Maximising growth and sawlog production from *Acacia* hybrid plantations in Vietnam

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Abstract

Management options to optimise sawlog production from *Acacia* hybrid (*A. mangium* × *A. auriculiformis*) combining thinning and fertiliser treatments were applied at six sites of varying resource availability across Vietnam. Stockings at planting varying from 2000 to 1111 trees ha^{-1} were thinned from 1333 to 450 trees ha^{-1} (representing 27 to 54% thinning %) at ages 2.0 to 5.6 years. Tree diameter (*DBH*) responses to thinning were greater in the south than in the north and south central regions. Application of fertiliser at thinning increased *DBH* and stand volume (*SV*), compared with the unfertilised treatment, regardless of thinning treatment. Early thinning (at age 2 – 3.6 years) to 450 or 600 trees ha^{-1} resulted in the greatest *DBH* for all diameter classes with a greater proportion of larger diameter logs. The 3-PG process-based model was applied to predict *DBH* and *SV* for all silvicultural treatments and ages. When thinning is conducted at 2-3.6 years after planting, the modelling showed that for medium and large-diameter sawlogs, the optimum rotation length is at least 5 – 7 years in the south and south central coast and 6 – 10 years in northern Vietnam.

Keywords Acacias, productivity, sawlogs, silvicultural practices, 3-PG model.

Introduction

In Vietnam, more than 1.5 Mha of *Acacia* plantations are grown primarily for pulpwood (VNFOREST, 2018) but high volatility in domestic and world pulp prices and the need for product diversification has increased interest in growing acacia plantations, particularly clonal *A.* hybrid (*A. mangium* × *A. auriculiformis*), for sawlog products (MARD, 2015). These plantations, of which half of the area are owned by smallholders, are commonly established at 1111 – 2500 trees ha^{-1} and managed on a rotation length of 5 – 8 years without thinning (Beadle et al. 2015; Nambiar et al. 2015). Historically, plantations systems grown for sawlog production usually require at least one thinning to manage stand stocking and increase the diameter of retained trees (Ladrach 2004; Beadle et al. 2013a; Ozbayram and Cicek 2018). Optimum thinning regimes have been tested and developed for a range of fast-growing plantation species including various temperate and tropical *Eucalyptus* spp. (Medhurst et al. 2001; Smith and Brennan, 2006; Cassidy et al. 2012). In contrast, there is a paucity of published research on thinning for fast-growing tropical *Acacia* spp. (Beadle et al. 2013a, b; Huong et al. 2016).

In fast-growing eucalypt plantations, intensity and timing of thinning have the most impact on product recovery (Smith and Brennan 2006; Glencross et al. 2011; Cassidy et al. 2012; Forrester et al. 2013a). These studies demonstrate that thinning regimes may require between 1 to 5 thinning events at both early and later ages depending on sawlog specifications at harvest (Medhurst et al. 2001; Kanninen et al. 2004; Glencross et al. 2011). In particular, early-age thinning has been shown to improve log size without increasing the vulnerability of a stand to windthrow as well maintain the benefits realised from high early growth rates across the rotation (Medhurst et al. 2001; Smith and Brennan 2006; Cassidy et al. 2012). For tropical acacia plantations in which stands reach canopy closure at age 2 years, there remain uncertainties about the intensity and timing of thinning, though an expectation that early- rather than later-aged thinning will be needed to reduce the risk of intraspecific competition (West 2014). In a comparison of thinning treatments of *A.* hybrid in southern Vietnam, Huong et al. (2016) concluded that a single thinning from 1111 trees ha^{-1} to 600 trees ha^{-1} at age 2 years or double thinning to 833 trees ha^{-1} then 600 trees ha^{-1} at age 2 and 3 years, respectively, would produce the highest diameter sawlogs. Early thinning at tree age 2.5 years of an *A.* hybrid plantation from 1000 to 600, 450 and 300 trees ha^{-1} was shown to rapidly increase sawlog values (defined as log DBH >15 cm in small-end diameter) in central Vietnam (Beadle et al. 2013b). While the findings from these studies suggest that acacia plantations with relatively low initial stockings can be managed to produce sawlogs, initial stockings in Vietnam are more commonly at least 1600 tree ha^{-1} and often higher (Beadle et al. 2015); how to manage these plantations for sawlogs remains unclear. Furthermore, in Vietnam, *A.* hybrid plantations are mainly grown by smallholders requiring a quick return on investment; consequently, the aim is to reduce the rotation length but this may comprise maximising the recovery of sawlog.

Thinning in combination with fertilisation is widely practised for many forest plantation species (Snowdon and Waring 1995; Valinger et al. 2000; Mäkinen et al., 2005; Forrester et al., 2012). However, in Vietnam, many growers, particularly smallholders, use little or no inorganic fertiliser and/or manure at establishment due to the costs of fertiliser and associated labour (Dung et al. 2013). This contrasts with recommendations from other studies, which demonstrate a higher requirement for phosphorus (P) in leguminous tree species such as *Acacia* compared to non-leguminous tree species (Sprent 1999). Other studies have shown that application of P fertilizer alone improved early growth rates for *Acacia* plantations, compared to no fertiliser controls, especially on low fertility sites (Beadle et al. 2013b; Dung et al. 2013). Whether application of P fertiliser in *A.* hybrid plantations grown in Vietnam can be of wider benefit remains to be investigated.

This study used both empirical mensuration and process-based modelling (3-PG model, Hung et al. 2016) to estimate the wood yields, tree diameter sizes and the rotation lengths for producing sawlogs under different thinning and fertiliser application practices that have been applied in *A*. hybrid plantations in Vietnam with initial stand stocking varying from 1111 to 2000 stems ha^{-1}.

Materials and methods

Study area

The study area was composed of six experimental trials located in north (Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3), south central coast (Binh Dinh) and south (Dong Nai) Vietnam (Fig. 1). The sites represent a broad range of soils, topographies and climates under which *A.* hybrid is planted in Vietnam (Online resource 1). The study sites in the north and south central coast are hilly (⩽15% slopes) compared to the flat site in the south (⩽5% slope). The climate across these sites is monsoon tropical with the monsoon pattern varying in duration and intensity (Lap 1999). Meteorological variables such as mean monthly air temperature, daily solar radiation, and mean annual precipitation of each experimental site are presented in Online resource 1. Dry season (assumed as monthly precipitation < 40 mm) ranges from 3 to 4 months per year across sites (Hung et al. 2016). The soils are mainly highly acidic and usually shallow (< 100 cm). The key soil properties in the top 10 cm soil depth are clay loam or silty clay loam (clay 13.6 – 28.9%), pH_{H_2O} 3.4 – 5.7, soil organic carbon 1.1 – 2.7%, total soil N 0.04 – 0.16%, avail. P 1.8 – 11.1 mg kg^{-1}, exchangeable Ca 0.01 – 0.18 cmol kg^{-1}, K 0.07 – 0.12 cmol kg^{-1} and Mg 0.06 – 0.09 cmol kg^{-1} (Online resource 1).

These plantations were established between 2006 and 2010 (Online resource 1). The slash was retained at Tuyen Quang, Ba Vi-1 and Dong Nai and burnt at Ba Vi-2, Ba Vi-3 and Binh Dinh prior to planting. Across all trials, the planting hole size was 40 × 40 × 40 cm. Stocking at planting ranged from 1111 trees ha^{-1} up to 2000 trees ha^{-1} At planting, trees across all trials received basal N:P:K fertiliser and/or superphosphate (16 to 50 kg P ha^{-1}), which was spread at the bottom of the planting hole and then backfilled with soil. An additional 2 kg of cattle manure per tree was applied in Ba Vi-2 and Ba Vi-3 only. Either one *A.* hybrid clone or a mixture of several clones were planted at each site (Online resource 1). Hand-weeding or glyphosate (1.92 kg ha^{-1}) were used to control weeds for at least the first two years after planting. Tip pruning was applied to remove 50% of the length of potentially competing leaders and branches in the first year to produce a single leader. Lift pruning was undertaken to 2.5 m above ground before thinning to reduce branch competition. These silvicultural practices were applied across all sites and are similar to those applied in commercial plantations with one exception. The fertiliser rates applied in this study are higher than those applied in commercial plantations e.g. 10 kg P ha^{-1} (Son 2006).

