Alberta (including the Stand Dynamics System, the Monitor Plot System, and the Regenerated Yield and Standards Initiative) suggest that well-tended regenerated stands may demonstrate some very impressive early growth up to 30 years of age, but naturally seeded stands are catching up, and in some cases, even surpassing the height growth of the well-tended stands within 30 years.

The ubiquitous proofs and feelings about the increased site productivity for regenerated stands provide one of the most effective ways for the investigator to claim that the regenerated stands are growing better than the natural stands. However, whether or not such proofs and feelings can actually be realized, or are consistent with the reality (in which the available timber resources as a whole may have been gradually declining over time, because of increased conservation and protection? multiple-use? a shrinking forest land base? insufficient regeneration effort in the past? over-cutting? overestimation by models? others?), is still open for discussion. There might be some danger if these proofs and feelings are used to suggest that the existing natural stands should be cut in a larger quantity (so that they give ways to regenerated stands, which are presumably growing on "elevated" sites and will accumulate more volumes in a shorter time period).

In summary, whether or not the proofs and feelings about the increased site potential for regenerated stands are able to be converted into increased volume productions and AAC calculations, should be interpreted with great caution. Volume productions and AAC calculations are influenced by many additional factors and constraints (e.g., stand density, assumed rotation age, adjacency, "green-up" period, and the available timber production land bases excluding reserved areas, riparian zones, etc.), in addition to the increased site index predicted from the growth intercept models based on a few years of early height growth above a conveniently selected base height.

The Assumption of A Constant Site Index for Regenerated Stands

When the growth intercept approach is used to predict site index for a regenerated stand at a young age (e.g., <20 or 30 years), the predicted site index is often assumed to be "fixed" for the regenerated stand throughout its life. When this site index value is compared to the site index value obtained from an adjacent (paired) natural stand that is much older (e.g., 120 or 150 years) than the regenerated stand, an assumption is implicitly involved. This assumption states that the predicted site index for the regenerated stand at such a young age is going to remain unchanged throughout the entire rotation (or even longer than the rotation).

Whether or not the above assumption can hold over such a long time period is very difficult to verify. Many site index developers have noted that at young ages, "site index estimates are highly uncertain", "height gives little or no information about site index", and "height growth and site index predictions are unrealistic and cannot be reliably estimated with height measurements from very young trees" (see Huang 1994, pp.39-40 and p.90 for the literature on this topic and pp.42-43 for the possible reasons behind this phenomenon). A valid concern is that, if there is little basis for believing that the site index value predicted for a 150-year-old natural stand applies to the same stand when it was 20 years old, then there is very little reason to believe that the site index value estimated for a 20-year-old regenerated stand is going to apply to the same stand once it reaches 150 years old. Such a concern may appear simplistic and extreme, but it is not unreasonable and has some very important implications in comparing the growth and yield between natural and regenerated stands. A plot of site index versus age will give an indication of the age influence on site index predictions. However, since the range of ages (from regenerated stands) in the plot is usually limited (e.g., to less than 30 years), one may not be able to rely solely on such a plot (in pine stands, there is also a changing density problem).

In order to arrive at an informed decision about the potential over- or under-estimations from the use of the growth intercept approach, the over- and under-estimations at young and old ages from the conventional site index equations are discussed. A procedure for calibrating the over- and under-estimations is described below based on a hypothetical example. At least in theory, a similar procedure also exists for calibrating the over- or under-estimations of the site index predictions from the growth intercept approach.

The Over- and Under-estimations of Site Index at Young and Old Ages in Natural Stands

Assuming that a conventional site index equation in the form of Ht=f(SI, age) or SI=f(Ht, age) fitted on the data from natural stands is available, it can be used to predict site index for any given number of stands. Ideally, if the site index equation behaves well, the plot of the predicted site index against stand age should follow the site index-age relationship described in the top graph of Figure 24, which means that the site index predictions should be independent of the age factor. In reality, the site index-age relationship usually resembles those depicted in graph (a) or (b) of Figure 24, with that shown in (a) appearing more common, which suggests

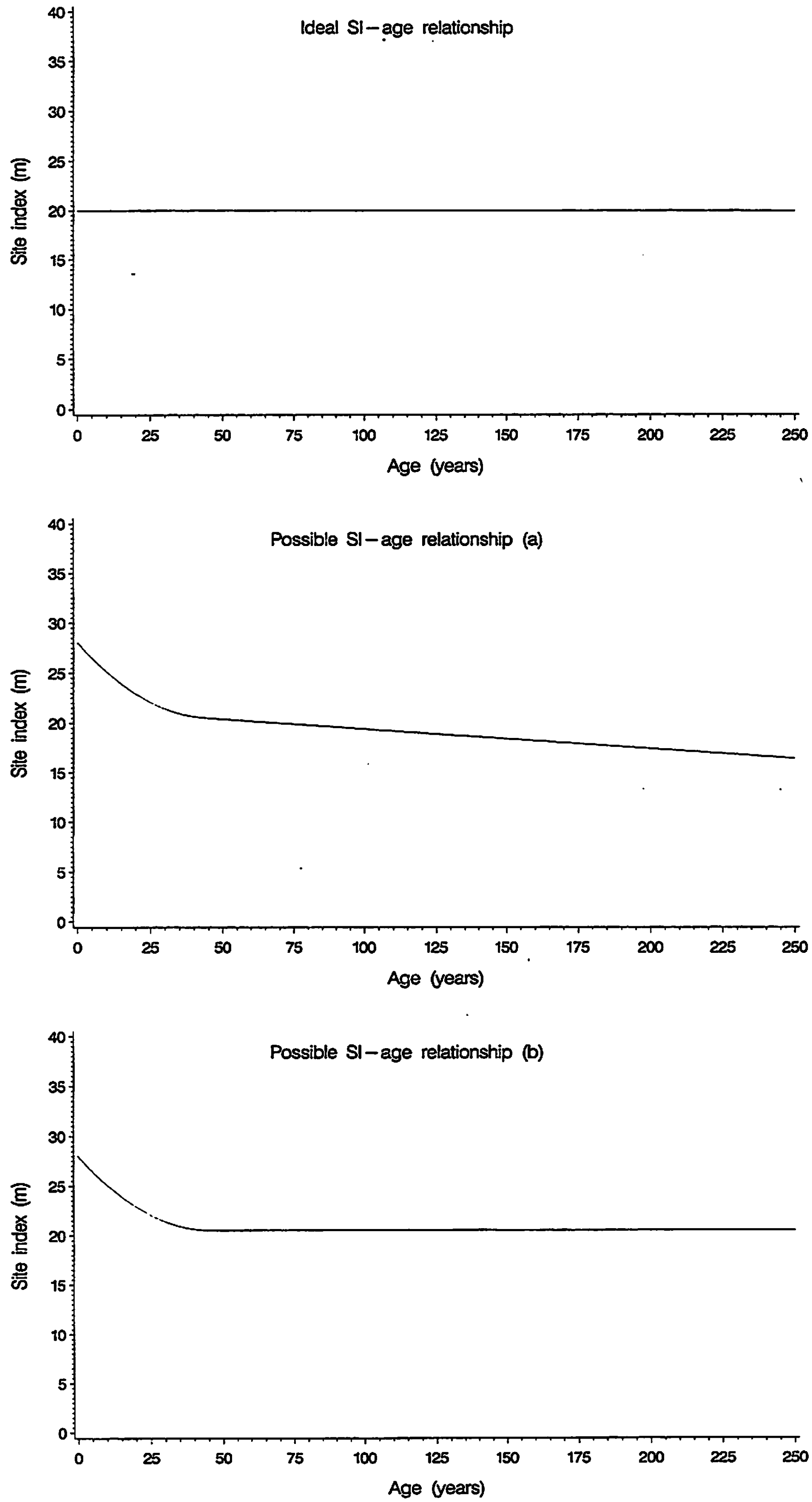

Figure 24. An illustration of possible site index-age relationships in natural stands.

that young ages are associated with high site index and old ages with low site index (see Huang, pp.39-43 and pp.88-91). This phenomenon could be caused by the fact that the conventional site index models expressed by Ht=*f*(SI, age) or SI=*f*(Ht, age) are usually estimated from trees that are older than for example, 30 years of breast height age, and that the models are often forced to pass through the origin or 1.3 m to satisfy biological interpretations. There are many other reasons could also be used to explain this phenomenon (e.g., the samples taken, the remaining population of the stands, and the common practice of harvesting good trees on good sites first, see Monserud 1984), but the point here is that younger trees/stands are frequently associated with higher site index, and older trees/stands with lower site index.

When the site index-age relationship illustrated in (a) of Figure 24 occurs, two options are available:

(1). Abandon the site index equation. Find a new and better site index equation that satisfies the ideal site index-age relationship as depicted in Figure 24. This option is easier to say than to do it. Sometimes the difficulties of finding such an equation can be insurmountable. There is also a problem caused by the remaining population of the stands, in which old stands are generally associated with poorer sites and young stands with better sites (Monserud 1984).

(2). Adjust or correct the existing site index equation. This option seems to be more reasonable at this time. A four-step procedure is presented as a "quick and dirty" approach for correcting the over- and under-estimations of site index predictions at young and old ages (see Figure 25):

Step-1. Plot the site index-age data, fit a SI=*f*(age) equation as shown in Figure 25.

Step-2. Based on the fitted equation, predict the site index at age 50 (reference age). The predicted site index is labelled as SI50. This SI50 can be considered as the "true" site index value.

Step-3. Predict the site index at any other age from SI=*f*(age). Compare the predicted site index to SI50. Calculate the correction factor C and the percentage difference between the site indices. For practical convenience, the correction factors and the percentage differences corresponding to various ages or age classes can be listed in a table (see for example, Table 4).

Step-4. Based on the correction factors shown in Table 4, the site index values predicted at young and old ages can be corrected. For example:

(1). If the predicted site index value for a 20-year-old stand is 25 m, the corrected site index is: 25/1.12745=22.17 m.

(2). If the predicted site index value for a 200-year-old stand is 20 m, the corrected site index is: 20/0.84804=23.58 m.

Note that the above illustrations are based on the hypothetical example shown in Figure 25. Actual site index correction factors for major Alberta tree species compatible with any selected site index system will be published in a separate report. Since there is an allowable error for the site index predictions (see the dashed lines around the "true" site index value), corrections for the site index predictions may not be essential when the corrected site index value is found to be within the allowable error. For example, based on Figure 25, it is not necessary to make site index corrections when the site trees used to estimate the site index are between approximately 25 to 150 years of age. Only when the age of the trees are beyond this range, do the corrections make a statistical sense. This may explain why most of the conventional site index models can be used without causing any significant problem when they are applied over a typical range of age classes (e.g., between 25

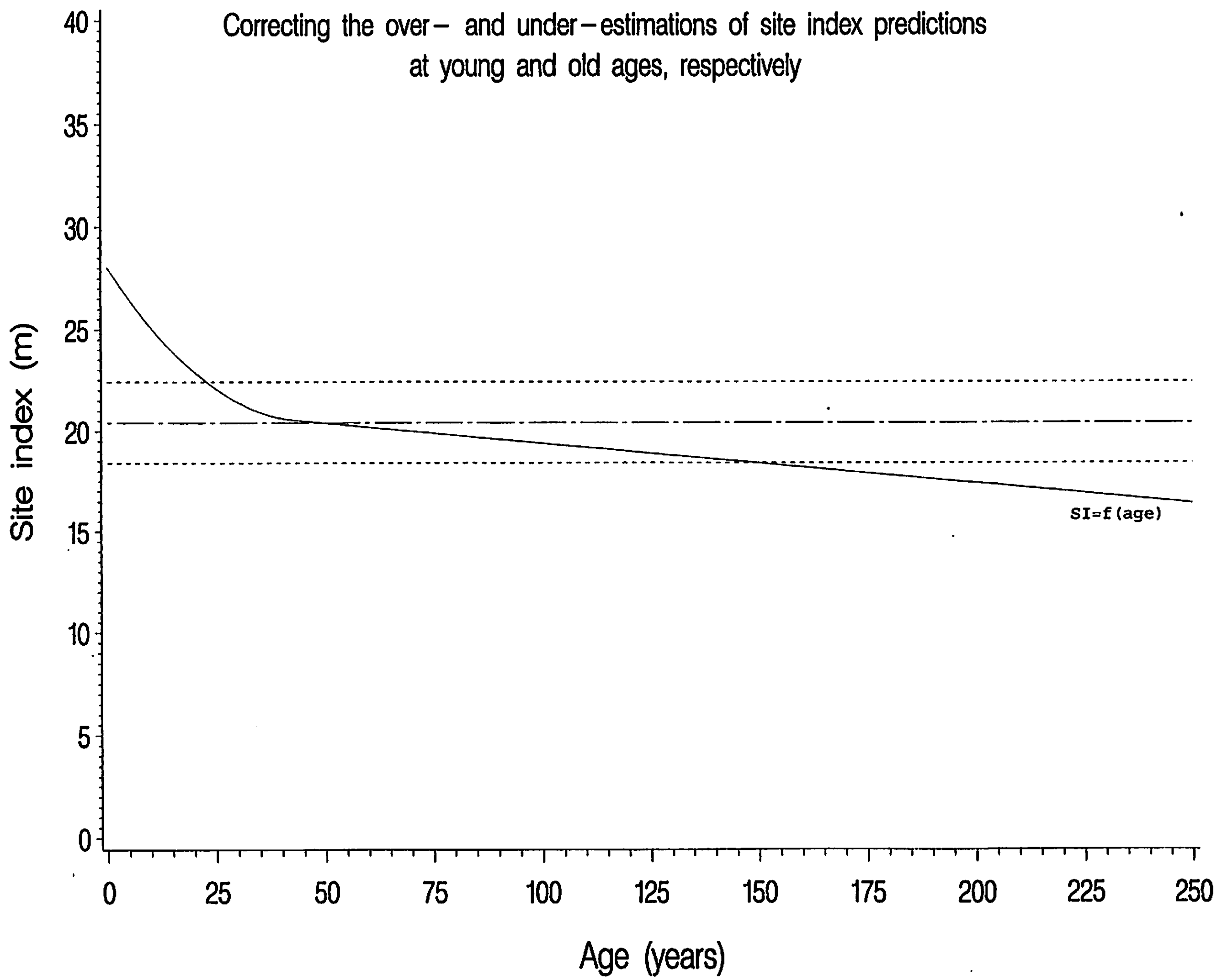

Figure 25. Correcting the over- and under-estimations of site index predictions at young and old ages: an illustration.

to 150 years breast height age).

Table 4. Site index correction factors: a hypothetical example based on Figure 25.

Age	SI (m)	SI50 (m)	Correction factor C (SI/SI50)	Over-/under-estimation* $(C - 1)\times 100\%$
5	26.5	20.4	1.29902	29.9020
10	25.0	20.4	1.22549	22.5490
15	23.9	20.4	1.17157	17.1569
20	23.0	20.4	1.12745	12.7451
25	22.0	20.4	1.07843	7.8431
30	21.5	20.4	1.05392	5.3922
35	21.0	20.4	1.02941	2.9412
40	20.6	20.4	1.00980	0.9804
45	20.5	20.4	1.00490	0.4902
50	20.4	20.4	1.00000	0.0000
55	20.3	20.4	0.99510	-0.4902
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
180	17.7	20.4	0.86765	-13.2353
200	17.3	20.4	0.84804	-15.1961
225	16.8	20.4	0.82353	-17.6471
250	16.5	20.4	0.80882	-19.1176

*Note: a positive number indicates an overestimation, a negative number indicates an underestimation.

(It appears that if the above correction procedures are operational, there is almost no need to develop separate growth intercept models for the sake of predicting site index in juvenile stands, except maybe that the growth intercept models can be used to predict site index without requiring measurements on tree height and age).

Inferences Based on A Paired-plot System

The paired-plot system was introduced by Udell and Dempster (1986) in the Weldwood FMA area. In recent years, it has received growing attention, primarily as the method for comparing the growth and yield between natural and regenerated stands.

While the virtues of the paired-plot system are obvious, it may still be beneficial to discuss some of the finer points involved in making inferences based on such a system. To do this, an example of a paired-plot system is provided in Figure 26 for illustrations.

Apparently, based on the calculated site index values shown in Figure 26, one may conclude that the site productivity (as measured by site index) of the regenerated stand has been increased. This is because $SI_R > SI_N$. The percentage of the increase can be calculated as: $(21 - 18)/18 = 16.67\%$.

Caution: if density and age have no impact on site index predictions, the above conclusion is correct. However, if either one of them has a significant impact on site index predictions, the above conclusion may become less defendable. Here are some potential reasons for answering why:

Figure 26. Possible overestimations and difficulties: an illustration based on a paired-plot system.

Regenerated stand (SI_R=21 m) Stand density at Age=20 years: 1500 trees/ha	Natural stand (SI_N=18 m) Stand density at Age=150 years: 1500 trees/ha

Note: site index for the regenerated stand (SI_R) is predicted from a growth intercept model. Site index for the natural stand (SI_N) is predicted from either the conventional site index equation, or the growth intercept model if the annual height growth increments above the base height are easily discernable.

(1). <u>The density factor (assuming age has not impact)</u>:

The predicted site index (SI_N=18 m) for the natural stand, obtained when the stand is 150 years old with a density of 1,500 trees/ha, is usually assumed to be constant over the entire rotation. This means that at age 20 (comparable to the regenerated stand), the natural stand has a site index of 18 m as well. At age 20 however, this stand may have well over 1,500 trees per ha. Since a higher density may be associated with a slower height growth and a lower site index, an 18 m site index may in fact become 21 m or more if the stand density is equal to that of the regenerated stand at the same age. Therefore, an apparently smaller site index value for the natural stand does not necessarily indicate a poorer site potential for the natural stand. On the other hand, the predicted site index for the regenerated stand (SI_R =21 m), obtained when the stand is 20 years old with a stand density of 1,500 trees per ha, will probably be altered as the density changes over time. A possible solution for evaluating or correcting the density factor is to examine the following function:

$$SI_R = f(SI_N, Density_N, Density_R)$$

where: SI_R = site index for regenerated stands, SI_N = site index for natural stands, $Density_R$=density for regenerated stands, and $Density_N$=density for natural stands.

(2). <u>The age factor (assuming density has not impact)</u>:

Age has perhaps, a more notable impact on site index predictions. Many are aware of the phenomenon described earlier, in which the site index was usually overestimated at young ages and underestimated at old ages. If the corrected site index value for the natural stand illustrated in Figure 26 is 20 m, the percentage increase of the regenerated site index becomes: (21 - 20)/20 = 5.00%, a number that is smaller than 16.67% obtained when the age correction factor was not applied. A possible solution for evaluating the age impact is to examine the following function:

$$SI_R = f(SI_N, Age_N, Age_R)$$

where: SI_R = site index for regenerated stands, SI_N = site index for natural stands, Age_R=regenerated stand age, and Age_N=natural stand age.

An ideal growth intercept equation should produce site index predictions that are independent of the age factor, which means that the SI_R-Age_R relationship should be a horizontal line, much like the ideal SI_N-Age_N line illustrated in Figure 24. Since the range of the ages from regenerated stands is usually limited (e.g., to less than 20 or 30 years), one should still interpret the result carefully even though a consistent site index estimate is evident for the first 20 or 30 years (because a predicted site index is often extended, directly or indirectly, beyond this age range when used in other analyses).

