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GROWTH PREDICTION MODEL FOR *EUCALYPTUS* HYBRID IN INDIA

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The present study aimed to develop allometric equations and time series analysis for prediction of height and diameter at breast height (DBH) growth with age and density for clonal *Eucalyptus* hybrid in India. We measured height and DBH of *Eucalyptus* hybrid of genotype 3020 planted at three spacings up to 7 years and analysed stand stability of the tree against wind. Stand stability index increased as inter-tree spacing and age increased and was constant after the age of 5 years. The regression equation developed was highly significant and the adjusted coefficient of determination for the model was very high. The equation accounted for 95% variation in height and diameter calculated by the developed models with same age and spacing. Logistic growth curve model for time series analysis explained variation up to 93.8% in height and 93.3% in diameter. *Eucalyptus* plantation raised by macropropagation technique obtained stand stability after the age of 5 years. The regression models in its exponential form can be used effectively to predict the height, diameter and age at varied spacings. The developed growth models will help forest managers in the preparation of large-scale plantation logging inventories.

Keywords: Clonal plantation, stand stability, growth model, age, spacing

INTRODUCTION

Shrinking productivity of natural forests has highlighted the importance of plantations in meeting the global demand for wood and wood products, which could triple by 2050 (Hakamada et al. 2017). Among tree species used in forest plantations, *Eucalyptus* constitutes a large share of the world economy in relation to pulpwood, plywood and solid wood production (Dhakad et al. 2018). *Eucalyptus* was introduced in India in later part of the 18th century. Presently, it is estimated to be grown in over 3 million ha, about 80% of which is under agro/farm forestry. India has about 10% of the world's *Eucalyptus* plantation. Every year around 150,000 ha of *Eucalyptus* plantation is grown in India, creating employment in rural areas (Juhari 2017).

Forest managers are constantly faced with challenges to make decisions regarding the choice of species, clone/variety and planting density for biomass production. All major management decisions require information on growth and yield at the different spacings for the sustainable management of forests. Policymakers would generally use a growth and yield model to depict regional and national trends such as sustainable harvest level or carbon sequestration potential to set effective policies. These estimates would also help forest management meet the demand–supply ratio.

The imperative measure for tree and stand stability in temperate trees against snow and in broadleaved trees in the tropics against wind velocity and wind pressure is a ratio of height and diameter (Vospernik et al. 2010). Height:diameter ratio is a good predictor of snow and wind damage whereas live crown ratio is not. Variations in height:diameter ratio is largely the result of plant density and age (Wonn 1998). Plantation architecture and tending operations consistently show that inter-tree spacing is inversely correlated to height:diameter ratio. Supplementary growing space provided through initial thinning allows remaining trees to maintain rapid diameter growth, thus increasing taper (Dimitri & Keudell 1986, Wonn & O'Hara 2001). Highest height:diameter ratios are observed in open-grown trees and trees at minimum stand density. Wide spacing or early thinning is the best way to reduce ratio of height and diameter. Later thinning is not as effective as heavy thinning done early during stand development because the response of stand declines with age (Dimitri & Keudell 1986, Wonn & O'Hara 2001).

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Height growth is one of the most characteristic biological feature of a tree. It is generally accepted that tree height depends not only on age, diameter and species but also on planting density and site quality (Petras et al. 2014). The estimation of tree volume and stand dynamics heavily relies on accurate height–diameter models. Height is usually defined by regression models, where tree height is the function of its diameter (Mehtatalo et al. 2015). A number of tree height–diameter models have been developed for tropical and temperate tree species (Fang & Bailey 1998, Loopez-Sanchez et al. 2003, Temesgen et al. 2007). These height–diameter models can be used to predict missing tree heights from measured diameter at breast height (DBH, 1.37 m above the soil surface) and indirectly predict height growth (Larsen & Hann 1987, Huang et al. 1992, Hann 2006). Accurate prediction of tree height and DBH is essential for forest inventory, model simulation and stand management (Zhang et al. 2014). Height–diameter models were initially defined using simple mathematical functions, such as polynomial function (Naslund 1929), fractional polynomials (Michailoff 1943) and the exponential functions (Freese 1964). Tree- and stand-level variables (as predictors) were used in regression model for estimation of standing tree growth (Wykoff 1990, Zhang et al. 2004).

