Long-Term Trends in Height Growth of Jack Pine in North Central Ontario

J.C.G. Goelz and T.E. Burk

ABSTRACT. Although most investigations of long-term growth trends of trees involve description of radial growth of trees, investigation of height growth of dominant and codominant trees also warrants attention for two significant reasons-the dependent variable is largely independent of stand density and it represents an index of stand productivity. Residuals from a height growth equation for jack pine (*Pinus banksiana* Lamb.) were used to examine long-term trends in height growth. No consistent long-term trend was apparent; however, a period of superiorgrowth was identified during the 1960s. Short-term changes in climatic variables could account for a short duration of increased growth. As anthropogenic factors, such as air pollution, did not exhibit a trend coincident with the growth trend, they do not represent a reasonable explanation. An additional benefit of detailed examination of trends in residuals is the ability to uncover misidentification of models. The examination may suggest an inappropriate form for the equation was used, or may suggest that importantvariables are missing from the model. FOR. SCI. 44(1):158–164.

Additional Key Words. Anthropogenic factors, climate, dendrochronology, model identification, site index.

THE GROWTH RECORD PROVIDED by tree rings has been used as a phytometer to indicate the influence of climate or potential anthropogenic factors (Innes and Cook 1989). Tree growth in a given period is determined by genetics, ontogeny, initial size, competition, site quality, climate, and other, possibly anthropogenic, factors. For a given tree, genetics and site quality may be considered constant over time. All other factors vary over time. Most previous research has proceeded by removing the effect of one or more factors, then attributing any residual trend to a remaining factor or group of factors, either by graphical procedures or by expanding a model to include another predictor. The shape of the trend may indicate which factors are a likely cause. For example, a factor that consistently increases over time may be related to a residual trend that consistently increases and an abrupt change in growth may be caused by a specific event like hurricane or fire. Data for unaccounted-for factors may be poor or unavailable. Alternatively, raw growth data is graphed and irregularities are subjectively identified and possible explanations for the irregularities are offered. Several approaches have been taken to investigate long-term growth trends, but a consensus on the cause of observed growth declines has not been embraced by all; for example, there is considerable dissent regarding the growth decline in southern pines (Zeide 1992, VanDeusen 1992, Bechtold et al. 1991, Hyink 1991). Rather than actually testing hypotheses, most analyses result in a more formalized generation of hypotheses.

Tree rings provide several types of growth sequences (Duff and Nolan 1953). Typically only the radial growth record has been used to investigate long-term growth trends, although LeBlanc et al. (1987) and LeBlanc and Raynal (1990) used stem analysis to investigate growth trends in natural stand and plantation-grown conifers. Height growth of dominant and codominant trees is relatively independent of competition and even-aged stand dynamics. This provides a great advantage over radial growth; fewer variables need to be considered in modeling or subsequent investigation of residual trends. The resulting parsimony of a growth model will affect significance of predictor variables when the additional variables necessary to describe competition may be collinear with previously entered variables. Van Deusen (1990, 1992), and Reams and Peterson (1992), among others, have suggested that a growth trend they observed was caused by stand dynamics. However, their graphs do not provide direct evidence relating stand dynamics to the trends they observed. Rather, stand dynamics was a reasonable explanation, given the pattern of growth, and this factor overshad-

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owed any effect of pollution. As sufficient data were not available to remove the effect of stand dynamics, these researchers could not identify a lesser effect of pollution, if it existed. Van Deusen (1990) indicates that, while attributing a decline in radial growth of red spruce (*Picea rubens* Sarg.) to stand structure, "any other influential factors operating in these stands would be easier to uncover if stand structure effects were removed." By investigating height growth patterns of site index trees, at least one potentially confounding predictor variable is eliminated.

In addition, height growth of dominant and codominant trees is directly related to stand-level productivity. Site index is defined as the height, at a previously specified base age, of trees that have always been dominant or codominant and healthy (Carmean 1975). Loucks (1984) also suggested that site index should be used as a tool to investigate risk from acidic deposition. Goelz et al. (1988) suggested that height growth of dominant and codominant trees should be the preferred single measure of tree growth for investigating long-term tree growth.

Our objectives for this study are to: (1) investigate long-term trends in height growth of trees as an alternative to the typical investigations of long-term trends in radial growth; (2) provide a simple methodology comprising a suitable height-growth equation and plots of subsets of residuals, and (3) give an example using an existing data set for jack pine in northern Ontario.