(3). The combined effect of density and age:

Site index predictions may also be affected by the joint effect of stand density and age. A relationship between the site indices from natural and regenerated stands, that takes account of the age and density factors, can be established:

$$SI_R = f(SI_N, Age_N, Density_N, Age_R, Density_R)$$

At least in theory, such a relationship can be used to evaluate and correct age and density effects, if such effects exist. In reality, however, it may still be very difficult to do this because a compatible index of stand density that can be used in both the natural and regenerated stands, is still not available in Alberta. Comparing stand densities based on number of trees per ha alone is good only when the trees in both stands have approximately the same size (i.e., the same DBH). Future work will attempt to establish a stand density index that is based on number-size relationship (or number-size-stand age relationship). Such a relationship may take the form shown in Figure 27, which essentially grows the tree numbers to a "reference tree size", so that the numbers can be compared on a common base. It is designed to achieve a "harmonized" density measure for stands having different sizes. It is apparent that such an idea is almost identical to the site index approach in which the heights at various ages are compared based on a common "reference age".

Inferences based on a paired-plot system are more complicated by the switching of the populations and the switching of the site index methods, as well as the assumption that states that the predicted site index for the regenerated stand at such a young age is going to remain unchanged throughout the entire life of the stand. The conventional site index approach is developed from and applied for mature fire-origin natural stands, while the growth intercept approach is fitted using data from mature natural stands but is primarily applied in young regenerated stands. There is a possibility that the differences in the site index predictions between natural and regenerated stands may be caused by the switching of the target populations and the switching of the site index methods (in addition to stand density and age influence). It is not uncommon that even for the same data set from the same population, the derived results can be drastically different if a different model, or a different

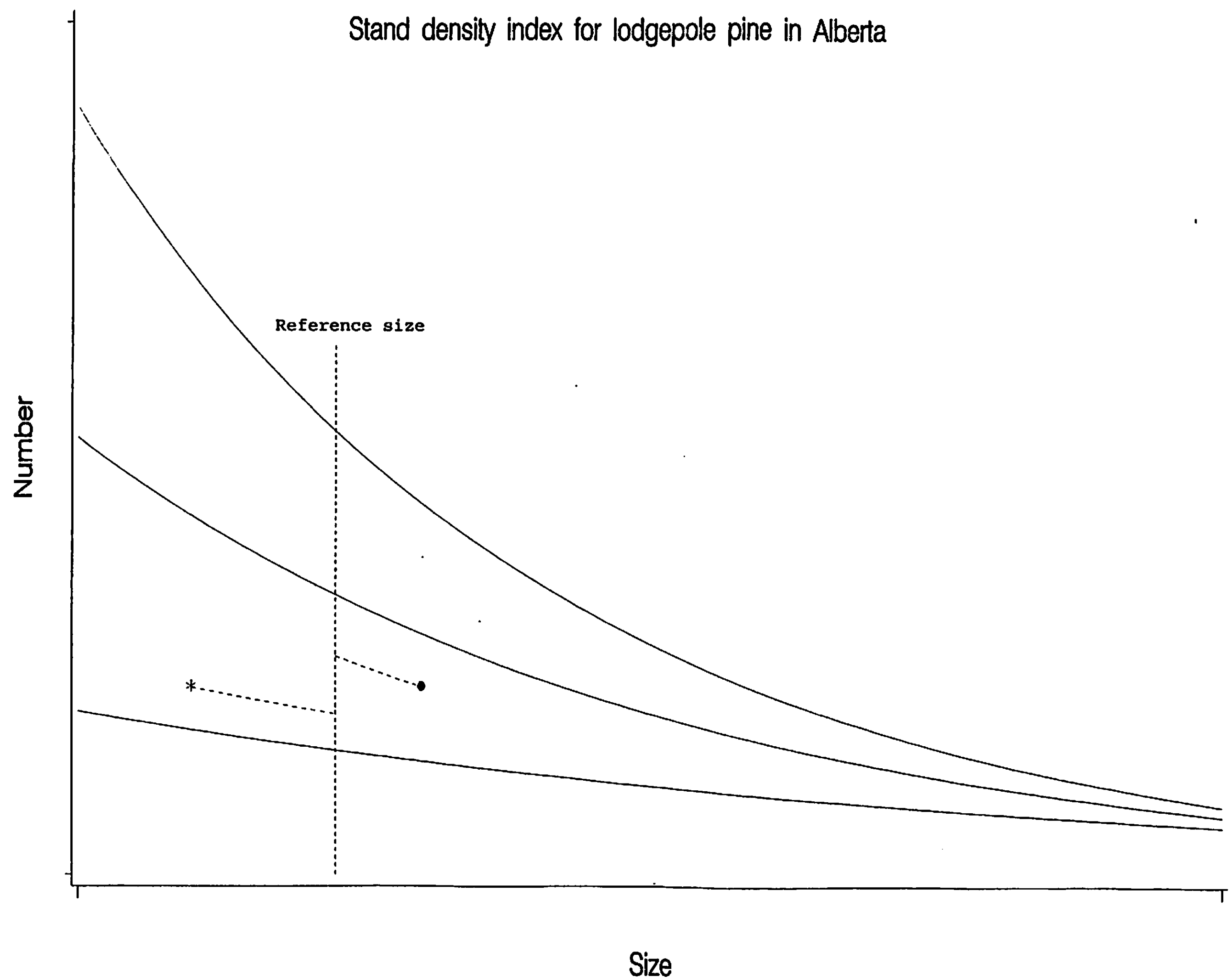

Figure 27. A stand density index based on the number-size (trees/ha-DBH) relationship. This relationship grows the numbers to a "reference size", so that the numbers can be compared on a common base.

approach is implemented.

In order to evaluate the consequence of switching the populations and switching the site index methods, the site index value for a natural stand can be predicted based on both the conventional site index approach and the growth intercept approach, and the discrepancy between the site index predictions evaluated. The site index for a regenerated stand can also be predicted based on both the growth intercept approach and the conventional site index approach, and the discrepancy between the site index predictions evaluated as well. Such analyses could be conducted from the data set used in this study, but this would be a digression from the main purposes of this study. In practice, comparison of the site index values between a natural stand and a regenerated stand can be conducted in the following manner:

(1). Predict the site index for the natural stand, based on the conventional site index approach.

(2). Predict the site index for the regenerated stand, based on the growth intercept approach.

(3). Observe the age of the regenerated stand. Correct the predicted site index value from step (1), based on the observed age and an appropriate correction factor (as illustrated in Table 4). This corrected site index is assumed to be the actual site index for the natural stand when it has the same age as that of the regenerated stand.

(4). Compare the predicted site index for the regenerated stand to the corrected site index for the natural stand obtained in (3). This may provide a more realistic picture about how well the regenerated stand grows compared to the natural stand at the comparable age.

Of course, the "distortion" of site index predictions caused by other factors such as stand density may need to be corrected as well, but this is more involved and will not be discussed here. At this time, it is safe to say that, if site index corrections are not made, it is very likely that the biggest site index increase will occur in locations where the natural stands are very old and dense.

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10.0 Appendices

Appendix 1.

Estimated Coefficients, Formulated Site Index Prediction Table, and Fitted Curves

Based on Method I

This appendix provides:

Table A1. The estimated coefficients, the root mean squared error (RMSE) and the coefficient of determination (R^2) for Method I (equations [1a]-[1c]).

Table A2. The growth intercept-based site index prediction table for lodgepole pine in Alberta. Site index is predicted from the observed average annual growth intercept in t-years above the base height h_0. In most practical circumstances, a base height of $h_0 \geq 0.8$ m and a $t \geq 3$-years are recommended to be used.

Figures A1-A6. The growth intercept-based site index curves for lodgepole pine in Alberta. These curves show the expected height growth patterns on various sites.

Table A1. Fit statistics for models [1a]-[1c] based on different t and h_0 values.

Subegion	Equation	h_0 (m)	t (years)	Estimate b_0	b_1	b_2	b_3	b_4	RMSE	R^2
Provincial	[1a]	1.3	1	6.277692	0.205562	0.043887	0.240436	0.922530	1.830	0.935
			2	6.474066	0.231114	0.050717	0.353065	0.930599	1.691	0.945
			3	6.695617	0.267730	0.050678	0.344613	0.937693	1.657	0.947
			4	6.545890	0.247695	0.055050	0.426452	0.932130	1.613	0.950
			5	6.431852	0.227735	0.059855	0.526582	0.919781	1.590	0.951
		0.8	1	6.113057	0.169754	0.049810	0.367678	0.908904	1.852	0.934
			2	6.123238	0.167660	0.062366	0.566879	0.897033	1.731	0.942
			3	6.376533	0.205812	0.062451	0.549108	0.906160	1.636	0.948
			4	6.484675	0.223651	0.064293	0.560175	0.917727	1.568	0.952
			5	6.484021	0.226864	0.063589	0.560410	0.917772	1.543	0.954
		0.5	1	7.090123	0.267507	0.036529	0.099177	0.919095	1.957	0.926
			2	6.920713	0.263099	0.043433	0.230883	0.917039	1.880	0.932
			3	6.773922	0.246041	0.055447	0.439293	0.901879	1.745	0.941
			4	6.630887	0.227944	0.064521	0.568628	0.895234	1.656	0.947
			5	6.479387	0.208319	0.072971	0.682062	0.890795	1.562	0.953
		0.3	1	6.914630	0.229954	0.034784	0.075547	0.906015	2.012	0.922
			2	6.731554	0.218521	0.045406	0.282797	0.891034	1.885	0.931
			3	6.680921	0.220159	0.052243	0.391489	0.891111	1.836	0.935
			4	6.845981	0.243403	0.057664	0.468392	0.891315	1.720	0.943
			5	6.659106	0.222789	0.066079	0.590232	0.884041	1.651	0.947
Lower Foothills	[1c]	1.3	1	5.906038	0.100000	0.045832	0.269004	0.899392	1.366	0.971
			2	5.904541	0.100000	0.051363	0.375359	0.911888	1.317	0.973
			3	5.911864	0.100000	0.053531	0.446025	0.897614	1.302	0:973
			4	5.880261	0.100000	0.053344	0.433869	0.905611	1.336	0.972
			5	5.870087	0.100000	0.054564	0.451327	0.909124	1.362	0.971
		0.8	1	5.930940	0.100000	0.037210	0.066759*	0.902055	1.535	0.963
			2	5.909943	0.100000	0.048332	0.321967	0.894598	1.437	0.968
			3	5.926231	0.100000	0.052603	0.404156	0.892073	1.373	0.970
			4	5.929629	0.100000	0.054853	0.455973	0.890241	1.329	0.972
			5	5.908976	0.100000	0.055310	0.474475	0.892719	1.320	0.973
		0.5	1	6.023649	0.100000	0.037827	0.073281*	0.901518	1.542	0.963
			2	5.981152	0.100000	0.043378	0.198348	0.896551	1.502	0.965
			3	5.976253	0.100000	0.052164	0.391252	0.879798	1.437	0.968
			4	5.972702	0.100000	0.057111	0.480397	0.878691	1.392	0.970
			5	5.964167	0.100000	0.058200	0.513515	0.878462	1.354	0.971
		0.3	1	6.082450	0.100000	0.034114	-0.006050*	0.899359	1.540	0.963
			2	6.031822	0.100000	0.037758	0.082430	0.890265	1.531	0.963
			3	6.011688	0.100000	0.043589	0.214003	0.882211	1.494	0.965
			4	6.021166	0.100000	0.052504	0.406171	0.862985	1.422	0.968
			5	6.002600	0.100000	0.056158	0.473581	0.864859	1.392	0.970

Note: * indicates an insignificant estimate at $\alpha=0.05$.

Table A1. Fit statistics for models [1a]-[1c] based on different t and h_0 values (continued).

Subegion	Equation	h_0 (m)	t (years)	Estimate b_0	b_1	b_2	b_3	b_4	RMSE	R^2
Upper foothills	[1c]	1.3	1	5.275857	0.100000	0.038349	-0.023963*	1.186280	1.525	0.948
			2	5.284776	0.100000	0.050887	0.162449	1.185592	1.428	0.955
			3	5.260611	0.100000	0.053653	0.188730	1.201209	1.440	0.954
			4	5.267867	0.100000	0.060176	0.273649	1.197314	1.398	0.957
			5	5.285264	0.100000	0.056503	0.267022	1.166602	1.318	0.961
		0.8	1	5.278507	0.100000	0.052669	0.237983	1.159977	1.392	0.957
			2	5.355887	0.100000	0.058793	0.314264	1.138180	1.365	0.959
			3	5.353487	0.100000	0.062410	0.361995	1.130387	1.311	0.962
			4	5.350284	0.100000	0.069135	0.423317	1.140707	1.298	0.963
			5	5.361340	0.100000	0.071492	0.449197	1.135405	1.295	0.963
		0.5	1	5.510671	0.100000	0.066995	0.500781	1.058154	1.226	0.967
			2	5.418348	0.100000	0.062301	0.428150	1.085925	1.288	0.963
			3	5.401732	0.100000	0.068995	0.477590	1.101710	1.298	0.963
			4	5.425556	0.100000	0.074034	0.529202	1.087443	1.249	0.965
			5	5.438287	0.100000	0.083334	0.603518	1.094514	1.198	0.968
		0.3	1	5.436801	0.100000	0.056361	0.270948	1.136921	1.352	0.959
			2	5.470643	0.100000	0.066095	0.428035	1.105653	1.247	0.965
			3	5.472266	0.100000	0.076692	0.548416	1.091262	1.254	0.965
			4	5.443937	0.100000	0.079791	0.565169	1.102090	1.260	0.965
			5	5.462018	0.100000	0.083156	0.597262	1.092055	1.230	0.966
Sub-alpine	[1a]	1.3	1	4.956698	0.224996	0.026144	-0.004278*	0.841186	1.107	0.939
			2	4.656307	0.189608	0.053340	0.420196	0.862913	1.020	0.948
			3	4.793895	0.209069	0.071191	0.613094	0.876942	0.941	0.956
			4	5.723186	0.316036	0.050123	0.400120*	0.862414	0.928	0.957
			5	5.465760	0.281048	0.055987	0.486993	0.857582	0.916	0.958
		0.8	1	4.482325	0.156550	0.029978	0.067092*	0.847151	1.125	0.937
			2	3.720528	0.053944*	0.065666	0.522118	0.881229	1.066	0.943
			3	4.463398	0.168050	0.050326	0.347893*	0.877969	1.052	0.945
			4	4.331142	0.145676*	0.064028	0.499944	0.883758	1.010	0.949
			5	4.482722	0.165030*	0.064443	0.516884	0.883577	0.986	0.951
		0.5	1	4.285630	0.136652*	0.027749	0.003387*	0.850528	1.171	0.931
			2	4.879359	0.217924	0.025694	-0.054493*	0.859598	1.156	0.933
			3	4.941464	0.223821	0.026132	-0.040575*	0.858304	1.145	0.934
			4	4.765520	0.205971	0.032258	0.072812*	0.866439	1.124	0.937
			5	5.190014	0.255054	0.037573	0.166635*	0.868507	1.070	0.943
		0.3	1	3.351716	-0.007400*	0.080823	0.594046	0.846941	1.147	0.934
			2	4.633903	0.168607	0.031453	0.089936*	0.841596	1.144	0.935
			3	4.459312	0.157686*	0.036324	0.150352*	0.856106	1.143	0.935
			4	4.981595	0.220167	0.028630	0.022523*	0.852098	1.133	0.936
			5	4.847126	0.209128	0.032054	0.081234*	0.858136	1.126	0.937

Note: * indicates an insignificant estimate at α=0.05.

Table A1. Fit statistics for models [1a]-[1c] based on different t and h_0 values (continued).

Subegion	Equation	h_0 (m)	t (years)	Estimate b_0	b_1	b_2	b_3	b_4	RMSE	R^2
Weyerhaeuser FMA	[1a]	1.3	1	6.424981	0.220783	0.049404	0.258556	0.951058	1.818	0.944
			2	6.602661	0.245332	0.052684	0.307561	0.960984	1.734	0.949
			3	6.745730	0.271034	0.051182	0.288443	0.958948	1.695	0.951
			4	6.627441	0.255660	0.055828	0.377920	0.950626	1.633	0.955
			5	6.507630	0.233148	0.060066	0.480512	0.933125	1.616	0.956
		0.8	1	5.710258	0.090122	0.063029	0.591771	0.885036	1.938	0.936
			2	5.894864	0.123011	0.072993	0.688599	0.903695	1.795	0.945
			3	6.217121	0.173885	0.070329	0.626523	0.917707	1.699	0.951
			4	6.376142	0.201544	0.067763	0.571133	0.934157	1.625	0.955
			5	6.426476	0.214254	0.065180	0.537509	0.937236	1.595	0.957
		0.5	1	7.236957	0.287911	0.034599	0.006163*	0.941021	2.103	0.925
			2	7.052578	0.281740	0.037927	0.077850*	0.940740	2.054	0.928
			3	6.650277	0.227217	0.055638	0.427175	0.911439	1.896	0.939
			4	6.248123	0.163501	0.073352	0.696984	0.884247	1.786	0.946
			5	6.164072	0.149498	0.079882	0.783041	0.876904	1.664	0.953
		0.3	1	7.491865	0.293706	0.028705	-0.120766*	0.933084	2.164	0.920
			2	7.482524	0.310140	0.031394	-0.063949*	0.933569	2.050	0.928
			3	7.119941	0.280129	0.039048	0.101469*	0.934134	2.033	0.930
			4	6.858836	0.245793	0.054183	0.390733	0.908007	1.879	0.940
			5	6.361589	0.175991	0.071092	0.659889	0.877226	1.792	0.945
Weldwood	[1b]	1.3	1	4.078785	0.126838	0.043445	0.276811	0.793824	1.725	0.926
			2	4.125192	0.128501	0.072696	0.684503	0.799196	1.535	0.941
			3	4.371353	0.186702	0.083729	0.754844	0.828049	1.522	0.942
			4	4.330595	0.178586	0.080175	0.726871	0.827719	1.518	0.942
			5	4.209323	0.152070	0.097794	0.899104	0.825849	1.493	0.944
			10	4.146697	0.116441*	0.151916	1.349751	0.805239	1.400	0.950
		0.8	1	4.465984	0.190474	0.044359	0.233035*	0.819071	1.689	0.929
			2	4.644796	0.218675	0.054394	0.405031	0.807439	1.610	0.935
			3	4.778297	0.249791	0.060189	0.461256	0.815778	1.509	0.943
			4	4.837484	0.262667	0.078727	0.658916	0.825592	1.442	0.948
			5	4.681920	0.233927	0.091379	0.808927	0.818434	1.416	0.950
			10	4.365451	0.176087	0.134023	1.155229	0.810236	1.439	0.948
		0.5	1	4.670467	0.196258	0.046523	0.262557*	0.814791	1.724	0.926
			2	5.590624	0.344117	0.061277	0.402216	0.845810	1.575	0.938
			3	6.028113	0.411437	0.050747	0.262299*	0.847553	1.496	0.944
			4	5.781335	0.388707	0.055032	0.316752	0.848184	1.441	0.948
			5	5.529124	0.360663	0.069621	0.503227	0.845943	1.385	0.952
			10	4.610406	0.223456	0.122352	0.998517	0.830722	1.403	0.951
		0.3	1	3.998200	0.074346*	0.055148	0.397332	0.789067	1.745	0.924
			2	4.716221	0.190017	0.069332	0.525722	0.808045	1.619	0.934
			3	5.289383	0.281854	0.092296	0.707133	0.820492	1.476	0.946
			4	5.812607	0.366742	0.060827	0.411105	0.830964	1.457	0.947
			5	5.884244	0.383809	0.059554	0.400078	0.830676	1.419	0.950
			10	4.840676	0.256040	0.111879	0.895871	0.837809	1.377	0.953

Note: * indicates an insignificant estimate at α=0.05.

