Title: Modelling growth of *Eucalyptus spp*. on New Zealand dryland micro-sites

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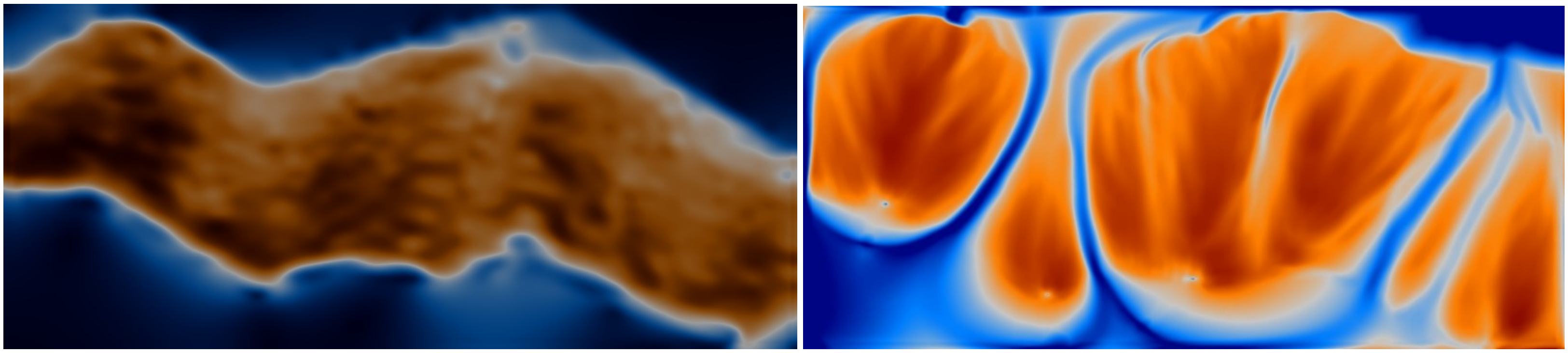

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Introduction

New Zealand's planted forests are mainly established on low valued land, especially land that is not useful for pastoral agriculture. Much of the low value land is found in hill country, which is characteristically heterogeneous, which results in heterogeneous production within the stand (Apiolaza et al., 2011; Millner & Kemp, 2012). The issue of heterogeneity has previously been reported for juvenile trees (Ares & Marlats, 1995; Bathgate et al., 1993; Larson et al., 2008).

Radiata pine (*Pinus radiata*) is widely planted throughout NZ and its growth is generally not greatly affected by microsite heterogeneity. However, reductions in growth have been reported under extreme conditions, such as high altitude or low rainfall zones (Kirschbaum et al., 2011). Where radiata pine productivity is limited by environmental conditions, other species may be more suitable. For example, *Eucalyptus bosistoana and E. globoidea*, the subject of this research, may be better suited to dry environments. While these species are potentially better suited to very dry environments, there is anecdotal evidence that their growth is highly variable within a site, due to environmental heterogeneity. Though *Eucalyptus* spp. play only a minor role in New Zealand forestry at present (Apiolaza et al., 2011), there is potential for them to be more widely planted if forest managers were more confident in their growth potential. This requires a better understanding of their growth and survival on a variety of sites.

The Eucalypt Action Group produced a first step in this direction with their small-scale siting maps for 16 different *Eucalyptus* species. These maps provided an understanding of potential *Eucalyptus* spp. suitability at a regional scale. Unfortunately, the resolution of these maps prevents their use in an operational setting and so it is unlikely that these maps alone will provide forest managers with the confidence they need to plant Eucalyptus. The next step towards this will need to explore *Eucalyptus* spp. response to its growing environment at a finer resolution. This will allow managers to effectively match species to individual sites.

Materials and Methods

Study sites

Four experimental sites for micro-site study have chosen. The sites are planted with two species of interest *Eucalyptus bosistoana* and *Eucalyptus globoidea*. Three sites are situated in Marlborough and the fourth site is situated in Hawke's Bay, New Zealand. All the sites have predominantly warm, dry and settled weather during the summer months. Winter days often start with a frost, but are usually mild overall. Typically, summer daytime maximum air temperature ranges from 20℃ to 26℃, but occasionally rise above 30℃. On the other hand, winter daytime maximum air temperature ranges from 10℃ to 15℃ (NIWA, 2015a).