Little is known about height:diameter ratios and susceptibility of clonal eucalypts plantation to wind damage. With advanced laser scanning technologies, tree diameter and age can be predicted using remotely-sensed tree height for simulation of tree growth. The present study was, therefore, aimed at: (1) working out height:diameter ratio for stand stability in *Eucalyptus* hybrid plantation against wind firmness, (2) estimating the growth potential of genotype 3020 *Eucalyptus* hybrid with different planting density up to its rotation, and; (3) developing future prediction models for height and diameter with respect to age and plant density.

MATERIALS AND METHODS

Study area

The field experiment was set up in April 2008 at Punjab Agricultural University Ludhiana, India (30° 45' N, 75° 40' E; 274 m above mean sea level) (Figure 1). The site experiences subtropical semi-arid climate with four distinct seasons, namely, autumn (February to March), hot and dry summer (April to June), hot and humid monsoon (July to September), and winter (October to January). The site receives 500–750 mm rainfall annually, which is not evenly distributed and most of it (i.e. 75–80%) is received from July to September. The soil has developed under semi-arid condition. The soil is sandy loam to clayey with a normal reaction (neither acidic not basic). The alluvial soil of the central zone has slight alkalinity and salinity problems (Singh et al. 2017).

Field sampling and growth measurements

Eucalyptus hybrid (genotype 3020) with three spacings, namely, 3 m × 3 m (S_1), 3 m × 4 m (S_2), and 3 m × 5 m (S_3) were used in this study with six replications in a randomised complete block design. Spacing S_1 is taken as control to achieve maximum profitability and wood growth for pulp and energy plantation. In total, we evaluated 540 trees (30 trees (plot size) × 3 planting densities × 6 replications). Growth rates were determined from tree height and DBH measured every year in March up to its rotation of 7 years. Statistical analysis was carried out using SAS Version 9.4. The significance of fixed effects was tested using *F* test. Interaction and distribution for height and diameter at different spacing and age was analysed. From the individual tree data output, we obtained the averages for height and DBH of trees grown at all three spacings. Height:diameter ratios (dimensionless) were calculated for all spacings by dividing mean tree height (m) by the mean DBH (cm) of selected trees every year till rotation age.

Growth prediction models for height and diameter growth

Before establishing the allometric equation, scatter plots were used to see whether the relationship between independent and dependent variables was linear. Algometric relationship between the independent and dependent variables were tested through linear regression statistics. Independent variables were age and spacing while the dependent variables, height and DBH. Model comparison and selection were based on average deviation,

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Figure 1 Location of study site in Ludhiana, Punjab, northern India

slope coefficient of the regression, Akaike information criterion, confidence interval of the predictions and paired *t*-test. Coefficients of determination more than 90% are reported in this paper and taken to be the criteria for best fit of the model. The average deviation was computed from the absolute difference between predicted and observed height and DBH (Basuki et al. 2009).

Response variable Y was predicted by a polynomial function of explanatory variable X. We estimated the intercept (a) and slope of line (b) using the following formula:

$$Y_i = a + bX_i \qquad (1)$$

where, a and b = scaling coefficients, Y = height (m) or/and diameter (cm), and X = predictive variable corresponding to time (years or referred as age; for this study i = 1, 2, 3,...., 7). Linear regression models were created separately using tree height and DBH as independent variables.

The relationship between the two measured height and DBH, was expressed here as linear allometric function through regression model with the exponential form:

$$Y = a \times (X)^b \qquad (2)$$

Allometric equation that compensates for the linear function is given below:

$$\text{Log}(Y) = \log(a) + b[\log(X)] \qquad (3)$$

The residual, its standard error, and the studentised residual (residual divided by its standard error) are presented for each observation.

Logistic growth curve model for time series data

Time series analysis presents data summary and description, model development and parameter estimation, and prediction of a future value (i.e. forecasting). Time series regression was carried out using PROC MODEL. The ordinary least squares procedure was used for parameter estimate of single linear regression. The model

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used current values of the dependent variables as functions of past values of the dependent and independent variables. These past values were referred to as lagged values, and the variable x_{t-i} was called lag i of the variable x_t. Using the tree data, we fitted the following equation given by Erdman and Little (1998):

$$Y_t = a\ lag_1(Y) + b\ lag_2(Y) + c \quad (4)$$

$$Y_t = a\ (Y_{t-1}) + b\ (Y_{t-2}) + c \quad (5)$$

where, a, b and c = scaling coefficients, Y = height (m) or/and diameter (cm), and X = predictive variable corresponding to time (age in years).