Methods

We chose to use a stem analysis data set for jack pine (*Pinus banksiana* Lamb.) that is familiar to us. Jack pine is sensitive to sulfur dioxide (Davis and Wilhour 1976) and ozone (Davis and Gerhold 1976) and has intermediate tolerance to fluoride (Weinstein 1977). Holdaway (1990) found that sulfate deposition was more strongly related to growth of jack pine than 21 other species studied in the Lake States region. The trees harvested for this study occur in a relatively remote area in northern Ontario with very low deposition rates (Garner et al. 1989). Kelso et al. (1992) found that sulfate deposition and lake acidity peaked in the late 1970s in a similar area to the east of our study area. Emission rates are extremely low for oxides of sulfur and nitrogen (National Research Council 1983). Thus the results of this study may indicate potential effects of pollutants on a sensitive tree species at low levels of deposition.

Data collection is discussed more completely in Carmean and Lenthall (1989). Plots were located in north central Ontario; 109 plots were used for model estimation and an additional 32 plots were used for verification of the initial model. Each plot represents a different stand. Plots were subjectively selected to represent the range of site quality and soils in the region. Three to five jack pine trees were destructively sampled at each plot; trees were felled in 1981, 1983, and 1984. The trees were sectioned at the stump, at 0.75, 1.3, 2.0 m, and at 1 m intervals to 13 m and at 0.5 m intervals thereafter. Age at each section height was determined in the laboratory. Carmean's (1972) correction was used to estimate actual height at each section age. The individual trees on a plot were averaged into a single series of height-age pairs. The plot average was used to provide height measurements at 5 yr increments above breast height. Breast height age was used because early height growth is erratic and does not necessarily reflect productivity.

The data were used to fit a height growth equation that allows prediction of height at any age, given height at some other known age; specifics regarding the model are presented by Goelz and Burk (1992). Certain characteristics of the model were essential for application to the objectives of this paper. Base-age specific site index equations will produce a residual plot similar to an hourglass laid on its side when residuals are plotted against age-residuals will be small when age is close to base age. Preliminary efforts with the data set and the model of Carmean and Lenthall (1989) indicated that this artifact could potentially be misinterpreted, or could obscure, any real trends in the data. Thus no base-age specific site index equation is suitable for the purpose of this paper.

Given a set of stem analysis data from site index trees, as site index proceeds from low to high, the shape of the curves will change as well as their magnitude. Usually, trees with the lowest site index will evidence a flatter, more linear curve while trees with the highest site index will have a much more rapid approach to the asymptote; thus the curves for different site classes diverge for young trees, then tend to become parallel or converge at older ages. If individual curves are fit to relatively narrow classes of site index, most of the variability of curve shape across site will be recovered (Carmean 1972). However, if an equation is fit to data pooled across site index, the trend in curve shape across site index will be underestimated. Goelz and Burk (1992) indicated that this observation was a "regression towards the mean" phenomenon, although it is more appropriate to term it an "errors-in-variables" problem (Fuller 1987) as it results from the assumption that height at base age (site index) is measured without error. This problem could become important when subsets of residuals based on age and site index are plotted. Goelz and Burk (1992) used an ad hoc procedure in an attempt to remove the errors-in-variables problem.

Finally, for the purpose of this paper, autocorrelation and heteroscedasticity of the error term should be addressed so that the residuals are scaled appropriately regardless of age or site quality. Our methods for doing this are presented below, and in more detail in Goelz and Burk (1992). The residuals that we plot have been weighted and adjusted for autocorrelation.