Experiment design and treatments

The experiments at each trial site were designed as randomized complete blocks, with 3 – 5 replicates. There was a total of 157 sample plots, each consisting of a minimum of 36 trees. Each plot had a double row of buffer trees along the plot boundaries that received the same thinning and fertiliser at thinning treatments. Gross plot sizes ranged from 432 to 630 m^2 while net plot sizes (the measured plot) ranged from 252 to 368 m^2.

Thinning treatments included various thinning intensities (thinning from 2000, 1667 and 1111 trees ha^{-1} to 1333, 1000, 900, 600, 667 or 450 trees ha^{-1}) and thinning ages (2 to 5.6 yr) (Table 1). Thinning to 600 trees ha^{-1} at age 2 yr were examined at Tuyen Quang, Ba Vi-1 and Dong Nai. A progressive thinning treatment to 833 trees ha^{-1} at age 2 yr and then 600 trees ha^{-1} at age 3 yr was examined at Dong Nai. The effects of thinning intensity at age ⩾3 yr on growth responses were evaluated at Ba Vi-2, Ba Vi-3, Binh Dinh and Dong Nai. Combinations of thinning intensity and time of thinning (thinned at different tree ages: 3.6, 4.6 and 5.6 yr) were tested at Ba Vi-3. At

Tuyen Quang, Ba Vi-1 and Ba Vi-2, for each thinning intensity, three fertiliser treatments were immediately applied after thinning including 1) no additional fertiliser (F_0), 2) 17.8, 50 and 8.9 kg ha^{-1} of N, P and K fertiliser, respectively (F_1), and 3) 17.8, 50 and 8.9 kg ha^{-1} of N, P and K fertiliser, respectively, plus multi-element fertiliser (F_2) (Table 1). Further descriptions of the thinning and fertiliser treatments are available in Beadle et al. (2013b).

Stand growth and yield

Total tree height (*H*, m) and diameter at breast height (*DBH*, cm) of all individual trees and stem number (*N*, trees ha^{-1}) in each sample plot were measured at six-monthly intervals from 2009 to 2015. These measurements were used to calculate plot mean *DBH* and stand volume (*SV*, m^3 ha^{-1}). The individual tree volume (*V*, m^3 tree^{-1}) was calculated as:

$$V = \frac{\pi}{4} \times DBH^2 \times H \times f \qquad (1)$$

Where *f* is a stem form factor for *A*. hybrid (*f* = 0.495) (Binh, 2003). *SV* was then calculated as the sum of *V* of all individual trees in each plot and expressed on a per hectare basis. Tree age is the age at which the trees were measured after planting.

Diameter classes were divided into four groups according to wood products: *DBH* <10 cm (pulp wood), 10 cm ⩽ *DBH* <13.9 cm (small sawlogs, low value) and 14 cm ⩽ *DBH* <17.9 cm (medium sawlogs) and *DBH* ⩾18 cm (large sawlogs).

Application of 3-PG model

3-PG is a model of forest productivity that uses the Beer-Lambert law to calculate photosynthetically active radiation absorbed by the canopy (as determined from leaf area index) through the photosynthesis process to net primary production. The model has been parameterised and applied widely for different purposes and species growing under current and future climate (Almeida et al. 2004a; Garcia-Gonzalez et al. 2016, Almeida and Sands 2016). The model is capable of producing a range of outputs of interest to the forest managers (Almeida et al. 2004b). The 3-PG model was recently parameterised and validated to quantify the effects of regional differences in climate and soil fertility on *A.* hybrid productivity in Vietnam (Hung et al. 2016). In this study, the same model was used to examine the effects of thinning and fertiliser treatments on the yield of medium and large sawlogs for an adopted rotation length up to 15 yr.

In the model, an empirical soil fertility index (*FR*) ranges from one (no nutritional limitations) to zero (extremely infertile). For the six sites examined in this study, *FR* values had been determined by a previous study which involved the measurement of both soil physical and chemical parameters to determine the growth modifier for FR (Hung et al. 2016) and ranged from 0.3 to 0.8. For the plots that received fertiliser at thinning (i.e. F_1 and F_2), it was assumed that the application of fertiliser increased the initial *FR* by 10% - a value obtained from empirical evidence for *Eucalyptus grandis* × *urophylla* (Stape et al. 2004). For the thinned plots that received no fertiliser at thinning (F0), the *FR* values were the same values as for the of control plots (Table 1).

Monthly modelled *DBH* and *SV* of each treatment from 1 to 15 years were used to identify the time predicted for each treatment to reach the required mean *DBH* for both medium and large sawlogs, defined as minimum harvest ages for each log type. The measured *DBH* and *SV* responses to thinning and fertiliser at thinning were also used to identify the most successful management practice to produce sawlogs of a given size at harvest.

Statistical analysis

As the treatments and timing of measurements were different, each site was analysed separately. Survival rate (82.1 – 96%) was similar regardless of thinning and fertiliser treatments from tree age 4.9 to 5.7 years (data not shown). At Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3, effects of thinning, fertiliser or timing of thinning treatments on *DBH* and *SV* were analysed by two-way analysis of variance (ANOVA) within a repeated measure framework (tree age) assuming a randomised block design with thinning, fertiliser or timing of thinning treatments as fixed factors. At Binh Dinh and Dong Nai, growth responses were analysed by one-way ANOVA within a repeated measure framework (tree age) with thinning treatment as a fixed factor. Effects of thinning, fertiliser or timing of thinning treatments on diameter classes, 10-13.9 and 14-17.9 and ⩾18 cm at final measurement, were analysed by two-way ANOVA at Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3 and one-way ANOVA at Binh Dinh and Dong Nai. Due to lack of data, diameter classes <10 and ⩾18 cm were only modelled. The assumptions of ANOVA such as homogeneity of variance and the Gaussian distribution were checked by the use of quantile–quantile plots and residual plots for all variables. Fisher's protected least significant difference (LSD at P <0.05) post-hoc tests were used to determine differences among treatment means. All analyses were performed using GenStat, 12th edition (VSN International Ltd, Hemel Hempstead, UK 2011).

The fit between predicted and observed *DBH* and *SV* values were assessed by calculating the coefficient of determination (r^2), model efficiency (*EF*) (Loague and Green, 1991) and the root mean square error (*RMSE*) (Soares et al. 1995) as follows:

$$EF = \frac{\sum_{i=1}^{n}(O_i-\bar{O})^2 - \sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \qquad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i-Pi)^2}{n}} \qquad (3)$$

where *Pi* and *Oi* are the predicted and measured values respectively, $\bar{O}$ is the mean of the observed values, and *n* is the total number of measurements.

Results

Effects of thinning regimes on DBH and SV

Significant responses of *DBH* and *SV* to thinning intensity occurred at Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3, but there were no significant differences in *SV* between T_{450} and T_{600} at Ba Vi-3. At Binh Dinh and Dong Nai, thinning intensity did not affect *DBH*, but *SV* in thinned treatments was significantly lower than in the unthinned treatment (Online Resources 2 and 3).