According to this equation, height or diameter (denoted by Y) for year 't' was linearly related to the height/diameter 1 and 2 years ago. The correlogram, partial correlogram and inverse correlogram were the plots for auto-, partial and inverse correlation functions respectively. These correlation functions are used to detect non-randomness in data and to identify the appropriate time series model (Box & Jenkins 1976). Autocorrelation was calculated in the context of a single variable measured annually between any two measurements, Y_s and Y_t, on a single parameter in a sequence of measurements Y_1, Y_2, ... ,Y_n. Plant height and diameter were expected to be serially correlated because unusually vigorous or poor growth in one year tended to carry over to the next year. Partial correlation measured the linear dependence of one variable after removing the effect of another variable that affected both variables. Time-series methods assumed that the data were equally spaced in time. Therefore, the following discussion was limited to equally spaced series (i.e. the measurements y_1, y_2,... ,y_n were made at times $t_0 + d, t_0 + 2d, ... , t_0 + nd$, where d = fixed interval between observations.

RESULTS

Tree growth and stand stability

Height increment in the first year was highest at 71.18% in S_3 over S_1 spacing and in the seventh year, the height increment in S_3 over S_1 spacing was 3.48% (Table 1). Compared with S_1 values,

Table 1 Observed tree values and simulation of height:diameter ratio

Year	Spacing	Height			Diameter			Height:diameter ratio
		Mean	Increment (%)*	SD	Mean	Increment (%)*	SD	
1	S_1	2.88	0	0.39	1.10	0	0.06	262.12
	S_2	3.57	23.95	0.44	1.32	20.00	0.03	270.89
	S_3	4.93	71.18	1.44	1.48	34.55	0.04	334.46
2	S_1	5.83	0	0.88	3.38	0	0.15	172.41
	S_2	6.56	12.52	0.44	3.87	14.50	1.38	169.51
	S_3	7.07	21.27	0.41	4.83	42.90	0.18	146.21
3	S_1	9.13	0	0.88	5.47	0	0.10	167.07
	S_2	9.57	4.82	0.44	6.48	18.46	0.17	147.56
	S_3	10.23	12.05	0.44	7.87	43.88	0.08	130.08
4	S_1	10.33	0	0.88	8.17	0	0.66	126.53
	S_2	10.97	6.20	0.44	9.18	12.36	0.33	119.49
	S_3	11.23	8.71	0.44	9.50	16.28	1.06	118.25
5	S_1	12.97	0	0.64	11.00	0	0.73	117.88
	S_2	13.28	2.39	0.44	11.52	4.73	0.69	115.34
	S_3	13.55	4.47	0.41	12.20	10.91	0.98	111.07
6	S_1	13.47	0	0.66	12.40	0	1.04	108.60
	S_2	13.67	1.48	0.62	13.10	5.65	1.03	104.33
	S_3	14.05	4.31	0.84	13.92	12.26	1.39	100.96
7	S_1	15.25	0	1.00	14.48	0	1.45	105.29
	S_2	15.55	1.97	0.75	14.53	0.35	1.35	107.02
	S_3	15.78	3.48	0.88	14.92	3.04	1.81	105.81

Values are replicated means of all individuals; N = 6; *increment (%) over S_1 spacing; SD = standard deviation; S_1, S_2, S_3 = 3 m × 3 m, 3 m × 4 m and 3 m × 5 m respectively

DBH increment at spacing S_3 in the first year was 34.55% and it increased to 43.88% in the third year but decreased in seventh year to 3.04% (Table 1). *Eucalyptus* hybrid stand was prone to wind damage in early age of plantation due to higher height:diameter ratio (334.46). Height:diameter ratios were lowest in the sixth year at S_3 (100.96) and at S_1 (105.29) in the seventh year (Table 1). These results indicated that annual growth rate was higher for plant height at initial age with low density (S_3 spacing) due at intense competition for light among individuals. Plantation architecture and spacing trial consistently showed that height:diameter ratio decreased as inter-tree spacing increased. Interaction and distribution of observed height and diameter for this genotype 3020 *Eucalyptus* hybrid are depicted in Figure 2.