Table A2. Predicted site index based on the average annual growth intercept in t-years above the base height h_0.

h_0 (m)	t (years)	Average annual growth intercept (m/year) in t-years above h_0																			
		0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
		Predicted site index (m) (subregion = provincial)																			
1.30	1	9.8	11.9	13.3	14.4	15.3	16.1	16.8	17.4	17.9	18.4	18.9	19.3	19.8	20.1	20.5	20.8	21.2	21.5	21.8	22.0
	2	8.6	11.0	12.7	14.1	15.2	16.1	17.0	17.7	18.4	19.0	19.6	20.1	20.6	21.1	21.5	21.9	22.3	22.7	23.0	23.4
	3	8.1	10.6	12.4	13.8	15.0	16.0	16.9	17.7	18.5	19.2	19.8	20.4	21.0	21.5	22.0	22.4	22.9	23.3	23.7	24.1
	4	7.7	10.3	12.2	13.7	14.9	16.0	16.9	17.7	18.5	19.2	19.8	20.4	20.9	21.4	21.9	22.4	22.8	23.2	23.6	24.0
	5	7.2	9.9	11.9	13.5	14.8	15.9	16.9	17.7	18.5	19.2	19.8	20.4	21.0	21.5	21.9	22.4	22.8	23.2	23.5	23.9
0.80	1	9.3	11.7	13.3	14.5	15.4	16.3	17.0	17.6	18.2	18.7	19.1	19.6	19.9	20.3	20.7	21.0	21.3	21.6	21.9	22.1
	2	7.8	10.6	12.5	14.0	15.3	16.3	17.1	17.9	18.6	19.2	19.7	20.2	20.6	21.1	21.4	21.8	22.1	22.4	22.7	23.0
	3	7.5	10.3	12.3	13.9	15.2	16.3	17.2	18.1	18.8	19.5	20.1	20.6	21.1	21.6	22.0	22.4	22.8	23.2	23.5	23.9
	4	7.2	10.1	12.1	13.8	15.1	16.3	17.3	18.1	18.9	19.6	20.3	20.9	21.4	21.9	22.4	22.8	23.2	23.6	24.0	24.3
	5	7.1	9.9	12.0	13.6	15.0	16.1	17.1	18.0	18.8	19.5	20.2	20.8	21.3	21.8	22.3	22.7	23.2	23.6	23.9	24.3
0.50	1	10.2	12.3	13.8	15.0	15.9	16.8	17.5	18.2	18.8	19.3	19.9	20.4	20.8	21.3	21.7	22.1	22.5	22.8	23.2	23.5
	2	9.3	11.6	13.2	14.5	15.6	16.6	17.4	18.1	18.8	19.5	20.1	20.6	21.1	21.6	22.1	22.5	22.9	23.4	23.7	24.1
	3	8.0	10.7	12.6	14.2	15.5	16.6	17.5	18.4	19.2	19.9	20.5	21.1	21.7	22.2	22.7	23.2	23.6	24.1	24.5	24.8
	4	7.3	10.2	12.3	14.0	15.4	16.6	17.6	18.5	19.3	20.0	20.7	21.3	21.9	22.4	22.8	23.3	23.7	24.1	24.5	24.9
	5	6.7	9.7	12.0	13.8	15.3	16.5	17.6	18.5	19.3	20.1	20.7	21.3	21.8	22.3	22.8	23.2	23.6	24.0	24.3	24.6
0.30	1	11.2	13.1	14.4	15.4	16.3	17.0	17.6	18.2	18.7	19.2	19.6	20.1	20.5	20.8	21.2	21.5	21.8	22.1	22.4	22.7
	2	9.7	12.1	13.8	15.0	16.1	16.9	17.7	18.4	19.1	19.6	20.2	20.7	21.2	21.6	22.0	22.4	22.8	23.1	23.5	23.8
	3	8.8	11.5	13.3	14.7	15.9	16.8	17.7	18.5	19.2	19.8	20.4	21.0	21.5	22.0	22.4	22.8	23.2	23.6	24.0	24.3
	4	7.9	10.8	12.8	14.4	15:7	16.8	17.8	18.7	19.5	20.2	20.9	21.5	22.1	22.6	23.1	23.6	24.0	24.5	24.9	25.3
	5	7.3	10.3	12.4	14.1	15.6	16.7	17.8	18.7	19.5	20.2	20.9	21.5	22.1	22.6	23.1	23.5	23.9	24.3	24.7	25.0
		Predicted site index (m) (subregion = lower foothills)																			
1.30	1	12.1	14.0	15.2	16.0	16.7	17.2	17.7	18.1	18.5	18.9	19.2	19.4	19.7	19.9	20.1	20.4	20.5	20.7	20.9	21.1
	2	10.9	13.1	14.6	15.6	16.4	17.1	17.7	18.2	18.6	19.0	19.4	19.7	20.0	20.3	20.5	20.7	21.0	21.2	21.3	21.5
	3	10.0	12.5	14.1	15.3	16.2	16.9	17.6	18.1	18.6	19.0	19.4	19.8	20.1	20.4	20.6	20.9	21.1	21.3	21.5	21.7
	4	10.1	12.6	14.1	15.2	16.2	16.9	17.5	18.1	18.5	19.0	19.3	19.7	20.0	20.3	20.5	20.8	21.0	21.2	21.4	21.6
	5	9.9	12.4	14.0	15.2	16.1	16.9	17.5	18.1	18.5	19.0	19.4	19.7	20.0	20.3	20.6	20.8	21.0	21.3	21.5	21.6
0.80	1	14.3	15.4	16.2	16.7	17.1	17.5	17.8	18.1	18.3	18.5	18.7	18.9	19.1	19.3	19.4	19.6	19.7	19.8	19.9	20.1
	2	11.5	13.6	14.9	15.9	16.6	17.2	17.7	18.2	18.6	19.0	19.3	19.6	19.9	20.1	20.4	20.6	20.8	21.0	21.2	21.3
	3	10.7	13.0	14.5	15.6	16.5	17.2	17.8	18.3	18.8	19.2	19.5	19.9	20.2	20.4	20.7	20.9	21.1	21.3	21.5	21.7
	4	10.1	12.6	14.2	15.4	16.3	17.1	17.7	18.3	18.8	19.2	19.6	19.9	20.3	20.5	20.8	21.1	21.3	21.5	21.7	21.9
	5	9.8	12.3	14.0	15.2	16.2	16.9	17.6	18.2	18.7	19.1	19.5	19.9	20.2	20.5	20.8	21.0	21.2	21.5	21.7	21.8
0.50	1	14.5	15.7	16.4	17.0	17.4	17.8	18.1	18.4	18.7	18.9	19.1	19.3	19.5	19.6	19.8	19.9	20.1	20.2	20.3	20.4
	2	13.1	14.8	15.8	16.5	17.1	17.6	18.1	18.4	18.8	19.1	19.3	19.6	19.8	20.0	20.2	20.4	20.6	20.8	20.9	21.1
	3	11.0	13.3	14.8	15.9	16.7	17.4	18.0	18.5	18.9	19.3	19.7	20.0	20.3	20.6	20.9	21.1	21.3	21.5	21.7	21.9
	4	10.0	12.6	14.3	15.5	16.5	17.3	18.0	18.5	19.0	19.5	19.9	20.2	20.5	20.8	21.1	21.4	21.6	21.8	22.0	22.2
	5	9.6	12.3	14.0	15.3	16.3	17.2	17.9	18.5	19.0	19.4	19.8	20.2	20.5	20.8	21.1	21.4	21.6	21.8	22.0	22.2
0.30	1	15.3	16.2	16.8	17.3	17.6	17.9	18.2	18.4	18.6	18.8	18.9	19.1	19.2	19.4	19.5	19.6	19.7	19.8	19.9	20.0
	2	14.4	15.6	16.4	17.0	17.4	17.8	18.1	18.4	18.7	18.9	19.1	19.3	19.5	19.7	19.8	20.0	20.1	20.2	20.4	20.5
	3	13.0	14.7	15.8	16.6	17.2	17.7	18.1	18.5	18.8	19.2	19.4	19.7	19.9	20.1	20.4	20.5	20.7	20.9	21.1	21.2
	4	11.0	13.3	14.8	15.9	16.8	17.5	18.1	18.6	19.1	19.5	19.9	20.2	20.5	20.8	21.0	21.3	21.5	21.7	21.9	22.1
	5	10.2	12.8	14.4	15.6	16.6	17.4	18.0	18.6	19.1	19.5	19.9	20.3	20.6	20.9	21.2	21.4	21.7	21.9	22.1	22.3

Note: Shaded values shown in the Table are recommended to be used in practice.

Table A2. Predicted site index based on the average annual growth intercept in t-years above the base height h_0 (continued).

h_0 (m)	t (years)	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
		Average annual growth intercept (m/year) in t-years above h_0																			
		Predicted site index (m) (subregion = upper foothills)																			
1.30	1	13.6	14.4	14.8	15.2	15.5	15.7	15.9	16.1	16.3	16.4	16.5	16.7	16.8	16.9	17.0	17.1	17.2	17.2	17.3	17.4
	2	12.2	13.6	14.5	15.1	15.6	16.1	16.4	16.7	17.0	17.3	17.5	17.7	17.9	18.1	18.3	18.4	18.6	18.7	18.8	19.0
	3	12.0	13.5	14.4	15.1	15.6	16.1	16.5	16.8	17.1	17.3	17.6	17.8	18.0	18.2	18.4	18.5	18.7	18.8	19.0	19.1
	4	11.2	13.1	14.2	15.0	15.6	16.2	16.6	17.0	17.3	17.6	17.9	18.1	18.4	18.6	18.8	18.9	19.1	19.3	19.4	19.6
	5	11.1	12.9	14.0	14.8	15.5	16.0	16.4	16.8	17.2	17.5	17.7	18.0	18.2	18.4	18.6	18.8	19.0	19.1	19.3	19.4
0.80	1	11.2	12.9	14.0	14.7	15.3	15.8	16.2	16.6	16.9	17.2	17.5	17.7	17.9	18.1	18.3	18.5	18.7	18.8	19.0	19.1
	2	10.8	12.8	14.0	14.9	15.6	16.2	16.6	17.1	17.4	17.8	18.0	18.3	18.6	18.8	19.0	19.2	19.4	19.5	19.7	19.8
	3	10.3	12.5	13.8	14.8	15.6	16.2	16.7	17.1	17.5	17.9	18.2	18.5	18.7	19.0	19.2	19.4	19.6	19.7	19.9	20.0
	4	9.8	12.2	13.7	14.8	15.6	16.3	16.9	17.3	17.7	18.1	18.4	18.7	19.0	19.2	19.4	19.6	19.8	20.0	20.2	20.3
	5	9.6	12.1	13.7	14.8	15.7	16.4	16.9	17.4	17.8	18.2	18.5	18.8	19.1	19.3	19.6	19.8	19.9	20.1	20.3	20.4
0.50	1	8.9	11.6	13.3	14.5	15.5	16.3	16.9	17.5	18.0	18.4	18.7	19.1	19.4	19.6	19.9	20.1	20.3	20.5	20.7	20.8
	2	9.5	11.9	13.4	14.5	15.3	16.0	16.6	17.1	17.6	17.9	18.3	18.6	18.9	19.1	19.4	19.6	19.8	20.0	20.1	20.3
	3	9.1	11.7	13.3	14.5	15.4	16.2	16.8	17.3	17.8	18.2	18.5	18.8	19.1	19.4	19.6	19.8	20.0	20.2	20.3	20.5
	4	8.8	11.5	13.3	14.5	15.5	16.3	17.0	17.5	18.0	18.4	18.8	19.1	19.4	19.6	19.8	20.1	20.3	20.4	20.6	20.8
	5	8.2	11.2	13.1	14.5	15.6	16.5	17.2	17.8	18.3	18.7	19.0	19.4	19.6	19.9	20.1	20.3	20.5	20.7	20.8	21.0
0.30	1	11.4	13.3	14.4	15.3	15.9	16.4	16.9	17.3	17.6	17.9	18.2	18.5	18.7	18.9	19.1	19.3	19.5	19.7	19.8	20.0
	2	9.8	12.2	13.8	14.9	15.7	16.4	17.0	17.5	18.0	18.3	18.7	19.0	19.2	19.5	19.7	19.9	20.1	20.3	20.5	20.6
	3	8.7	11.5	13.3	14.7	15.7	16.5	17.2	17.7	18.2	18.6	19.0	19.3	19.6	19.8	20.1	20.3	20.5	20.7	20.8	21.0
	4	8.5	11.4	13.3	14.6	15.7	16.5	17.2	17.7	18.2	18.6	19.0	19.3	19.6	19.8	20.1	20.3	20.5	20.6	20.8	20.9
	5	8.3	11.3	13.2	14.7	15.7	16.6	17.3	17.9	18.3	18.8	19.1	19.4	19.7	20.0	20.2	20.4	20.6	20.8	20.9	21.1
		Predicted site index (m) (subregion = sub-alpine)																			
1.30	1	8.5	9.7	10.5	11.1	11.6	12.0	12.4	12.7	13.0	13.3	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0	15.1	15.3
	2	6.9	8.8	10.1	11.1	11.9	12.6	13.1	13.7	14.1	14.6	14.9	15.3	15.6	15.9	16.2	16.5	16.7	17.0	17.2	17.4
	3	5.8	8.1	9.7	10.9	11.9	12.8	13.5	14.2	14.8	15.3	15.7	16.1	16.5	16.9	17.2	17.5	17.8	18.0	18.3	18.5
	4	6.0	8.1	9.7	11.0	12.1	13.0	13.9	14.7	15.4	16.0	16.6	17.2	17.8	18.3	18.8	19.2	19.7	20.1	20.5	20.9
	5	5.9	8.1	9.7	11.0	12.1	13.0	13.9	14.6	15.3	15.9	16.5	17.0	17.5	18.0	18.5	18.9	19.3	19.7	20.0	20.4
0.80	1	9.0	10.1	10.7	11.2	11.7	12.0	12.3	12.6	12.8	13.1	13.3	13.4	13.6	13.8	14.0	14.1	14.2	14.4	14.5	14.6
	2	7.6	9.3	10.4	11.1	11.7	12.2	12.5	12.8	13.1	13.3	13.5	13.7	13.8	14.0	14.1	14.2	14.3	14.4	14.5	14.6
	3	7.5	9.2	10.3	11.2	11.9	12.5	12.9	13.4	13.8	14.1	14.5	14.8	15.0	15.3	15.5	15.8	16.0	16.2	16.4	16.6
	4	7.0	9.0	10.2	11.2	12.0	12.6	13.2	13.6	14.0	14.4	14.7	15.0	15.3	15.5	15.8	16.0	16.2	16.3	16.5	16.7
	5	6.7	8.8	10.1	11.2	12.0	12.7	13.3	13.8	14.2	14.7	15.0	15.3	15.6	15.9	16.2	16.4	16.6	16.8	17.0	17.2
0.50	1	9.5	10.3	10.8	11.2	11.5	11.8	12.0	12.2	12.4	12.5	12.7	12.8	13.0	13.1	13.2	13.3	13.4	13.5	13.6	13.7
	2	8.9	10.0	10.7	11.2	11.7	12.1	12.4	12.7	12.9	13.2	13.4	13.6	13.8	14.0	14.2	14.3	14.5	14.6	14.8	14.9
	3	8.8	9.9	10.7	11.2	11.7	12.1	12.5	12.8	13.1	13.3	13.6	13.8	14.0	14.2	14.4	14.6	14.7	14.9	15.0	15.2
	4	8.5	9.8	10.6	11.3	11.8	12.2	12.6	13.0	13.3	13.6	13.9	14.2	14.4	14.6	14.8	15.1	15.2	15.4	15.6	15.8
	5	7.7	9.3	10.4	11.3	12.1	12.7	13.3	13.8	14.2	14.7	15.1	15.5	15.8	16.1	16.5	16.8	17.1	17.3	17.6	17.9
0.30	1	8.3	9.9	10.9	11.5	12.0	12.3	12.5	12.7	12.9	13.0	13.1	13.2	13.2	13.3	13.3	13.4	13.4	13.4	13.4	13.5
	2	8.9	10.1	10.9	11.4	11.9	12.3	12.7	13.0	13.3	13.5	13.8	14.0	14.2	14.4	14.6	14.7	14.9	15.0	15.2	15.3
	3	8.7	10.0	10.8	11.4	11.9	12.3	12.7	13.0	13.3	13.5	13.8	14.0	14.2	14.4	14.6	14.8	15.0	15.1	15.3	15.4
	4	8.6	9.9	10.7	11.4	11.9	12.3	12.7	13.1	13.4	13.7	14.0	14.2	14.5	14.7	14.9	15.1	15.3	15.5	15.7	15.8
	5	8.5	9.8	10.6	11.3	11.9	12.3	12.8	13.1	13.5	13.8	14.1	14.3	14.6	14.8	15.1	15.3	15.5	15.7	15.8	16.0

Note: Shaded values shown in the Table are recommended to be used in practice.

