Modelling height-diameter relationship for *Pinus wallichiana* trees for Lete and Kunjo of Mustang district

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Quantification of height-diameter relationship helps in better understanding of stand dynamics. Height-diameter models can be used as necessary inputs to growth and yield models and growth simulation systems. The researchers developed height-diameter models with 364 Blue pine (*Pinus wallichiana*) tree data from Lete and Kunjo Village Development Committees (VDCs) of Mustang district. Eighteen non-linear models were calibrated, among which, Weibull model described the largest proportion of height variation (R^2_{adj} = 0. 9362). Gunary and Chapman-Richards' models also appeared almost identical to Weibull model in terms of fit statistics and graphical appearance. The researchers recommend Weibull model for predicting total heights of Blue pine trees for the VDCs covered by the study.

Key words: Blue pine, height-diameter models, modelling, Mustang district

The measurements of individual tree height and diameter are essential component of forest inventories. Tree heights are used for estimating volume, site index, growth and yield, succession and carbon budget models (Peng, 2001). Although, theoretically, height can be measured on standing trees, practically, it is expensive, tedious and time consuming due to stand conditions and land configurations. Therefore, with many permanent or temporary sample plot systems, diameters for all trees, but height of only a few sample trees are measured. Alternatively, indirect estimation of tree heights can be made from diameter at breast height (dbh) which can be easily and accurately measured in relatively low cost. But for this, a site-and species-specific model describing a height-diameter relationship is necessary. Height-diameter model can be developed using accurately measured heights and diameters from individual trees sampled from every stand within a forest. Height-diameter models are used to predict missing heights on the stands or permanent sample plots (Hasenauer and Monserud, 1997; Nord-Larsen, 2006; Nord-Larsen *et al.,* 2009; Sharma *et al.,* 2011). For height prediction purpose, several height-diameter models have been developed (Fang and Bailey, 1998; Huang *et al.,* 2000; Huang *et al.,* 1992; Moore *et al.,* 1996; Newton and Amponsah, 2007; Sharma, 2009; Trincado *et al.,* 2007; Zhang *et al.,* 2004).

For a given species, height-diameter relationship differs from stand to stand due to variations in site quality and silvicultural treatments, and even within the same stand, due to variations in competition among individuals (Calama and Montero, 2004; Pretzsch, 2009; Vanclay, 1994). The climatic changes, changes of stand attributes (stand density), species provenance and combination of genetic potential, physiological and morphological response to environmental factors also affect height-diameter relationship. However, modelling height-diameter relationship by incorporating all those measures would be very complicated (Thornley, 1999; and literatures cited therein) would become costly. Height-diameter relationship is highly site-dependent and, therefore, not constant over time even within the same stand (Curtis, 1967). A single height-diameter curve cannot be used for prediction of all possible height-diameter relationships that may exist within a forest.

The level of this variation can be significantly reduced through incorporation of individual stand dynamics (stand density, site index, dominant height, mean diameters, competition index) into height-diameter models (Adame *et al.,* 2008; Crecente-Campo *et al.,* 2010; Dorado *et al.,* 2006; Newton and Amponsah, 2007; Schmidt *et al.,* 2011; Sharma and Parton, 2007; Sharma and Zhang,

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2004; Temesgen and Gadow, 2004). This approach, also known as comprehensive approach, may avoid a possibility of establishing stand-specific height-diameter relationship (Schmidt *et al.,* 2011). However, getting all stand-based attributes would not be easy and cost effective, and therefore, are rarely considered for the general purpose models (Fang and Bailey, 1998; Huang *et al.,* 2000; Leduc and Goelz, 2009; Lu and Zhang, 2011; Sharma, 2009).

Blue pine (*Pinus wallichiana*) constitutes one of the most important vegetation types in Mustang district (Chhetri *et al.,* 2004). It occurs between 1800 m and 3600 m elevation, and very occasionally up to 4400 m (Jackson, 1994). A strong light demanding tree species in the youth onwards, it grows under moderate shade for many years. It is very sensitive to fire. While the saplings are frequently killed by fire, the large trees often succumb.