The form of the model was based upon the Richards' (1959) equation. The equation form is represented by Equation (1).

$$\hat{H} = 1.3 + (H_1 - 1.3)\left(\frac{1 - e^{(-b_1 (H_1/A_1)^{b_2} A_1^{b_3} A_2)}}{1 - e^{(-b_1 (H_1/A_1)^{b_2} A_1^{b_3} A_1)}}\right)^{b_4} + e_{ij} \quad (1)$$

H_2 represents predicted height, H_1 represents predictor height, or site index, A_2 represents age at predicted height, A_1 represents age at predictor height, or base age, and the b_i are parameters. The procedure used to estimate the equation was designed to remove the effect of errors-in-variables (Goelz and Burk 1996). Nonconstant variance was corrected by weighting (Goelz and Burk 1992). Autocorrelation was addressed by expanding the error term of Equation (1) to Equation (2) (Goelz and Burk 1992).

$$e_{ij} = \rho e_{i-1,j} \gamma e_{i,\ j-1} + \varepsilon_{ij} \qquad (2)$$

The parameter ρ represents the autocorrelation between the current residual and $e_{i-1\ j}$ the residual from estimating the previous observation of H_2 using H_1 as a predictor variable. The parameter γ represents the relationship between the current residual and $e_{i,j-1}$, the residual from estimating H_2 using previous observation of H_1 as a predictor variable. Thus, given heights at 5 yr increments, if height is predicted at age 25 (i), from height at age 50 (j), then $e_{i-1,j}$ represents theresidual from predicting height at age 20 using height at age 50 as a predictor, and $e_{i,j-1}$ represents the residual from predicting height at age 25, using height at age 45 as a predictor. White noise is indicated by ε_{ij}. The form of Equation (2) was incorrect in Goelz and Burk (1992) and is correct here.

The weighted residuals were used to determine the presence of long-term trends in height growth. Residuals were plotted against year at the end of the 5 yr growth increment. As the age of the sample trees varies from 50 to 160 yr, year does not correspond to age across the entire data set. Equation (1) and minor modifications of equation (1) have subsequently been used on other data sets, and it fits them well (Payandeh and Wang 1994, Huang 1994, Huang et al. 1994).

Although the methodology of Goelz and Burk (1992) was intended to remove any trend in residuals related to the predicted or predictor height or age, this was only approximately achieved. Thus a pattern could be uncovered by plotting a subset of the residuals. The residuals are adjusted for autocorrelation and nonconstant variance and thus are unitless. If trends in residuals are consistent across all base ages, the results are much more compelling in suggesting long-term growth trends. If trends occur for only a subset of site quality, this may provide evidence regarding possible mechanisms for that trend. For example, if a long-term reduction in height growth was only observed for low site quality stands, then a factor that may more strongly affect such stands may be invoked as a possible cause. Thus, subsets of residuals defined by classes of H_1 (site index) and A_2 were plotted for a range of base ages.

Results

Residuals are plotted against year in Figure 1. The residuals are only those obtained using a base age of 50 yr. Residuals obtained from estimating height at base age were not plotted. A line was drawn through the data using the LOWESS algorithm of Cleveland (1979); LOWESS is a scatterplot smoother that uses locally weighted regression to specify a robust, nonparametric regression line. Although the line fluctuates. there is no consistent trend.

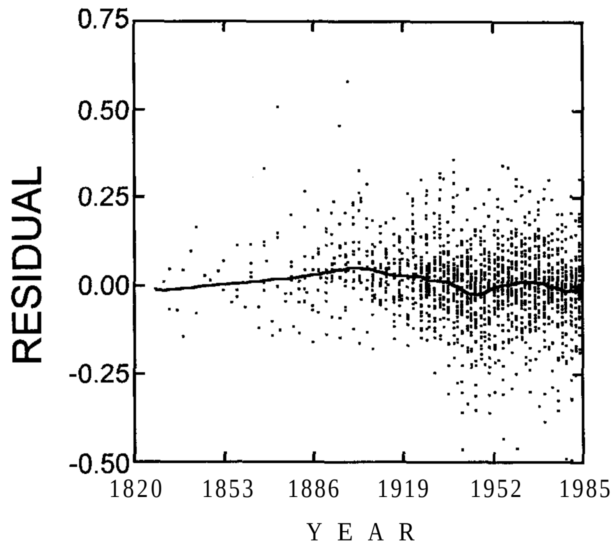

Figure 1. Residuals from fit of Equation (1). Only residuals for A_2 = 50 are plotted. Line is drawn by the LOWESS algorithm.