Growth prediction models for height and diameter growth

Height and diameter significantly increased with plantation age and spacing. Prediction of height and diameter using the spacing and age in this study can be made near to observed values for the *Eucalyptus* hybrid (Table 2). The model *F* statistic was significant ($F = 2419.77$, $p < 0.05$) indicating that the model accounted for significant portion of variation in height and diameter. The r^2 value indicated that the model accounted for 95% of the variation for both data (Figure 3). Regression equations developed were highly significant based on 7 years growth observations. An increase in height was supported by highly significant p values which reflected the significant of *t* values calculated for height and DBH for all spacings. DBH showed a reverse trend from height with respect to spacing. Annual increases in height and DBH at S_1, S_2 and S_3 spacings were 2.01, 1.92 and 1.78 m, and 2.28, 2.29 and 2.24 cm, respectively (Table 2). Height decreased at different spacings because in trees, height growth was faster in the seedling phase and thereafter diameter growth started increasing in the pole stage onward.

Plots of the fitted relationship for each fit confirmed the ability of a function to adequately describe the mean configuration of the data. The fitted model and residual plots for calibration for both growth components are shown in Figure 3. Assumptions of constant error variance were not desecrated in the plot of residuals against predicted values and quantile for each fit for both height (Figure 3a) and DBH (Figure 3b). These figures also depicted and validated the resulting models compared with the individual fit in terms of fitted model and residual distribution.

The fit diagnostics for height and diameter indicated that plots of residual and studentised residual versus predicted value exhibited no obvious pattern (Figure 3). The plot of studentised residual versus leverage did not show outlying data points. Only a few points were outlined. However, the plot of Cook's D distance versus observation number revealed that few points were just the data points for the endpoint growth parameters. These points showed up as apparent outliers because the deviation of the linear model from the underlying quadratic behaviour in the data showed up most effectively at these endpoints. The developed model successfully forecasted the performance of the dependent variable through points on the plot of the dependent variable versus the predicted values that were located along the 45° line.

The normal quantile plot of the residuals and the residual histogram for height and diameter were stable with the assumption of Gaussian errors (Figure 3). This occurred as the residuals with the quadratic behaviour were confined by the developed linear model. The plot of the dependent variable versus the predicted value demonstrated a quadratic form around the 45° line that represented an ideal fit. The residual–fit plot, including the quantile plots of the centered fit and the residuals, illustrated that curve was centered fit. For inappropriate models, the spread of the residuals was often greater than the spread of the centered fit. In this case, the residual-fitted plot showed that the linear model confined the increasing trend in the data and, hence, accounted for much of the variation in the response.

Logistic growth curve model for time series data

Logistic growth curve model statistics of linear regression for time series data are presented in Table 3. There are 7-year observations as the tree species rotation was 7 years for pulpwood in the tropics and the model was single linear, so significance tests on the parameters had great importance. The significance tests and associated probabilities indicated that all parameters were