Table A2. Predicted site index based on the average annual growth intercept in t-years above the base height h_0 (continued).

h_0 (m)	t (years)	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
		Average annual growth intercept (m/year) in t-years above h_0																			
		Predicted site index (m) (subregion = Weyerhaeuser FMA)																			
1.30	1	9.8	12.0	13.6	14.8	15.8	16.6	17.3	18.0	18.6	19.2	19.7	20.1	20.6	21.0	21.4	21.7	22.1	22.4	22.8	23.1
	2	9.0	11.5	13.2	14.5	15.6	16.6	17.4	18.2	18.8	19.5	20.0	20.6	21.1	21.6	22.0	22.4	22.8	23.2	23.6	23.9
	3	8.7	11.2	12.9	14.3	15.4	16.4	17.3	18.1	18.8	19.5	20.1	20.7	21.2	21.7	22.2	22.7	23.1	23.5	23.9	24.3
	4	8.2	10.8	12.6	14.1	15.3	16.3	17.2	18.1	18.8	19.5	20.1	20.7	21.2	21.7	22.2	22.7	23.1	23.5	23.9	24.3
	5	7.7	10.4	12.4	13.9	15.2	16.2	17.2	18.0	18.8	19.5	20.1	20.7	21.2	21.7	22.2	22.6	23.0	23.4	23.8	24.2
0.80	1	8.7	11.4	13.3	14.6	15.7	16.6	17.3	17.9	18.4	18.9	19.3	19.6	20.0	20.3	20.5	20.8	21.0	21.2	21.4	21.5
	2	7.4	10.5	12.6	14.2	15.5	16.5	17.4	18.2	18.8	19.4	19.8	20.3	20.7	21.0	21.3	21.6	21.8	22.1	22.3	22.5
	3	7.4	10.4	12.5	14.2	15.5	16.6	17.5	18.3	19.1	19.7	20.2	20.8	21.2	21.6	22.0	22.4	22.7	23.0	23.3	23.6
	4	7.5	10.4	12.5	14.1	15.5	16.6	17.5	18.4	19.1	19.8	20.4	20.9	21.4	21.9	22.3	22.7	23.1	23.4	23.7	24.0
	5	7.5	10.4	12.5	14.0	15.4	16.5	17.4	18.3	19.0	19.7	20.3	20.8	21.4	21.8	22.3	22.7	23.1	23.4	23.8	24.1
0.50	1	10.6	12.7	14.1	15.2	16.1	16.9	17.7	18.3	18.9	19.4	20.0	20.4	20.9	21.3	21.7	22.1	22.5	22.8	23.2	23.5
	2	10.1	12.2	13.7	14.9	15.8	16.7	17.4	18.1	18.7	19.3	19.9	20.4	20.8	21.3	21.7	22.1	22.5	22.9	23.2	23.6
	3	8.4	11.1	12.9	14.4	15.6	16.7	17.6	18.4	19.1	19.8	20.4	21.0	21.5	22.0	22.5	22.9	23.3	23.7	24.1	24.4
	4	7.1	10.2	12.4	14.2	15.6	16.7	17.7	18.6	19.3	19.9	20.5	21.0	21.5	21.9	22.3	22.6	23.0	23.3	23.5	23.8
	5	6.6	9.8	12.1	14.0	15.5	16.7	17.7	18.6	19.4	20.0	20.6	21.1	21.5	21.9	22.3	22.6	22.9	23.2	23.4	23.6
0.30	1	11.4	13.4	14.7	15.7	16.5	17.2	17.8	18.4	18.9	19.4	19.8	20.2	20.6	20.9	21.3	21.6	21.9	22.2	22.5	22.7
	2	10.7	12.7	14.2	15.3	16.2	17.0	17.7	18.4	18.9	19.5	20.0	20.5	20.9	21.3	21.7	22.1	22.5	22.8	23.1	23.5
	3	10.1	12.3	13.8	15.0	16.0	16.9	17.7	18.4	19.0	19.6	20.2	20.7	21.2	21.6	22.1	22.5	22.9	23.3	23.7	24.0
	4	8.5	11.2	13.1	14.6	15.9	16.9	17.9	18.7	19.5	20.1	20.8	21.4	21.9	22.4	22.9	23.4	23.8	24.3	24.7	25.0
	5	7.3	10.4	12.6	14.3	15.7	16.9	17.9	18.7	19.5	20.1	20.7	21.2	21.7	22.1	22.5	22.9	23.3	23.6	23.9	24.1
		Predicted site index (m) (subregion = Weldwood FMA)																			
1.30	1	10.3	12.1	13.2	14.0	14.6	15.2	15.6	16.1	16.4	16.8	17.1	17.3	17.6	17.8	18.1	18.3	18.5	18.7	18.8	19.0
	2	7.4	10.1	12.0	13.4	14.5	15.4	16.2	16.8	17.3	17.8	18.2	18.6	19.0	19.3	19.5	19.8	20.0	20.2	20.4	20.6
	3	6.4	9.2	11.3	13.0	14.3	15.4	16.3	17.1	17.8	18.4	18.9	19.4	19.8	20.2	20.5	20.9	21.2	21.4	21.7	21.9
	4	6.6	9.4	11.4	13.0	14.3	15.4	16.2	17.0	17.7	18.2	18.8	19.2	19.6	20.0	20.3	20.7	20.9	21.2	21.5	21.7
	5	5.8	8.8	11.0	12.8	14.2	15.4	16.3	17.1	17.8	18.3	18.8	19.2	19.6	19.9	20.2	20.5	20.7	20.9	21.1	21.3
	10	3.9	6.9	9.6	11.9	13.8	15.3	16.6	17.5	18.3	18.8	19.3	19.7	19.9	20.2	20.4	20.6	20.7	20.9	21.0	21.1
0.80	1	10.0	11.9	13.2	14.2	14.9	15.6	16.2	16.7	17.2	17.7	18.1	18.4	18.8	19.1	19.4	19.7	20.0	20.2	20.5	20.7
	2	8.5	10.9	12.5	13.8	14.8	15.7	16.5	17.2	17.8	18.4	18.9	19.4	19.8	20.3	20.6	21.0	21.4	21.7	22.0	22.3
	3	7.7	10.3	12.1	13.5	14.7	15.7	16.6	17.4	18.1	18.7	19.3	19.9	20.4	20.9	21.3	21.7	22.1	22.5	22.9	23.2
	4	6.5	9.3	11.5	13.2	14.6	15.8	16.8	17.7	18.5	19.3	19.9	20.5	21.1	21.6	22.1	22.5	22.9	23.3	23.7	24.1
	5	5.8	8.8	11.1	12.9	14.4	15.7	16.8	17.7	18.5	19.2	19.8	20.4	20.9	21.3	21.8	22.2	22.5	22.9	23.2	23.5
	10	4.5	7.6	10.2	12.4	14.1	15.6	16.7	17.6	18.4	19.0	19.6	20.0	20.4	20.7	21.0	21.3	21.5	21.7	22.0	22.2
0.50	1	10.1	12.2	13.6	14.6	15.5	16.2	16.9	17.5	18.0	18.5	18.9	19.3	19.7	20.1	20.4	20.7	21.0	21.3	21.6	21.8
	2	7.5	10.3	12.3	14.0	15.4	16.7	17.8	18.8	19.7	20.6	21.4	22.1	22.9	23.5	24.2	24.8	25.4	25.9	26.5	27.0
	3	7.4	10.1	12.1	13.7	15.2	16.5	17.7	18.8	19.8	20.7	21.6	22.5	23.3	24.1	24.8	25.5	26.2	26.9	27.6	28.2
	4	7.3	10.0	12.0	13.6	15.1	16.3	17.5	18.5	19.5	20.4	21.3	22.1	22.9	23.6	24.3	25.0	25.6	26.3	26.9	27.4
	5	6.6	9.5	11.6	13.4	14.9	16.2	17.4	18.5	19.5	20.4	21.2	22.0	22.8	23.5	24.1	24.8	25.4	26.0	26.5	27.0
	10	5.0	8.2	10.8	12.8	14.5	15.9	17.0	18.0	18.8	19.4	20.0	20.6	21.0	21.4	21.8	22.1	22.5	22.8	23.0	23.3
0.30	1	11.1	13.0	14.2	15.1	15.7	16.2	16.7	17.1	17.4	17.7	17.9	18.2	18.4	18.6	18.7	18.9	19.1	19.2	19.3	19.5
	2	8.7	11.5	13.4	14.8	15.9	16.9	17.7	18.4	19.1	19.6	20.1	20.6	21.0	21.4	21.8	22.1	22.4	22.7	23.0	23.3
	3	6.7	9.9	12.4	14.3	15.9	17.2	18.4	19.4	20.3	21.1	21.8	22.5	23.1	23.7	24.2	24.7	25.1	25.6	26.0	26.4
	4	7.3	10.1	12.2	14.0	15.5	16.8	18.0	19.1	20.1	21.0	21.9	22.7	23.5	24.2	24.9	25.6	26.2	26.8	27.4	28.0
	5	7.1	9.9	12.0	13.8	15.3	16.7	17.9	19.0	20.0	21.0	21.9	22.7	23.5	24.3	25.0	25.7	26.4	27.0	27.6	28.2
	10	5.4	8.6	11.1	13.1	14.8	16.2	17.3	18.3	19.1	19.9	20.5	21.1	21.6	22.1	22.6	23.0	23.4	23.7	24.1	24.4

Note: Shaded values shown in the Table are recommended to be used in practice.

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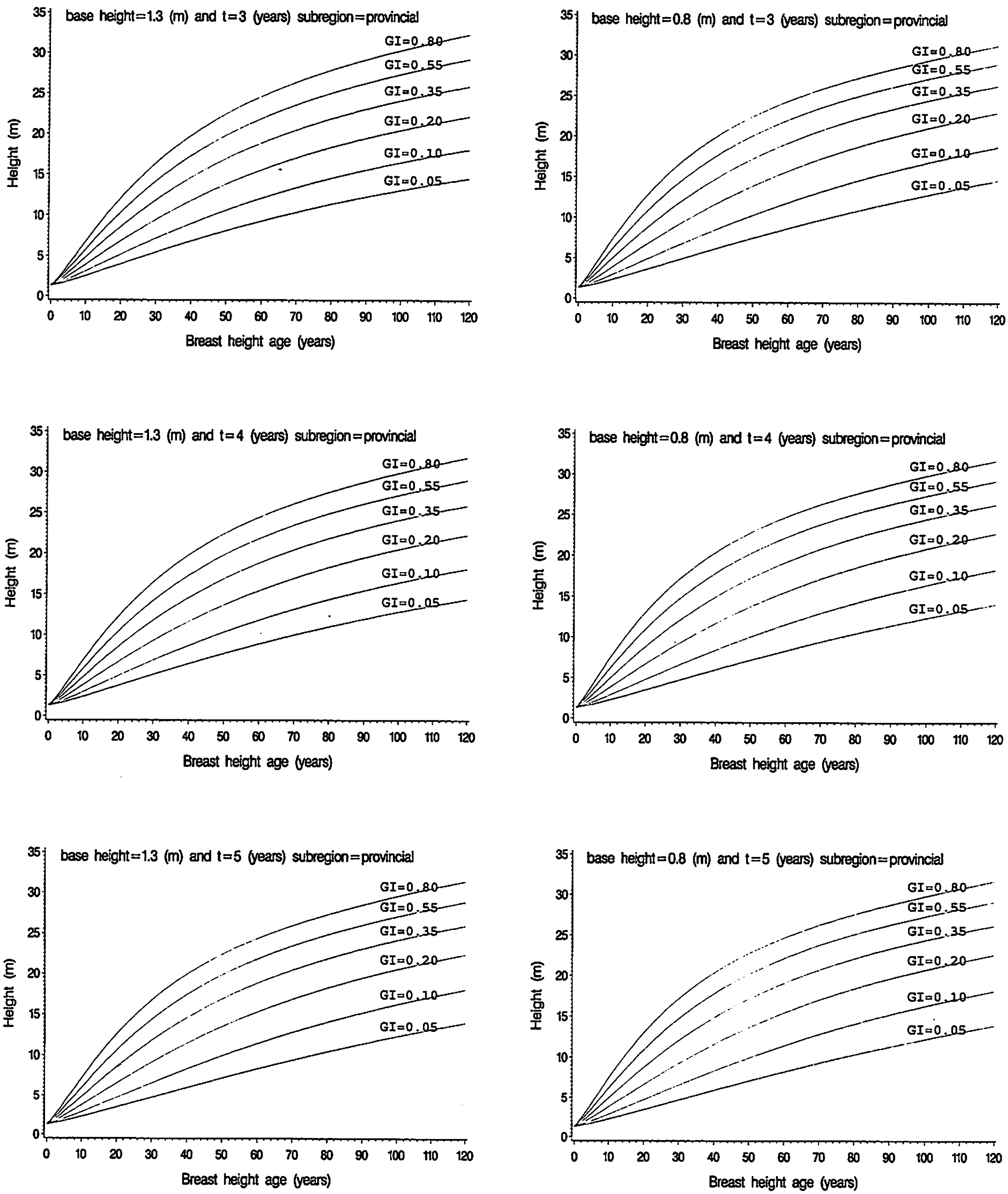

Figure A1. The growth intercept-based site index curves for combined natural subregions, generated from equation [1a]. Estimated coefficients are shown in Table A1.

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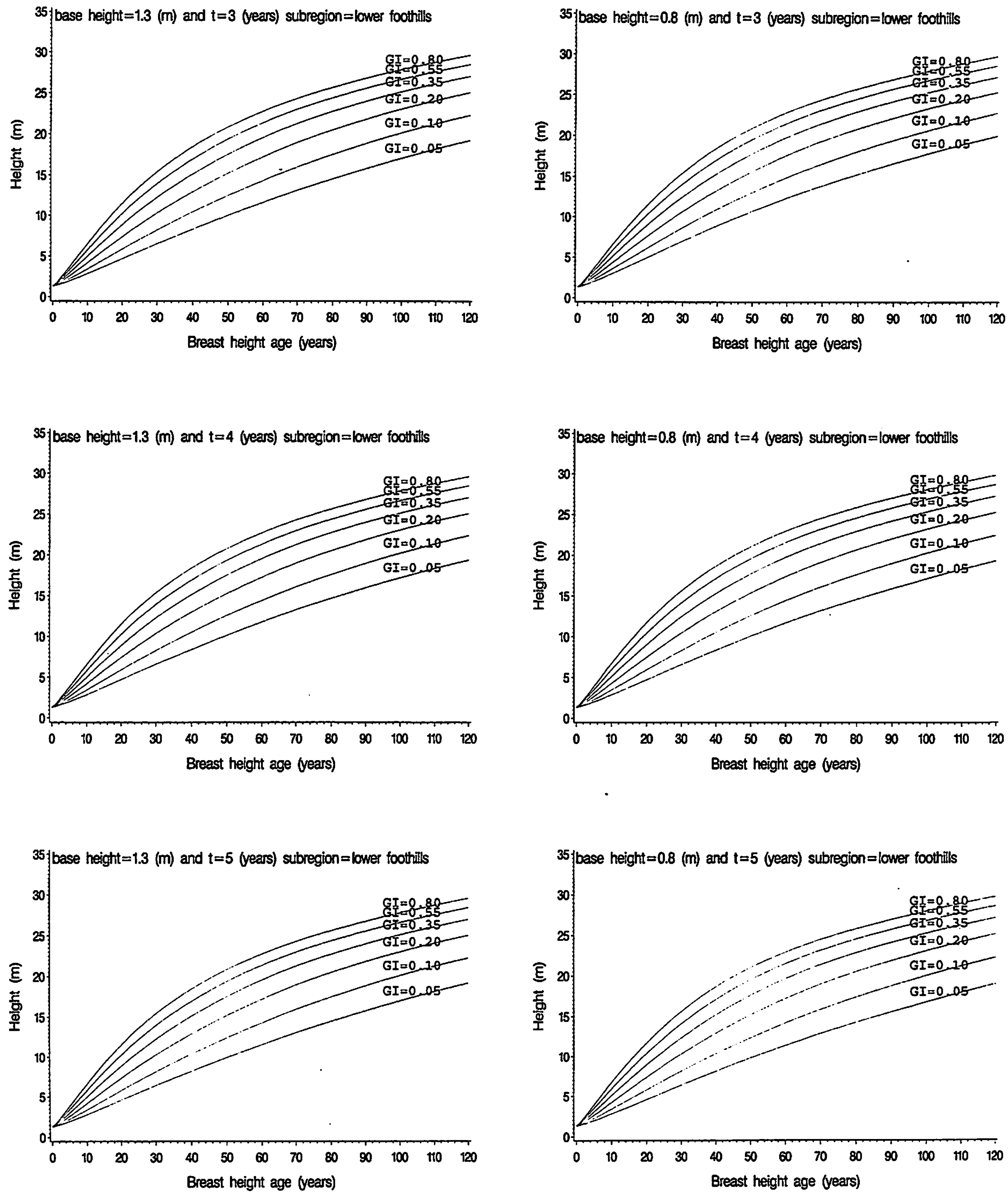

Figure A2. The growth intercept-based site index curves for the lower foothills subregion, generated from equation [1c]. Estimated coefficients are shown in Table A1.

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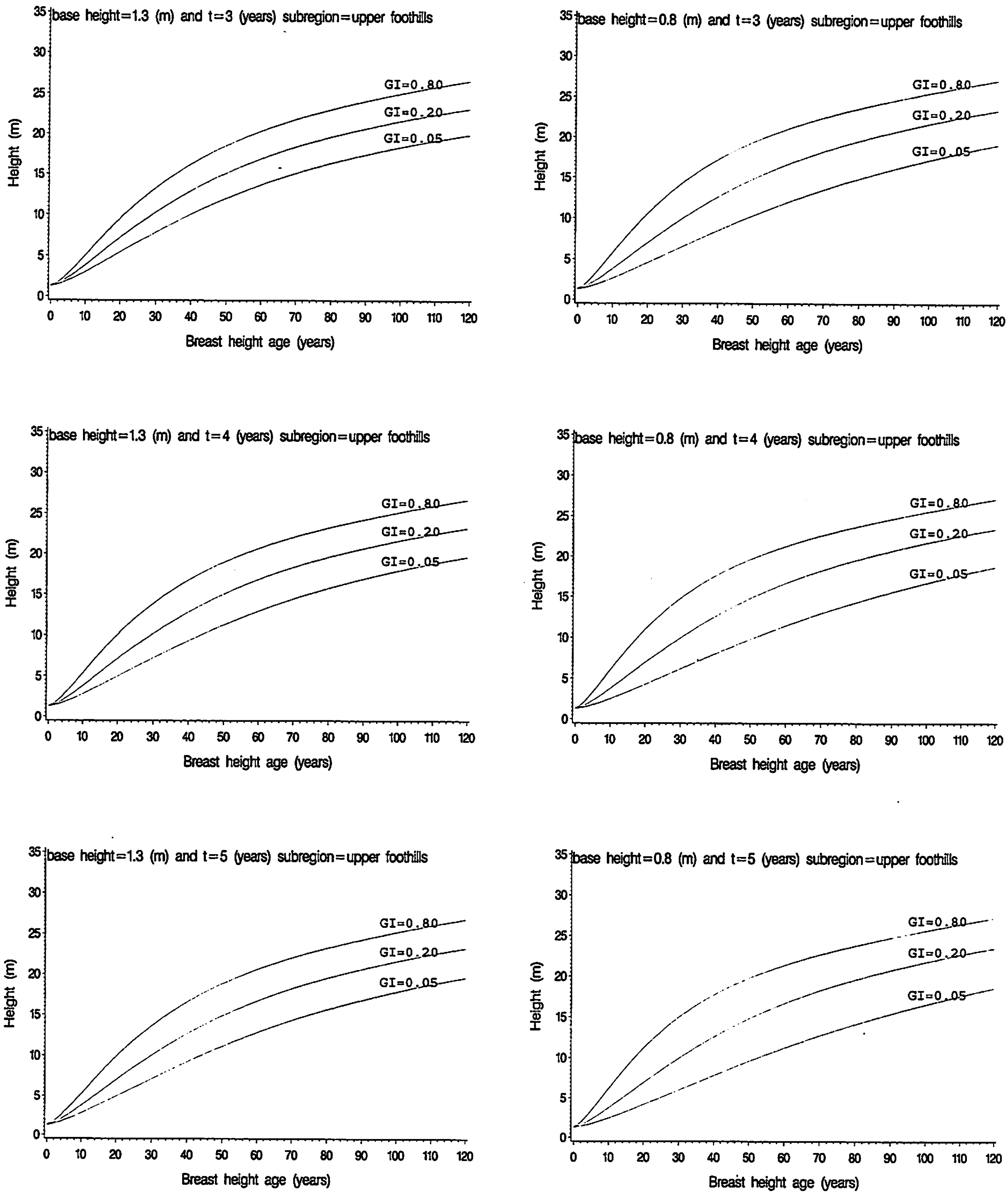

Figure A3. The growth intercept-based site index curves for the upper foothills subregion, generated from equation [1c]. Estimated coefficients are shown in Table A1.