The soils at these sites formed from loess and are classified as pallic argillic soil (New Zealand Department of Scientific and Industrial Research, 1968) commonly categorised as flaxbourne soil. Pallic argillic soils are clay accumulations found as thin subsoil bands. They occur predominantly in the seasonally dry eastern part of the North and South Islands and in the Manawatu. They cover 12% of New Zealand. According to The Land Resource Information System (2015) the sites have very low productivity, high slope.

The soil data and average climatic data provided above highlight a problem that this research will attempt to resolve. There is almost certainly differing environmental conditions between and even within the four study sites. But, nationally available climatic and soil data are at too coarse a spatial resolution to show heterogeneity. This study will undertake environmental micro-site characterisation to resolve this issue.

Data collection

Tree data

There are approximately 30,000 trees at the four experimental sites. The height (h), diameter at breast height (DBH), tree family (genotype) and tree status (dead or alive) was measured for all trees. All tree measurement was undertaken during November-January and June-August for past two years. Figure 1 shows a simple trajectory of the height growth of *E. globoidea* over time at different plots in Avery's site.

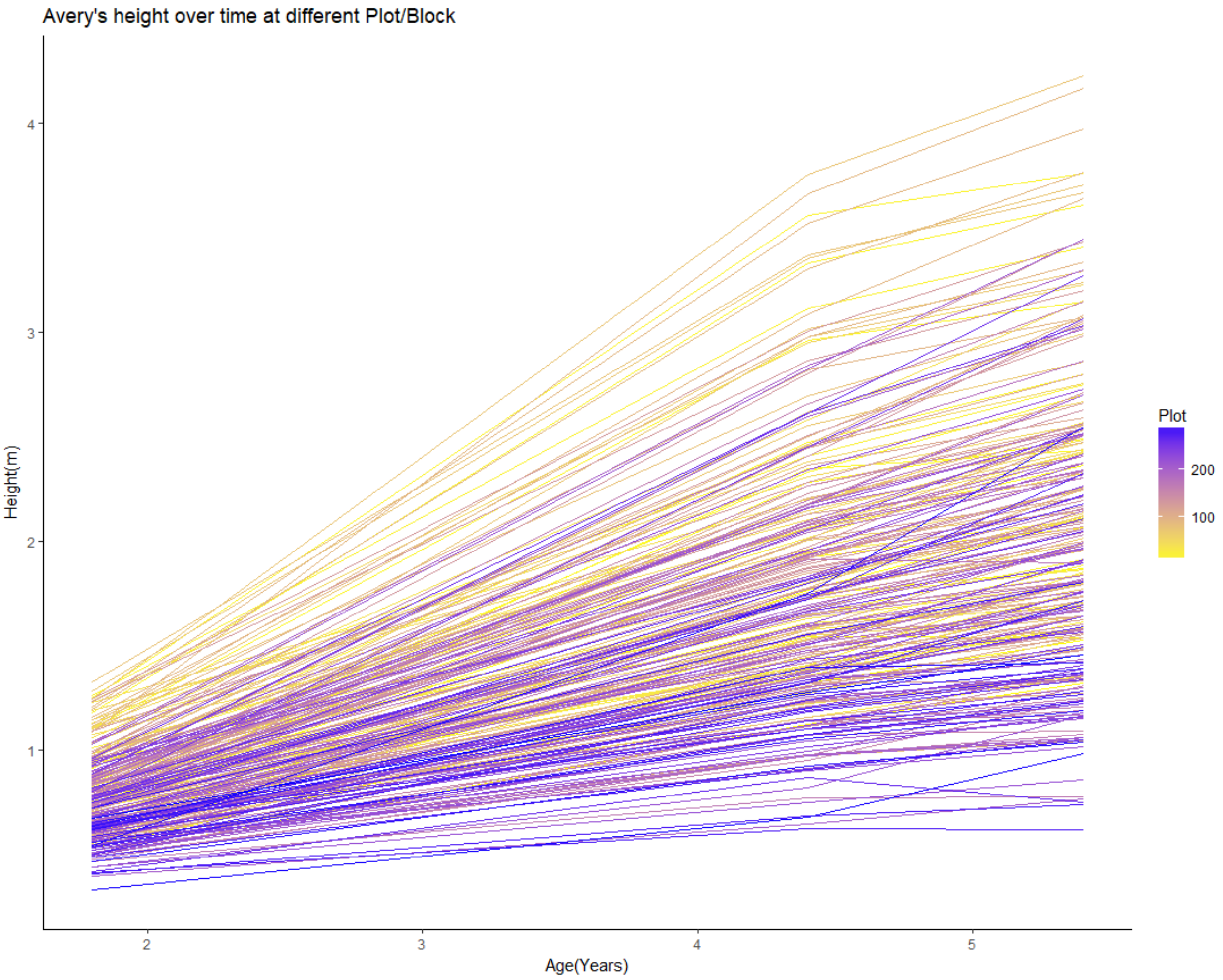

Figure 1. *E. globoidea* height with time at different plots

Topographic data