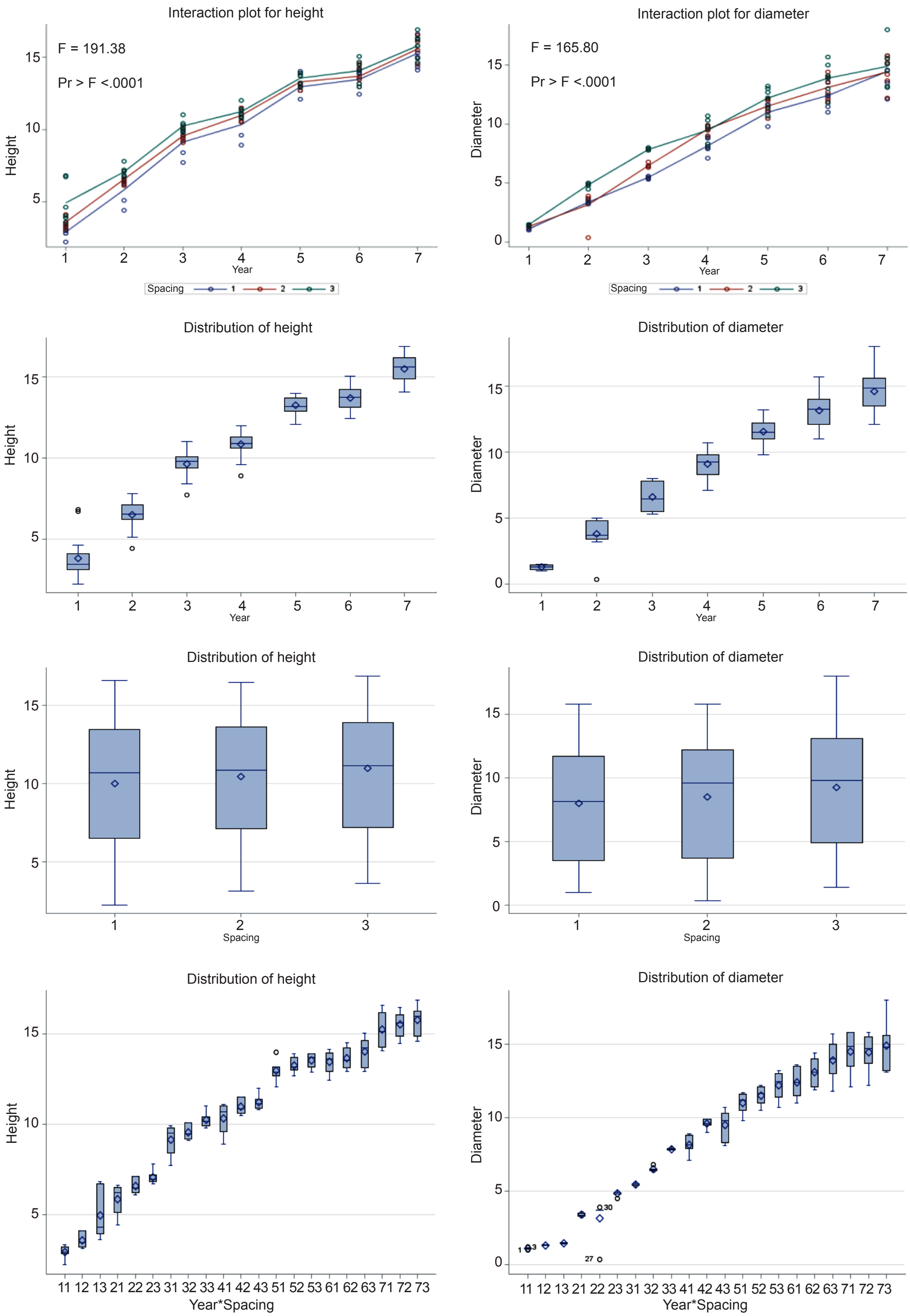

Figure 2 Interaction and distribution of observed height and diameter for *Eucalyptus* hybrid for different spacing

Table 2 Regression statistics for consecutive growth periods

Parameter	Spacing	Regression equation	CV	CGR	|t| value
Height (H)	S_1	H = 1.95 + 2.01T	44.32	28.52	4.68**
	S_2	H = 2.76 + 1.92T	40.55	24.82	4.95**
	S_3	H = 3.86 + 1.78T	35.59	20.17	6.27**
DBH	S_1	DBH = -1.10 + 2.28T	61.60	48.28	4.84**
	S_2	DBH = -0.66 + 2.29T	58.52	45.93	4.60**
	S_3	DBH = 0.27 + 2.24T	53.09	40.33	3.89*

S_1, S_2, S_3 = 3 m × 3 m, 3 m × 4 m and 3 m × 5 m respectively, CV = coefficient of variation, CGR = compound growth rate, T = time (age in year), |t| = *t* value; * denotes the significant values ($p < 0.05$), ** denotes highly significant values ($p < 0.01$)

significantly different from zero. The model fits the data well as the adjusted coefficient of determination value indicated 93.67% of the variation in height and 93.28% in diameter. Height increased significantly with a regression coefficient of 0.748 for S_1 and non-significant for S_2 and S_3 spacing. However, only S_3 spacing was found non-significant for diameter growth.

Figures 4a and c showed residuals, actual values, predicted values, Cook's D plot and quantile–quantile plots. The residuals were not independent and the model could be modified to describe the remaining non-random errors. The residuals were identically normally distributed only for height. Cook's D distance versus observation number revealed that few points were just data points for initial point height and endpoint diameter. Thus, we concluded that the model was adequate for the change in growth series, and there was no point in trying more complex models. Figures 4b and d were more useful in depicting the model fit. These autocorrelation function plots illustrated the degree of correlation with past values of the series as a function of the number of periods in the past (i.e. the lag) at which the correlation was computed.

