Silvicultural implications arising from a simple simulation model for *Endospermum medullosum* in Vanuatu

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SUMMARY

Whitewood (*Endospermum medullosum*) is a tree species that shows promise for plantation timber production in Vanuatu, but few growth data are available to inform yield forecasts. Three simple relationships summarizing stand dynamics, namely height-age, diameter-height-stocking, and mortality-basal area relationships, were calibrated with data from 15 plots to form the basis of a model for silvicultural and management decisions. Despite the simplicity of the model, it offers predictions consistent with independent data. The model suggests that the optimal silviculture involves planting 635 stems/ha, thinning at 20 and 26 years, and clearfelling at age 36 when trees have a diameter of 55 cm dbh. However, many options offer a net present value within 5% of this nominal optimum. The flexibility to vary the timing and intensity of harvests over a wide range while maintaining good financial returns, coupled with good growth and timber properties, suggests that whitewood warrants further domestication and promotion in Vanuatu.

Keywords: Whitewood, Endospermum medullosum, growth model, yield forecast, silviculture, simulation

Implications à dimensions sylviculturelles émanant d'un simple modèle de simulation pour l'Endospermum medullosum à Vanuatu

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Le bois blanc (*Endospermum medullosum*) est une essence d'arbre prometteuse pour la production de bois de coupe en plantations à Vanuatu, mais peu de données de croissance sont disponibles pour informer les prédictions de production. Trois relations simples, synthétisant la dynamique des plants: âge et hauteur, la relation diamètre/hauteur, et les relations entre la mortalité et la base, ont été calibrées avec des données provenant de 15 plants, pour former la base d'un modèle destiné à informer les décisions de sylviculture et de gestion. Malgré la simplicité du modèle, ce dernier offre des prédictions confirmées par des données indépendantes. Le modèle suggère qu'une sylviculture optimale comprendrait la plantation de 635 individus par ha, un élagage à 20 et 26 ans, et une coupe à 36 ans, quand les arbres auraient atteint un diamètre de 55 cm dbh. Toutefois, plusieurs options présentent une valeur actuelle nette dans une marge à 5% de cet optimum nominal. La flexibilité de varier le moment et l'intensité des récoltes sur une grande surface, tout en préservant des bénéfices financiers appréciables, ainsi qu'une croissance solide et des propriétés du bois maintenues,suggèrent que le bois blanc mérite une domestication et une promotion plus poussées à Vanuatu.

Implicaciones silvícolas resultantes de un modelo de simulación simple para *Endospermum medullosum* en Vanuatu

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Madera blanca *(Endospermum medullosum)* es una especie arbórea prometedora en Vanuatu para la producción de madera en plantaciones, pero hasta la fecha son pocos los datos de crecimiento disponibles como para poder hacer pronósticos sobre el rendimiento. Se calibraron tres relaciones simples que resumen la dinámica de un rodal, como son las relaciones entre altura-edad, diámetro-altura-existencias, y mortalidad-área basal, por medio de datos de 15 parcelas, los cuales constituirían la base de un modelo de decisiones silviculturales y de gestión. A pesar de su simplicidad, el modelo ofrece predicciones compatibles con datos independientes. El modelo sugiere que la silvicultura óptima consiste en la plantación de 635 árboles/ha, la realización de raleos a los 20 y 26 años, y una tala rasa a los 36 años, cuando los árboles han alcanzado un DAP de 55 cm. Sin embargo, son muchas las opciones que ofrecen un valor actual neto dentro del 5% de este óptimo nominal. Esta flexibilidad de poder variar el turno y la intensidad de las talas dentro de un amplio intervalo, manteniendo a la vez un excelente rendimiento financieros, junto con un aceptable crecimiento y unas buenas propiedades de la madera, sugiere que madera blanca merece ser domesticada y fomentada en Vanuatu.

INTRODUCTION

One of the challenges in domesticating a tree species is the provision of reliable estimates of growth and commercial utility (Nichols and Vanclay 2012). Objective forecasts require a growth model, but most modelling approaches are demanding of data (Vanclay 1991, Weiskittel 2011). However, Vanclay (2010) has recently proposed an approach that allows objective forecasts with minimal data. The innovation in this approach was to identify three robust uni-variate relationships that can be extrapolated safely and can be calibrated with modest amounts of data that are easily obtainable. These relationships include height-age, height-diameter (Vanclay 2009a) and self-thinning relationships (Vanclay and Sands 2009) that describe the major dynamics of young plantations, and are consistent with information routinely gathered for plantation management and monitoring. This paper seeks to demonstrate the approach with whitewood (*Endospermum medullosum*) plantings on the island of Espiritu Santo in Vanuatu (Thomson 2006), and to explore the implications arising from the model for the future management of whitewood plantings in the south west Pacific region.

The Government of Vanuatu adopted a National Forest Policy in 1998 (Department of Forests 1999) that aimed to establish 20,000ha of plantation, but the implementation of this has progressed slowly (Aru *et al.* 2012). Whitewood was identified as having good plantation potential, with fast growth and advantageous wood properties (Thomson and Uwamariya 2003, Thomson 2006, Tungun 2002, Viranamangga *et al*. 2012). Relatively detailed soil and resource mapping had been carried out and is available on a spatial database (Bellamy 1993, Quantin 1982). This information was used to stratify the existing plantations and select a subset representative of the geographic range, soil type, age class, silviculture and general health of the plantations (Grant *et al*. 2012). This subset of sites was investigated for the establishment of growth plots and twenty eight circular 0.05 ha plots (22.6 m radius) were established within these plantations during 2007/2008 and regularly remeasured. Eleven of these 28 plots have incomplete details regarding planting date and silviculture, and two are mixed-species plots, so the remaining 15 plots formed the basis for model development.

COMPONENTS OF THE MODEL

The simulation model is based on a published model (Vanclay 2010) and comprises three key components: a growth model to predict stand dynamics; several mensurational relationships to infer total and merchantable volume, and some financial tools to allow basic economic analyses.