Effects of thinning intensity × tree age interaction on DBH and SV

Both *DBH* and *SV* were significantly influenced by thinning intensity × tree age interaction across all trials (Online Resources 2 and 3). At Tuyen Quang and Ba Vi-1, *DBH* was significantly greater compared to unthinned treatments five months after thinning ($T_{600/2}$) (Fig. 2a, b). These differences remained significant at final measurement. In contrast, thinning treatments had no significant immediate effect on *DBH* when thinning was carried out at age ⩾3 years at Ba Vi-2, Binh Dinh and Dong Nai, (Fig. 2c-e). Instead, significant thinning effects were observed later, at age 4.4 – 7.4 years, with the magnitude and timing of these differences to thinning intensity varying across trials (Fig. 2). Similarly, at Binh Dinh, the effect of thinning treatment was observed later, at tree age 5.3 years when *DBH* (13.3 cm) was the highest in $T_{667/3}$ compared to $T_{1000/3}$ and $T_{1333/3}$ (12.6 and 12.2 cm, respectively), and NT_{2000} (12.0 cm) (Fig. 2d). At Dong Nai, significant responses of *DBH* to all thinning treatments were first observed at tree age 4.4 years with *DBH* of $T_{600/2}$, $T_{600/3}$ and $T_{800/2}T_{600/3}$ being significantly larger than NT_{1111}.

However, this response was not sustained for $T_{600/3}$ at tree age 4.9 years and there were no significant differences in *DBH* between $T_{600/2}$ and $T_{800/2}T_{600/3}$ (Fig. 2e).

Across all trials, thinning treatments significantly reduced *SV* immediately after the thinning event (Online Resources 2 and 6). For example, *SV* of $T_{600/2}$ in Tuyen Quang, Ba Vi-1 and Ba Vi-2 and $T_{600/3.5}$ in Ba Vi-2 were significantly lower compared to unthinned treatments and this significant treatment effect was sustained until the final measurement (Online Resource 6). At Binh Dinh, by tree age 5.4 year, *SV* of $T_{1000/3}$ and $T_{1333/3}$ treatments were similar but both were significantly higher than $T_{667/3}$ and lower than NT_{2000} (Online Resource 6). At Dong Nai, by tree age 3.7 years, *SV* of $T_{600/2}$, $T_{600/3}$ and $T_{800/2}T_{600/3}$ was similar and all significantly lower than those of NT_{1111}. These differences remained significant at final measurement (Online Resource 6).

Effects of thinning intensity × timing of thinning × tree age interaction on DBH and SV

The effects of thinning intensity (NT_{1667}, T_{450}, T_{600} and T_{900}) and timing of thinning (3.6, 4.6 and 5.6 years) on *DBH* and *SV* varied across treatments at Ba Vi-3 (Fig. 3). When measured at age 7.4 years, the *DBH* of all thinned treatments were greater than those of unthinned treatments, but the *SV* was lower compared to unthinned treatments (Fig. 3 and Online resource 7).

When trees were thinned at tree age 3.6 years, the effect was first observed seven months after thinning (Fig. 3a). In particular, *DBH* was significantly higher as thinning intensity increased and this response was sustained until tree age 7.6 years ($T_{450} > T_{600} > T_{900}$). In contrast, for trees thinned at tree age 4.6 and 5.6 years, significant thinning responses were observed 13 and 15 months later, respectively (Fig. 3b, c). Specifically, the *DBH* of all thinned treatments were similar, regardless of thinning intensity though they were all significantly higher than the unthinned treatment (Fig. 3b, c).

The *SV* of all the thinned treatments was significantly lower compared to unthinned treatments immediately after the thinning event (Online Resource 7). For trees thinned at tree age

3.6 years, these differences remained significant until the final measurement (Online Resource 7). However, when trees were thinned at tree age 4.6 and 5.6 years, *SV* between T_{450} and T_{600} were similar, though both treatments were significantly lower than either T_{900} or NT_{1667} (Online Resource 7).

Effects of fertiliser application at thinning × tree age on DBH and SV

Significant responses of *DBH* to the F_2 treatment at thinning were observed four or five months after fertiliser application at Tuyen Quang and Ba Vi-1 (Online Resource 2, Fig. 4a, b); the response was observed at a later stage (1.7 years) after fertiliser application at Ba Vi-2 (Fig. 4c). At Tuyen Quang, fertiliser had a significant effect on *DBH* at the final measurement, however the magnitude of this response did not vary between F_1 and F_2 treatments (Fig. 4a). At Ba Vi-1 and Ba Vi-2, *DBH* of the F_2 treatment was significantly greater than those in the F_1 and F_0 treatments at 5.4 and 7.1 years, respectively (Fig. 4b, c).

At Tuyen Quang, fertiliser treatment had no effect on *SV* (Online Resource 8). In contrast, at Ba-Vi-1 and Ba Vi-2, the *SV* of the F_2 treatment was significantly greater compared to both the F_1 and F_0 treatments, 0.6 and 1.7 years, respectively after fertilising and these differences were maintained until the final measurement (Online Resource 8).

Effects of silvicultural treatments on DBH classes

At Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3, thinned treatments had significantly higher percentage of trees in the 14 – 17.9 cm than the 10 – 13.9 cm class compared to the unthinned treatment (Table 2 and Online Resource 4). However, at Ba-Vi 3, the percentage of trees in the 10 – 13.9 cm and 14 – 17.9 cm *DBH* classes for the T_{450} treatment was significantly higher than T_{900} and T_{600} treatments. At Binh Dinh, thinning treatment had no significant influence on *DBH* classes (Table 2). At Dong Nai, only the 10 – 13.9 cm class was affected by thinning treatment.

In particular, $T_{800/2}T_{600/3}$ had 62% less trees with this class than NT_{1111} treatment. The percentage of trees in the 14 – 17.9 cm class in all thinned treatment showed greater values compared to NT_{1111} treatment except for Binh Dinh (P = 0.062) (Table 2).

At Ba Vi-1, diameter classes were unaffected by fertiliser (Online Resource 4). In contrast, a significantly higher percentage of trees in the 14 – 17.9 cm class was observed in the F_1 and F_2 treatments than the F_0 treatment at Ba Vi-2; there were no significant differences between F_1 and F_2 treatments (Table 3). At Tuyen Quang, only the F_2 treatment significantly increased trees in the 14 – 17.9 cm class (Table 3).

Thinning intensity × fertiliser interaction had a significant effect on diameter classes at both Tuyen Quang and Ba Vi-1 only (Table 4). At Tuyen Quang, the percentage of trees in the 14 – 17.9 cm class was highest under $T_{600/2}F_2$ followed by $T_{600/2}F_1$. The percentage of trees in this class was similar in NT_{1111} at Tuyen Quang, regardless of fertiliser treatment. At Ba Vi-1, fertiliser had no effect on the percentages of trees in the 10 – 13.9 cm class under $T_{600/2.}$ In contrast, significantly higher percentage of trees were observed in the F_2 but not in the F_1 nor F_0 treatments in NT_{1111}.

At Ba Vi-3, timing of thinning significantly influenced the percentage of trees in the 10 – 13.9 cm but not the 14 – 17.9 cm class (Online Resource 4); a significantly lower percentage of trees in the 10- 13.9 cm class were observed for trees thinned at age 3.6 yr than those thinned at age 4.6 and 5.6 (i.e. thinning age 3.6 yr: 23.6 ± 6.2%; thinning age 4.6 yr: 32.2 ± 6.2%; thinning age 5.6 yr: 38.7 ±6.6%).