DISCUSSION

Tree height and DBH of *Eucalyptus* hybrid were affected by plant spacing and age (Table 1). In the earlier years, individual tree attained height growth much faster than diameter growth but the reverse trend was observed in later ages. An experiment at one site over the course of a single year does not provide statistically based insights into other years and locations. However, the patterns of growth in relation to plant spacing were so clear that we expected trees in other years and locations would show similar trends. A similar study was carried out in two plantations, i.e. *Eucalyptus saligna* in New South Wales, Australia and an unthinned plantation of *Eucalyptus grandis* in Coffs Harbour, Australia (Borough et al. 1978) which were planted at 2.4 m × 2.4 m (1740 trees per ha). After 15 years, the diameters for *E. saligna* and *E. grandis* was 18.0 and 19.7 cm respectively.

Height:diameter ratios are an important measure of stand stability. Tree stability becomes jeopardised when height:diameter ratios exceed a threshold level of 80:1 although some variations may occur within species (Wonn 1998). Near to this threshold value, trees are relatively stable and protected from wind damage (Wonn 1998). In the present case, height:diameter ratio reached near to threshold level in the sixth and seventh years for different spacings, which were rotation ages for pulp production. Plantation was more susceptible to wind damage as height:diameter ratio increased. Height:diameter ratio was primarily a function of spacing, allowing for the control of stand stability through density management. To effectively maintain height:diameter ratios below threshold levels throughout stand development, wide spacing should be encouraged early during stand development. Similarly, a decrease pattern of height and diameter ratios with increasing age and an increase in stand density were reported when using different models (Wonn 1998, Vospernik et al. 2010). Therefore, variations in height and diameter ratio were largely a result of spacing.

Tree growth models employ linear regression to describe the change in the size/response variate with respect to explanatory variate. The use of the linear model is very common in forestry/agroforestry. These models provide the