Stand dynamics

The growth model relies on three equations that estimate height (H, equation 1), diameter (D, 2), and self-thinning relationships (3):

$$H = \beta_1 (t - 0.5)^{0.5} \quad [1]$$

$$D = \beta_2 (H - 1.3)/\ln N \quad [2]$$

$$dN/N = -2(G/G_{max})^3 dD/D \quad [3]$$

where t is age (years), H is top height (m), N is stocking (stems/ha), D is diameter (mean dbh over bark, cm), G is the observed stand basal area (m^2/ha), and G_{max} is the maximum carrying capacity of the site (m^2/ha). Equation 1 estimates top height from the time since planting, using a simple uni-variate relationship (Vanclay 2010). There are many other more flexible equations, but Zeide's (1993) comprehensive analysis led him to conclude that the top height growth trajectory is inherently imprecise and should be viewed as a broad alley rather than a single line. Zeide (1993) clearly favoured a few two-parameter equations, all of which preserved one common feature: that growth expansion is proportional to the current size of a tree, a feature of equation 1. Whilst these two-parameter equations are superior when sufficient calibration data are available, they have limited utility in the early stages of domestication when few growth data are available. Equation 1 offers a first approximation that allows objective and defensible growth predictions to be made with very few calibration data (Vanclay 2010).

Equation 2 establishes the relationship between mean tree size and stand density, and predicts stand mean diameter from top height and stocking. Extensive empirical testing has demonstrated that this relationship remains stable over long periods for even-aged stands, across a wide range of species and sites (Vanclay 2009a).

Equation 3 predicts the expected reduction in stocking likely to be observed per unit of diameter increment, given the estimates carrying capacity of the site (i.e., maximum attainable stand basal area; Vanclay and Sands 2009). This equation is derived from successive differences of self-thinning trajectory as stands approach the self-thinning frontier (Reineke 1933, Yoda 1963), and the coefficient of –2 implies the existence of a limiting basal area (Vanclay and Sands 2009), a concept widely applied in growth models (e.g., Skovsgaard and Vanclay 2008). This relationship implies that as a stand approaches the limiting density, any diameter growth will be matched by a corresponding reduction in stocking, and that this mortality increases with the cube of the basal area. Thus it predicts negligible mortality at low basal areas, with mortality rates increasing so that stand density can never greatly exceed the specified maximum basal area.

These three relationships are of interest because they are robust in data-poor situations, are easy to calibrate, and are safe to extrapolate, but it is emphasised that these offer reliable approximations rather than the precise estimates obtainable from more sophisticated site-specific models. Each of these three relationships relies on a single estimated parameter, a design feature that aligns with biology, and that confers robustness despite limited data. These relationships account for the main plant dynamics that occur within monospecific plantings, and rely on stand-level data that are routinely gathered for forest monitoring and management.

Mensurational and financial aspects

Key mensurational relationships are derived from published literature. West (2004, p.42) offered a generic equation to estimate total under-bark stem volume:

$$V_u = 0.281\ (D/100)^{1.91}\ H^{1.02} \qquad [4]$$

where V_u is total stem volume (m^3, under bark), D is stem diameter (cm dbh over bark), and H is tree height (m). Total stem volume is significantly more than sawlog portion, so it is appropriate to apply a reduction to adjust for the prevailing utilization standards. Shiver and Brister (1992) offered a convenient equation to estimate stem volume to a nominated utilization limit:

$$V_d = V_u\ (1 - d^{3.4138} D^{-3.3125}) \qquad [5]$$

where V_d is the volume to a nominated merchantable diameter limit d (cm, under bark).

Financial analyses and optimization studies require estimates of the sawlog values. Such data are often difficult to obtain, and are locally specific as they depend on species, infrastructure and local markets. In the absence of real data, estimates of intrinsic value may indicate the relative utility of sawlog material of different dimensions. Sutton's (1973) review of price-size gradients revealed large differences in prices, but revealed that an inverse relationship often exists between size and stumpage value, a pattern also evident in other studies (Vanclay 1985). Thus the intrinsic value of whitewood logs is estimated as

$$Val = \beta_3 + \beta_4/D \qquad [6]$$

where *Val* is the intrinsic log value ($\$/m^3$).

CALIBRATING THE MODEL: DATA AND METHODS

The growth model was calibrated using the 15 plots established in Santo during 1994–2004, and remeasured on three or four occasions during 2008–2011. Table 1 offers a brief overview of the scope of these plots, whilst a more complete listing is provided in Table 2. Table 1 summarises the means and ranges of all measures, whereas Table 2 reports particular measures, and thus the means may differ between these two tables. Top height was estimated as the mean of the tallest two trees within the 0.05 ha plot, except in a few instances where the largest measurement appeared to be in error and the 2nd and 3rd tallest trees were used to derive top height. Stocking refers to all species on any plot, but unless otherwise indicated, mean diameters refer only to whitewood trees. The soils in these plots have been described by Grant *et al.* (2012).

Most plots used in the analysis are pure whitewood, but a few plots contain some fruit trees. For instance, in plot 17, two out of 19 trees are smaller fruit trees, and in plot 25, three out of 25 trees are smaller fruit trees, but because of the young age (<14 years) and wide spacing (5 × 5 m), the consequences for whitewood growth is assumed to be minimal. In Plot 13, every 6th tree is a Natangura (*Metroxylon warburgii*, a palm sometimes used for 'vegetable ivory'), and the initial stocking is high enough (2500 stems/ha) that competition is inevitable, but the fruit trees are of comparable size (whitewood 26.9, fruit trees 25.2 cm dbh in 2008) so whitewood growth trends should remain indicative. Where plots contain other species, the stockings and basal areas report all trees, but mean diameters and top heights are based on whitewood trees only.

Although these data span a reasonable range of conditions (Table 1), they represent a modest database for constructing models, encompass a range much smaller than the norm (Vanclay *et al.* 1995), and lack designed experiments that enable efficient calibration of density-dependent responses (Vanclay 2006). In particular, the calibration data includes only one plot that had been thinned during monitoring (horizontal line in Figure 1), and few plots with natural mortality (diagonal lines in Figure 1). Thus this simulation model should be viewed as an indicative first approximation rather than a definitive and durable model. Nonetheless, simple models such as this have an important role to inform stakeholders and assist planning.