A digital elevation model (DEM) for all the sites was produced using a survey grade global navigation satellite system (GNSS). GNSS points were established on an approximately regular 5-meter grid at each site. The GNSS points were interpolated into a DEM for each site. Different methods (Figure 2) and resolutions (Table 1) were tested to optimise the interpolation process. Candidate DEMs were tested using a leave one out validation technique, whereby 90% of GNSS points were used to interpolate the DEM and 10% of GNSS points were used to validate the DEM. Absolute error (AE) (Eq 1), Sum of absolute error (SE) (Eq 2) and Mean absolute error (MAE) (Eq 3) were calculated and compared for candidate DEMs with differing spatial resolutions. The best combination of method and resolution yielded a DEM with minimal quantitative and qualitative error. The optimal spatial resolution for the DEM was 0.5 m.

$$AE = X_{interpolated} - X_{measured} \ldots\ldots\ldots (1)$$

$$SAE = \sum_{i=1}^{n} AE \ldots\ldots\ldots (2)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |X_i - X| \ldots\ldots\ldots (3)$$

Where, X=*Elevation* and n=Number of observations.

Finally, the focal statistics tool was applied over the final DEM surface to remove interpolation artefacts, thereby rendering a smoother surface.

Next, various surfaces were derived from the DEM. These surfaces include slope, aspect, curvature, wetness index, topographic exposure and land surface roughness. The land surface roughness were calculated by following Jenness (2004). All other topographic analyses and calculations were realised through either ArcMap (ESRI, 2012) or System for automated geoscientific analysis (SAGA) (Conrad et al., 2015).

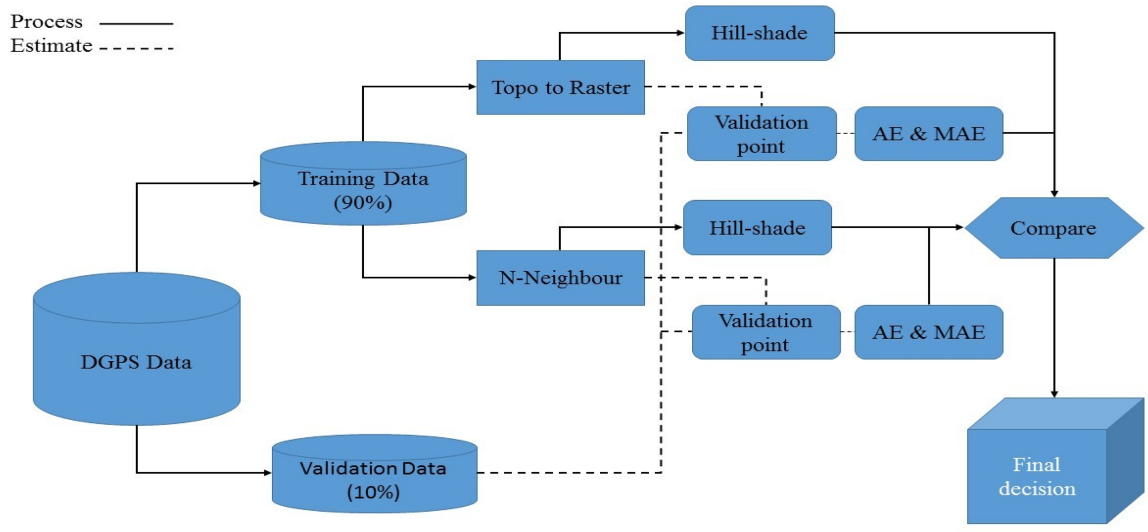

Figure 2. Example process and test to produce DEM

Table 1. Comparison between two methods of interpolation at different resolutions.