The species which constitutes a total stem volume of about 4.1 million m^3 (1.1 %) in Nepal (DFRS, 1999) is a prominent tree species for afforestation at higher elevations. Its growth rate is slower than that of Chir pine (*Pinus ruxburghii*). However, its wood is comparatively much stronger. While the wood is used as a major timber source in Mid Hills, the bark is also used as roofing material (Kyastha, 1986). It offers a good economic share to communities in Mid Hill region. The Community Based Natural Forest and Tree Management in the Himalaya Project (ComForM Project) has started a long-term study on development of local communities and their interaction with Blue pine forests as the main livelihood resource in Mustang district (Meilby *et al.,* 2006). There are only a few literatures reporting quantitative researches on Blue pine forest in Mustang (Wagle and Sharma, 2012; Wagle, 2007). Thus, the researchers intended to develop height-diameter models for Blue pine forests in Lete and Kunjo VDCs of Mustang district by using height-diameter pairs as modelling variables. The height-diameter models will be used for prediction of heights, so that volume and yield estimation could be made easy. The height-diameter models thus developed will serve as important tools for forest management in the district.

Materials and methods

Study area

The study was conducted in Blue pine forest of Lete and Kunjo VDCs of Mustang district, which are located between 28° 24' N and 29° 20' N Latitude, and between 83° 30' E and 84° 10' E Longitude (Fig. 1). The study area lies within the working area of the Annapurna Conservation Area Project (ACAP). The elevation varies from 1372 m to 8167 m, representing sub-tropical, temperate and alpine climate types. Vegetations cover about 4.05 % of the district. Among eight vegetation types of the district, Blue pine is the most important one (Chhetri *et al.,* 2004). Lete and Kunjo VDCs have also been included into the study area of the Community Based Natural Forest and Tree Management in the Himalaya Project (ComForM Project). For long term study purpose, this project has divided forests of Lete and Kunjo VDCs into 12 strata (Meilby *et al.,* 2006). The present study focuses only on Blue pine dominated stands, irrespective of physical boundary of the strata.

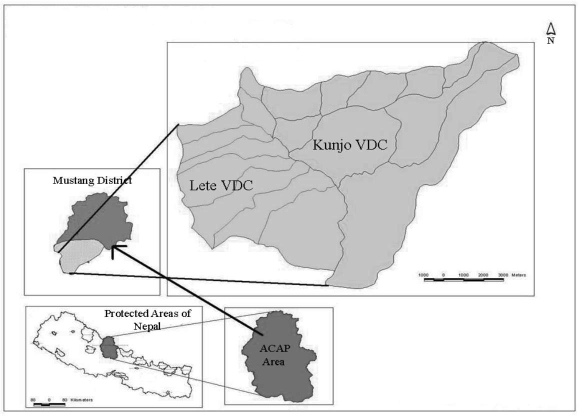

Fig. 1: Study area

Data

Some 27 to 35 Blue pine trees were selected from each diameter class (with 10 cm interval) from Lete and Kunjo VDCs, with representation of all possible stand densities and site qualities, and were numbered. The diameter at breast height (dbh) and total height of each sample tree were measured in precisions of 0.1 cm and 0.1 m, respectively. In this way, 184 trees from Lete and 180 trees from Kunjo were measured. Diseased, deformed, moribund, and top broken trees were discarded from sample.

Data summary is presented in table 1.

Table 1: Data summary

dbh class (cm)	Statistics	Lete		Kunjo	
		dbh (cm)	height (m)	dbh (cm)	height (m)
0-10	Mean	5.7	4.8	7	4.7
	Min.	2.8	2.9	3.53	2.25
	Max.	9.8	8.75	9.8	7.9
	No. of obs.	30	30	28	28
10-20	Mean	15.4	10.6	14.9	10.7
	Min.	10.3	6.5	10.2	7
	Max.	19.9	16.5	19	16.6
	No. of obs.	35	35	29	29
20-30	Mean	24.8	15.9	25	16.7
	Min.	21	10.8	20.3	10.8
	Max.	29.9	22.65	29.9	23.4
	No. of obs.	32	32	29	29
30-40	Mean	34.2	19.7	35.3	21.5
	Min.	30.1	13.75	30.1	18
	Max.	39.5	24.15	39.8	26.2
	No. of obs.	29	29	34	34
40-50	Mean	44.9	25	45.2	26.1
	Min.	40.3	21.4	40.8	19
	Max.	49.8	30.2	49.7	31
	No. of obs.	28	28	33	33
> 50	Mean	63.3	28.5	56.2	28.3
	Min.	50.7	23.9	50.7	20.5
	Max.	87.2	35.05	69.5	32.4
	No. of obs.	30	30	27	27
Overall	Mean	30.7	17.1	30.9	18.2
	Min.	2.8	2.9	3.53	2.25
	Max.	87.2	35.05	69.5	32.4
	No. of obs.	184	184	180	180