These data were used to fit Equations 1 and 2, and parameter estimates are presented in Table 3. Figure 2 illustrates the fitted equation $H=5.3(\text{age}-0.5)^{0.5}$ along with the calibration data on which it is based. The standard errors reported in Table 3 recognise that remeasures are not independent, and represent standard errors derived from the 15 plot values rather than from the 51 remeasures. Similarly, the confidence intervals reported in Table 3 represent that 2nd largest and 2nd smallest plot trends, and are thus non-parametric 75% confidence intervals. Probability theory suggests that 15 plots should partition the range of possible scenarios into 16, and the expectation is that about 2/16ths of possible scenarios would be greater than the 2nd greatest value, and that about 12/16ths or 75% of possible scenarios would occur between the 2nd greatest and 2nd smallest values. Whilst 75% confidence intervals are a little unconventional (the norm being 95%), they nonetheless serve as useful indicators of the utility of estimates presented in Table 3.

In Figure 2, four plots (apparently with highest and lowest site index) have been plotted with distinct symbols (+plots 3 and 17, × plots 5 and 6). Dashed lines indicate the same relationship fitted independently to the plots with the second greatest and second smallest values, and serve as non-parametric 75% confidence intervals. These apparent site differences are rather small, and may simply reflect natural variation and sampling errors.

TABLE 1 *Summary of data available for model calibration*

Variable	Min	Mean	Max
Age (years)	4	12	18
Initial Stocking† (N/ha)	167	594	2500
Top height (m)	8	20	26
Diameter (cm dbh)	12	29	46
Basal area (m^2/ha)	4	27	50

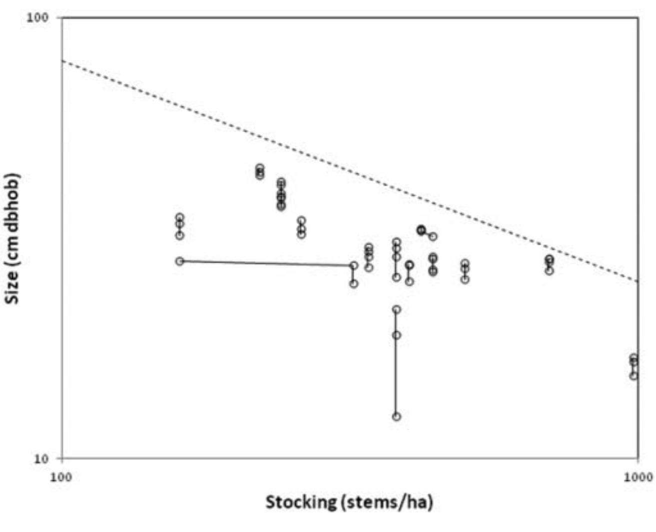
† Initial stocking based on nominal spacing between trees, not on trees/plot.

TABLE 2 *Summary of selected plot data*

Plot No	Year planted	Spacing (m)	Nominal initial stocking	No of trees in plot 2008		Whitewood mean dbh (cm)		Top height 2010	Basal area 2010	Eqn 1 β_1	Eqn 2 β_2
				All	Whitewood	2008	2010				
1	1994	5 × 5	400	23	22	32	33	22	36	5.5	9.7
3	1998	8 × 3	417	22	22	26	28	25	30	6.7	7.7
4	1998	8 × 3	417	20	20	25	28	19	24	5.2	9.7
5	1995	5 × 5	400	13	13	32	35	20	25	5.1	10.3
6	2001	3 × 3	1111	50	49	15	17	16	23	5.0	8.7
7	2004	3 × 4	833	18	18	12	22	16	14	5.8	9.1
12	1995	5 × 5	400	13	12	34	37	24	26	5.8	9.7
13	1993	2 × 2	2500	42	35	27	29	26	50	6.0	8.3
14	1996	4 × 4	625	20	19	27	31	23	29	6.0	8.7
17	1998	5 × 5	400	19	17	29	31	24	27	6.8	8.4
22	1998	6 × 2	833	16	16	25	28	21	10	5.5	9.9
24	1993	6 × 10	167	12	12	37	39	23	29	5.3	10.7
25	1997	5 × 5	400	25	22	27	29	22	33	5.8	9.0
26	1998	5 × 10	200	8	8	32	35	20	16	5.4	9.7
27	1995	10 × 5	200	13	11	44	46	23	37	5.9	11.6
Average		4 × 4	620	21	20	26	29	22	27	5.7	9.4

Figure 3 illustrates the diameter growth pattern with respect to age (left), and with respect to the height-stocking index documented by Vanclay (2009a, right). The parameter 9.3 obtained from calibrating this relationship is the same as that of Queensland rainforest timber species *Flindersia brayleyana* (Vanclay 2009a), which has several ecological characteristics similar to whitewood. Several individual plot trajectories exhibit a slope less than the general trend D = 9.3(H–1.3)/Ln(N), and growth plots should be maintained so that these trajectories can be monitored. Four plots are marked with distinct symbols (+, ×), with plots 24 and 27 (shown as +) and plots 3 and 13 (shown as ×). Some of these differences appear density related, as plots 24 and 27 are amongst the lowest stocking (160 – 200 stems/ha) whereas plot 13 had a high initial stocking (2500 stems/ha) and heavy thinning.

FIGURE 1 *Size-density diagram illustrates the range of data available for model calibration. The dashed line indicates the assumed limiting basal area Gmax=50 m²/ha (Table 3)*