Resolution (m)	**Topo-raster**		**Natural neighbour**	
	SAE	**MAE**	**AE**	**MAE**
0.1	55.038	0.195	38.168	0.138
0.2	56.075	0.199	38.780	0.140
0.3	55.140	0.196	39.026	0.142
0.4	57.498	0.204	39.026	0.142
0.5	**55.721**	**0.198**	**40.366**	**0.146**
0.6	60.015	0.213	44.688	0.162
0.7	58.796	0.208	43.728	0.158
0.8	61.045	0.216	44.688	0.162

Soil data

Each of the four experimental sites were stratified by aspect and slope. A total of 45 soil pit locations were distributed throughout the aspect/slope strata. Soil pits were excavated with a small digger and soil samples were collected from each pit. The physical properties of soil samples and pits were described according to Gradwell (1972). In addition, soil profile depth, rooting depth, and soil permeability were measured for each pit. Moreover, a set of subsample from these pits were tested at Lincoln University soil physics lab to assess the moisture retention characteristics of the soil at different horizon depth, which further extended to calculate the root available water (RAW) (Allen et al., 1998).

Besides this, top 10 cm of soil was sampled at each pit location for the chemical analysis. Chemical analysis includes Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Cation exchange capacity (CEC), P^H, Total Carbon (C), Total Phosphate (P), Total Nitrogen (N), Potentially available Nitrogen (N), Carbon and Nitrogen ratio (C/N). The chemical analyses have been undertaken by Hill Laboratory following their standard procedures.

Finally, soil moisture was recorded with HOBO soil moisture logging systems within each strata. Each of the loggers is equipped with three sensors installed at 20 cm soil depth and set at recording intervals of 30 minutes for data logging.

Climatic data

Climatic data for the study comes from a variety of sources. Independent meteorological stations were established in all four experimental sites. Each of the stations was equipped with radiation, temperature, and moisture loggers and wind and rain sensors. Moreover, the experimental trials were equipped with an additional 25 temperature sensors and 5 soil moisture loggers (3 sensors in each) to measure variation across all aspects and slopes. All the loggers including the meteorological stations were set to collect data at 30-minute intervals. In addition, we have access to virtual climatic station network (VCSN) data from the New Zealand National Institute of Water and Atmospheric Research (NIWA) for the study sites. This network estimates daily rainfall, potential evapotranspiration, air and vapor pressure, maximum and minimum air temperature, soil temperature, relative humidity, solar radiation, wind speed and soil moisture on a regular (~ 5 km) grid covering the whole of New Zealand. The estimates are produced every day, based on the spatial interpolation of actual data observations made at climate stations located around the country (NIWA, 2015b).

Data from the weather stations and additional temperature loggers were collected and mean monthly maximum temperature were calculated for the total period (April, 2015-April, 2017) (Figure 3). The difference in temperature from the independently situated weather station to inside stand temperature logger will be modeled with a linear mixed effect modelling procedure by assigning fixed and random effect (Bates et al., 2014) and develop a temperature modifier.