Modelling growth and sawlogs yields

The accuracy of the predictions of *DBH* and *SV* varied with treatments across trials. The *EFs* of *SV* ranged from 0.55 to 0.98 (*RMSEs* = 1.88 – 27.71), and for *DBH* from 0.53 to 0.96 (*RMSEs* = 0.97 – 2.48) (Fig. 5 and Online Resource 5). From the model predictions of *DBH* in the unthinned treatment, the rotation length required to obtain medium sawlogs (14 – 17.9 cm *DBH*) was approximately half that for large sawlogs (⩾18 cm *DBH*) (Online resource 8). For a hypothetical 15-year rotation, predicted *SV* in the thinned treatments was 5 – 20% less than in the unthinned treatments across all trials. The minimum predicted rotation length required to produce medium logs ranged between 4.8 – 8.3 years for all thinned treatments compared to 6.2 – 12.8 for all unthinned treatments (Online resource 9); for large logs, it was respectively between 7.3 – 12.7 years and 10.4 – >15 years.

At Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3, no large sawlogs were predicted for any unthinned treatment at the end of a 15-yr rotation. In contrast, at Bing Dinh and Dong Nai, all thinning intensities including the unthinned treatment were predicted to produce both medium and large sawlogs within a 15-yr rotation. At Ba Vi-3, the rotation length required to grow the trees for either medium or large diameter logs would be shorter by 0.5 to 1.7 yr if thinning was carried at age 3.6 yr compare to ages 4.6 or 5.6 yr. Heavy early age thinning also predicted less time would be required to produce sawlog products compared to lighter early age thinning. At Tuyen Quang, Ba Vi-1 and Ba Vi-2, simulations with fertiliser application at thinning predicted rotation lengths for medium sawlogs would be between 0.5 to 2.6 yr shorter compared with thinning only and control treatments. The model was more accurate in predicting *DBH* and *SV* for treatments in the north (Tuyen Quang, Ba Vi-1, Ba Vi-2, Ba Vi-3) and south-central coast (Bing Dinh) than the more highly productive site in south Vietnam (Dong Nai).

The mean annual increment (MAI) observed and modelled for *A. hybrid* ranged from 15 to 33 m^3 ha^{-1} $year^{-1}$; Dong Nai and Binh Dinh (25 and 30 m^3 ha^{-1} $year^{-1}$, respectively) were higher than Ba Vi and Tuyen Quang (14 to 23 m^3 ha^{-1} $year^{-1}$).

Discussion

Growth responses to thinning

Thinning to 450 or 600 trees ha^{-1} at age 2 – 3.6 years produced the highest percentage of larger *DBH* classes although there was lower *SV* recovery in all thinned stands especially those thinned to 450 trees ha^{-1}. Increased *DBH* increment of retained trees due to early thinning has been reported also in other studies on hardwood species especially *Eucalyptus* (Medhurst et al. 2001; Forrester et al. 2012). The *DBH* growth response to thinning indicates that intraspecific competition prior to thinning may occur as early as age 2 yr in *A.* hybrid, which is not surprising given that acacia species grown in short-rotation tropical plantations, including *A.* hybrid, have a potential for very high early growth rates (Beadle et al. 2013a). Early thinning especially at higher intensities may reduce this intraspecific competition reducing leaf area index temporarily (West 2014) and potentially improve efficiency in nutrient and water use (Medhurst et al. 2002).

At Ba –Vi 3, all thinning treatments improved *DBH* regardless of thinning age, however, the greatest thinning responses occurred at age 3.6 yr, most likely because the capacity of trees to respond is reduced as growth rates decline with the intensification of intra-specific competition at later-age thinning (Huong et al. 2016). Previous studies have shown growth responses of *E. nitens* to be comparable for trees thinned at age 3.2 or 13.2 yr, five years after thinning, at least on high-quality sites (Medhurst et al. 2001; Forrester et al. 2013b). In contrast, thinning a productive *E. globulus* plantation at age 11 yr produced no growth response in the retained trees by age 13 yr (Gerrand et al. 1997).

Thinning did not necessarily increase *DBH* or the proportion of larger *DBH* class in all treatments and regions. For example, at Binh Dinh, thinning from 2000 to 677 but not 1000 and 1333 tree ha^{-1} increased *DBH* while none of the thinning treatments increased the proportion of larger *DBH* suggesting that the benefits of thinning may not be fully realised at very high initial stocking rates. Even at lower initial stocking rates, thinning did directly translate into larger *DBH*.

At Ba Vi-1, despite significant increases in *DBH*, at only 9%, this site had the lowest proportion of larger logs across all trials after thinning from 1111 to 600 trees ha^{-1} at age 2 yr. Ba Vi-3 and Dong Nai were the two sites producing higher percentage of trees with medium and high *DBH* in all treatments.

Growth responses to fertiliser

Application of fertilisation at thinning increased individual tree growth, regardless of thinning treatment and only increased the proportion of medium-sized diameter classes when combined with thinning at Tuyen Quang but not at Ba Vi-1 and Ba Vi-2. In this study, fertilisation at thinning was conducted at the less productive northern sites only therefore this response to fertiliser is probably driven by low P levels in the soil. Lateritic low pH (3.4 – 4.4) soils strongly fix P and available P was only 1.8 – 4.9 mg kg^{-1}. Xu and Dell (2003) found that low pH and available P in soils are key factors that often result in an increase of eucalypt growth in response to P fertiliser application in China. A significant growth response to fertiliser was observed at Ba Vi-2, where slash and litter had been removed. These results suggest that retaining litter may be an important management strategy for reducing the requirement for fertiliser inputs.

Less nutrient limiting sites may not require P fertiliser at thinning and the total amount of P fertiliser per tree applied at planting may be sufficient to obtain a thinning response (Huong et al. 2016). Nutritional requirements however, may change over successive rotations, depending on soil type, growth rates, and inter-rotation management practices (Beadle et al. 2015).

Modelling the effects of thinning and fertilisation on stand growth

The 3-PG model has been previously used to simulate response to thinning (Rodríguez et al. 2002; Landsberg et al. 2005; Pérez Cruzado et al. 2011) and fertilization (Stape et al. 2004; Wei et al. 2014; Subedi and Fox, 2016). This study showed that 3-PG was able to predict stand growth for different regions and thinning treatments with acceptable accuracy at least for the period when measurements were made i.e. up to 7.4 years after planting. Model accuracy varied among the sites. This observed variation in model accuracies between regions and sites could potentially be due to the fact that calibration of the model was based on a single parameter set developed for one site (Ba Vi) for a limited number of clones (four out of the seven clones only), accuracy of climatic data between sites and distance from the weather stations, and the uncertainties of the effect of fertilisation on the FR values or the combination of these factors. For improved accuracy, future work could also focus on how well the model predicts LAI in response to management practices (Gonzalez-Benecke et al. 2016). That said, the model accuracy observed in this study was similar to those reported for *Eucalyptus grandis* (Almeida et al. 2004a) and *Eucalyptus nitens* (Gonzalez-Garcia, 2016) and in mixed species plantations (Forrester and Tao, 2016). This is the first time the 3-PG model has been applied to predict diameter classes and thinning treatments for *A. hybrid* plantations. The model predictions of MAI are similar to those reported for *A. hybrid* in Central Vietnam (e.g. > 25 m^3 ha^{-1} $year^{-1}$, Beadle et al. 2013a) and for *Acacia mangium* in Sumatra, Indonesia (22 to 35 m^3 ha^{-1} $year^{-1}$, Harwood and Nambiar, 2014).