Residuals for subsets of A_2 at a base age of 50 are plotted against year in Figure 2. The lines are calculated with LOWESS. Figure 2a reflects A_2 = 20, Figure 2b reflects A_2 = 30, Figure 2c reflects A_2 = 40, and Figure 2d reflects A_2 = 60. In figures 2a-2d, there is a depression, or trough. When A_2 = 20 the trough is in the early 1940s, when A_2 = 30, the trough is in the early 1950s, when A_2 = 40, the trough is in the late 1950s to early 1960s, and when $A2$ = 60, the trough is in the late 1970s. These dates all correspond to A_1 occurring in the early 1970s. Thus the effect is of increased growth in the 5 yr period ending in the early 1970s, increasing the height at base age used to predict height at A_2, rather than decreased growth as represented by the troughs. In other words, the predictor variable is high, the predicted variable is not necessarily low. If the trough stayed in the same location as A_2 was increased, this would represent a fixed period of decreased growth. As the trough proceeds across the year as A_2 is increased, growth only appears to be depressed relative to a period of increased growth during a fixed period for A_1.

Residuals for subsets of A_2 for a base age of 25 are plotted against year in Figure 3. The plot for A_2 = 30 (Figure 3a) indicates a level trend that fluctuates. The plot for A_2= 40 (Figure 3b) indicates an upturn starting in the early 1960s. The upturn appears to begin in the early 1960s and continue to the most recent measurement for A_2 = 60 (Figure 3c).

Discussion

These figures indicate that a period of improved growth began some time after 1960 and extended for about a 10 yr period. An alternative explanation is that all trees that became 50 yr old during the early 1970s represented a subpopulation that was very different than the other trees in the data set. As those trees represent a broad range of site types, this is not likely. Although Figure 3c indicates a growth increase extending to the most recent measurements, this is likely indicative of increased growth over the immediately preced-