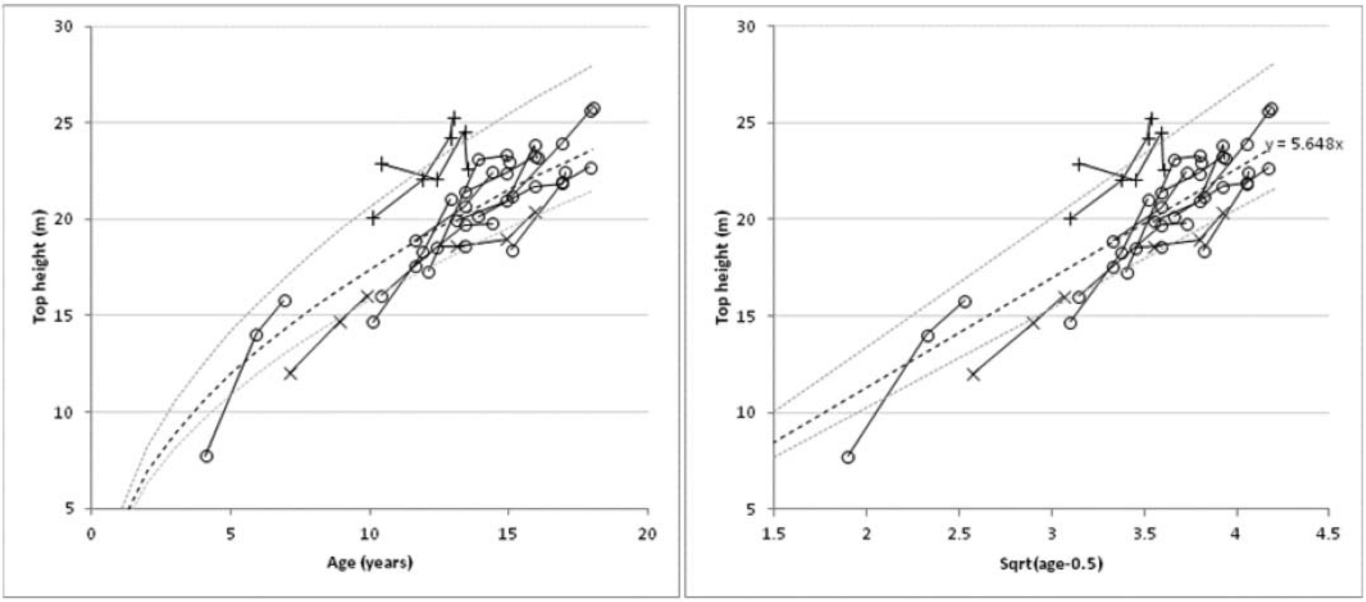


In Figure 3, Plot 27 (top right, shown as +) appears particularly anomalous, and there are several plausible explanations. Its large diameters (Table 2) may have formed buttresses, the plot area may be incorrect (with 13 trees when 10 are expected, given the nominal spacing), or the two smaller trees of non-target species (*Hernandia moerenhoutinana* and *Pometia pinnata*) may not compete (and hence could be omitted from the stocking count) – any of these explanations would move these points closer to the general trend. However, the most likely explanation is errors in height

TABLE 3 *Parameter estimates for growth equations (Equations 1–3)*

Equation	Parameter	Estimate	Standard error	Non-parametric 75% confidence interval
1	β_1	5.6	0.52	5.1, 6.7
2	β_2	9.3	1.00	8.3, 10.6
3	G_{max}	50		
6	β_3	100		
6	β_4	1500		

FIGURE 2 *Height growth patterns showing trends for the mean (dashed line) and extreme plots (dotted lines)*



measurements, as the height estimates for this plot are particularly variable, both within the plot, and from measure to measure. This plot 27 has been omitted from the calculation of β_2 as 9.3.

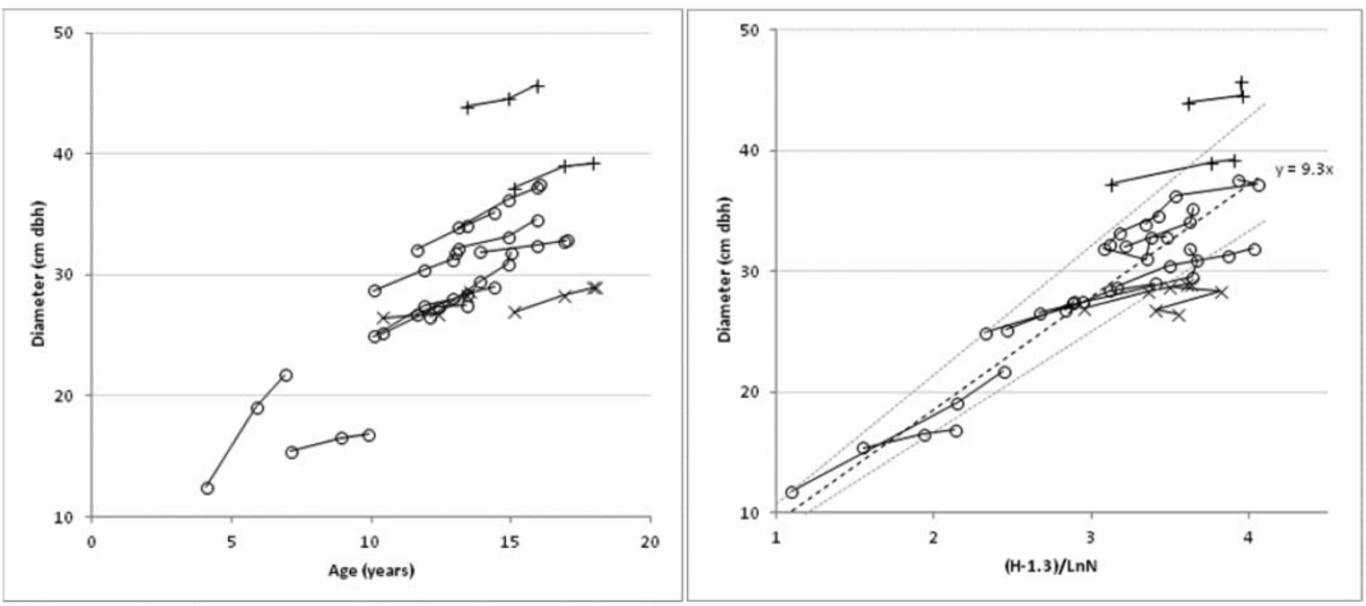
Data observed in plantations in Vanuatu are uninformative about the maximum basal area required for Equation 3, so estimates have been derived from other sources. Data published for whitewood in comparable locations (Jaffre and Veillon 1995, Keppel *et al.* 2010) suggest that 50 m^2/ha is a reasonable estimate of maximum basal area, a value that is consistent with that observed in other tropical hardwood plantations (e.g., Perez and Kanninen 2005). Figure 1 illustrates that all existing plot data in Vanuatu remain well below this assumed maximum basal area.

Similarly, it has proved impossible to gather reliable local data to inform calibration of equation 6, but anecdotal data suggest that the simple relationship Val=100–1500/D seems to apply in Santo, and assigns nil value to stems less than 15 cm diameter, \$50/m^3 to a stem of 30 cm diameter, and \$80/m^3 to a stem of 75 cm diameter.