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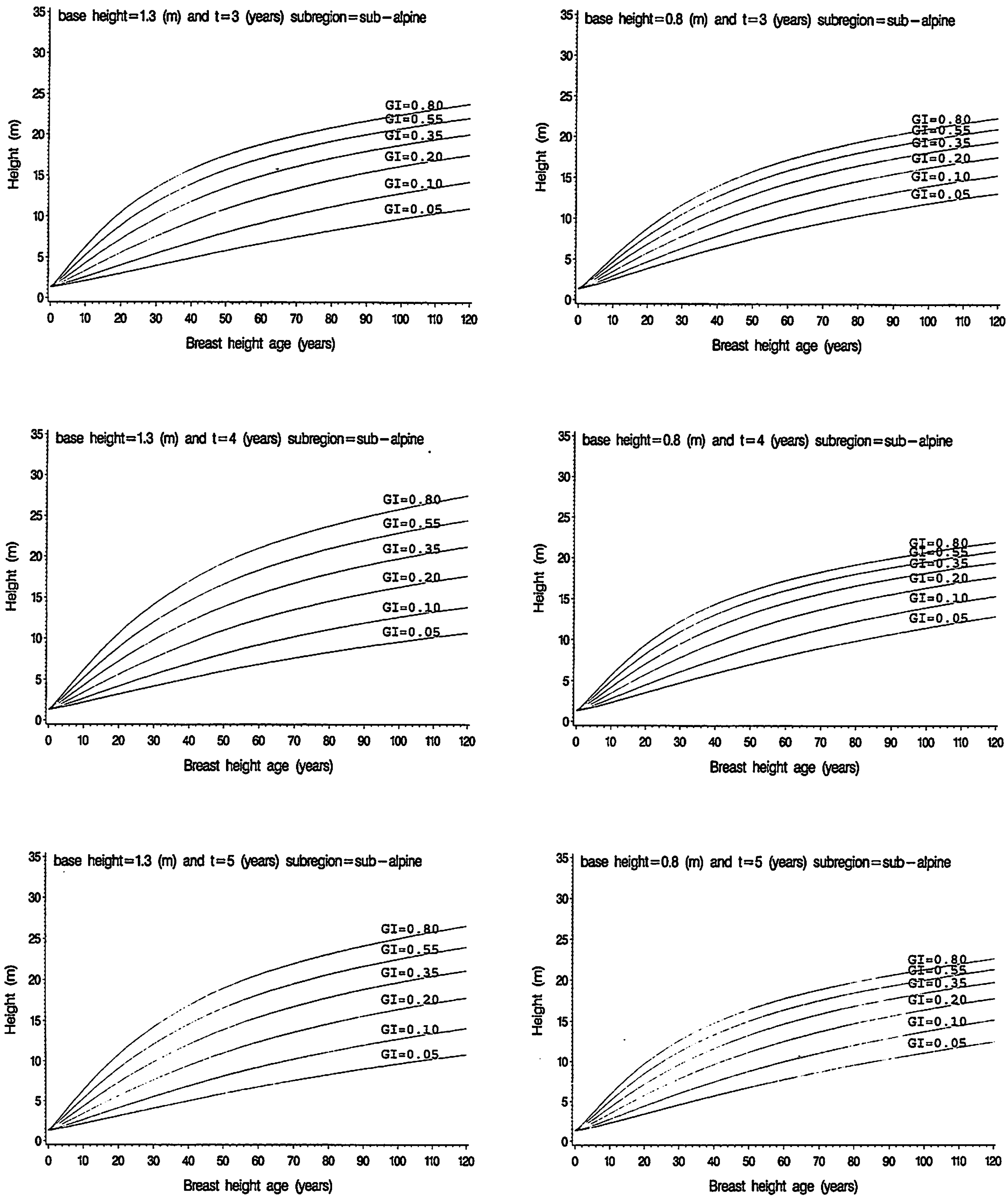

Figure A4. The growth intercept-based site index curves for the sub-alpine subregion, generated from equation [1a]. Estimated coefficients are shown in Table A1.

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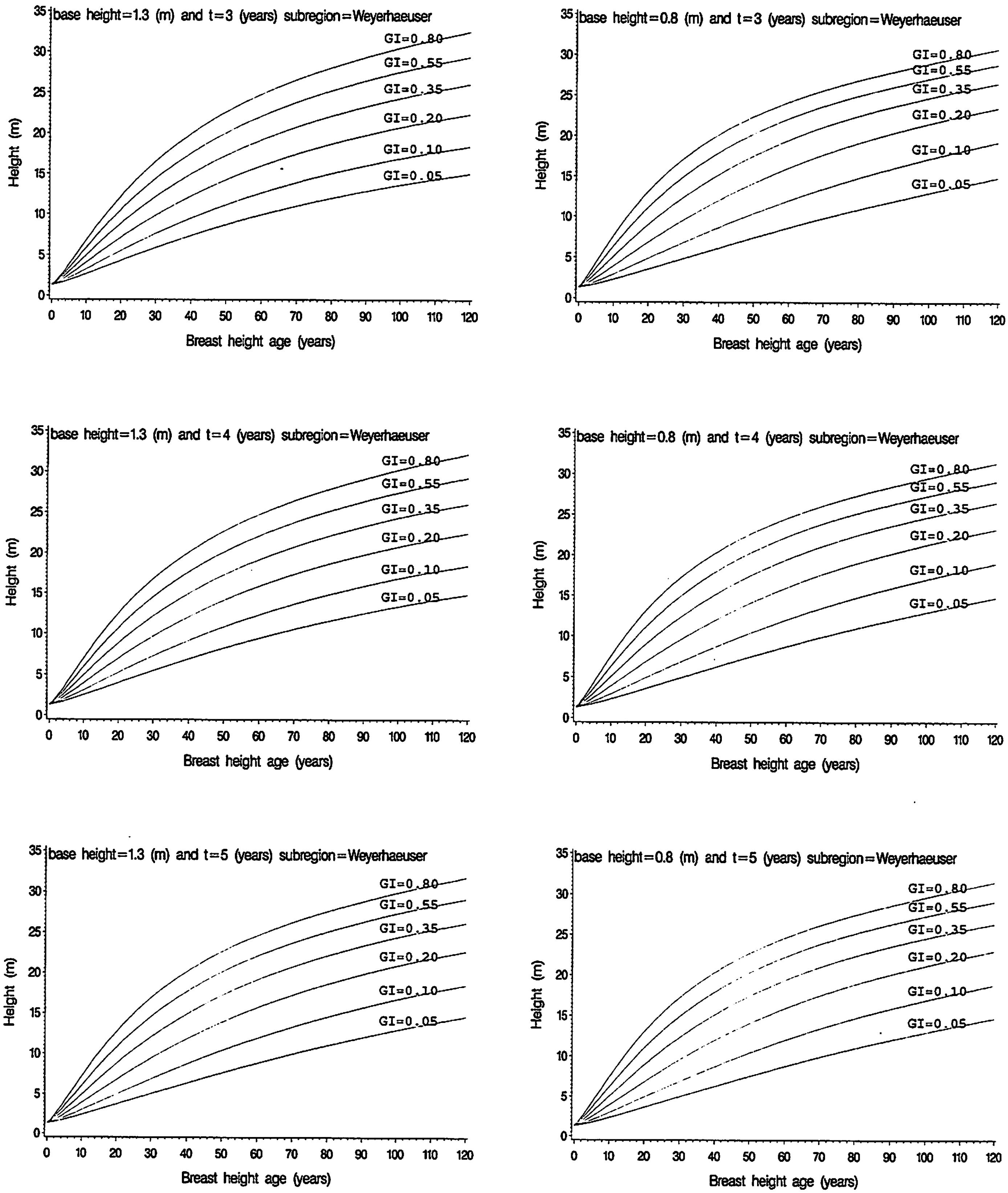

Figure A5. The growth intercept-based site index curves for the Weyerhaeuser FMA, generated from equation [1a]. Estimated coefficients are shown in Table A1.

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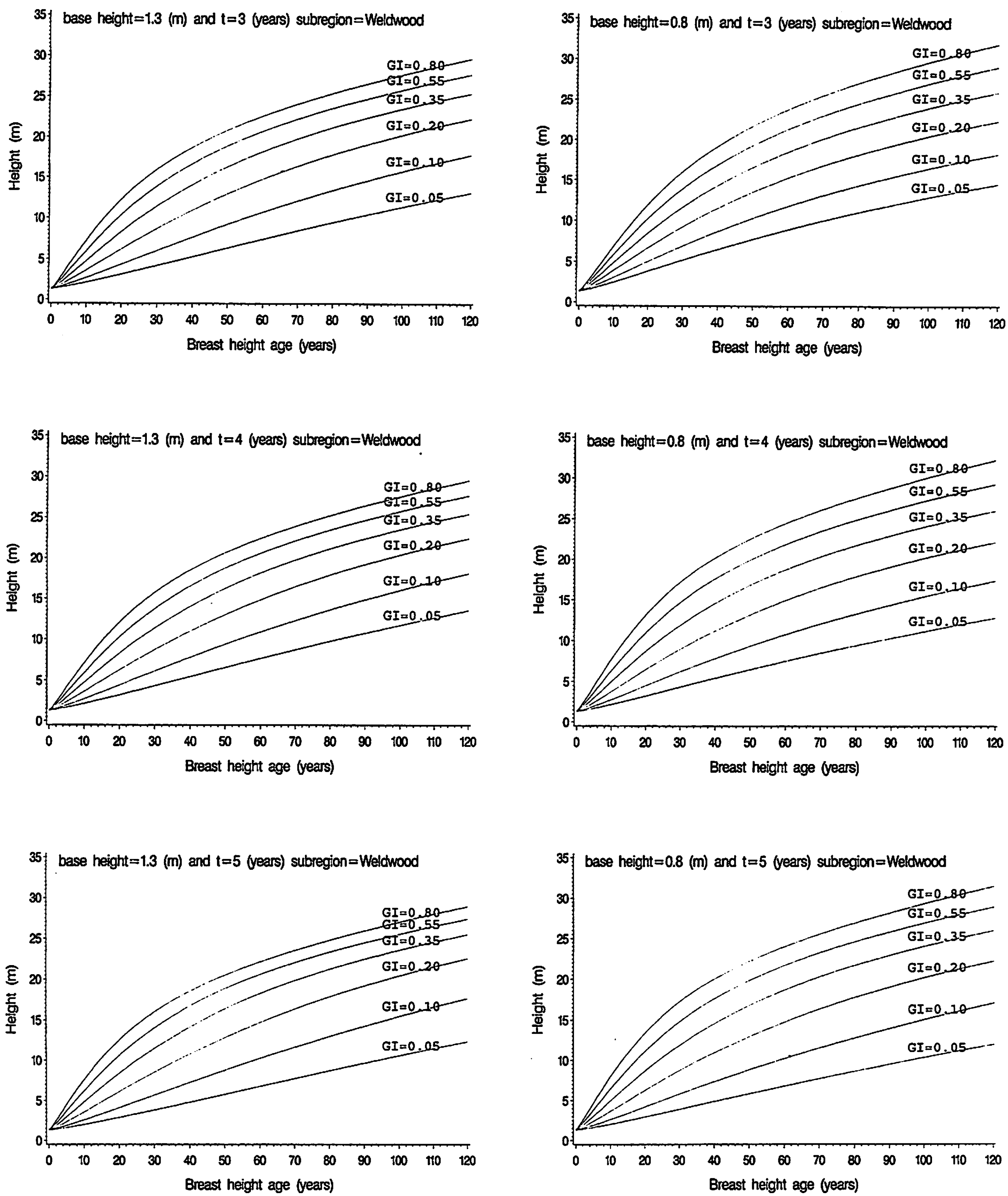

Figure A6. The growth intercept-based site index curves for the Weldwood FMA, generated from equation [1b]. Estimated coefficients are shown in Table A1.

Appendix 2.

Estimated Coefficients and Fitted Curves Based on Method II

This appendix provides:

Table A3. The estimated coefficients, the root mean squared error (RMSE) and the coefficient of determination (R^2) for Method II (equations [2a]-[2c]).

Figures A7-A12. The growth intercept-based site index curves for lodgepole pine in Alberta. These curves are generated using equations [2a]-[2c]. They show the expected height growth patterns on various sites.

Table A3. Fit statistics for models [2a]-[2c] based on different base height (h_0) values.

Subegion	Equation	h_0 (m)	t (years)	Estimate b_0	b_1	b_2	b_3	b_4	b_5	RMSE	R^2
Provincial	[2a]	1.3	1 to 5	6.456280	0.231682	0.051381	0.374435	0.888305	0.043267	1.688	0.945
		0.8	1 to 5	6.285842	0.194215	0.060162	0.521738	0.876894	0.036302	1.679	0.945
		0.5	1 to 5	6.811059	0.248575	0.051816	0.380438	0.845072	0.071200	1.779	0.939
		0.3	1 to 5	6.699240	0.218013	0.050071	0.364928	0.803616	0.100142	1.843	0.934
Lower foothills	[2c]	1.3	1 to 5	5.893762	0.100000	0.051094	0.383474	0.875860	0.033637	1.338	0.972
		0.8	1 to 5	5.912037	0.100000	0.048308	0.318540	0.866822	0.036509	1.415	0.968
		0.5	1 to 5	5.981182	0.100000	0.048064	0.304957	0.829760	0.068804	1.460	0.966
		0.3	1 to 5	6.027126	0.100000	0.042388	0.192347	0.824406	0.066814	1.492	0.965
Upper foothills	[2c]	1.3	1 to 5	5.270209	0.100000	0.049885	0.152341	1.156626	0.027021*	1.432	0.954
		0.8	1 to 5	5.339233	0.100000	0.061442	0.347209	1.171421	-0.028606*	1.335	0.960
		0.5	1 to 5	5.438234	0.100000	0.070071	0.501789	1.094761	-0.009524*	1.252	0.965
		0.3	1 to 5	5.448996	0.100000	0.068901	0.449078	1.042116	0.063890	1.278	0.963
Sub-alpine	[2a]	1.3	1 to 5	5.015914	0.233225	0.046917	0.358931	0.826683	0.035169	0.998	0.950
		0.8	1 to 5	4.272004	0.136006	0.050523	0.365456	0.832040	0.045568	1.056	0.944
		0.5	1 to 5	4.786697	0.205101	0.028919	0.018140*	0.844357	0.017275*	1.134	0.935
		0.3	1 to 5	4.570509	0.168281	0.034096	0.123839*	0.826894	0.028084*	1.135	0.935
Weyerhaeuser	[2a]	1.3	1 to 5	6.565211	0.242651	0.053528	0.341210	0.901112	0.053829	1.707	0.950
		0.8	1 to 5	6.097809	0.157421	0.067819	0.603778	0.894489	0.024477*	1.742	0.948
		0.5	1 to 5	6.819749	0.249598	0.050096	0.321764	0.869413	0.061828	1.923	0.937
		0.3	1 to 5	7.047514	0.265519	0.042362	0.177663	0.851566	0.079853	2.003	0.931
Weldwood	[2b]	1.3	1 to 5	4.184100	0.146512	0.069082	0.631910	0.771098	0.048500	1.579	0.937
		0.8	1 to 5	4.723317	0.238497	0.059082	0.453841	0.769301	0.061108	1.551	0.940
		0.5	1 to 5	5.352954	0.315282	0.058285	0.392267	0.754780	0.097709	1.544	0.940
		0.3	1 to 5	4.748520	0.201099	0.068690	0.543562	0.695944	0.141161	1.584	0.937
	[2b]	1.3	1 to 10	4.216741	0.150701	0.083786	0.801094	0.741474	0.055268	1.545	0.940
		0.8	1 to 10	4.610909	0.221917	0.075613	0.662213	0.722739	0.077718	1.509	0.943
		0.5	1 to 10	5.034852	0.277785	0.076940	0.629140	0.679901	0.121116	1.473	0.946
		0.3	1 to 10	4.747093	0.210744	0.083144	0.706832	0.616867	0.163781	1.493	0.944

Note: * indicates an insignificant estimate at $\alpha=0.05$.

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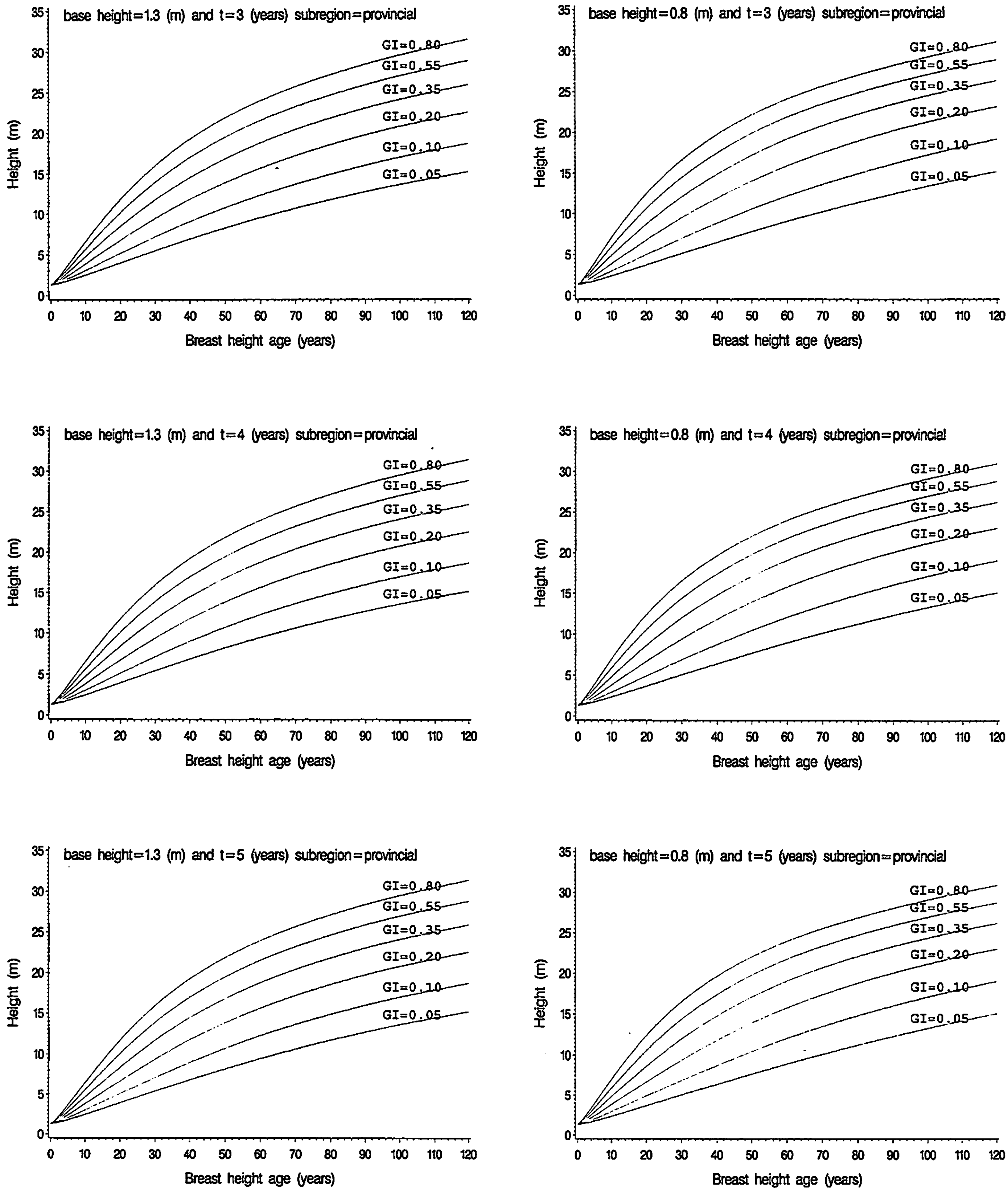

Figure A7. The growth intercept-based site index curves for combined natural subregions, generated from equation [2a]. Estimated coefficients are shown in Table A3.