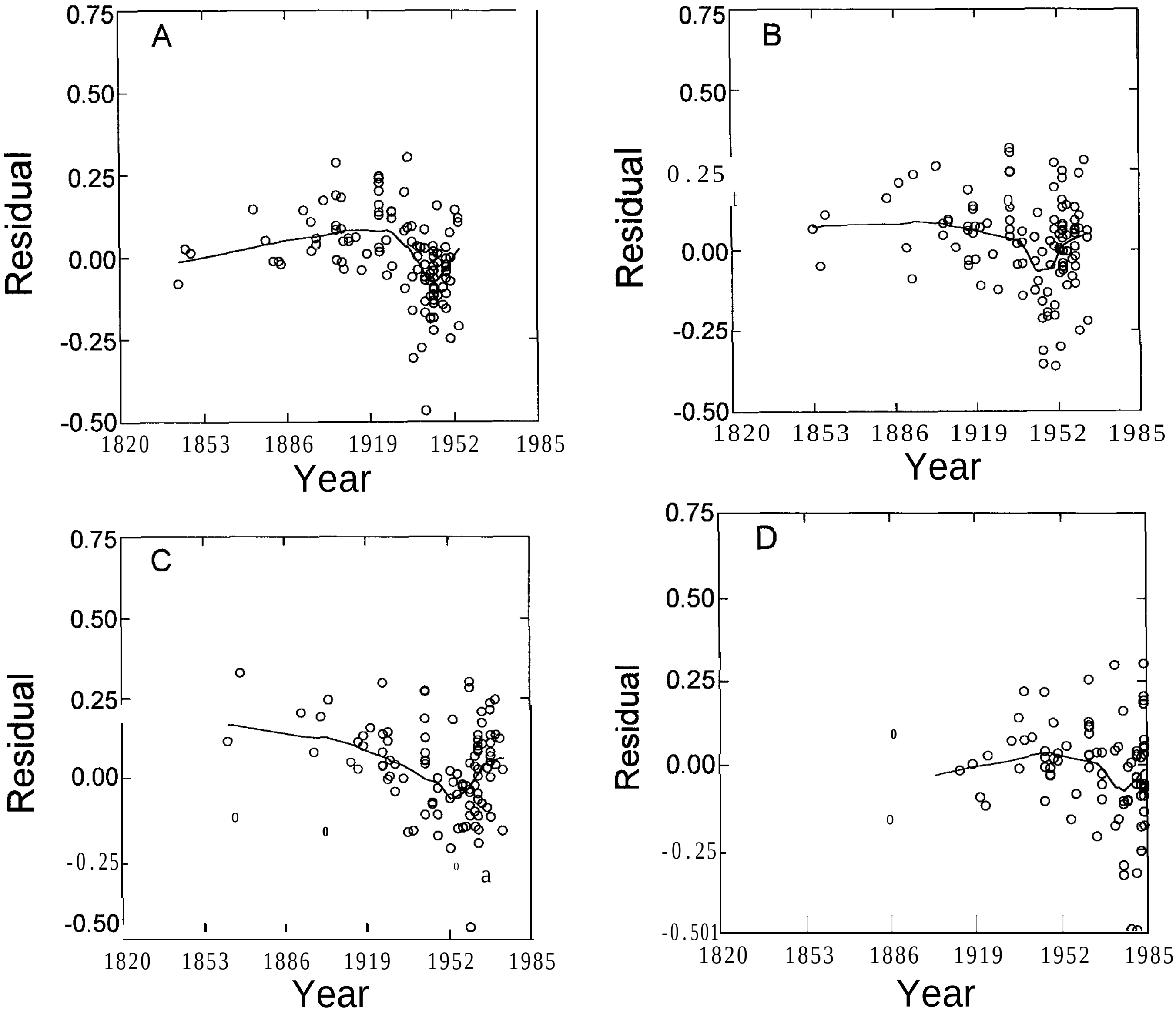

Figure 2. Subsets of residuals from Equation (1) with A, = 50: (2a) reflects A, = 20, 2b reflects A, = 30, 2c reflects A, = 40 and 2d reflects A, = 60. The lines are drawn by the LOWESS algorithm.

ing period. As the data consist of 5 yr growth intervals, it is impossible to precisely identify the timing of these increases; increased growth in any one year could result in higher growth rates for a given 5 yr period. Conversely, year-to-year fluctuations could potentially be averaged out. However, there does seem to be a discrete period of favorable growth although no continuous long-term trend was observed.

The description of long-term growth trends is done to determine whether the conditions of growth are changing over time. The assumptions of constant climate and absence of anthropogenic factors are implicit in all classical forest growth and yield modeling. The presence of a growth trend reveals an inadequacy of such models. Implicit in least squares estimation is the assumption that all factors not included in the model average out to provide a term that is identically and independently distributed as a $N(0, s)$. This is false for the jack pine height growth model; it is probably false for every model ever fit to biological data.

Thus, the model lacks some variables that influence height growth. Given that the model was lacking, emphasis shifts to describing what is lacking. As the only evident trend was a short period of increased growth, 1 or more years of favorable weather is a reasonable explanation for a short duration of increased growth. As anthropogenic factors, such as air pollution, do not exhibit a trend coincident with the growth trend-a discrete burst of pollutants of a few years' duration has not been observed for this region-they do not represent a reasonable explanation.

Although the height growth model of Goelz and Burk (1992) represents a biologically based model form and care was taken to minimize any trend in the residuals related to independent variables, another explanation for the observed pattern in the residuals could be that the model or the parameter estimation was intrinsically flawed. Such a flaw would likely be evident at the extremes of the growth series and a consistent trend would be evident in the residuals.