TESTING THE MODEL

Although whitewood has been viewed as a research priority for some time (Siwatibau and Boland 2002), there are few independent data with which to test the model. Ngoro (1988) reported that plantings in the Solomon Islands attain 30 m

Figure 3 *Diameter growth patterns*



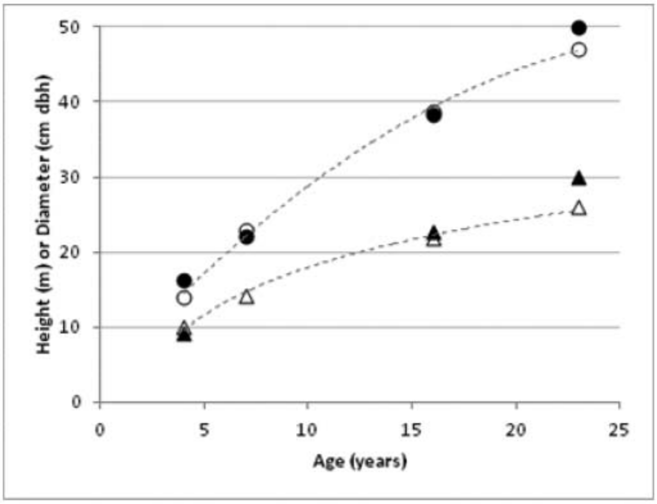
height and 50 cm diameter in 23 years, comparable to that expected in agroforestry situations in Vanuatu (with 190 stems/ha, the model predicts 27 m height and 46 cm dbh at age 23). Burslem and Whitmore (1996) record 2.7% mortality amongst stems over 10 cm dbh (excluding cyclone damage), similar to that predicted by the model for stands and stands with basal area approaching 40 m^2/ha. Marten (1972) reported that 6.6 year old plantations at Guadalcanal attained 22 cm dbh, the same as that of model predictions with 208 stems/ha (Table 4).

In Santo, Vutilolo *et al.* (2005) reported that the plantings of the East Coast Santo provenance attained a height of 9.2 m and a diameter of 16.3 cm dbh (range 16.1–16.8) in 4 year old trials planted with 833 stems/ha and reduced to an average of 633 stems/ha through natural mortality. This contrasts with model predictions of 10.4 m height and 14 cm dbh at age 4 with 633 stems/ha. A 2010 remeasure of 16 year old trial plantings at Lorum indicated a top height of 23 m, a mean diameter of 38 cm dbh, and a stocking of 190 stems/ha (Glencross, pers. comm.). This compares closely with simulations which suggest 22 m height and 39 cm diameter at age 16 (Figure 4).

IMPLICATIONS ARISING FROM THE MODEL

The model requires some financial data to offer useful silvicultural guidance, as the basic mensurational relationships do not offer a useful basis for optimization (Figure 5). Without financial data, the model tends to favour high initial stockings for what is essentially firewood production (Figure 5), and disregards the high natural mortality and small stem sizes that result when stocking exceeds 1000 stems/ha. To obtain more realistic guidance, it is necessary to introduce the possibility of a thinning, to recognise financial aspects of production, and to optimise for value rather than volume production (i.e., NPV rather than MAI). Hence to obtain useful insights from the model, it is necessary to discount future production, to assign a cost to each seedling, recognise annual maintenance costs (e.g., annual lease payments), and to deal with the intrinsic size-dependent value of the sawlogs harvested.

FIGURE 4 *Observed (% [black triangles]) and predicted heights (+ [white triangles]) and diameters (#,) [circles])*



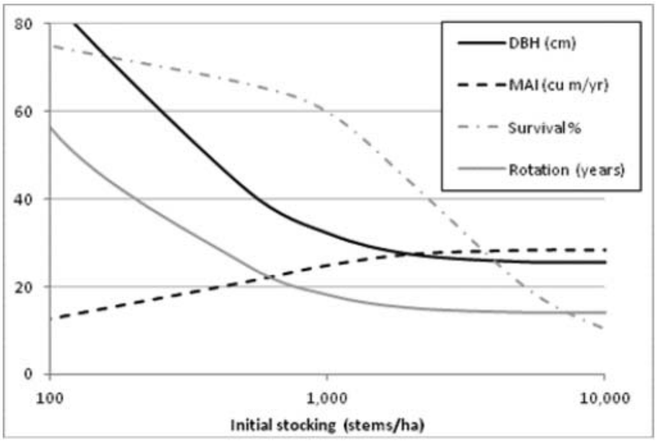
Given the assumed intrinsic value (Equation 6), a utilization limit of 15 cm small end diameter, an establishment cost of $165/ha plus $4.40/tree, plus a pruning cost of $0.90/tree, an annual maintenance cost of $5/year (Glencross, pers comm.), and a discount rate of 5%, the model predicts an optimal silvicultural regime with an initial stocking of 635 stems/ha, two thinnings at age 20 and 26 years, and a clearfall at age 36 yielding 134 stems at 55 cm dbh. However, the optimum is a broad plateau, with a wide range of conditions (e.g., initial stocking ±30%) that offer returns within 5% of the optimum (Table 5).

This regime would harvest 160 trees at 25 cm dbh after 20 years, 141 trees at 29 cm dbh at age 26, and clearfell 133 trees at 55 cm dbh at age 36. In total, 434 stems would be harvested, with about a third of the 635 planted stems lost to mortality. This estimated mortality is strongly dependent on the calibration of the model which assumes a maximum basal area of 50 m^2/ha based on literature (Jaffre and Veillon 1995, Keppel *et al.* 2010). This may be a conservative estimate, but any higher value would improve the prognosis presented in Table 5.

TABLE 4 *Independent observed data contrasted with model predictions*

	Attribute				Difference	
Source	**Age**	**Stem/ha**	**Height**	**Dbh**	**Height**	**Dbh**
Vutilolo *et al.* (2005)	4	633	9	16		
predicted	4	633	11	13	–15%	18%
Marten (1972)	7	?	?	22		
predicted	7	250	14	22	?	0%
Lorum trials	16	190	23	38		
predicted	16	190	22	37	3%	3%
Ngoro (1988)	23	?	30	50		
predicted	23	190	27	46	10%	8%
Average difference					–6%	7%

FIGURE 5 *Effect of initial stocking on production, assuming no thinning*



This regime is close to those recommended by Thomson (2006) who advocated planting 666–800 stems/ha, with a view to a final crop of 150–250 stems. He also observed that mature specimens commonly exhibit diameters of 50–80 cm dbh, and occasionally attain sizes exceeding 1 metre diameter above buttresses. Thomson also anticipated a mean annual increment (MAI) of 20–30 m^3/ha/yr, consistent with model projections. The prognosis in Table 5 more promising than that foreshadowed by Bartlett (2012), who envisaged an MAI of 19 m3/ha/yr with a 17 year rotation.