Modeling approach

The graphs of observed height against dbh showed a clear non-linear relationship. Altogether, 18 different non-linear mathematical functions were tested (Table 2). Theoretically, height-diameter relationship increases monotonically in the beginning and then increases asymptotically in the later stage (Lei and Parresol, 2001 cited in Schmidt *et al.,* 2011). The functions chosen in the study possess such properties. Many of them have previously been used by researchers for modelling tree or stands (Fang and Bailey, 1998; Huang *et al.,* 2000; Huang *et al.,* 1992; Leduc and Goelz, 2009; Newton and Amponsah, 2007; Sharma and Parton, 2007; Sharma, 2006; Sharma, 2009; Sharma *et al.,* 2011). Each function in Table 2 can be derived from the following general form:

$$H_i = 1.3 + f9D_i, b) + e_i \quad (1)$$

where H_i is total height of tree i (m), D_i is dbh of tree i (cm), b is a vector of parameters to be estimated, and e_i is a random error, and assumed to be independent and normally distributed with zero mean and a constant variance. A constant value 1.3 was added to avoid the prediction of H_i shorter than 1.3 m when D_i approaches zero.

Table 2: Mathematical models considered

Designation	Mathematical forms	References
M1	$H_i = 1.3 + b_1[1 - \exp(-b_2 D_i)]^{b_3} + \varepsilon_i$	Chapman-Richards [Richards (1959), Chapman (1961)] cited in Sharma (2009)
M2	$H_i = 1.3 + \left[D_i / (b_1 + b_2 D_i) \right]^3 + \varepsilon_i$	Näslund (1936)
M3	$H_i = 1.3 + b_1 \left[D_i / (b_2 + D_i) \right]^{b_3} + \varepsilon_i$	Näslund (1936)
M4	$H_i = 1.3 + b_1 \left[D_i / (1 + b_1 + b_2 D_i) \right]^{b_3} + \varepsilon_i$	Näslund (1936)
M5	$H_i = 1.3 + b_1 \left[1 - \exp\left(-b_2 D_i^{b_3}\right)\right] + \varepsilon_i$	Weibull (1951) cited in Zeide (1993)
M6	$H_i = 1.3 + D_i / \left(b_1 + b_2 D_i + b_3 \sqrt{D_i}\right) + \varepsilon_i$	Gunary (1970) cited in Ratkowsky (1990)
M7	$H_i = 1.3 + b_1 \exp\left(-b_2 D_i^{b_3}\right) + \varepsilon_i$	This study
M8	$H_i = 1.3 + b_1[1 - \exp(-b_2 D_i)] + \varepsilon_i$	Meyer (1940) cited in Calama and Montero (2004)
M9	$H_i = 1.3 + b_1 / \left(1 + b_2 \exp(b_3 D_i)\right) + \varepsilon_i$	Huang and Titus (1993) cited in Leduc and Goelz (2009)
M10	$H_i = 1.3 + \frac{b_1 D_i^2}{(D_i + b_2)^2} + \varepsilon_i$	Hossfeld (1822) cited in Sharma (2009)
M11	$H_i = 1.3 + \frac{D_i^{b_1}}{b_2 + b_3 D_i^{b_1}} + \varepsilon_i$	Hossfeld (1822) cited in Sharma (2009)
M12	$H_i = 1.3 + b_1 D_i / \left(b_2 + D_i\right) + \varepsilon_i$	This study
M13	$H_i = 1.3 + b_1 D_i / \left((D_i + 1) + b_2 D_i\right) + \varepsilon_i$	Bates and Watts (1980) cited in Calama and Montero (2004)
M14	$H_i = 1.3 + \frac{D_i^2}{\left(b_1 + b_2 D_i + b_3 D_i^2\right)} + \varepsilon_i$	Curtis (1967) cited in Huang *et al.* (1992)
M15	$H_i = 1.3 + D_i^2 / (b_1 + b_2 D_i)^2 + \varepsilon_i$	Huang and Ti (1993)92) cited in Leduc and Goelz (2009)
M16	$H_i = 1.3 + b_1 / \left(1 + 1 / b_2 D_i^{b_3}\right) + \varepsilon_i$	Ratkowsky and Reedy (1986) cited in Huang *et al.* (1992)
M17	$H_i = 1.3 + b_1 / [1 + b_2 \exp(-b3 D_i)] + \varepsilon_i$	Huang *et al.* (2000)
M18	$H_i = 1.3 + b_1 / [1 + \exp(b_2 - b_3 D_i)] + \varepsilon_i$	Ratkowsky (1990)