A 15-year rotation length was used with the objective to identify the minimum ages that trees achieve the desired class of *DBH* and to enable prediction of the volumes of pulpwood, medium and large sawlogs for different ages. As for the time series measurements, simulations suggest that heavy early age thinning associated with fertiliser application will produce larger log sizes in a shorter time, compared to low intensity and later-age thinning. Simulations indicate that a proportion of medium (*DBH* ⩾14 cm) and larger (*DBH* ⩾18 cm) sawlogs can be obtained in northern Vietnam within rotation lengths of 6 and 10 years, respectively. The rotation lengths projected in south and south central coast Vietnam were 5 years for medium and 7 years for large sawlogs. It is acknowledged that these estimations are based on a model that has been validated for stands up to age 7.4 years and beyond this age more data need to be collected to corroborate the modelling results. Nevertheless, these results point the potential options for silvicultural treatments and rotation lengths across Vietnam that may influence the decision making process to obtain saw logs in shorter rotations.

Conclusions

Our results showed the advantage of early thinning (at age 2-3.6 years) to a stocking of 450 or 600 trees ha^{-1} to maximise the percentage recovery of medium and large sawlogs within the shortest rotation and additional recovery of product for pulpwood. Fertiliser application at thinning increased individual tree growth, regardless of thinning treatment – the lack of response most likely reflecting the lower soil fertility of the northern sites. The range of responses observed in this study provide information of potential management across a range of thinning prescriptions and site qualities; the decision of what management is suitable for a particular region depends on the markets for thinned products and product values.

The 3-PG model adequately predicted the growth of *A.* hybrid plantations under thinning and fertilisation regimes, up to 7.4 years after planting. The model predictions suggested that the rotation of thinned stands with 5 – 7 years in south and central, and 6 – 10 years in north produces medium and large sawlogs. These results provide smallholders with information to assist with decision making of stands over the entire rotation to achieve production of the required diameter sizes in the shortest time possible and to optimise sustainable management of *A.* hybrid plantations in Vietnam.

Variability between species, sites, costs of inputs and the value of products shows that there is no single optimal fertilising, thinning intensity and age of thinning regime. Further recommendations to undertake thinning or fertiliser operations should include an examination of the potential effect of thinning on wood properties (e.g. wood density, stem taper) as well as socio-economic analyses that considers timber prices, costs of management practices, the applied discount rate, transport costs and the cash flow requirements of smallholders. Thus, the final assessment of the feasibility of intensive management can only be performed after an economic analysis (e.g. Cassidy et al. 2012) that needs to consider the risks associated with longer rotations, which remains a task of further study.

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Table 1 Description of thinning and fertiliser treatments applied across the six experimental trials. A fertility rating (*FR*) was used in 3-PG model and assigned for each treatment. *FR* index varied from 0 to 1 where 0 represents very low and 1 very high fertility

Trial (tree age)	Thinning intensity	Thinning code	Fertiliser at thinning (kg ha^{-1}) (N:P:K)	Fertiliser code	*FR*
Tuyen Quang (5.4 yr)	No thinning (1111 trees ha^{-1})	NT_{1111}	No fertiliser	F_0	0.30
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	No fertiliser	F_0	0.30
	No thinning (1111 trees ha^{-1})	NT_{1111}	17.8, 50, 8.9	F_1	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	17.8, 50, 8.9	F_1	0.33
	No thinning (1111 trees ha^{-1})	NT_{1111}	17.8, 50, 8.9, *	F_2	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	17.8, 50, 8.9, *	F_2	0.33
Ba Vi-1 (5.9 yr)	No thinning (1111 trees ha^{-1})	NT_{1111}	No fertiliser	F_0	0.30
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	No fertiliser	F_0	0.30
	No thinning (1111 trees ha^{-1})	NT_{1111}	17.8, 50, 8.9	F_1	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	17.8, 50, 8.9	F_1	0.33
	No thinning (1111 trees ha^{-1})	NT_{1111}	17.8, 50, 8.9, *	F_2	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	17.8, 50, 8.9, *	F_2	0.33
Ba Vi-2 (7.4 yr)	No thinning (1667 trees ha^{-1})	NT_{1667}	No fertiliser	F_0	0.30
	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	No fertiliser	F_0	0.30
	No thinning (1667 trees ha^{-1})	NT_{1667}	17.8, 50, 8.9	F_1	0.33
	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	17.8, 50, 8.9	F_1	0.33
	No thinning (1667 trees ha^{-1})	NT_{1667}	17.8, 50, 8.9, *	F_2	0.33
	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	17.8, 50, 8.9, *	F_2	0.33
Ba Vi-3 (7.4 yr)	No thinning (1667 trees ha^{-1}) at age 3.6 yr	$NT_{1667/3.6}$	No fertiliser	F_0	0.50
	Thinned to 900 trees ha^{-1} at age 3.6 yr	$T_{900/3.6}$	No fertiliser	F_0	0.50
	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	No fertiliser	F_0	0.50
	Thinned to 450 trees ha^{-1} at age 3.6 yr	$T_{450/3.6}$	No fertiliser	F_0	0.50
	No thinning (1667 trees ha^{-1}) at age 4.6 yr	$NT_{1667/4.6}$	No fertiliser	F_0	0.50
	Thinned to 900 trees ha^{-1} at age 4.6 yr	$T_{900/4.6}$	No fertiliser	F_0	0.50
	Thinned to 600 trees ha^{-1} at age 4.6 yr	$T_{600/4.6}$	No fertiliser	F_0	0.50
	Thinned to 450 trees ha^{-1} at age 4.6 yr	$T_{450/4.6}$	No fertiliser	F_0	0.50
	No thinning (1667 trees ha^{-1}) at age 5.6 yr	$NT_{1667/5.6}$	No fertiliser	F_0	0.50
	Thinned to 900 trees ha^{-1} at age 5.6 yr	$T_{900/5.6}$	No fertiliser	F_0	0.50
	Thinned to 600 trees ha^{-1} at age 5.6 yr	$T_{600/5.6}$	No fertiliser	F_0	0.50

	Thinned to 450 trees ha^{-1} at age 5.6 yr	$T_{450/5.6}$	No fertiliser	F_0	0.50
Binh Dinh (5.3 yr)	No thinning (2000 trees ha^{-1})	NT_{2000}	No fertiliser	F_0	0.60
	Thinned to 1333 trees ha^{-1} at age 3 yr	$T_{1333/3}$	No fertiliser	F_0	0.60
	Thinned to 1000 trees ha^{-1} at age 3 yr	$T_{1000/3}$	No fertiliser	F_0	0.60
	Thinned to 667 trees ha^{-1} at age 3 yr	$T_{667/3}$	No fertiliser	F_0	0.60
Dong Nai (4.9 yr)	No thinning (1111 trees ha^{-1})	NT_{1111}	No fertiliser	F_0	0.70
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	No fertiliser	F_0	0.70
	Thinned to 600 trees ha^{-1} at age 3 yr	$T_{600/3}$	No fertiliser	F_0	0.70
	Thinned to 800 trees ha^{-1} at age 2 yr, then thinned to 600 trees ha^{-1} at age 3 yr	$T_{800/2}T_{600/3}$	No fertiliser	F_0	0.70

*Macro- and micro-nutrients included: 80 KCl kg ha^{-1}, 6 $MnSO_4.H_2O$ kg ha^{-1}, 64 $FeSO_4.7H_2O$ kg ha^{-1}, 3.5 $ZnSO_4.7H_2O$ kg ha^{-1}, 2 $CuSO_4.xH_2O$ kg ha^{-1}, 0.45 H_3BO_3 kg ha^{-1}, 0.11 $Na_2MoO_4.2H_2O$ kg ha^{-1}, 12 $MgSO_4$ kg ha^{-1}.