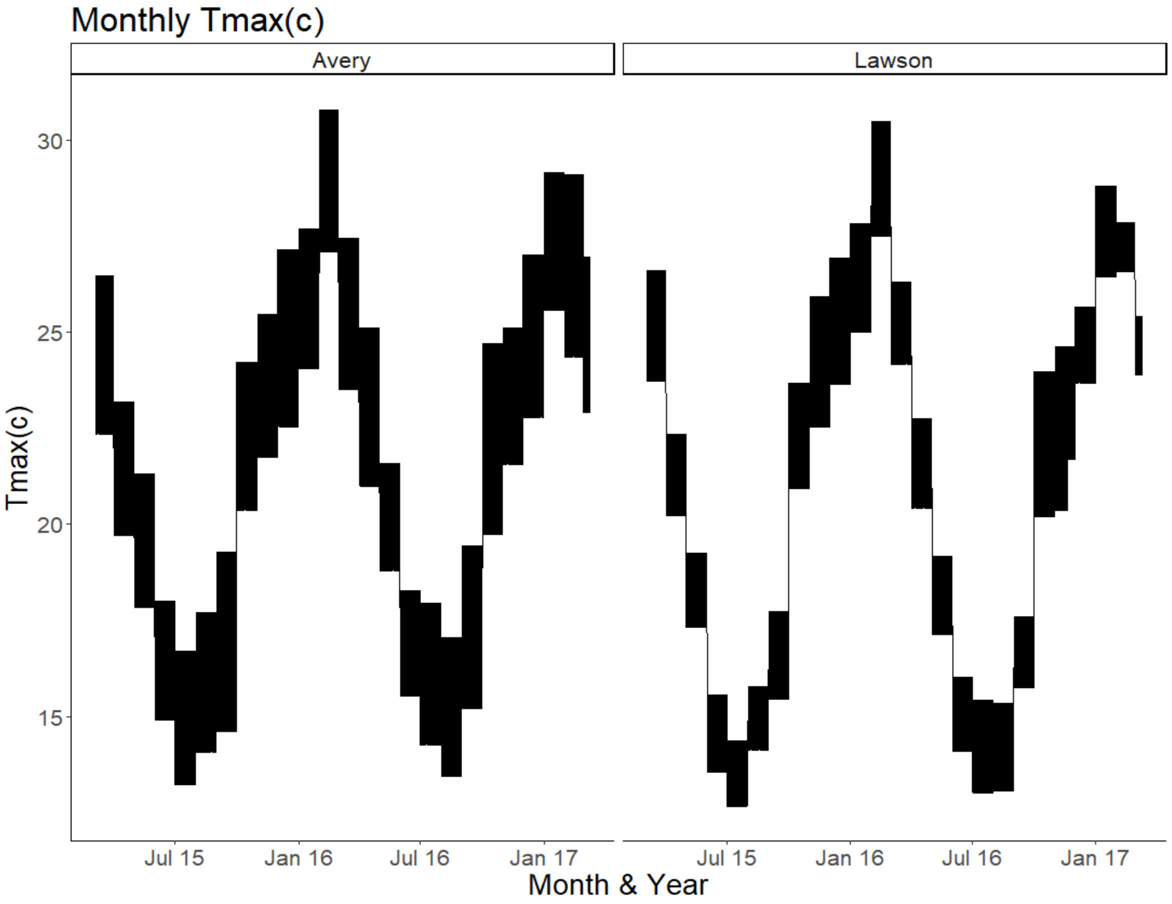

Figure 3. Mean monthly maximum temperature from the temperature loggers

Data analysis

Data preparation

Cook's distance, variance inflation factor (VIF) and graphical operations were undertaken to check for data normality and outliers. Trees noted as damaged or abnormal were left out from the modeling dataset.

Height yield model

Since Curtis (1972), stand-level and individual tree growth and yield models have been well explored (Clutter & Allison, 1974; Ek, 1974; Garcia, 1984; Monserud, 1984). But, unfortunately most growth models are developed for mature stands, which means the competition among trees is well defined (Zhang et al., 1996). Juvenile tree growth has not been modelled and reported in as much depth as modelling of mature trees (Avila, 1993; Mason & Whyte, 1997). Growth and yield models exploit the fact that starting stand dimensions indicate site quality, and modelling juvenile growth is more complex, because starting stand dimensions do not reflect site quality (Mason & Whyte, 1997; Zhang et al., 1996). However, juvenile stand yield has been found to have an exponential relationship with time (Eq 4). This is a widely used model for juvenile stands (Belli & Ek, 1988; Mason & Whyte, 1997). Moreover, as shown by Mason & Whyte (1997) the coefficients can be extended as a linear function (Eq 5 & 6) to include several independent variables and their interactions. Augmentation will be attempted in a later study. The study described here examines the simple fits of the model described in Eq. 4 to overall data and also to individual plots.

$$H_T = H_0 + \alpha T^{\beta} \quad (4)$$

$$\alpha = \alpha_0 + \alpha_1 V_1 + \cdots + \alpha_n V_n \quad (5)$$

$$\beta = \beta_0 + \beta_1 V_1 + \cdots + \beta_n V_n \quad (6)$$

Where, H_T= Height at given age, H_0=Initial height, T = Age, α & β =Coefficients and $V_1 \ldots V_n$ =Independent variables.