Note: H_i is total height of tree i (m), D_i is dbh of tree i (cm), b_1, b_2, b_3 are parameters to be estimated, and e_i is an error term.

Two locations, Lete and Kunjo, were coded with dummies (0 and 1) to represent both by a single model. This was reasonable because no large difference was seen between the ranges of most of the height-diameter pairs for two locations (Fig. 2). Smaller difference was due to site-specific productivity difference, and it could be described by dummy variables used as site-specific variables. For best performance, we assumed a parameter

(b_1) of each model (Table 2) as a linear function of location variable (site-specific variable) as below:

$b_i = c_i + c_2 \, location$ (2)

where c_1, c_2 = parameters to be estimated, and location variable comprises dummies (0 for Lete, 1 for Kunjo).The parameters related to location variable (i.e. site-specific parameters) and other parameters in the models were all simultaneously estimated (Huang *et al.,* 2000; Wagle and Sharma, 2012).

Parameter estimation and model evaluation

The parameters of the models (Table 2) were estimated with non-linear least square regression using PROC MODEL in SAS (SAS Institute Inc., 2008). The fitted models were evaluated on the basis of various criteria such as (1) significance of parameter estimates at 1 % level or even less (i.e., p d" 0.05), (2) logical and biological consistency of the estimated parameters, (3) histograms and probability plots of residuals, (4) graph of residuals against fitted values, (5) root mean squared error (RMSE) and adjusted coefficient of determination (R^2_{adj}) (Montgomery *et al.,* 2001), (6) Akaike information criterion (AIC): it is one of the most reliable criterion to compare the fitted models with differing parameter numbers. Smaller the AIC value, better would be the model (Burnham and Anderson, 2002), and (7) model curves overlaid on observed data. The examination of graphs helps understanding about whether models are based on theoretical basis and biological logics (Alder, 1995; Fang and Bailey, 1998). The curves generated with models were checked with respect to their biological realism.

Like many others (Soares *et al.,* 1995; Vanclay and Skovsgaard, 1997), the researchers also believe that validation is an important part of modelling, because validation increases the credibility and confidence about the developed models. However, the researchers did not perform that as they lacked independent data. Also, the researchers did not consider validation by splitting data as they had too small data set. The validation by data splitting does not provide any better information as compared to that obtained directly from the model fitted to the entire data set (Kozak and Kozak, 2003). Nevertheless, validating model with independent data is the best option, but it certainly becomes costly (Vanclay, 1994).

Results and discussion

The models (Table 2) were fitted to the data, and parameter estimates and fit statistics are presented in table 3. The parameter estimates of each model including parameters related to location variable (site-specific variable) were all significant at 1 % level or even less (p d" 0.01), and the estimated parameter values and signs are logical. In general, all models fitted to the data well with almost identical fit statistics. Among all, M5 showed the best fits (smallest RMSE and AIC and largest R^2_{adj}) followed by M6, M1, M16, M3 and so on, and M18 and M17 showed the poorest fits (largest RMSE and AIC, and smallest R^2_{adj}) followed by M9, M12 and so on.