Some landholders have expressed a preference for lower stockings (Thomson 2006), with initial stockings of 200 (8× 6 m) to 400 (5×5 m) stems/ha being suggested, so these deserve examination. Table 6 examines a near-optimal single-thinning rotation with these two alternatives. It also examines the theoretical optimal direct regime without thinning.

Table 6 illustrates that the stocking reductions in the wide-spaced options are partially offset by greater growth, but that there remains a net reduction in mean annual increment and in value produced (NPV). However, these reductions in timber productions may be offset by other opportunities, such as better pasture for livestock, or for agroforestry opportunities.

TABLE 5 *Apparent optimal regime based on simulations*

Activity	Year	Optimum	Range within 5% of optimum NPV
Plant	0	635	430–900 stems/ha
First Thin	20	33%	Year 15–25; 10–60% removal
2nd Thin	26	50%	Year 21–33; 7–80% removal
Harvest	36	clearfall	Year 28–45
NPV	36	$8,472	>$8,053
DBH at harvest	36	55	
MAI	36	23	

TABLE 6 *Examination of wide-spacing options*

Attribute	Wide-spacing regimes			Direct regime
Initial stocking (stems/ha)	606	400	208	440
Age of first thinning	21	24	27	-
Stems removed	53%	51%	45%	-
Age of clearfell (years)	33	34	35	27
NPV ($/ha)	8257	7949	6586	7280
Dbh at maturity (cm)	51	54	59	45
Stocking at final harvest	182	145	100	293
MAI (m^3/ha/ann)	22	20	16	20

The model presented here deals only with mean diameters, and does not account for the natural variation in stem size. With suitable data for calibration, accounting for such variation is a relatively simple enhancement (Vanclay 2009b), but would not be expected to alter conclusions substantially.

Whilst this is model is based on a robust approach (Vanclay 2009a,b 2010; Vanclay and Sands 2009), it is based on a small number of plots, monitored for a relatively short interval, so these results should be interpreted cautiously. Although model results are consistent with observed data, model predictions represent a considerable extrapolation. The logical approach is to maintain a modest monitoring effort, and to revise the model when a significant departure from predictions is observed (Vanclay 1991). Such a revision may involve development of a more sophisticated model built on the more extensive data that should then be available.

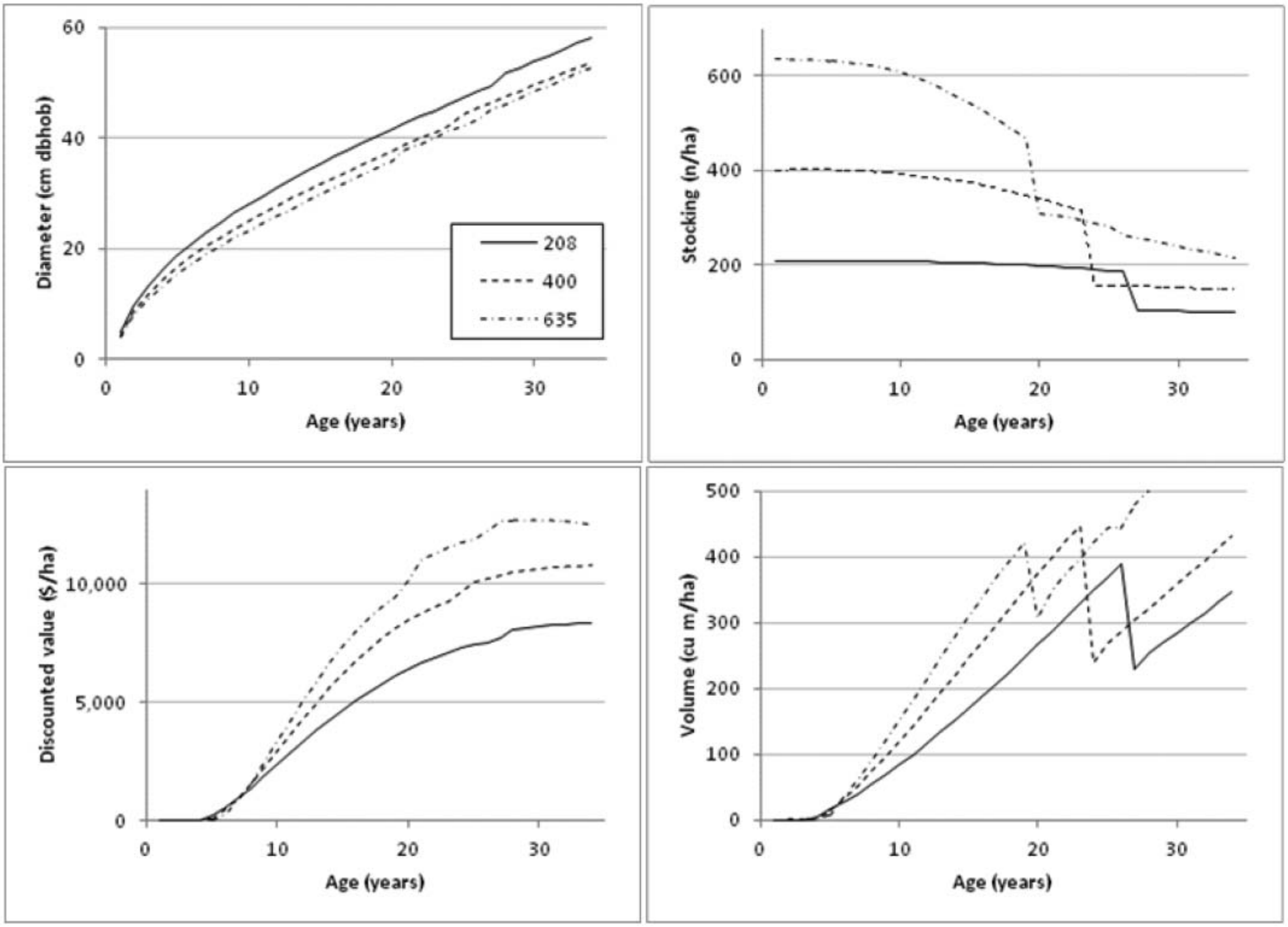
The model also takes no account of site productivity (Skovsgaard and Vanclay 2008), despite clear indications of site differences (Figure 2). Although it is a relatively simple matter to incorporate site index in the model, it may not be easy to determine site index in the field prior to planting. In many cases, soil properties offer a good guide to site productivity (e.g., Grant *et al.* 2010), but soils amenable to plantation forestry in Santo are rather uniform (Grant *et al.* 2012). Plant functional attributes (Vanclay *et al.* 1997) of associated vegetation may offer some insights into likely site productivity.