Table 2 Effect of thinning intensity on distribution of stem diameter classes (%) at final measurement age of six experimental trials in Vietnam. Different letters indicate that treatment means are significantly different at $P < 0.05$ within a diameter class

Trial (final tree age)	<10 cm	10 – 13.9 cm	14 – 17.9 cm	⩾18 cm
Tuyen Quang (5.4 yr)				
NT_{1111}	0	46.0b	54.0a	0
$T_{600/2}$	0.9	26.0a	73.1b	0
Ba Vi-1 (5.9 yr)				
NT_{1111}	35.1	64.2a	0.7a	0
$T_{600/2}$	1.2	89.8b	9.0b	0
Ba Vi-2 (7.4 yr)				0
NT_{1667}	5.3	76.1b	18.6a	0
$T_{600/3.5}$	0.4	50.6a	49.0b	0
Ba Vi-3 (7.4 yr)				
NT_{1667}	1.4	70.2c	28.3a	0.1
T_{900}	0	29.7b	70.0b	0.3
T_{600}	0	21.9b	76.0b	2.1
T_{450}	0	4.2a	88.1c	7.7
Binh Dinh (5.3 yr)				
NT_{2000}	11.0	72.5	16.5	0
$T_{1333/3}$	7.8	77.7	14.5	0
$T_{1000/3}$	1.0	84.9	14.1	0
$T_{667/3}$		72.8	27.2	0
Dong Nai (4.9 yr)				
NT_{1111}	9.3	41.5b	44.4	4.8
$T_{600/2}$	1.7	27.3ab	62.5	8.5
$T_{600/3}$	1.7	30.4ab	59.4	8.5
$T_{800/2}T_{600/3}$	1.8	15.7a	73.9	8.6

Table 3 Effect of fertiliser treatment on distribution of stem diameter classes (%) at final measurement age of three experimental trials in Tuyen Quang and Ba Vi-2. Different letters indicate that treatment means are significantly different at $P < 0.05$ within a diameter class

Trial (tree age)	<10 cm	10 – 13.9 cm	14 – 17.9 cm
Tuyen Quang (5.4 yr)			
F_0	4.9	85.7a	9.4a
F_1	0	84.4a	15.6a
F_2	0.5	72.5b	27.0b
Ba Vi-1 (5.9 yr)			
F_0	4.6	84.2	11.2
F_1	2.0	74.4	23.6
F_2	1.0	72.3	26.7
Ba Vi-2 (7.4 yr)			
F_0	3.9	76.3b	19.8a
F_1	4.3	61.6ab	34.1b
F_2	0.3	52.1a	47.6b

Table 4 Effect of thinning intensity × fertiliser interaction on distribution of stem diameter classes (%) at the final measurement age at Tuyen Quang and Ba Vi-1. Different letters indicate that treatment means are significantly different at $P < 0.05$ within a diameter class

Trial (tree age)	<10 cm	10-13.9 cm	14-17.9 cm
Tuyen Quang (5.4 yr)			
$NT_{1111}F_0$	7.1	87.2b	5.7a
$T_{600/2}F_0$	2.6	84.2b	13.2ab
$NT_{1111}F_1$	0	89.9b	10.1ab
$T_{600/2}F_1$	0	78.9b	21.1b
$NT_{1111}F_2$	1.1	88.8b	10.1ab
$T_{600/2}F_2$	0	56.1a	43.9c
Ba Vi-1 (5.9 yr)			
$NT_{1111}F_0$	46.0	54.0a	0
$T_{600/2}F_0$	1.8	94.7b	3.5
$NT_{1111}F_1$	42.2	57.8a	0
$T_{600/2}F_1$	1.9	86.8b	11.3
$NT_{1111}F_2$	17.2	80.8b	2.0
$T_{600/2}F_2$	0	87.7b	12.3

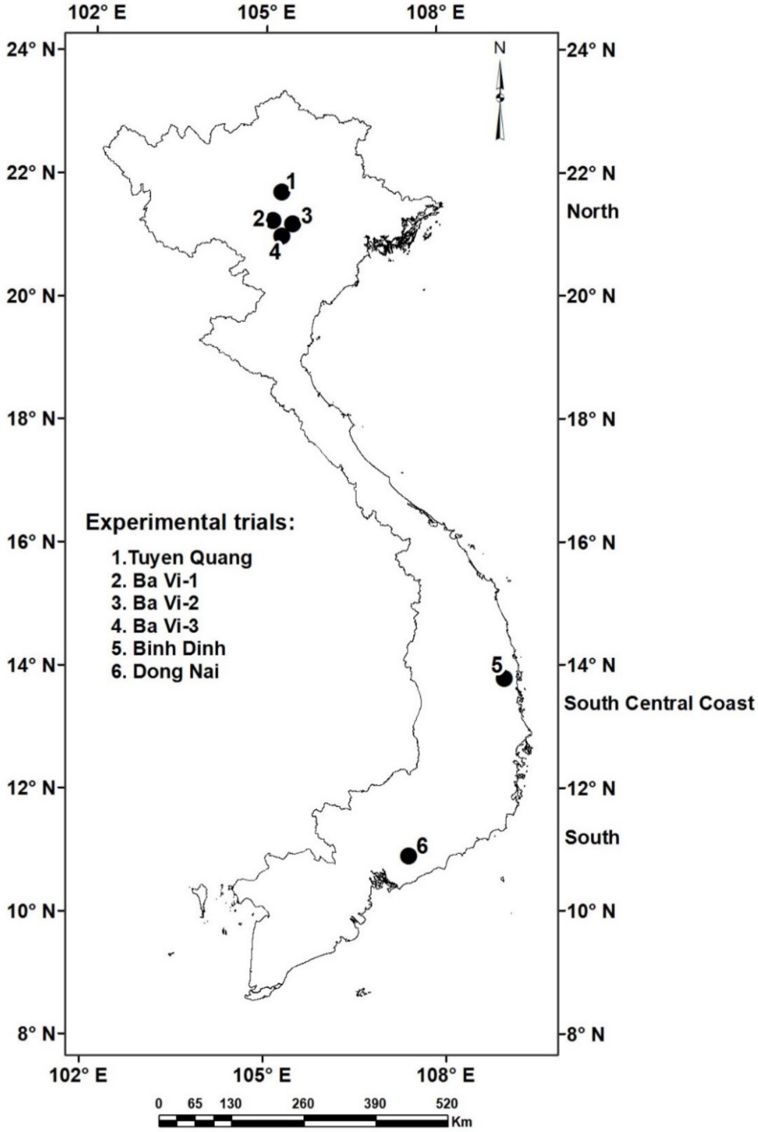

Fig. 1. Location of the six experimental trials in Vietnam.