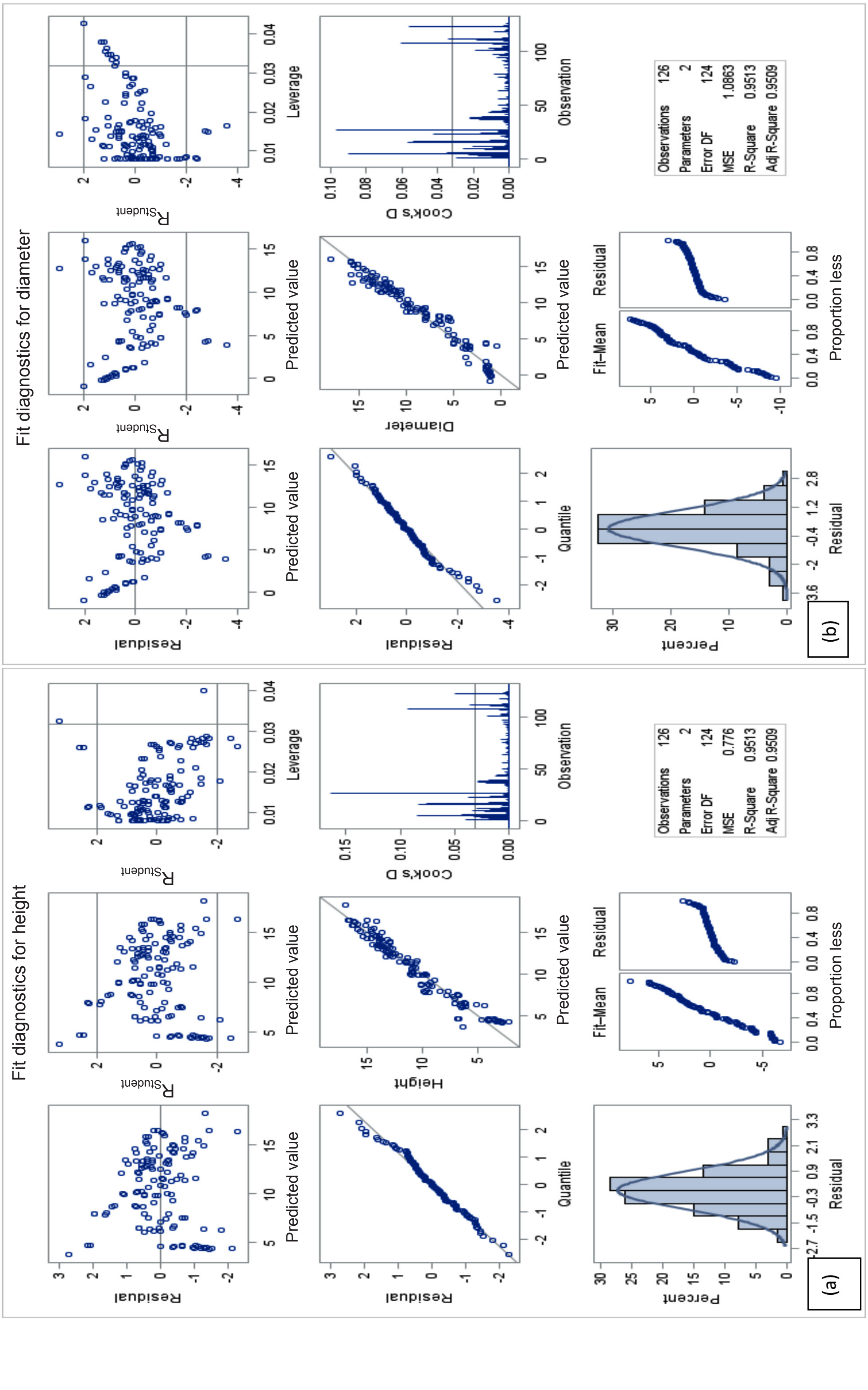

Figure 3 Panel of diagnostics plots and fit plots of linear regression for (a) height and (b) diameter (DBH); DF = degree of freedom, MSE = mean squared error, R^2 = coefficient of determination

Table 3 Logistic growth curve model estimates for time series data

Linear ordinary least squares summary of residual errors							
Equation	DF model	DF error	SSE	MSE	Root MSE	R^2	Adj R^2
Height	3	121	118.0	0.9749	0.9874	0.9367	0.9356
DBH	3	121	177.9	1.4705	1.2126	0.9328	0.9317

Linear ordinary least squares parameter estimates					
	Parameter	Estimate	SE	t	Pr > |t|
Height	S1	0.748634	0.0887	8.44	<.0001
	S2	0.218258	0.0881	2.48	0.0146
	S3	0.474979	0.2551	1.86	0.0650
DBH	S1	0.572583	0.0833	6.87	<.0001
	S2	0.400268	0.0831	4.81	<.0001
	S3	0.395696	0.2303	1.72	0.0883

DF = degree of freedom, SSE = sum of squared errors of prediction, MSE = mean squared error, R^2 = coefficient of determination, S_1, S_2, S_3 = 3 m × 3 m, 3 m × 4 m and 3 m × 5 m respectively, SE = standard error, |t| = t value

mathematical building blocks for simple and complex biological growth. Once these statistical assumptions are fulfilled, the linear model may be used for predictive purposes. In this study, we developed linear growth curve models separately for height and DBH. The model developed using height and diameter alone was found to be the best predictor for *Eucalyptus* tree, owing to high coefficient of determination. Similar studies were also conducted for biomass and volume estimation of other trees, e.g. Alamgir and Al-Amin (2008) in forest vegetation, Sharma (2009) in *Pinus roxburghii*, Sapkota and Meilby (2009) in *Shorea robusta*, Ajit et al. (2011) in *Populus deltoides* and Dong et al. (2016) in *Pinus koraiensis* and *Larix decidua*.

The common methods for estimating height–diameter models have taken the classical (frequents) approach based on the frequency interpretation of probability. The functions describing comprehensive and accurate relationships of height–diameter may incorporate additional variables describing stand density (e.g. stand basal area or number of trees) and site quality (e.g. site index) (Temesgen & Gadow 2004, Newton & Amponsah 2007). Height–diameter equations are crucial for estimating vertical forest structure, biomass and carbon storage. If height–age and DBH–age linear allometric models are available, it will be easier to estimate height or DBH on the basis of plantation age as height data collection is costly and time consuming. This may facilitate researchers to work out the area under plantation of varied ages which will help to manage the supply of raw materials from *Eucalyptus* hybrid plantations. This may also help in preparation of plantation logging inventories at large scale in *Eucalyptus* hybrid plantations in the Indian subcontinent. Thus, the models used in this study are the best feasible method to study the relationship of height and DBH with age and planting density for future growth predictions.

CONCLUSIONS

The growth of *Eucalyptus* hybrid trees is fast and height:diameter ratio is near to the 80:1 threshold value at rotation age among different spacings. This ratio was evidence of wind firmness required in tropical and subtropical climates. All predictive models developed in the present study gave better fit with high determination of coefficients for all plant densities. Height growth increased significantly with a regression coefficient of 0.748 at S_1 and non-significant at S_2 and S_3, while DBH significantly increased at S_1 and S_2. Time period explained 93.67% of the variation in height and 93.28% in DBH of observed population. Therefore, it was concluded that regression models could be used effectively to predict diameter and plantation age for the preparation of large-scale forest inventories using advanced airborne laser scanning technologies for height measurement. The developed equations could be used for a more accurate estimate of timber volume (growing stock) in public and private plantation in tropics.