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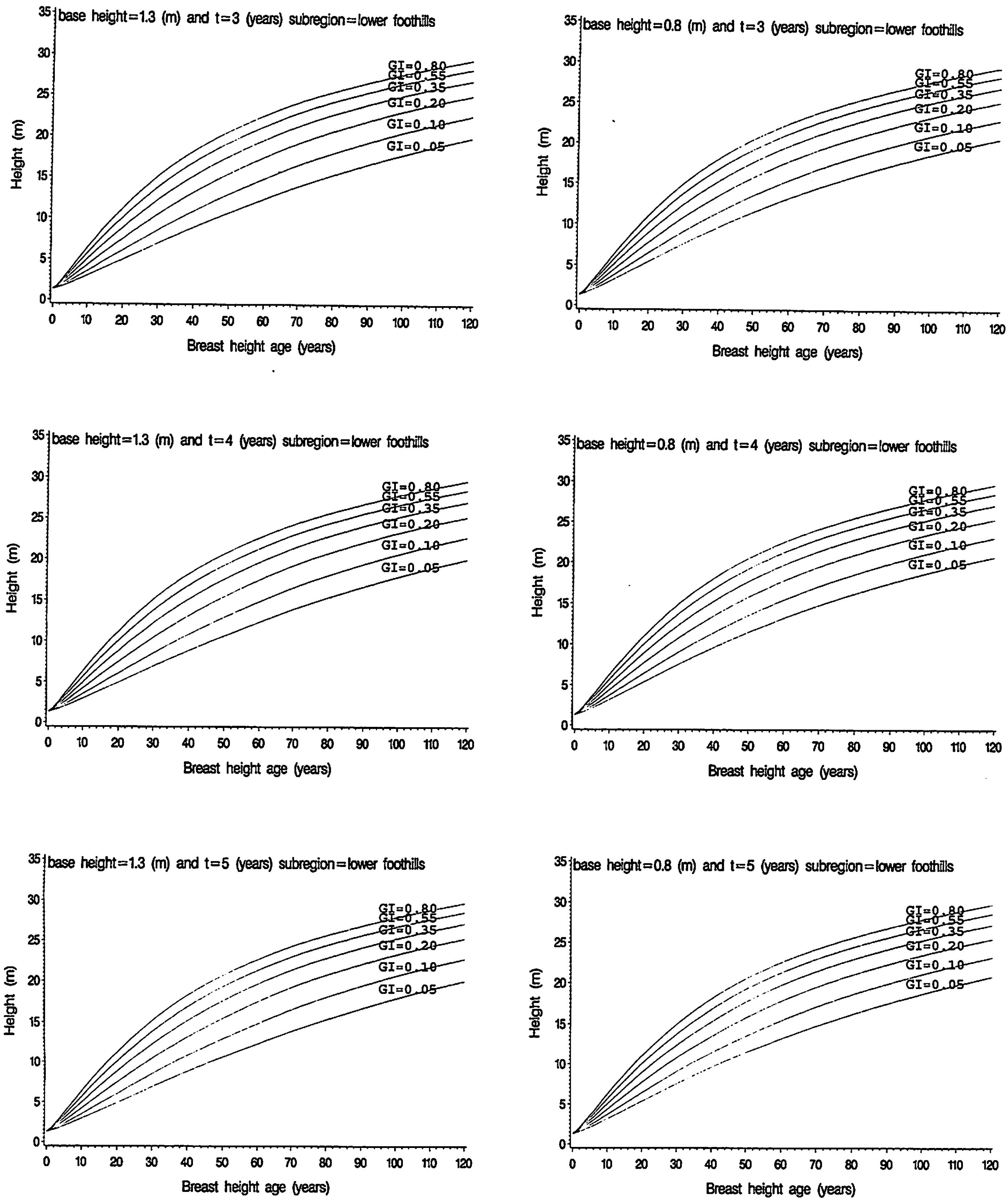

Figure A8. The growth intercept-based site index curves for the lower foothills subregion, generated from equation [2c]. Estimated coefficients are shown in Table A3.

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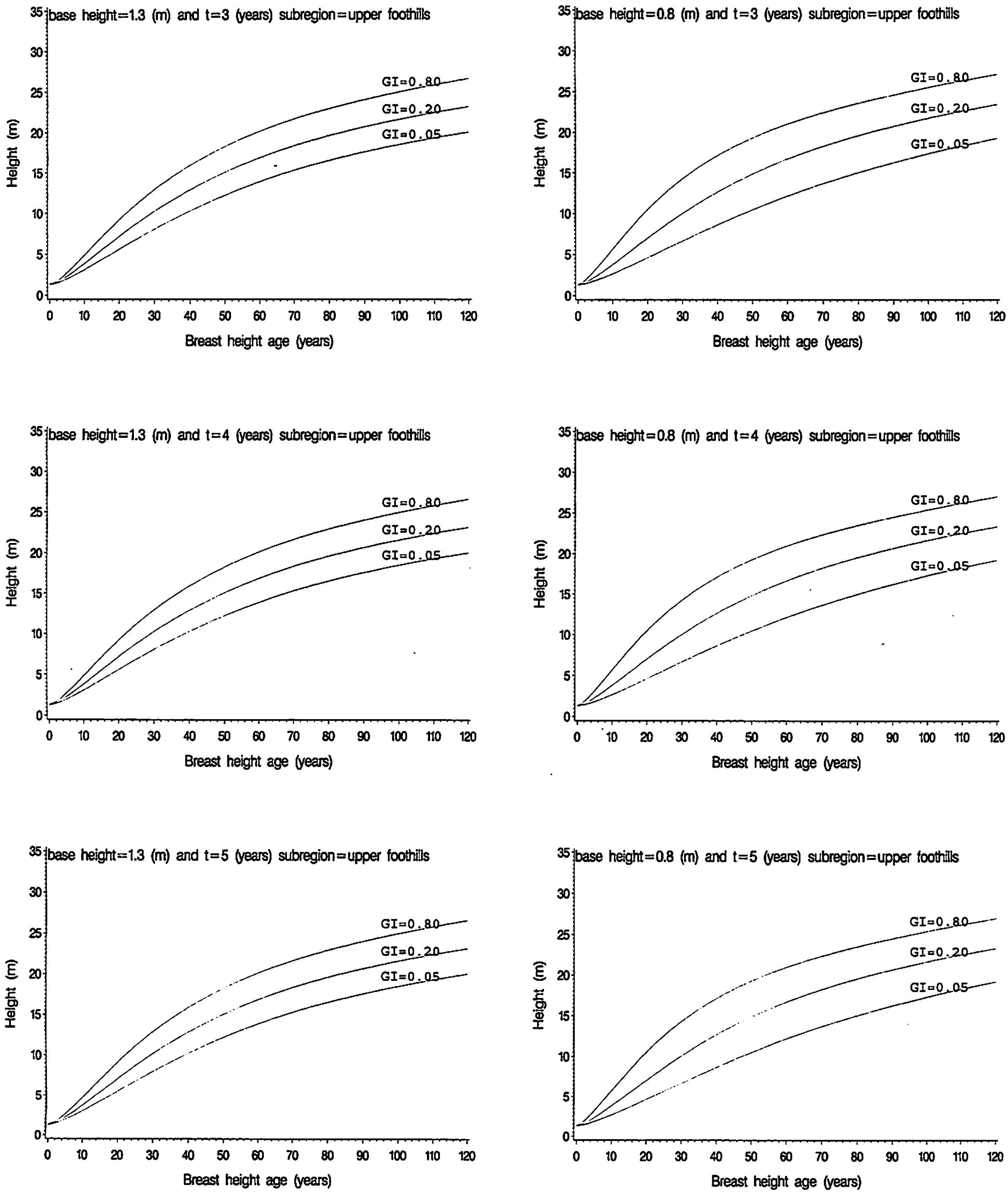

Figure A9. The growth intercept-based site index curves for the upper foothills subregion, generated from equation [2c]. Estimated coefficients are shown in Table A3.

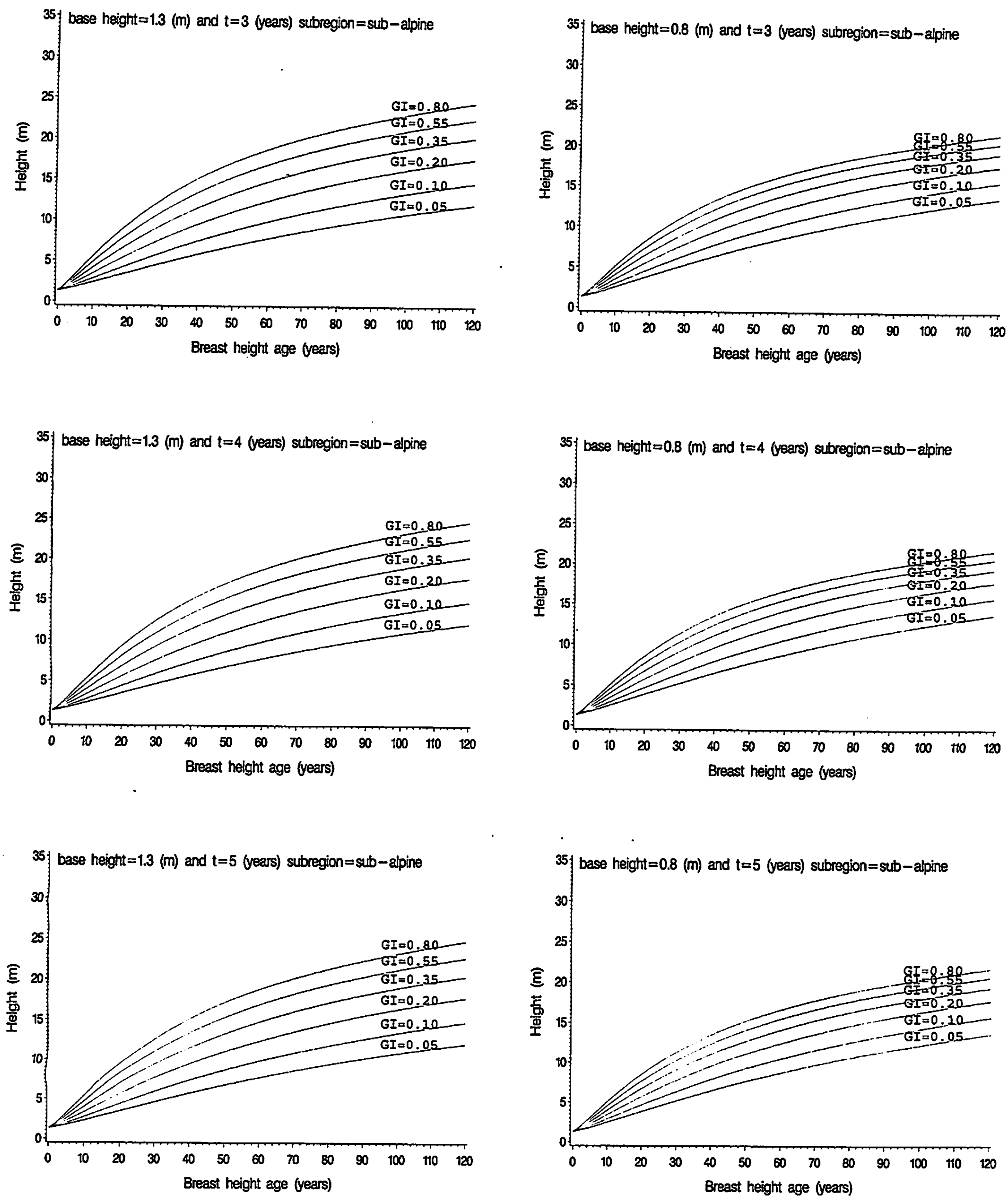

Figure A10. The growth intercept-based site index curves for the sub-alpine subregion, generated from equation [2a]. Estimated coefficients are shown in Table A3.

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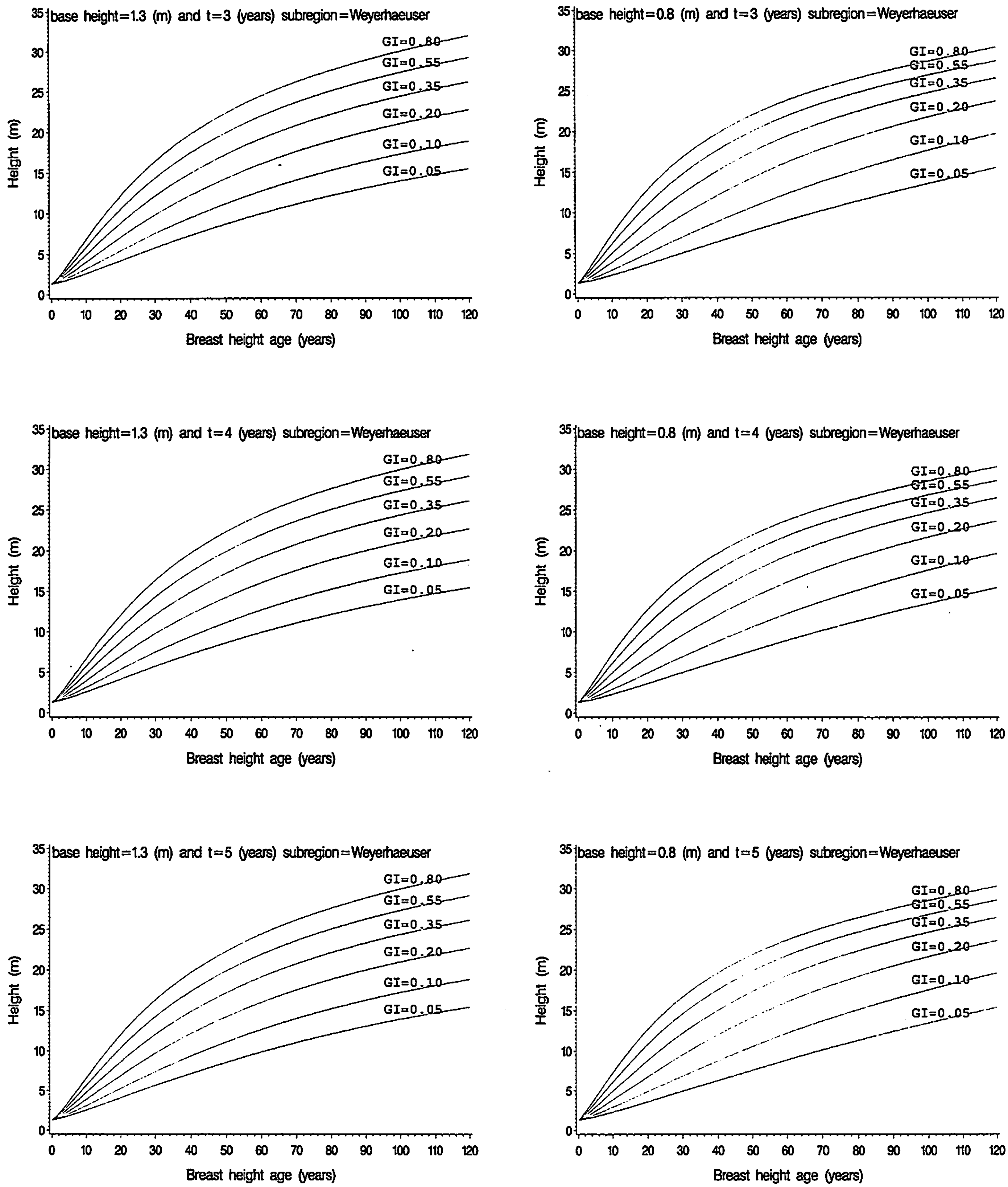

Figure A11. The growth intercept-based site index curves for the Weyerhaeuser FMA, generated from equation [2a]. Estimated coefficients are shown in Table A3.

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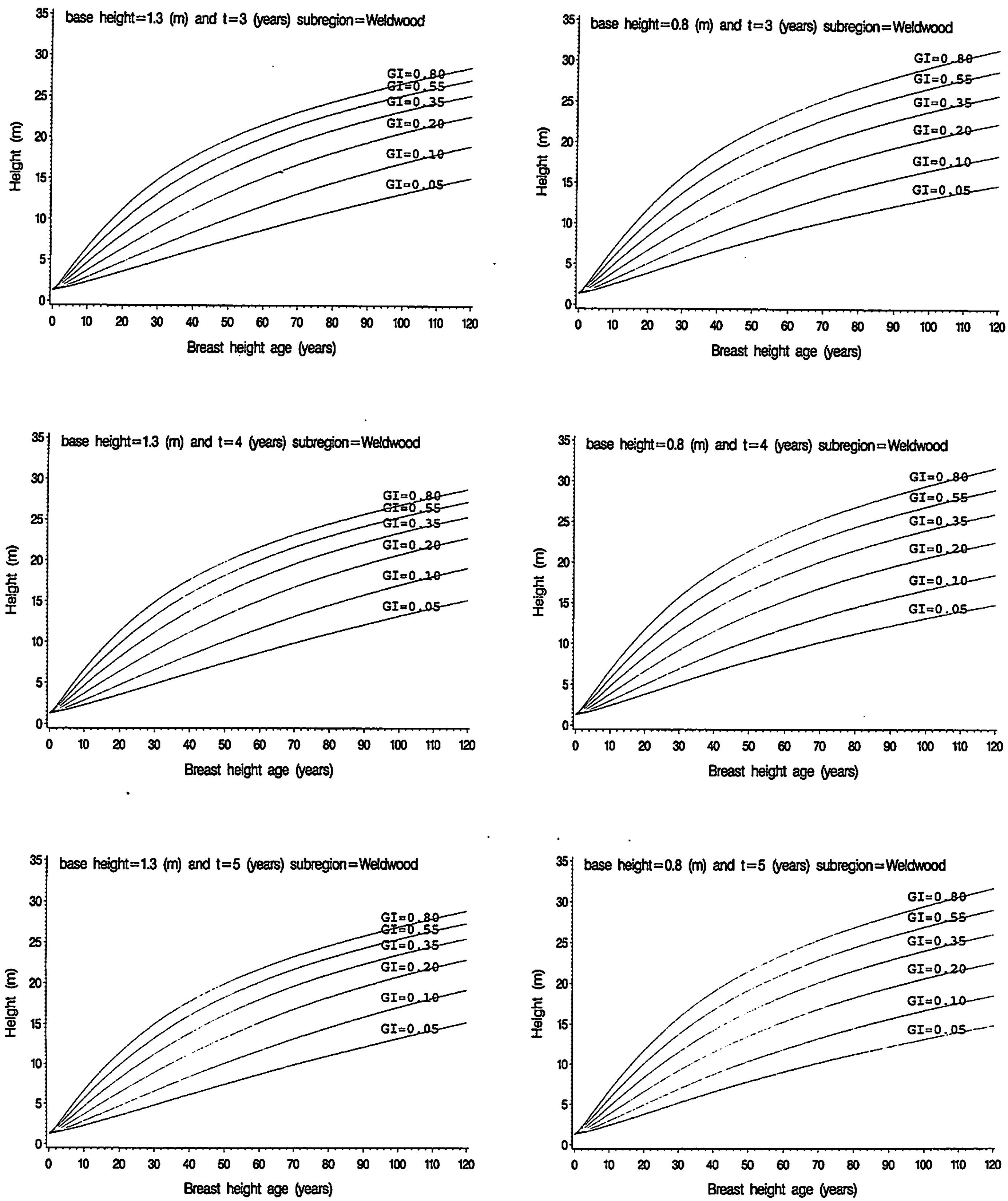

Figure A12. The growth intercept-based site index curves for the Weldwood FMA, generated from equation [2b]. Estimated coefficients are shown in Table A3.

Appendix 3.

Estimated Coefficients and Fitted Curves Based on Method III

This appendix provides:

Table A4.	The estimated coefficients, the root mean squared error (RMSE), and the coefficient of determination (R^2) for Method III (equation [3]).
Figures A13-A20.	Fitted site index curves overlaid on the original data.

Table A4. Fit statistics for model [3] based on different t and h_0 values.