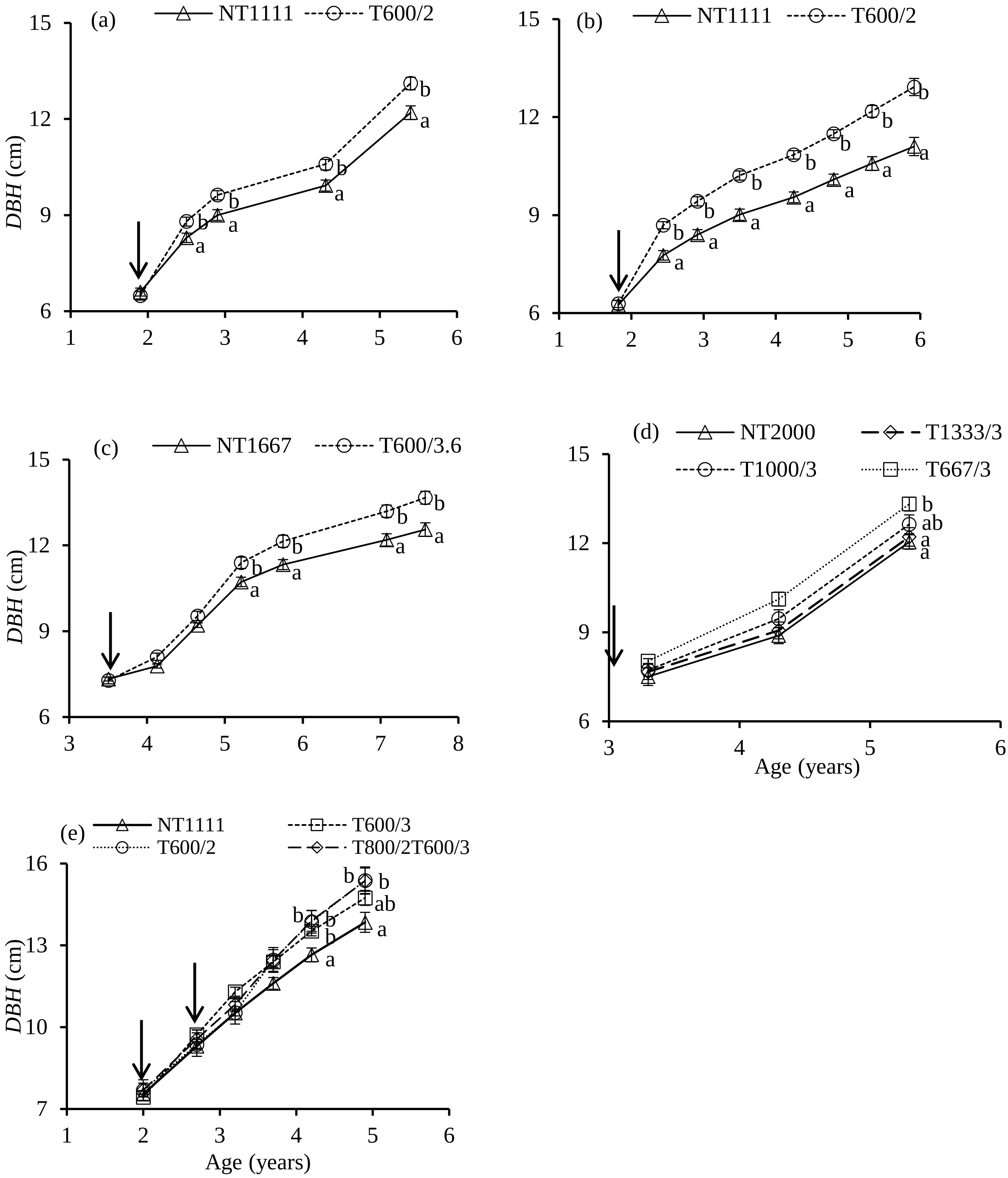

Fig. 2 Thinning intensity × tree age interaction on *DBH* (cm) at Tuyen Quang (a), Ba Vi-1 (b), Ba Vi-2 (c), Binh Dinh (d) and Dong Nai (e). Different letters indicate that means are significantly different at $P < 0.05$ within a measurement period. Arrows indicate the timing of thinning. See Table 2 for codes and description of treatments

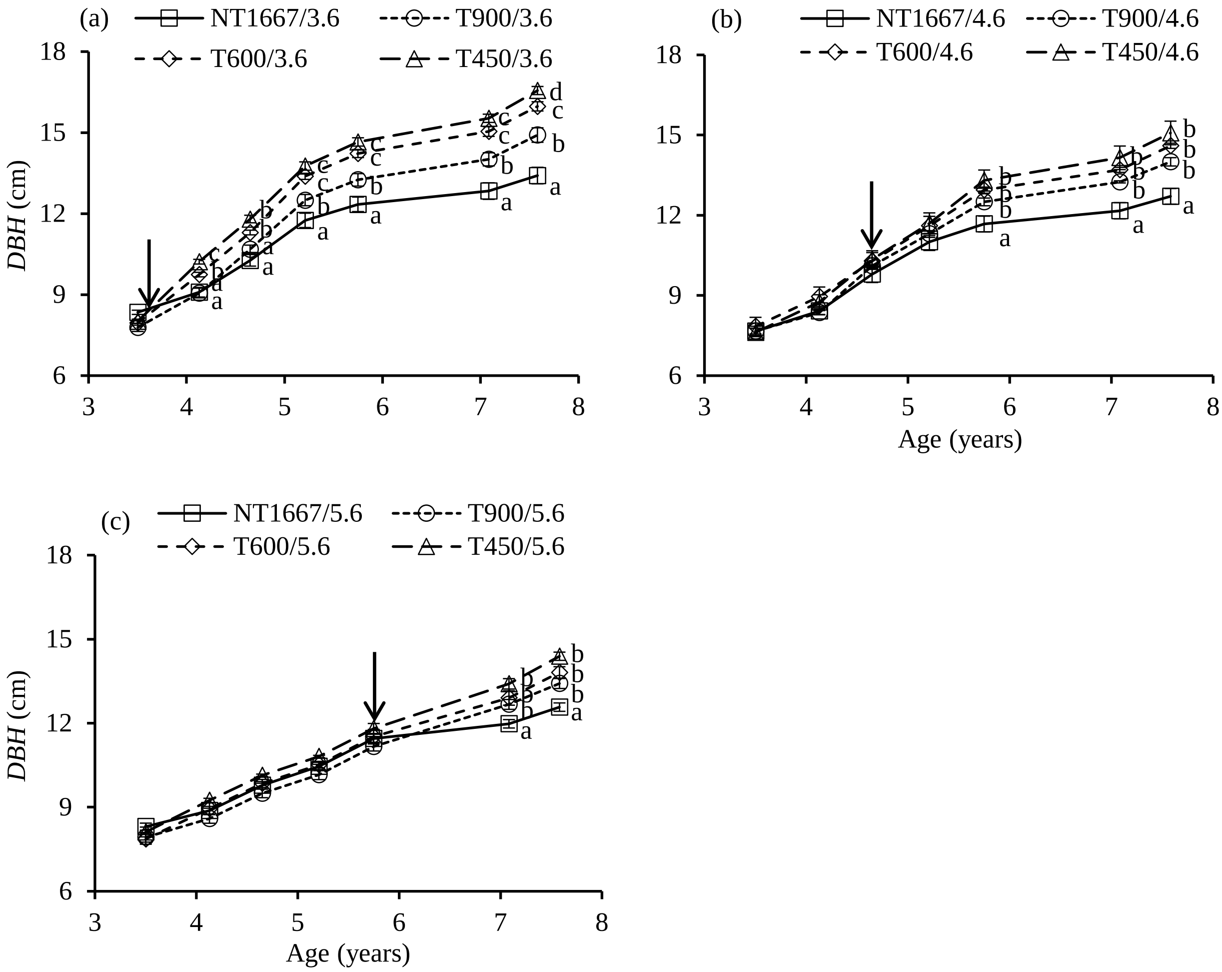

Fig. 3 Thinning intensity × timing of thinning x tree age interaction on *DBH* (cm) for three sites at Ba Vi-3. Different letters indicate that means are significantly different at $P < 0.05$ within a measurement period. Arrows indicate the timing of thinning. See Table 2 for codes and description of treatments