Table 3: Parameter estimates and fit statistics

	Parameter estimates				Fit statistics		
Models designation	c_1	c_2	b_2	b_3	**RMSE**	R^2_{adj}	**AIC**
M1	35.4895	1.6880	0.0277	1.2747	2.1458	0.9362	560.81
M2	2.4474	-0.1629	0.0732	1.5220	2.1574	0.9355	563.77
M3	52.3627	2.6925	32.7124	1.5150	2.1542	0.9357	563.67
M4	1.4470	-0.1628	0.0732	1.5217	2.1604	0.9353	565.77
M5	34.1267	1.5874	0.0120	1.1934	2.1449	0.9362	560.51
M6	2.3949	-0.0866	0.0408	-0.3402	2.1451	0.9362	560.58
M7	100.6136	5.4975	7.6948	-0.4318	2.1701	0.9347	569.01
M8	43.8929	2.4250	0.0161		2.1977	0.9330	577.22
M9	28.6053	0.9177	8.3887	-0.0835	2.2980	0.9268	610.73
M10	47.3770	2.3077	19.5773		2.1679	0.9348	567.29
M11	3.1471	-0.2649	1.3114	0.0220	2.1546	0.9356	563.82
M12	72.6786	4.2468	100.1679		2.2236	0.9314	586.76
M13	0.7255	0.0424	-0.9900		2.2206	0.9316	584.76
M14	7.0652	-2.0615	0.9314	0.0189	2.1839	0.9339	573.65
M15	2.9004	-0.1868	0.1437		2.1734	0.9345	569.12
M16	44.7041	2.2174	0.0074	1.3051	2.1496	0.9359	562.10
M17	28.6010	0.9175	8.3902	0.0835	2.2980	0.9268	610.73
M18	28.6120	0.9179	2.1266	0.0834	2.2980	0.9268	610.73

The researchers also examined each model's residual graphs (graphs of individual residuals and mean residuals calculated by height and dbh classes) and model curves overlaid on the observed data. Here, due to brevity of space, we present the graphs of the first three best models (M5, M6 and M1) and one poorest model (M18) (Fig. 2,3). Except models M9, M17 and M18, residual graphs of all other models showed no systematic bias across the observed dbh and height classes, and their fitted curves showed biologically logical properties. Most of the individual residuals of each model were found within 95 % confidence limit, and histogram of residuals looked like a bell shape. This indicates there is no sign of heteroscedasticity attributed to the models. The first three best models (M5, M6 and M1) seem to be very identical in terms of residual graphs also (Fig. 2). The logistic type of models (M9, M17 and M18) showed larger over-prediction for very small trees and under-prediction for very larger trees. The logistic types of functions seem to be less appropriate for more accurate height-diameter models (Sharma, 2009).

The height-diameter relationship increases monotonically in the beginning, reaches to inflection point and increases asymptotically in the later stage (Lei and Parresol, 2001 cited in Schmidt *et al.,* 2011). In the later stage, diameter needs to grow faster in order to firmly withstand whole stature of tree against the external force such as wind blow (Cato *et al.,* 2006; Khanna and Chaturbedi, 1994). Height position of curve after about 20 cm dbh for Kunjo (location = 2) might be due to faster growth of both diameter and height as compared to those in Lete (location = 1) (Fig. 3). It also suggests that height-diameter relationship may be site-specific, and therefore a single curve cannot be used for the prediction of all possible height-diameter relationships for larger forest area. But, this level of variations could be reduced by incorporating the individual stand dynamics (stand density, site index, dominant height, mean