Subregion	h_0 (m)	t (yrs)	Estimate b_0	Estimate b_1	RMSE	R^2	h_0 (m)	t (yrs)	Estimate b_0	Estimate b_1	RMSE	R^2
Provincial	1.3	1	21.681750	0.093682	2.941	0.350	0.8	1	22.601579	0.107399	2.832	0.397
		2	24.127641	0.138083	2.690	0.456		2	24.902862	0.150066	2.688	0.457
		3	25.382980	0.165213	2.645	0.474		3	25.968908	0.168170	2.544	0.513
		4	25.662611	0.171569	2.537	0.516		4	26.789100	0.183755	2.440	0.552
		5	26.548446	0.191076	2.468	0.543		5	26.915378	0.189375	2.401	0.567
	0.5	1	22.234089	0.091806	3.105	0.275	0.3	1	20.948051	0.065707	3.210	0.225
		2	24.172233	0.128226	2.920	0.359		2	23.276434	0.103398	2.922	0.358
		3	26.206234	0.163986	2.690	0.456		3	24.783039	0.131700	2.843	0.392
		4	27.233969	0.182667	2.549	0.511		4	26.487417	0.161605	2.656	0.469
		5	28.257048	0.202694	2.389	0.571		5	27.376038	0.179958	2.550	0.511
Lower Foothills	1.3	1	20.963641	0.053276	1.883	0.305	0.8	1	19.680201	0.028742*	2.146	0.097
		2	21.841637	0.071557	1.768	0.387		2	21.562134	0.065934	2.007	0.210
		3	22.568704	0.088510	1.777	0.380		3	22.212211	0.077377	1.905	0.289
		4	22.248101	0.083846	1.826	0.346		4	22.565200	0.085272	1.841	0.335
		5	22.485167	0.089592	1.879	0.307		5	22.726712	0.091372	1.829	0.344
	0.5	1	19.752537	0.026209*	2.172	0.075	0.3	1	17.974425	0.000025*	2.258	0.000
		2	20.672210	0.043678	2.114	0.123		2	19.765828	0.017642*	2.128	0.112
		3	22.210036	0.073266	2.014	0.204		3	20.183167	0.026719*	2.139	0.102
		4	22.886264	0.086692	1.943	0.259		4	21.028902	0.041461	2.088	0.144
		5	23.159700	0.094107	1.882	0.305		5	22.340991	0.064239	1.988	0.224
Upper Foothills	1.3	1	16.959374	0.015599*	2.300	0.078	0.8	1	18.833437	0.046372	2.051	0.266
		2	17.864132	0.027463*	2.201	0.155		2	19.938364	0.058251	1.970	0.323
		3	17.971904	0.029760*	2.195	0.159		3	19.944806	0.058767	1.926	0.353
		4	18.772350	0.041347	2.099	0.231		4	20.329778	0.064277	1.915	0.361
		5	18.501673	0.040232	1.936	0.223		5	20.518828	0.066800	1.897	0.372
	0.5	1	21.481559	0.082757	1.717	0.486	0.3	1	19.022412	0.040137	1.955	0.333
		2	20.473755	0.070587	1.860	0.396		2	20.922757	0.070229	1.746	0.468
		3	21.067248	0.078657	1.876	0.386		3	22.153090	0.090643	1.752	0.465
		4	21.827051	0.088186	1.793	0.439		4	22.102568	0.090307	1.792	0.440
		5	22.499354	0.097110	1.726	0.480		5	22.516900	0.095417	1.748	0.467
Sub-alpine	1.3	1	13.385304	0.040515*	1.952	0.149	0.8	1	12.957064	0.030507*	1.968	0.1349
		2	16.438409	0.094890	1.722	0.338		2	14.344356	0.058068*	1.827	0.2546
		3	19.170589	0.149606	1.554	0.461		3	15.019464	0.068273*	1.825	0.2562
		4	19.217991	0.147663	1.560	0.457		4	16.036757	0.085616	1.733	0.3294
		5	19.871633	0.159928	1.510	0.491		5	16.608979	0.096847	1.688	0.3637
	0.5	1	11.744819	0.012815*	2.086	0.028	0.3	1	13.242946	0.033038*	2.024	0.085
		2	12.713147	0.028328*	2.057	0.055		2	13.029701	0.029927*	2.023	0.086
		3	12.923081	0.031526*	2.031	0.078		3	13.058687	0.032024*	2.022	0.087
		4	13.506595	0.040913*	1.975	0.129		4	13.162406	0.033874*	2.019	0.090
		5	15.282263	0.070029*	1.870	0.219		5	13.555821	0.040807*	1.989	0.117

Note: * indicates an insignificant estimate at $\alpha=0.05$.

Table A4. Fit statistics for model [3] based on different t and h_0 values (continued).

Subregion	h_0 (m)	t (yrs)	Estimate b_0	b_1	RMSE	R^2	h_0 (m)	t (yrs)	Estimate b_0	b_1	RMSE	R^2
Weyerhaeuser FMA	1.3	1	22.636339	0.098198	2.805	0.461	0.8	1	23.228893	0.111050	2.711	0.497
		2	23.996168	0.124153	2.679	0.509		2	24.958523	0.144115	2.600	0.537
		3	24.566870	0.138241	2.619	0.530		3	25.851609	0.158255	2.475	0.580
		4	25.034651	0.148201	2.471	0.582		4	25.889147	0.158775	2.389	0.609
		5	25.686816	0.163284	2.400	0.610		5	25.800257	0.159342	2.343	0.624
	0.5	1	22.565547	0.092313	3.181	0.307	0.3	1	21.364658	0.067463	3.321	0.245
		2	23.426784	0.111610	3.060	0.359		2	22.982508	0.095774	3.019	0.376
		3	25.582197	0.149035	2.763	0.477		3	23.579430	0.109392	3.015	0.378
		4	26.763639	0.170141	2.582	0.543		4	25.615570	0.143361	2.753	0.481
		5	27.441943	0.182846	2.398	0.606		5	26.553577	0.162056	2.612	0.533
Weldwood FMA	1.3	1	19.352297	0.072855	3.032	0.161	0.8	1	19.869190	0.075107	3.005	0.176
		2	24.394451	0.163088	2.596	0.385		2	23.658936	0.140903	2.842	0.263
		3	28.326780	0.240709	2.546	0.408		3	25.298689	0.170145	2.649	0.360
		4	27.590339	0.227865	2.533	0.414		4	29.336335	0.243650	2.463	0.446
		5	29.021791	0.256716	2.479	0.439		5	30.842831	0.276583	2.397	0.476
		6	29.508347	0.268443	2.577	0.394		6	31.026176	0.282479	2.364	0.490
		7	30.257664	0.282830	2.607	0.379		7	30.719388	0.278965	2.414	0.468
		8	32.777481	0.332259	2.539	0.412		8	31.343499	0.293111	2.479	0.439
		9	35.042060	0.377299	2.440	0.456		9	32.077836	0.307884	2.499	0.430
		10	36.152826	0.402316	2.431	0.476		10	34.077192	0.348461	2.450	0.452
	0.5	1	20.244412	0.071332*	3.007	0.174	0.3	1	19.330135	0.051982	3.048	0.1519
		2	27.451113	0.185638	2.683	0.343		2	23.880223	0.117027	2.802	0.2834
		3	28.335155	0.205207	2.593	0.386		3	30.862684	0.225437	2.503	0.4279
		4	28.151499	0.205201	2.526	0.418		4	29.602241	0.216111	2.503	0.4282
		5	30.688515	0.252965	2.380	0.483		5	30.168305	0.230920	2.465	0.4452
		6	33.324764	0.302368	2.237	0.543		6	29.805329	0.228096	2.412	0.4690
		7	32.477537	0.294396	2.268	0.530		7	33.219095	0.290560	2.215	0.5521
		8	33.135232	0.310587	2.292	0.521		8	32.964317	0.291805	2.247	0.5389
		9	32.940615	0.306879	2.317	0.510		9	33.240556	0.301926	2.234	0.5442
		10	33.544036	0.320796	2.338	0.501		10	33.576260	0.309253	2.277	0.5269

Note: * indicates an insignificant estimate at α=0.05.

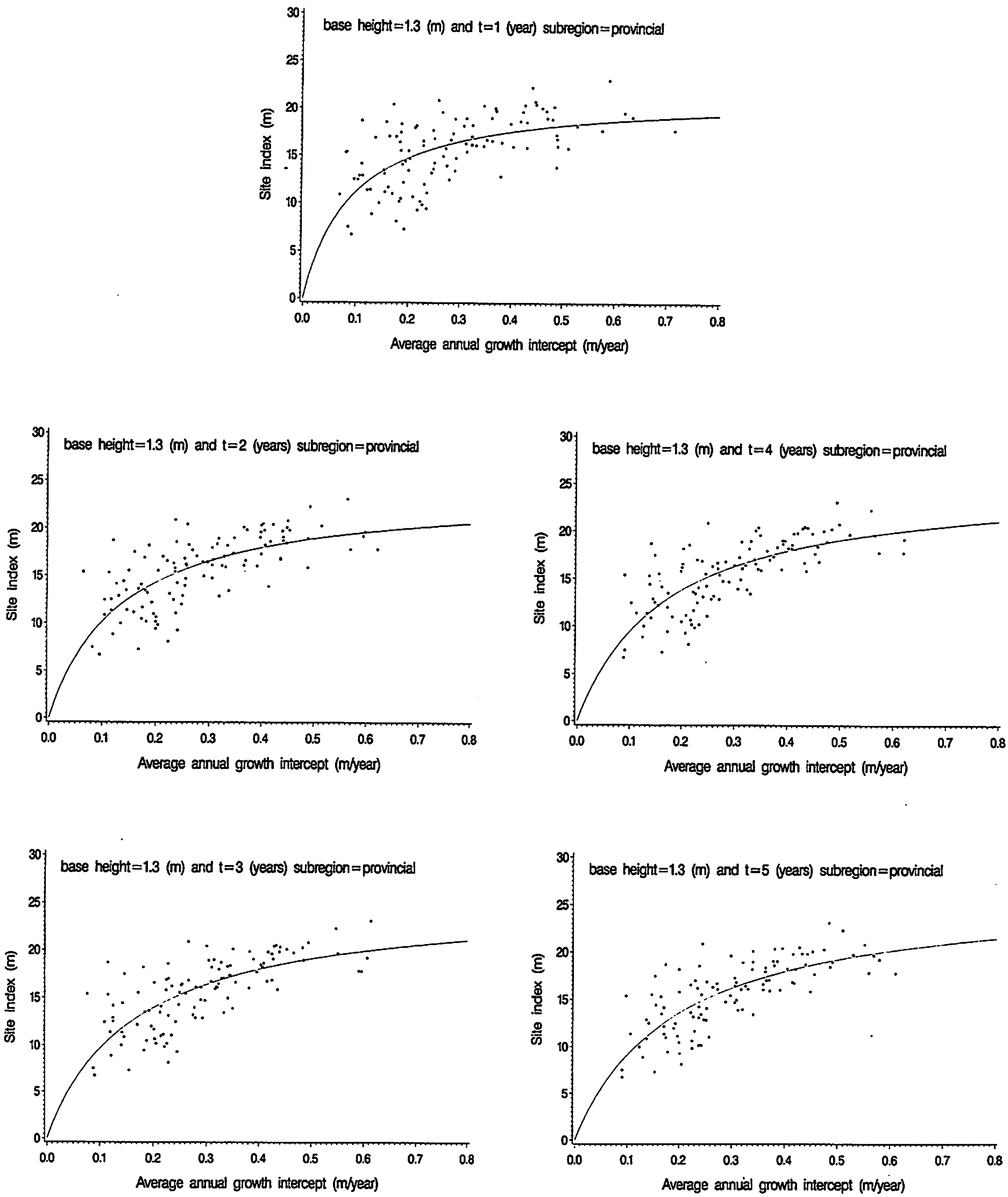

Figure A13. Fitted site index curves overlaid on the original data (subregion=provincial). The curves were generated using equation [3] with a base height of 1.3 m. Estimated coefficients for [3] are shown in Table A4.

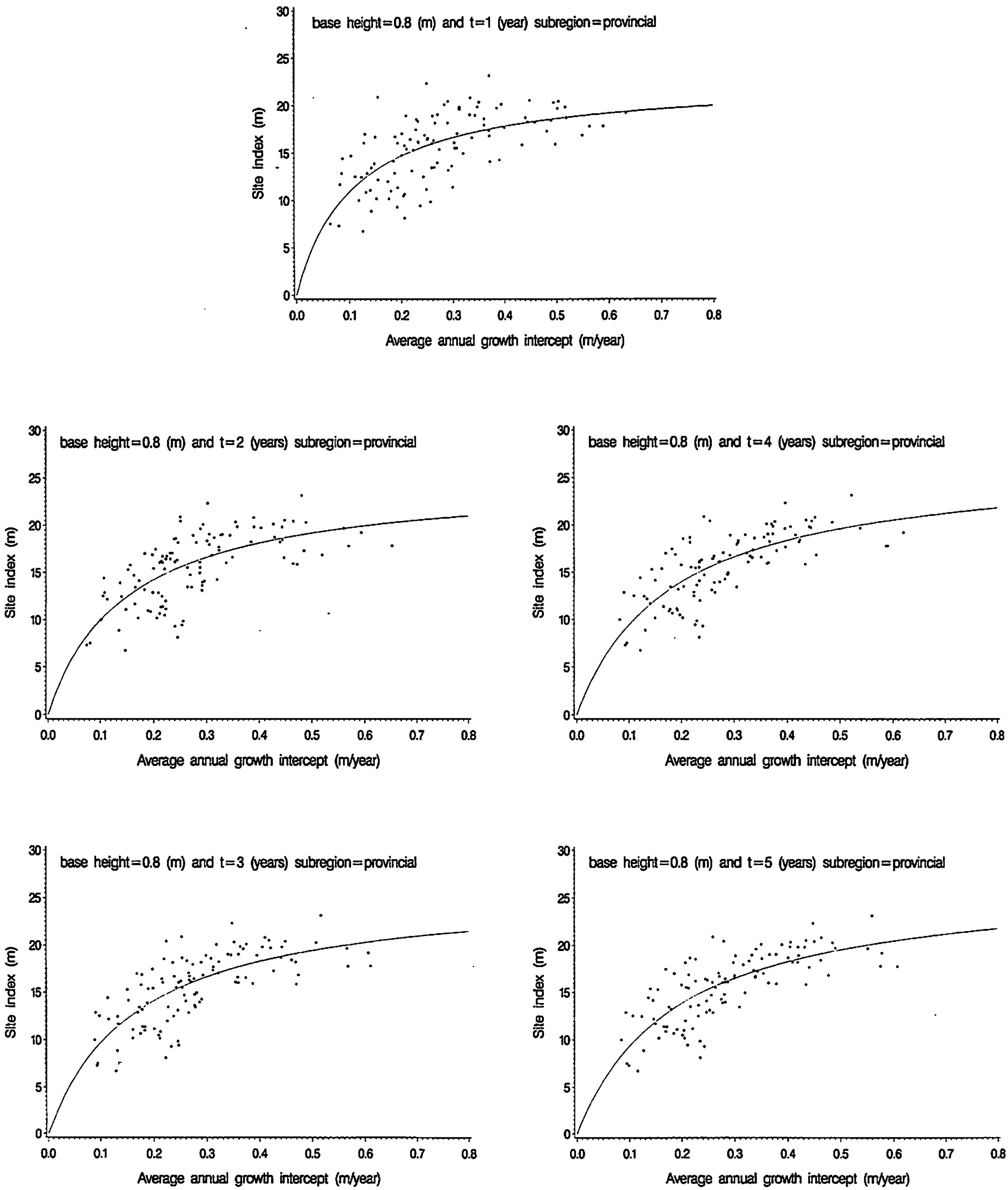

Figure A14. Fitted site index curves overlaid on the original data (subregion=provincial). The curves were generated using equation [3] with a base height of 0.8 m. Estimated coefficients for [3] are shown in Table A4.

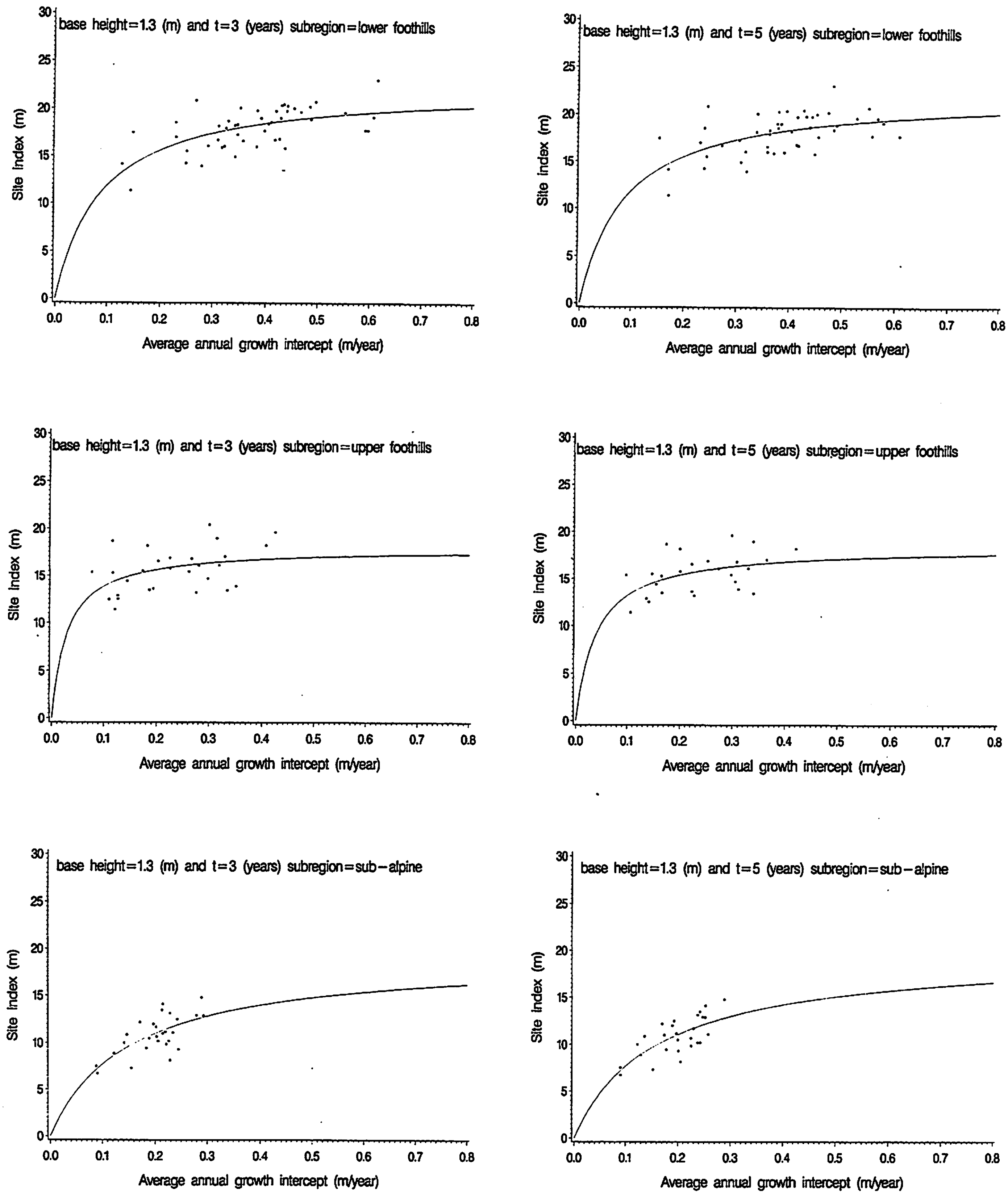

Figure A15. Fitted site index curves overlaid on the original data by natural subregions. The curves were generated using equation [3] with a base height of 1.3 m. Estimated coefficients for [3] are shown in Table A4.