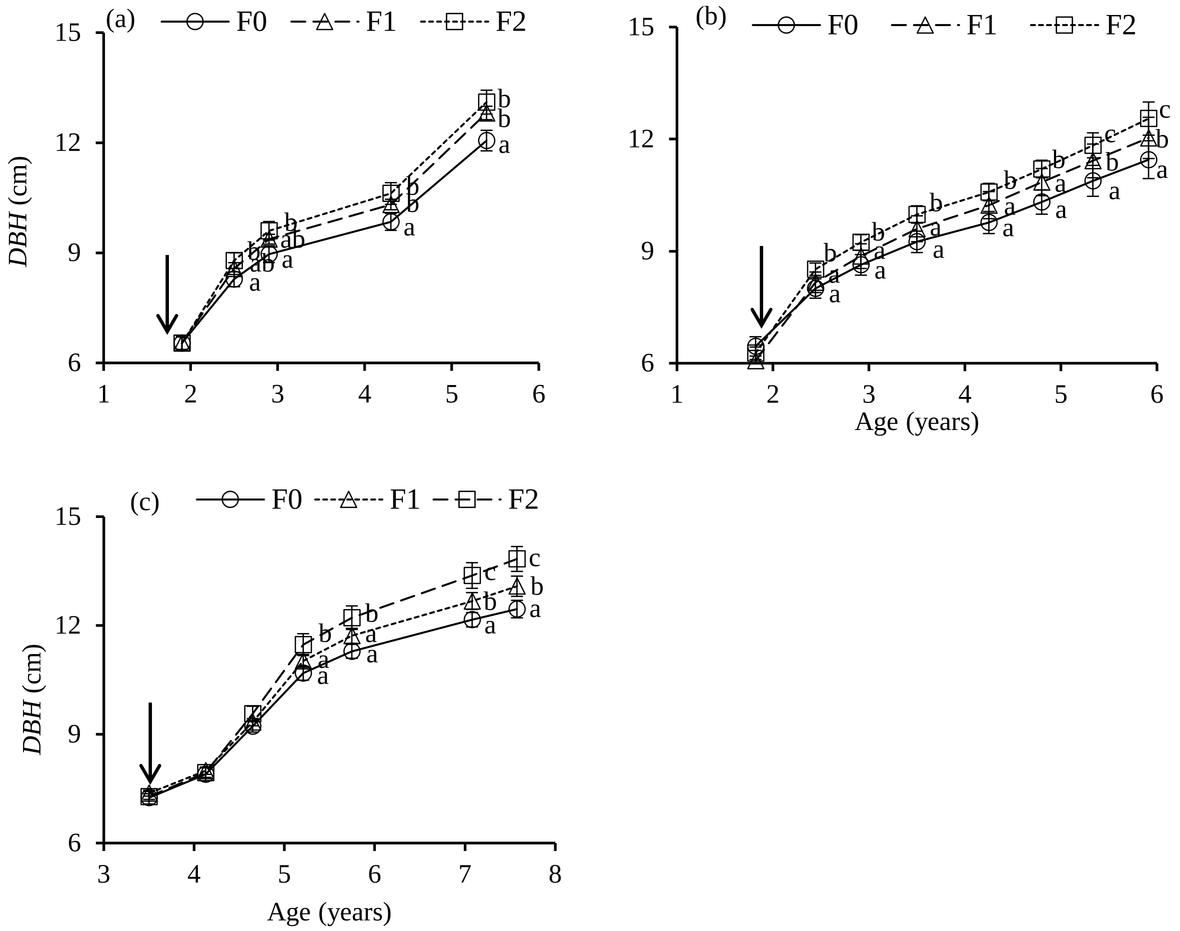

Fig. 4 Effect of fertiliser-at-thinning application × tree age interaction on *DBH* (cm) at Tuyen Quang (a), Ba Vi-1 (b) and Ba Vi-2 (c). Different letters indicate that means are significantly different at $P < 0.05$ within a measurement period. Arrows indicate the timing of fertiliser application. See Table 2 for codes and description of treatments

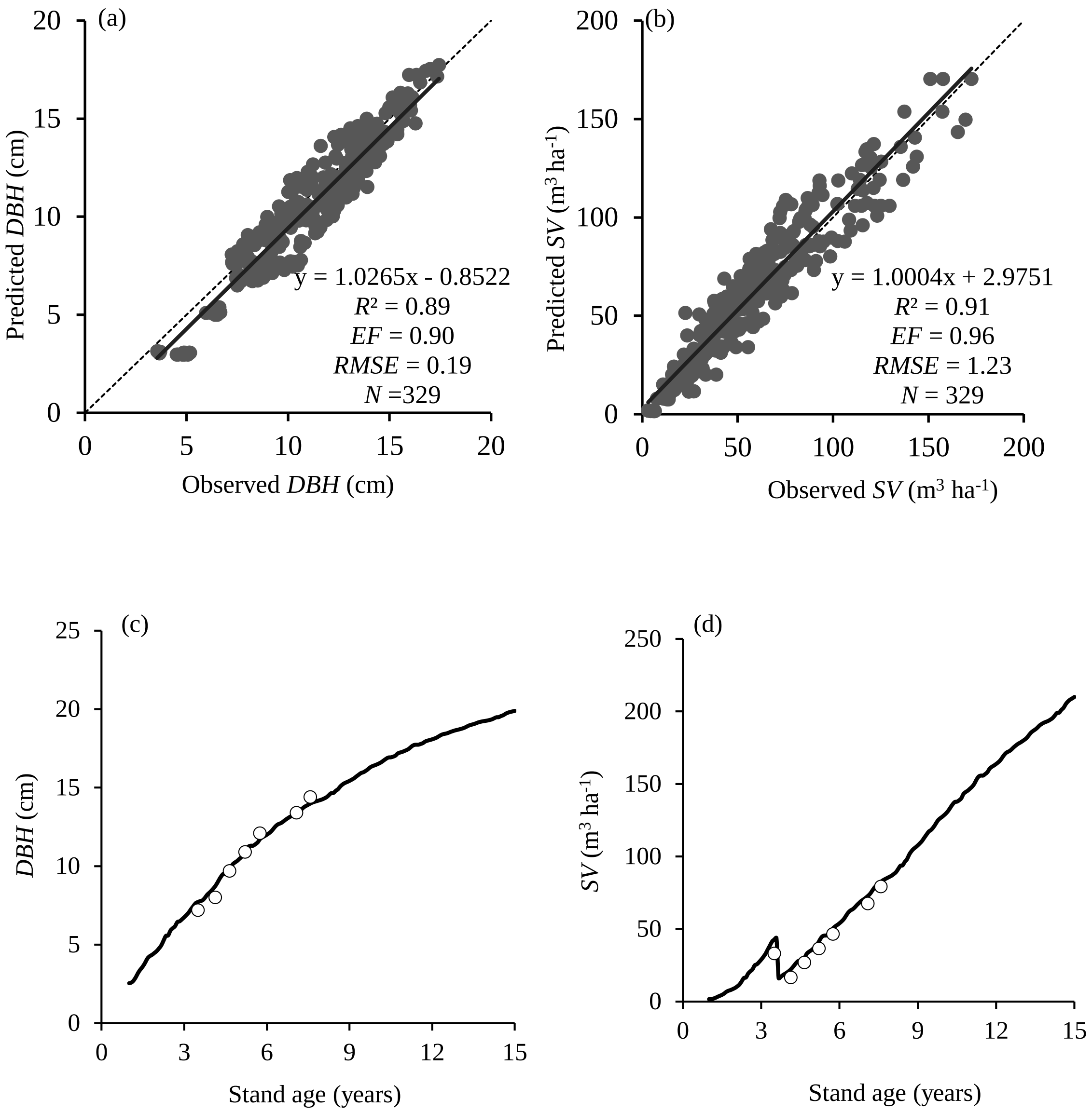

Fig. 5 Relationships between observed and predicted (a) *DBH* (cm) and (b) *SV* (m^3 ha^{-1}) as determined by 3-PG for all thinning and fertiliser treatments across six the experimental trials. Predicted (---) and observed (o) time series of (c) *DBH* (cm) and (d) *SV* (m^3 ha^{-1}) for Ba-Vi 2 site thinned from 1667 to 600 trees ha^{-1} at age 3.6 years. Dots represent means of 35 – 42 trees $plot^{-1}$