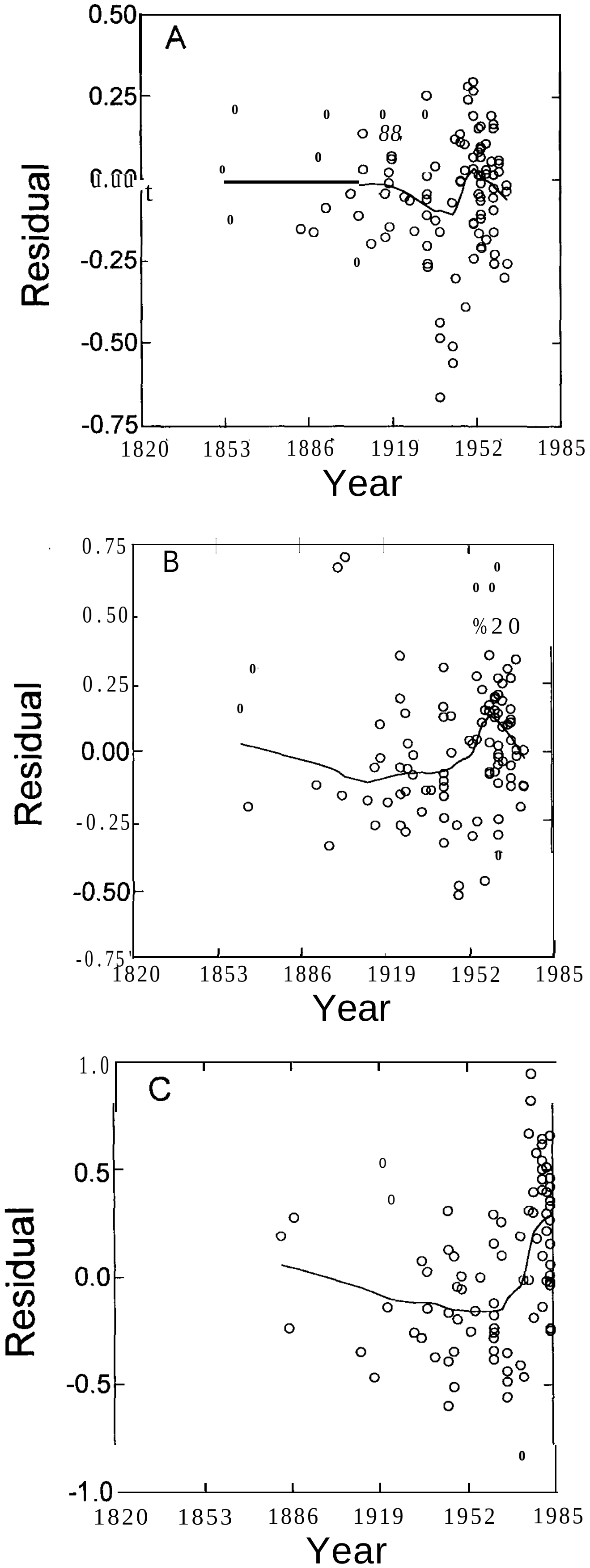

Figure 3. Subsets of residuals from Equation (1) with A_1= 25: 3a reflects A_2 = 30, 3b reflects A, = 40, 3c reflects A, = 60. The lines are drawn by the LOWESS algorithm.

Dependent on the form of the model, the trend could fluctuate, as the flawed growth trend might cross the true growth trend one or more times.

The effect of an inappropriate model is indicated in Figure 4. A data set was generated without error using arbitrary ages (10, 20, 30, 40, 50, 60, 70, 80, 90, 100 yr) and a Richards function model with parameter values that could reflect diameter growth. The periodic growth increments were fit to several simple models: quadratic and cubic polynomial, a power function and Hoerl's special functions (Daniel and Wood 1980; $Y = b_1 X^{b_2} c^{b_3 x}$). The power function fit most poorly (R^2 = 0.75, other models R^2 > 0.98). All of these functions produced a trend in the residuals when fit to the data generated by another model. As a true functional model describing tree growth is unknown and any model is necessarily an abstraction, a trend could be caused by the model selected. The model used in this article reflects biological theory and an estimation procedure intended to remove the trend caused by errors-in-variables. Another model may have produced consistent trends in residuals over time.

In the jack pine height growth example, there were two predictor variables: height at base age, and age. If several predictor variables are used in a model, the potential for a trend caused by a misidentified model increases. Thus a model must be rigorously tested before results are attributed to any missing variable. For example, the effects of stand dynamics may be removed from diameter growth (Bechtold et al. 1991). However, if the measure of stand density or stand dynamics does not enter the equation correctly, then an observed trend may be caused by a misidentified model. In the case of stand dynamics, numerous alternative measures of stand dynamics (basal area, number of trees, stand density index, stocking, stand age, species composition, among others) must be considered before the effects of stand dynamics may be considered to be removed. If multiple predictor variables enter the equation, they must enter in an appropriate way. As tree growth cannot be described by an analytic equation (an equation that conforms to known relationships or laws rather than to empirical or hypothetical relationships) and any model form is an abstraction, the effect of stand dynamics may only be approximately removed. Any apparent trend may be an artifact of the variable chosen, how the variable enters the equation, and other variables excluded from the model. Thus, the parsimony of site index equations is advantageous.

The investigation into long-term growth trends may thus be viewed as an exercise in model identification and verification, and not as a formal test of hypotheses. If a trend is evident, the model is lacking in some way. The form of the model may be improper, the estimation procedure may be inappropriate, or some factor may be missing from the model. All of these aspects of the model and data must be considered and one should not prematurely assume that a specific unmeasured factor is the sole explanation. If a factor is missing, identification and inclusion of the factor may be conducted or not, based on the expected use for the model and the availability of supplemental data.