USING THE MODEL

The model is available from the authors as an Excel spreadsheet (Figure 7). In Figure 7, the left pane reports the simulated data, and the right pane includes the model parameters (top right, shaded grey, password protected), utilisation and financial data (such as small end diameter and establishment costs), silvicultural data (such as initial number of plants and age of thinning), and a summary of simulation results (bottom right, shaded grey). The parameters in the 'silviculture' pane may be set by the user, or determined automatically using Excel's solver (as in the case of Figure 7).

Data displayed in the left pane is self-explanatory, and clearly labelled.

FIGURE 6 *Different stockings (top right) lead to relatively small differences in stem diameter (top left), larger differences in stand volume (bottom right) and large differences in discounted value (bottom left, excluding costs)*



The model also displays a graph of selected key data (Figure 8), and it is a simple matter for users to use Excel's capability to create additional graphs. Figure 8 illustrates the stocking, diameter, basal area and stand volume predicted with the optimal silvicultural regime (Table 5).

Figure 8 triggers a question about the diameter growth trajectory. There are few studies on long-term growth of this species, but amongst the scant publications are some observations that the "high growth rates of young trees is not maintained" (e.g., Burslem and Whitmore 1996). However, this species is generally classified as a "long-lived pioneer" (Whitmore 1975, Leps *et al.* 2001), such species often exhibit strong diameter increment until a sudden death (Metcalf *et al.* 2009), and attain large diameters (Sheil *et al.* 2006, Thomson 2006), so the trajectory illustrated in Figure 8 seems plausible.

PATHWAYS FOR IMPROVEMENT

Domestication of Whitewood

There is a temptation for many specialists to fine-tune parameters and techniques within their own domain of expertise, and while there are many important improvements that can be made along the whitewood value chain (ranging from weed control methods to choice of discount rate), the greatest need is to create a market. Unless there is viable market comprising growers, processors and consumers, most planted whitewood trees will not realize their full value, and these finer details will be largely irrelevant. There is sufficient knowledge about this species (Thomson 2006) to offer informed 'best bets' to guide the market, and the priority should be to facilitate the formation of a viable market, because the nature of this market will greatly overshadow any finessing of other assumptions. Stimulating understanding and confidence about opportunities (including growth rates, wood qualities, market opportunities) throughout the value chain are important steps in assisting the market to mature (Herbohn *et al*. 203).

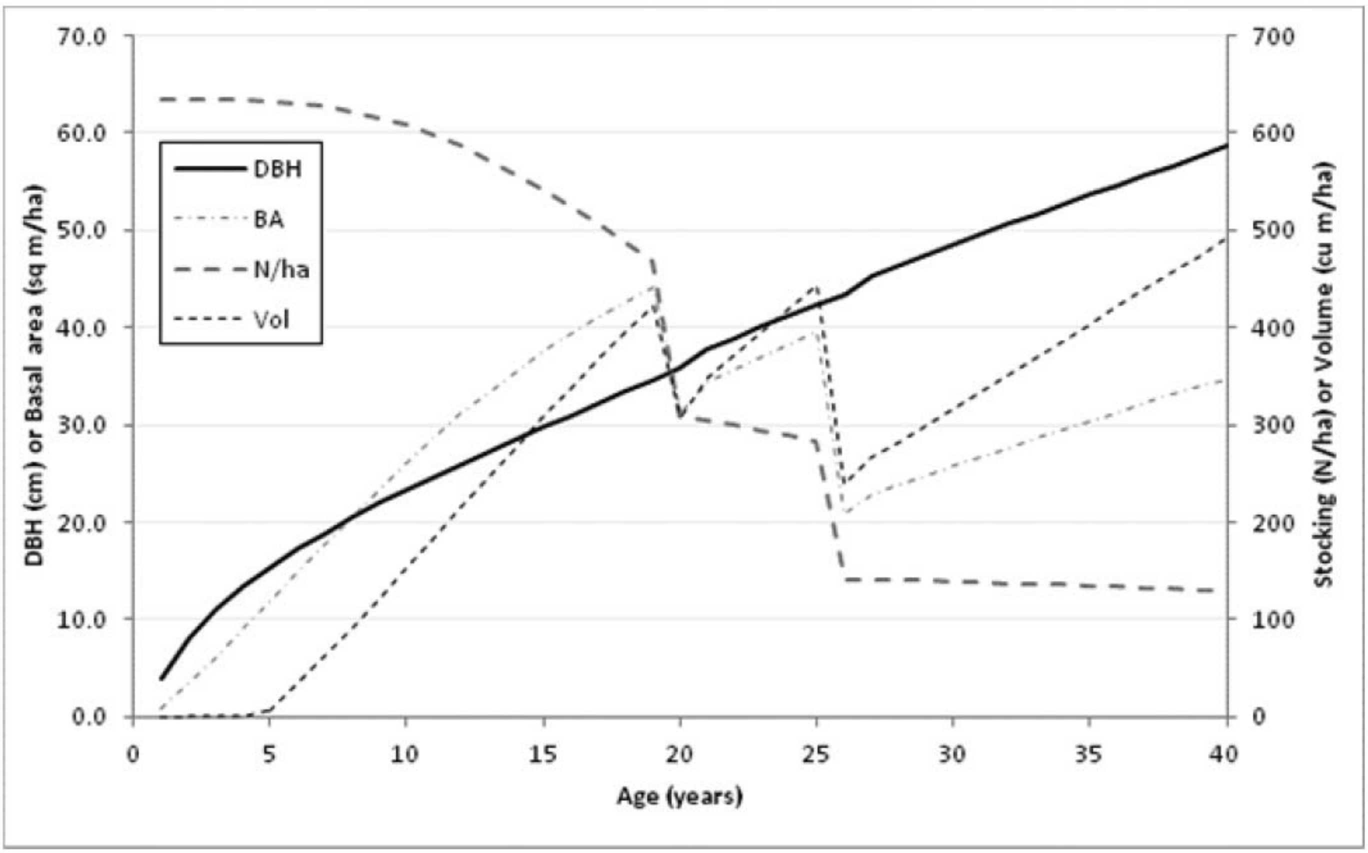
Model enhancements

The model presented here is a simple model, intended to offer a first approximation, but if it is to assist the domestication process, it should be as accurate as possible, and updated as new data become available. Several aspects of the model are weak, and could easily be improved and customised for