Results

Mensurational height yield model

The mensurational model (Eq 4) was fitted for both *E. globoidea* and *E. bosistoana* species. The residual analysis of the *E. globoidea* model indicated that the error ranged from -1 to 2m and the histogram shows that the errors were slightly negatively skewed (Figure 4). In contrast, the *E. bosistoana* model had a similar range of errors, but was slightly positively skewed (Figure 5). At the plot level, the model prediction is better than the overall fit (Figure 4). It narrows down the residual range from -0.2 to 0.3m. Which indicates the improvement at plot level prediction.

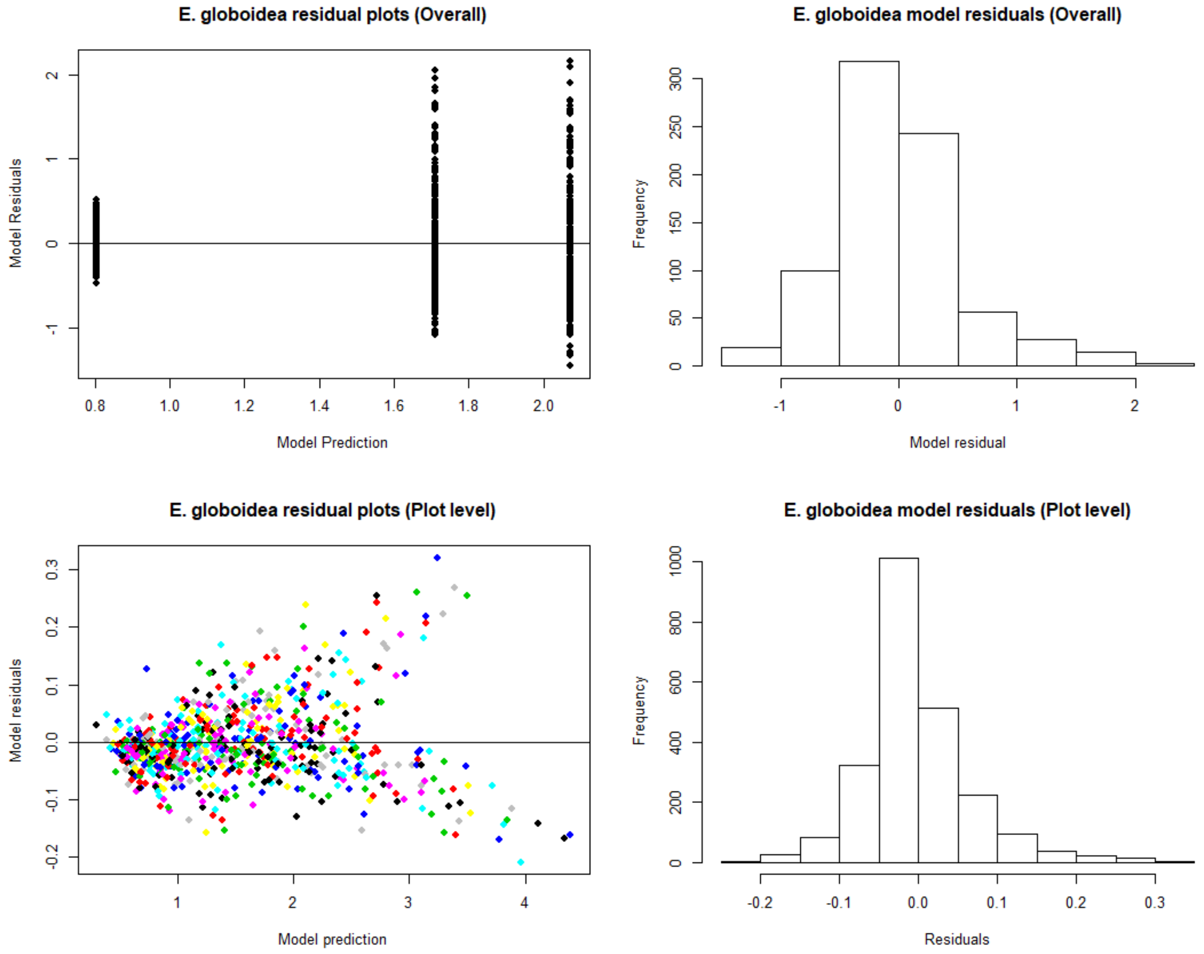

Figure 4. Residual plots from mensurational model of the *E. globoidea* (Overall & Plot level). Different colors indicate different plots.