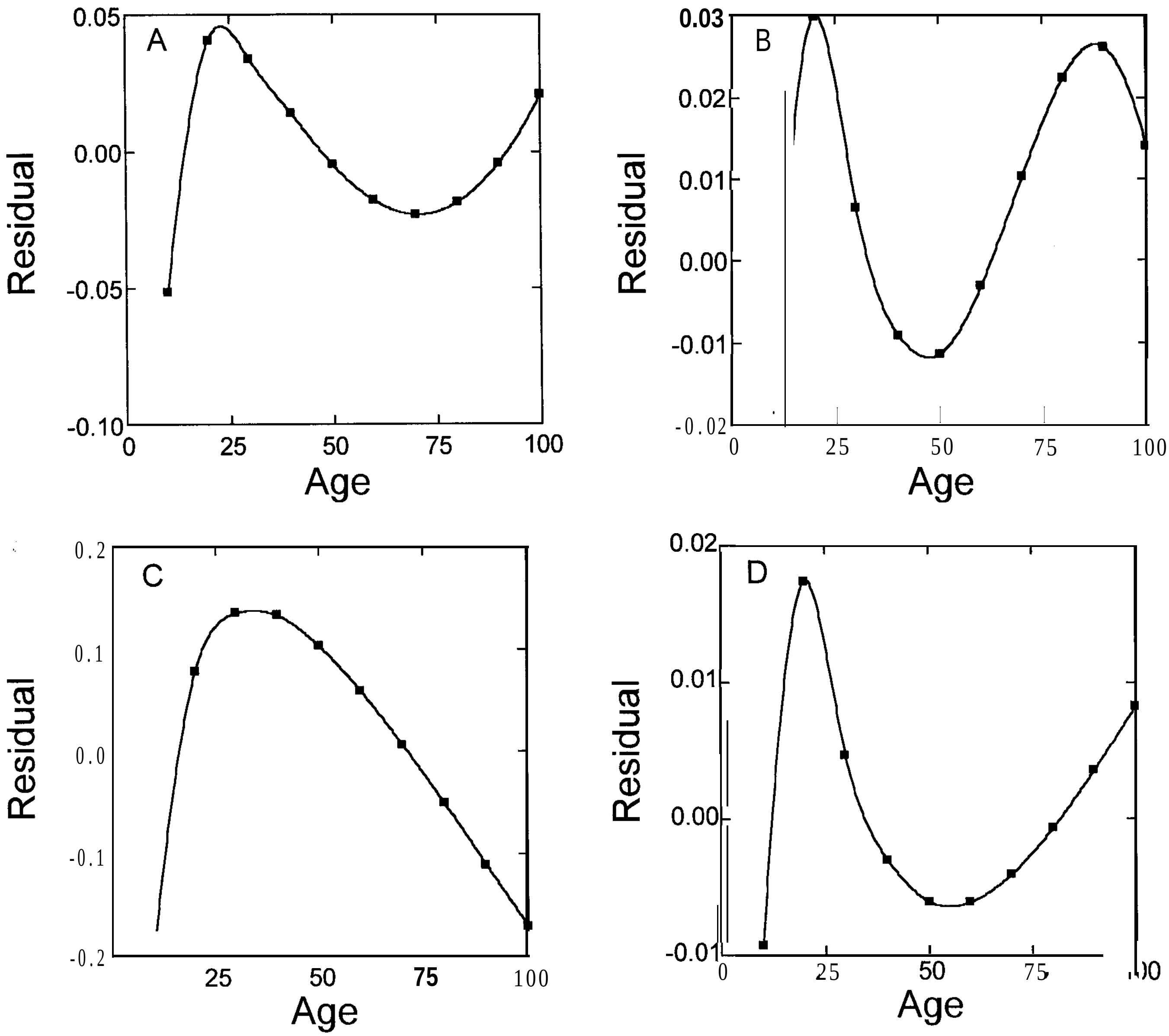

Figure4. Residuals obtained when data generated by a Richards'function are fit to alternative models: (a) quadratic polynomial; (b) cubic polynomial; (c) power function; (d) Hoerl's special function.

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