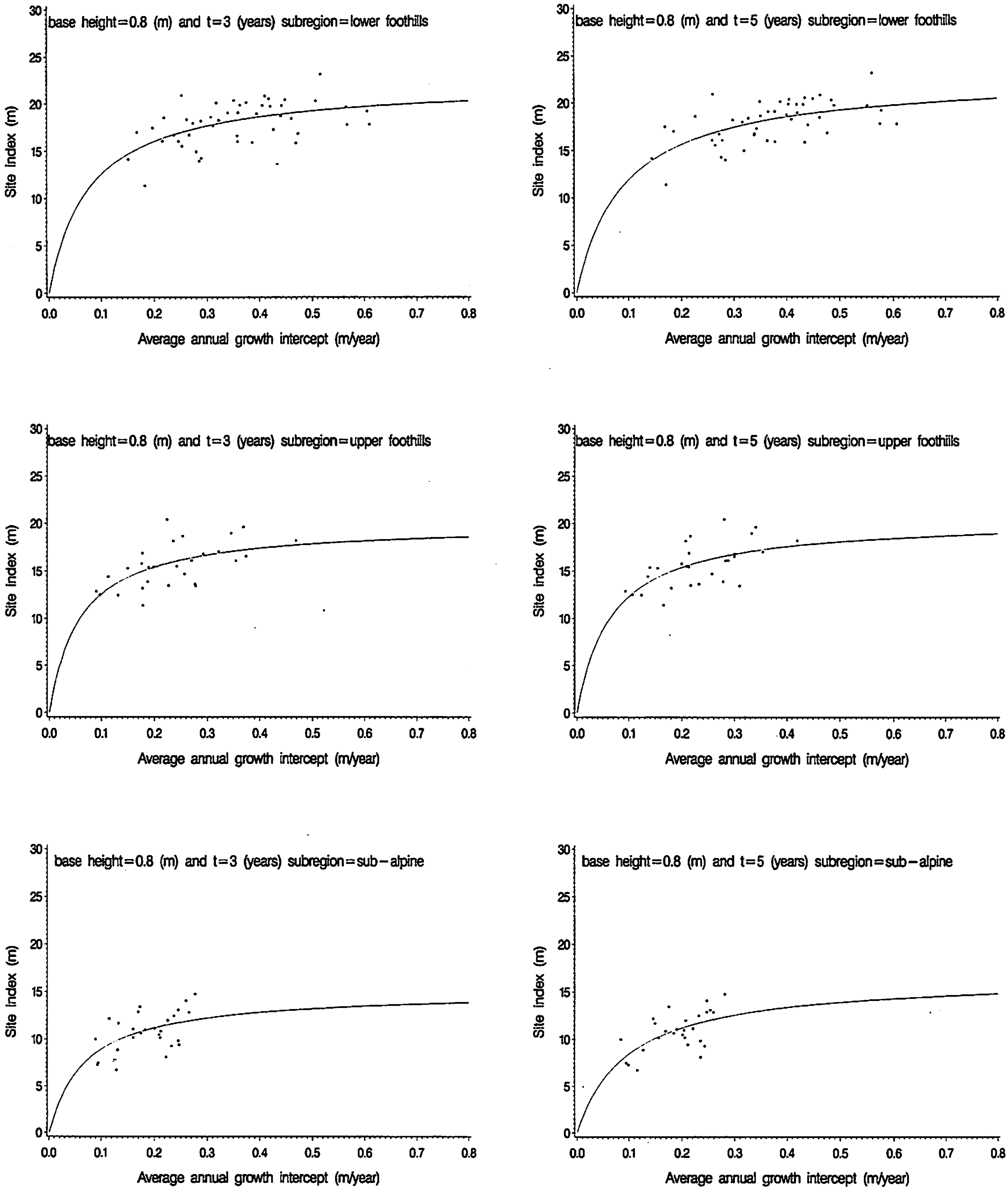

Figure A16. Fitted site index curves overlaid on the original data by natural subregions. The curves were generated using equation [3] with a base height of 0.8 m. Estimated coefficients for [3] are shown in Table A4.

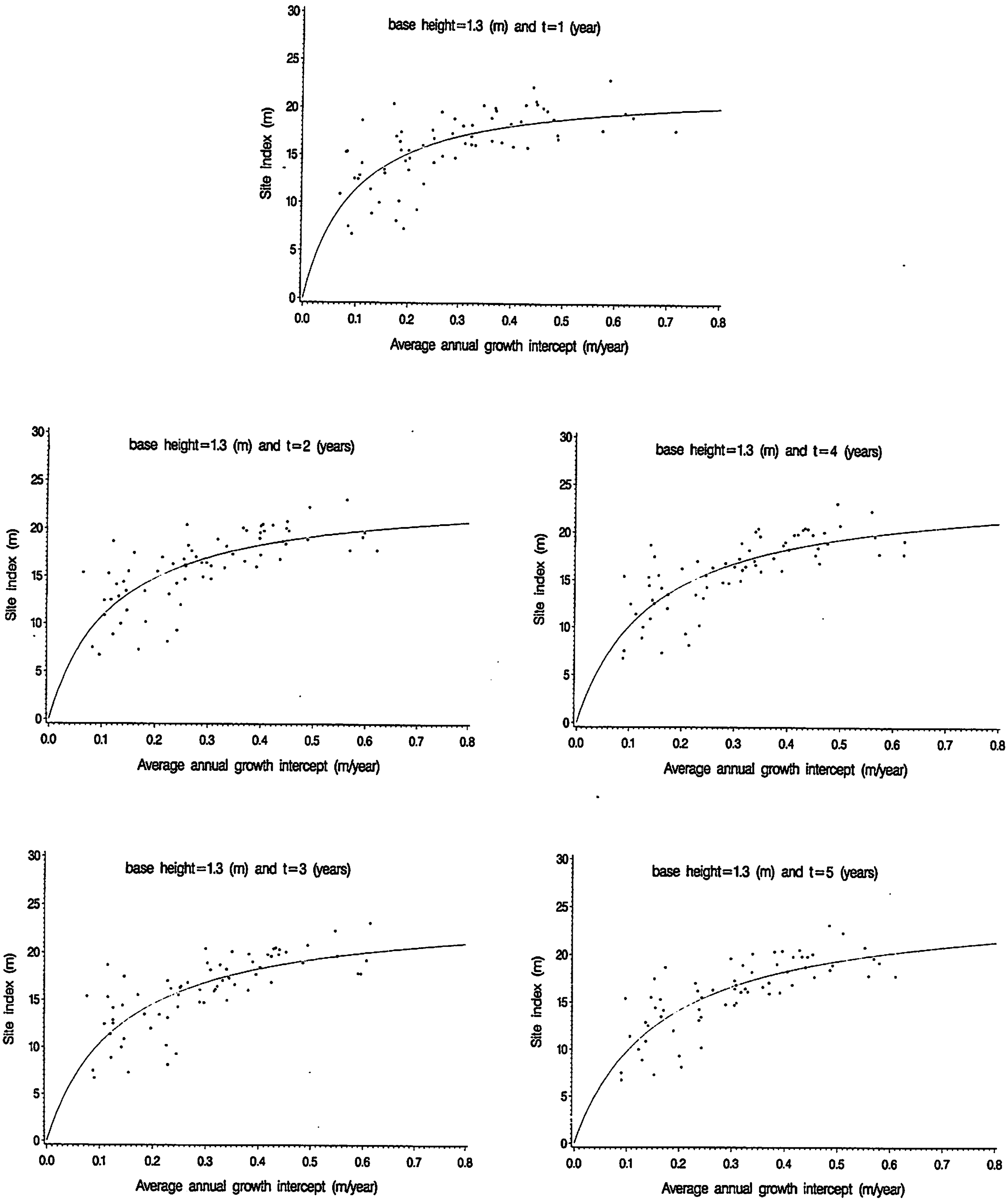

Figure A17. **Fitted site index curves overlaid on the original data for the Weyerhaeuser FMA. The curves were generated using equation [3] with a base height of 1.3 m. Estimated coefficients for [3] are shown in Table A4.**

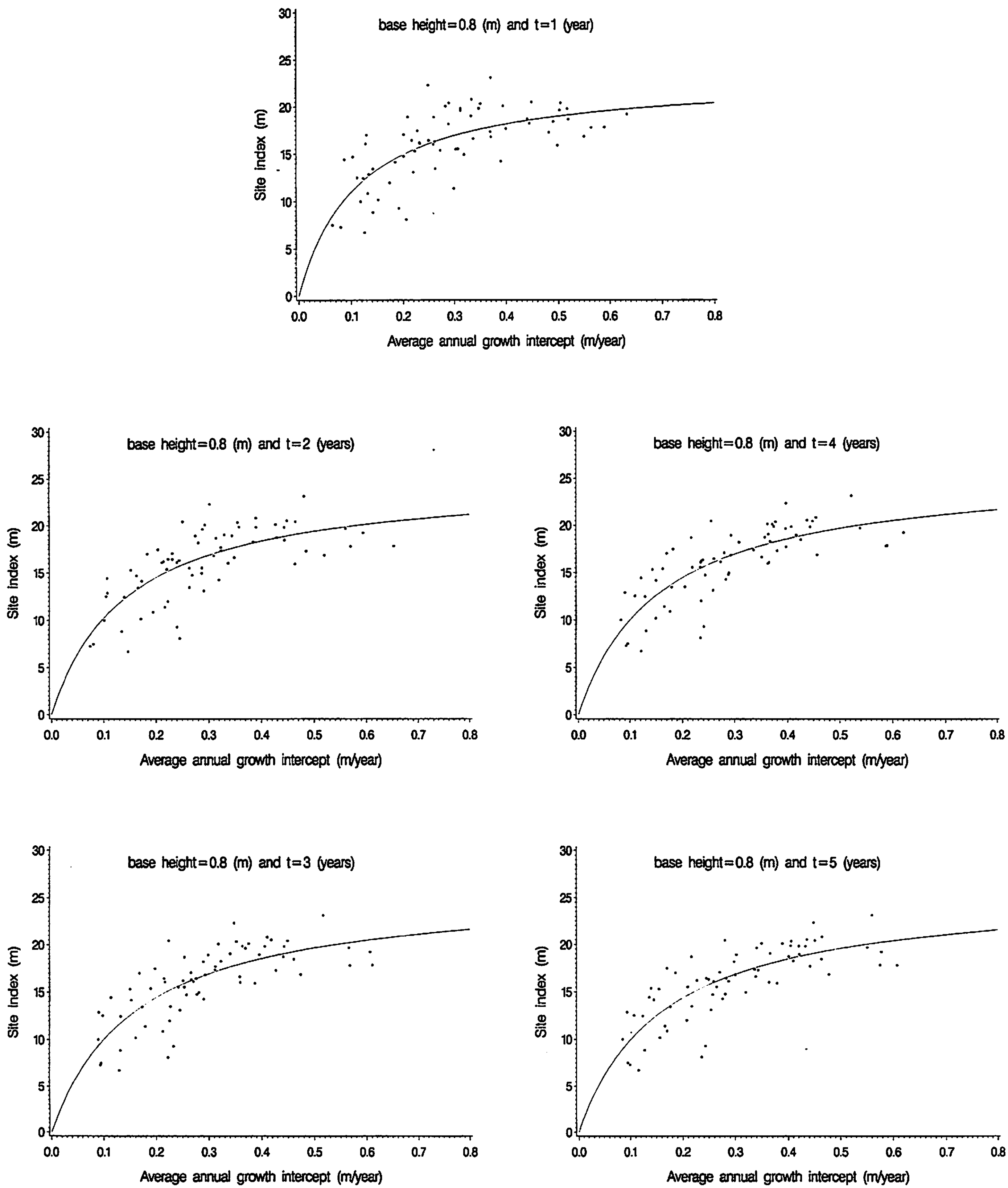

Figure A18. Fitted site index curves overlaid on the original data for the Weyerhaeuser FMA. The curves were generated using equation [3] with a base height of 0.8 m. Estimated coefficients for [3] are shown in Table A4.

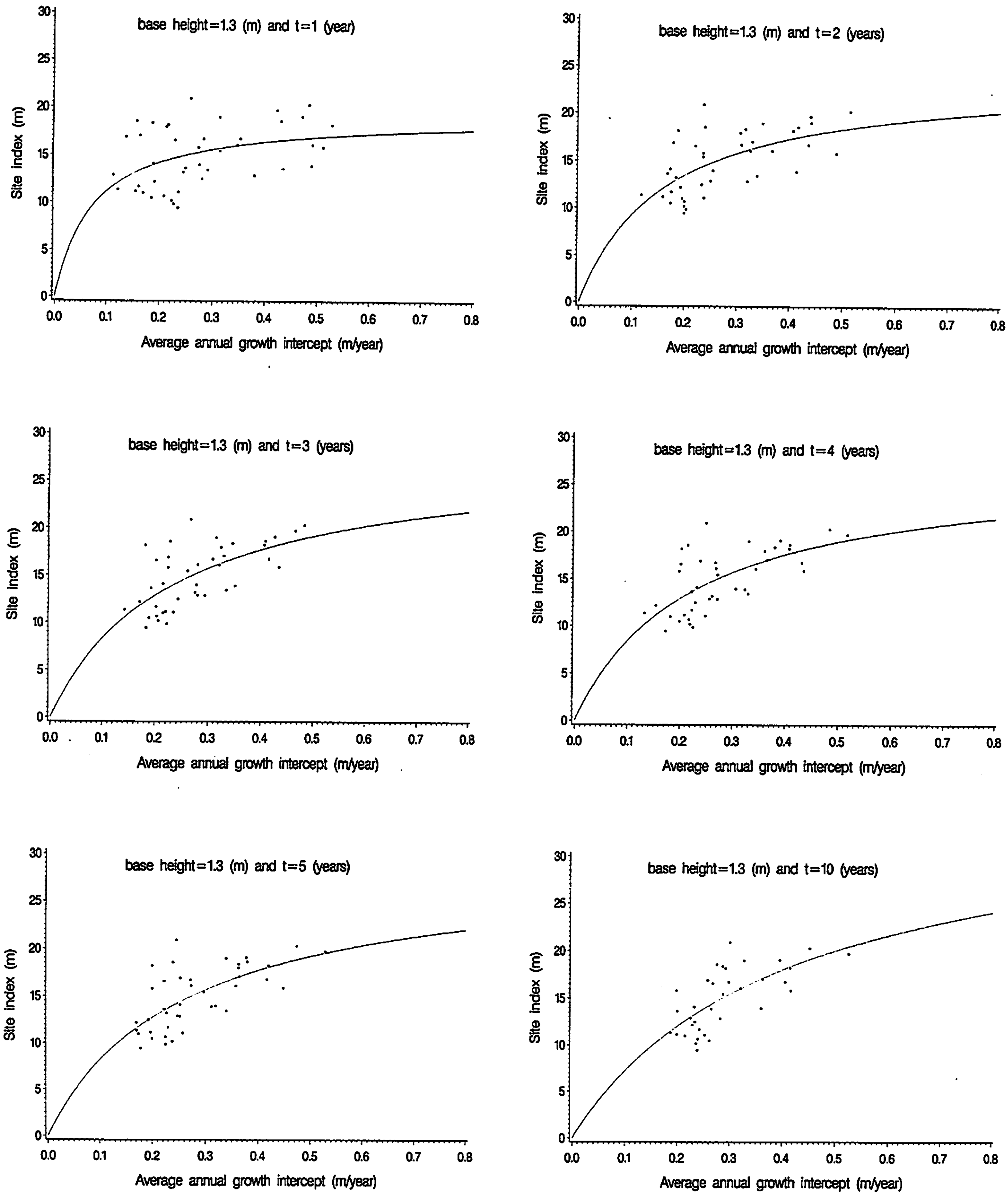

Figure A19. Fitted site index curves overlaid on the original data for the Weldwood FMA. The curves were generated using equation [3] with a base height of 1.3 m. Estimated coefficients for [3] are shown in Table A4.

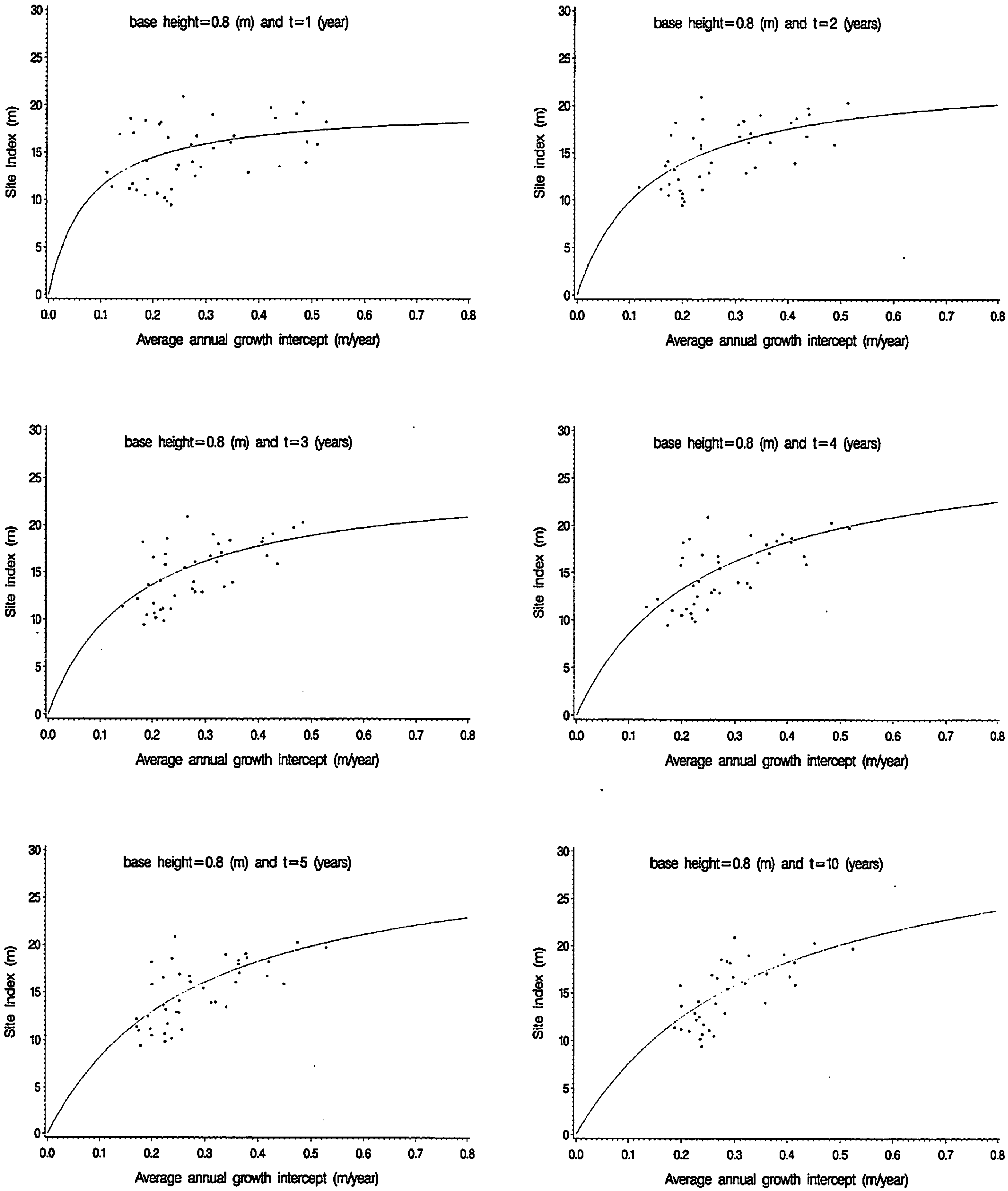

Figure A20. Fitted site index curves overlaid on the original data for the Weldwood FMA. The curves were generated using equation [3] with a base height of 0.8 m. Estimated coefficients for [3] are shown in Table A4.

Quote of the day:

I was asked the question: "Are we wasting trees and time by constructing these damned interminable site index curves?". I feel reluctant to say "Yes, It is time to damn all those antiquated site index curves and use only my growth types."

- Boris Zeide, Professor, University of Arkansas
In "To Construct Or Not To Construct More Site Index Curves?"
Western Journal of Applied Forestry 1994, 9(2): p.37.