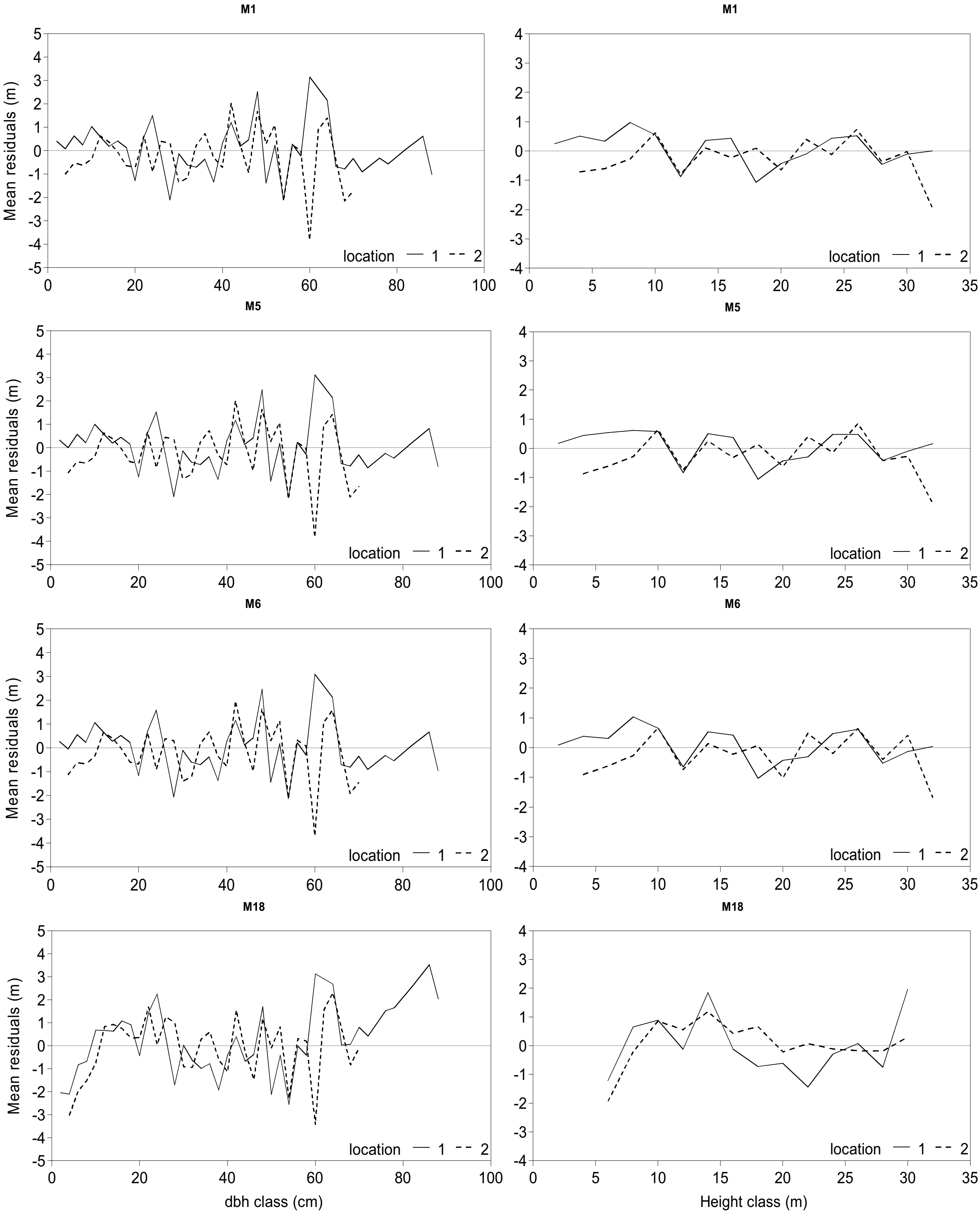

Fig. 2: Mean residuals in dbh class and mean residuals in height class

diameters, competitions) into the height-diameter models (Adame *et al.,* 2008; Crecente-Campo *et al.,* 2010; Dorado *et al.,* 2006; Newton and Amponsah, 2007; Schmidt *et al.,* 2011; Sharma and Parton, 2007; Temesgen and Gadow, 2004).

Each of the promising models (except M9, M17 and M18) showed almost identical prediction behaviors within the observed data range. Because of fewer observations, validation with data-splitting was not considered even though that validation is an important part of modelling

(Soares *et al.,* 1995; Vanclay and Skovsgaard, 1997). Some of the models might be flexible enough to be used for extrapolation purpose. However, it would be risky to do so without validation and verification. Most reliable way of checking model's prediction behavior beyond the ranges of the calibration data would be to test the fitted models against newly acquired data from different tree populations over a wider ranges of size, site qualities and stand conditions (Kozak and Kozak, 2003; Vanclay, 1994; Vanclay and Skovsgaard, 1997; Yang *et al.,* 2004). But getting such data, in general, would be very costly, and therefore are rarely attempted.