The mensurational models developed here only represent the mathematical relationship between tree height and time. In such a model, there is no potential for explaining the reasons that growth varied. This confirms the need to incorporate augmented modelling and physiological variables in models.

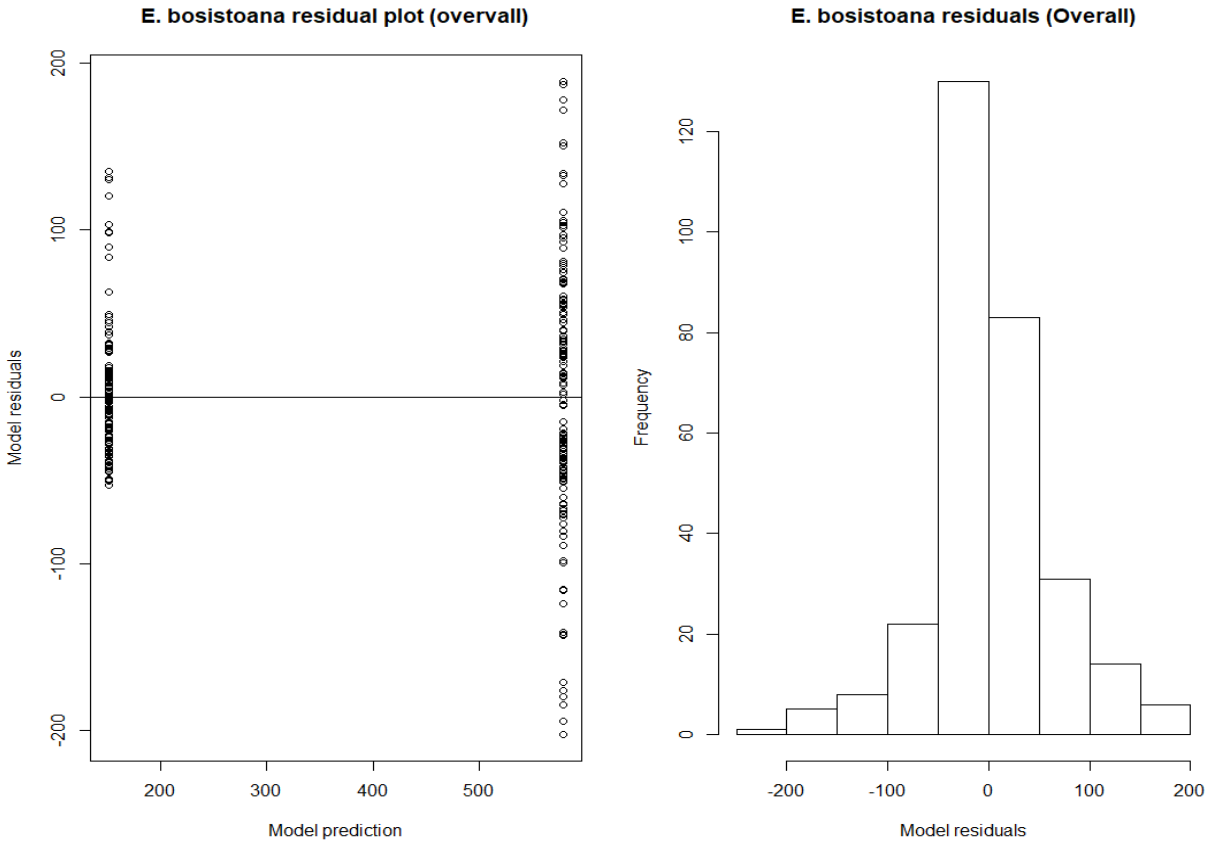

Figure 5. Residual plots from mensurational model of the *E. bosistoana* (Overall)

Further study

The mensurational models don't yield information about the underlying processes leading to variation in growth. However, it is evident that there are external factors which are playing a vital role in the growth of the trees at the early stages. It is necessary to identify and model those variables for precise prediction. For that, the coefficients are needed to extend linearly to find the significant factors and augment them to the final model to improve prediction and explain the variability.

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