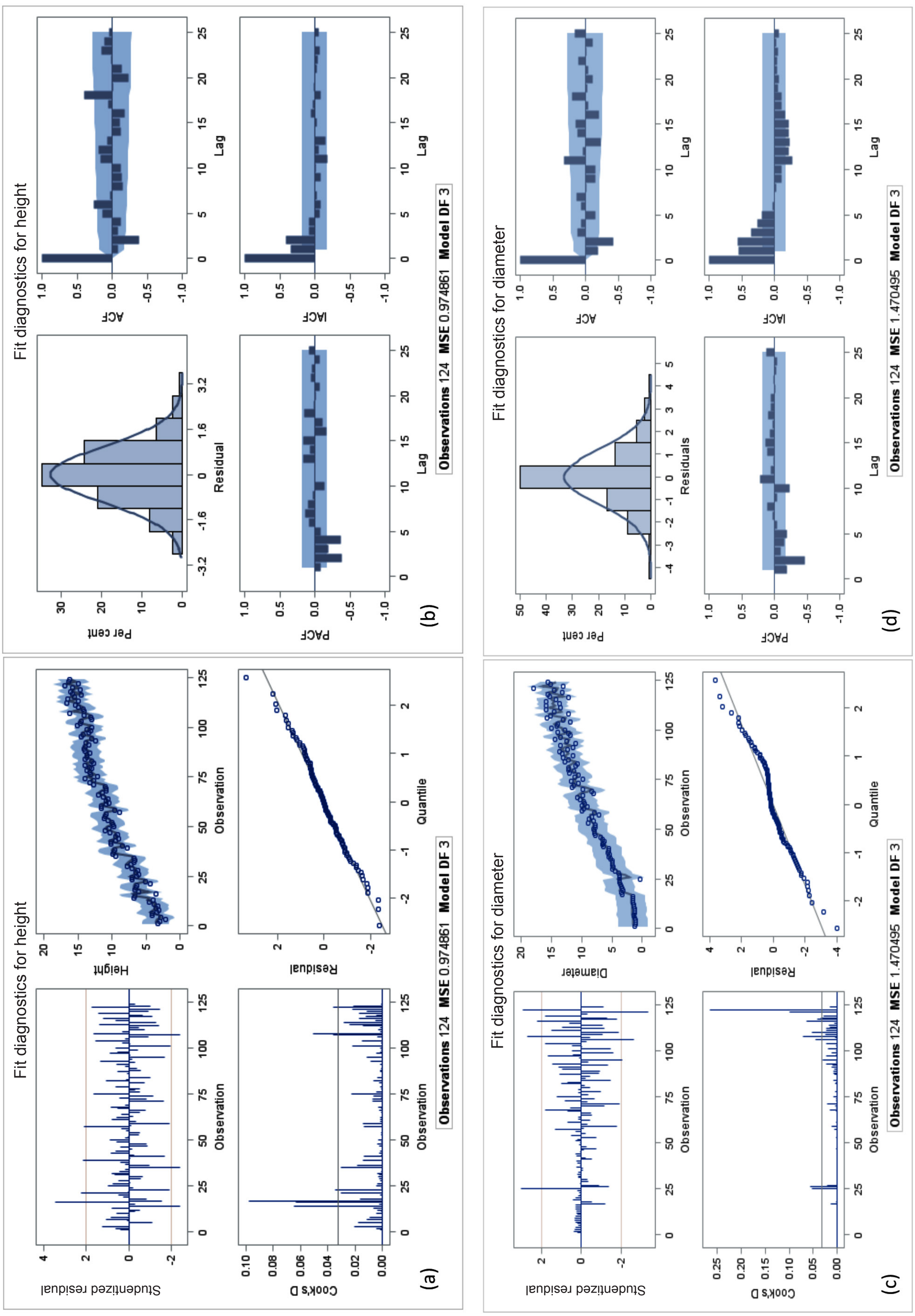

Figure 4 Diagnostics plots (a, c), trend and correlation plots (b, d) of time-series analysis in exponential regression models; DF = degree of freedom, MSE = mean squared error

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