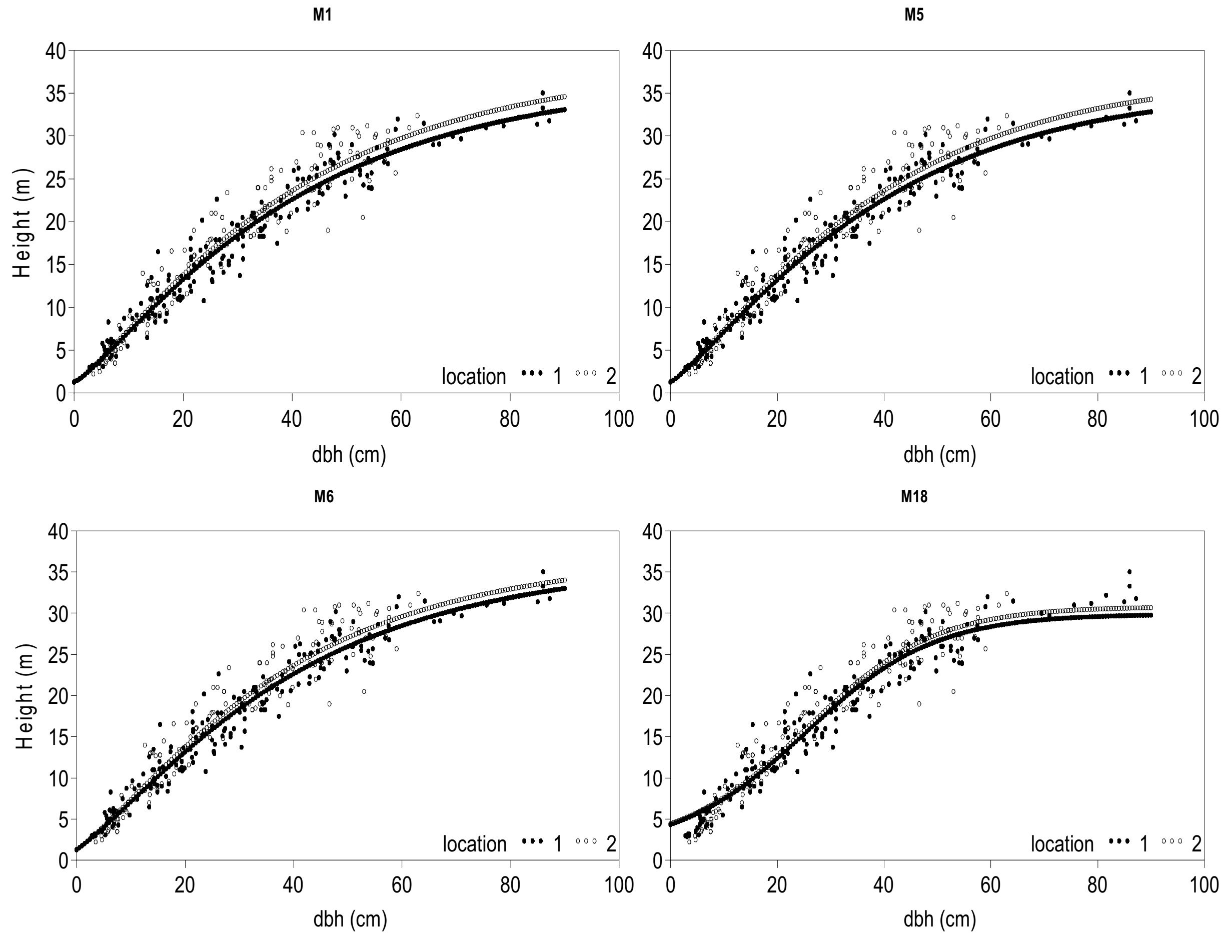

Fig. 3: Model curves overlaid on observed data

Conclusions

Among eighteen models calibrated, Weibull model (M5) showed the best fits (smallest RMSE and AIC, and largest R^2_{adj}) followed by M6, M1, M16, M3 and so on. Weibull model (M5) is recommended for the prediction of total height of Blue pine trees for Lete and Kunjo. Since the present models are site-specific, they may not necessarily be representative to the same species grown in other sites even within the same district. Prior to the application for Blue pine forests in places other than Lete and Kunjo, testing of this research's models is crucial. Formulation of the same dummy codes as in Eq. (2) is necessary while applying the models. The follow-up research on our models (i.e. recalibration, verification, and validation) with data from the widest possible tree sizes, ages, site qualities and stand conditions of Blue pine forests across Lete and Kunjo forest areas in Mustang district would be useful.

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