FIGURE 7 *Screen image from the whitewood model*

Age	Height	DBH	N/ha	BA	Vol/ tree	Standing Volume	Standing Value $	MAI vol	Cost	NPV $		Model parameters	Estimates
1	4.0	3.9	635	1	0	0	0	0.0	2,959	-2,959		h=root(A-.5)	5.65
2	6.9	8.1	635	3	0	0	0	0.0	5	-2,964		d=h/lnN	9.3
3	8.9	11.0	635	6	0	0	0	0.0	258	-3,222		Gmax	50
4	10.6	13.4	634	9	0.00	0	0	0.0	4	-3,226		Min SED	15
5	12.0	15.4	633	12	0.01	7	13	1.3	4	-3,216		Discount rate	5%
6	13.3	17.2	631	15	0.05	33	318	5.5	319	-3,231		Initial costs $/ha	165
7	14.4	18.9	627	18	0.10	61	892	8.7	4	-2,661		Establish cost $/tree	4.4
8	15.5	20.5	623	20	0.14	90	1,625	11.2	3	-1,931		Annual costs $/ha	5
9	16.5	21.9	616	23	0.20	120	2,450	13.4	3	-1,109		Prune1 cost $/tree	0.4
10	17.4	23.3	608	26	0.25	151	3,320	15.1	3	-242		Prune2 cost $/tree	0.5
11	18.3	24.7	598	29	0.31	183	4,199	16.6	3	634		Thinning cost $/ha	1600
12	19.2	26.0	586	31	0.37	215	5,061	17.9	3	1,494		Initial number	635
13	20.0	27.3	573	33	0.43	247	5,886	19.0	3	2,316		T1 age	20
14	20.8	28.5	558	36	0.50	278	6,658	19.9	3	3,085		T1 residual	0.66
15	21.5	29.8	541	38	0.57	309	7,366	20.6	2	3,790		T2 age	26
16	22.2	31.0	524	39	0.65	339	8,003	21.2	2	4,425		T2 residual	0.50
17	23.0	32.2	506	41	0.73	368	8,564	21.6	2	4,984		Clearfall age	36
18	23.6	33.4	488	43	0.81	395	9,050	22.0	2	5,468		Max Standing Val	13,132
19	24.3	34.6	469	44	0.90	422	9,461	22.2	2	5,877		Max MAI	22.7
20	24.9	35.8	310	31	0.99	308	10,204	15.4	605	6,016		Max NPV	8,472

FIGURE 8 *Simulated outputs for the optimal silviculture defined in Table 5*



Vanuatu. Several aspects warrant attention, listed here in priority order:

1. Volume equations (equations 4 and 5) are generic equations developed for other situations, and it is a relatively straightforward task (amenable as a student project) to acquire the data and create a model specifically for this species in Santo.
2. The assumed maximum basal area (50 m^2/ha) has major consequences for the simulated self-thinning of plantations, and is based on observations made by others, for other purposes, in other locations. A few unthinned plots monitored for several years would help refine this estimate (Skovsgaard and Vanclay 2008).
3. The height growth equation is generic, and whilst it is robust, it does not account for the particular traits of the species. A small investment in developing a specific equation for whitewood in Vanuatu would greatly increase the utility of, and confidence in predictions.

DISCUSSION

The apparent simplicity of the model and its basis in three uni-variate relationships belies the care taken in establishing and testing these relationships for a wide range of species and sites (Vanclay 2009a, 2010, Vanclay and Sands 2009). Similarly, a mere 15 plots may seem insufficient to calibrate a model and defies conventional advice regarding models for tropical forests (Vanclay 1991, Weiskittel *et al*. 2011), but the uni-variate nature of these relationships makes them inherently robust and amenable to calibration with minimal data. The simulation portrayed in Figure 8 is a bold prediction that represents a considerable extrapolation beyond the data-space represented within the calibration data (Vanclay *et al.* 1995), but is presented in an explicit and testable form consistent with scientific principles. Although reliant on a series of assumptions, the model represents the best objective advice for the management of whitewood plantings. However, it would be unwise to assume without further monitoring the 37-year regime outlined in Table 5. Instead, Table 5 should be viewed as a 'best bet' to guide an adaptive management approach (Sayer and Campbell 2003, Schreiber *et al*. 2004), and on-going monitoring should continually test the adequacy of the model. Fortunately, Tables 5 and 6 suggest that there is a broad plateau of near-optimal regimes that offer plantation managers great flexibility to vary silvicultural decisions and to seize market opportunities without compromising financial viability.

CONCLUSION

Findings from this study suggest that a useful growth model can be constructed from a modest database using Vanclay's (2010) equations. Tests with independent published data suggest that model predictions are reasonable, but these published data are insufficient in number and quality to allow formal statistical tests. The model appears adequate for mid-term planning, but monitoring should be continued, and should inform periodic review of the growth model.

The model suggests that an optimal silviculture for whitewood may be to plant 635 stems/ha, two thinning at age 20 and 26 years, and a clearfall at age 36 yielding 133 stems at 55 cm dbh. Alternatively, if the market for thinnings is weak, it may be preferable to plant 400 stems/ha, have a single thinning at age 24, and to clearfell at age 34 to yield 145 stems at 54 cm dbh. In either case, the projected financial returns are relatively insensitive to minor variations in these regimes, allowing forest managers considerable flexibility in selecting the initial spacing, the timing of harvests and the intensity of thinnings.

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