Southern Forests 2019: 1–12
Printed in South Africa — All rights reserved
This is the final version of the article that is
published ahead of the print and online issue

SOUTHERN FORESTS
ISSN 2070-2620 EISSN 2070-2639
https://doi.org/10.2989/20702620.2018.1555940

Effect of residue management and fertiliser application on the productivity of a *Eucalyptus* hybrid and *Acacia mangium* planted on sloping terrain in northern Vietnam

Nguyen Van Bich[1,2]*, Daniel Mendham[3], Katherine J Evans[1], Tran Lam Dong[2], Vo Dai Hai[2], Hoang Van Thanh[2] and Caroline L Mohammed[1]

[1] *Tasmanian Institute of Agriculture, University of Tasmania, Hobart, Tasmania, Australia*
[2] *Silviculture Research Institute, Vietnamese Academy of Forest Sciences, Hanoi, Vietnam*
[3] *CSIRO Land and Water, Hobart, Tasmania, Australia*
* *Corresponding author, email: nguyenvanbich@vafs.gov.vn*

Forest plantation growers in Vietnam commonly burn residues after harvesting and often apply suboptimal amounts of nutrients during plantation establishment. We examined whether the retention of forest residue, and application of phosphorus fertiliser at higher rates, can increase rates of growth. A factorial combination of residue management (burning vs retention) and phosphorus fertiliser application at planting (15 vs 100 kg ha^{-1}) treatments were applied at a steeply sloping site in northern Vietnam. Two adjacent experiments were established, one with *Acacia mangium* and the other with a *Eucalyptus* hybrid (*Eucalyptus urophylla* × *Eucalyptus pellita*). Standing volume and leaf area index in *A. mangium* were greater following burning; this was mostly attributable to the significantly higher survival rate of seedlings. Burning of residues was associated with increases in the number of large branches per tree, and a higher crown damage index (CDI). In the *Eucalyptus* hybrid, diameter and height responses to the higher rate of fertiliser were observed at age 6 and 12 months, but not beyond. High phosphorus application also led to higher CDI. Standard fertiliser treatment, applied in amounts equivalent to 17, 15 and 8 kg ha^{-1} of nitrogen, phosphorus and potassium, respectively, was adequate to meet the early growth requirement of eucalypt and acacia plantations at this site. The relatively low amounts of harvest residue and high fertility levels at the site may have masked more significant responses of trees to the silvicultural treatments applied in this study. On steep slopes, especially if soil is poorly fertile, harvest residue retention with adequate weed and termite control may be preferential to burning as it is closely correlated with reducing factors that negatively impact productivity, i.e. water run-off and soil erosion.

Keywords: branch size, burning harvest residue, crown damage index, phosphorus application, slope position, tropical plantation

Online supplementary material: Supplementary information for this article is available at https://doi.org/10.2989/20702620.2018.1555940

Introduction

Plantation forestry makes a crucial contribution to the economy of rural areas in Vietnam through the provision of export wood-chips, and timber for a growing domestic furniture industry (Nambiar et al. 2015). By 2013 and since the 1990s, approximately 3.4 million ha of mainly acacia and eucalypt plantations had been established (MARD 2014). They are managed on 5- to 8-year rotations, and many are located on sites with steep slopes (Sam and Binh 2001; Cao and Son 2014). The current inter-rotational practices involve repeated burning of residues and litter after harvesting with application of only low amounts of organic and/or inorganic nutrients at planting (Dung et al. 2012; Nambiar et al. 2015). There is a concern that soil fertility (Dong et al. 2014; Huong et al. 2015; Hung et al. 2017) and yields (Dung et al. 2005; Cao and Son 2014; Khiet 2014) have been declining and that current residue management practices will not be able to sustain potential yield (Dung et al. 2005, 2012; Huong et al. 2015; Nambiar et al. 2015). In addition, damage from insect pests and diseases is further reducing yields (Ngoc et al. 2011; Thu et al. 2012).

Mismanagement of site resources during the inter-rotational phase in a short-rotation silvicultural system can impact negatively on future productivity (Gonçalves et al. 2013). ‘Slash and burn’ cultivation in which the forest is clear cut, the wood removed and any remaining vegetation burnt is a traditional method of site preparation that is still used in plantation forestry in some countries, including Vietnam (Tran et al. 2011). This practice has been reported to have negative effects on the growth of eucalypts (Deleporte et al. 2008; Rocha et al. 2016), and the tree form of acacias (Eldoma et al. 2015). Burning of residues have been linked to the loss of up to 86% of nitrogen (N) and 60% of phosphorus (P) in smoke and through volatilisation, and the loss of P, potassium (K) and calcium (Ca) through leaching, wind-blown ash, surface run-off and erosion

(Gonçalves et al. 2007). Furthermore, nutrient losses have been shown to be greater on exposed sites and those with steep slopes (Edeso et al. 1999; De et al. 2008; Sidle et al. 2006). Fast-growing short-rotation plantation acacias and eucalypts require a large nutrient supply, especially of N, P and K, at planting (Melo et al. 2016, Mendham et al. 2017); burning on steeply sloping sites therefore has the potential to reduce this supply.

In contrast, retention of harvest residues has been shown to lead to increased growth of *A. mangium* in Indonesia (Hardiyanto and Nambiar 2014), *Eucalyptus grandis* in Brazil (Rocha et al. 2016) and *E. globulus* in Australia (Mendham et al. 2008). The increase in tree growth has been associated with the retention of nutrients (Huong et al. 2015), enhanced soil microbial activity (Mendham et al. 2002) and increased nutrient mineralisation (Nzila et al. 2002; O'Connell et al. 2004). On steep slopes, retention of residues from harvesting can also reduce water run-off and soil erosion (Edeso et al. 1999; Costantini and Lcoh 2002; Khan et al. 2016).

Supplying nutrients as fertiliser at planting is a common practice in short-rotation forestry, and often improves productivity on nutrient-deficient sites (Xu et al. 2001; Melo et al. 2016; Mendham et al. 2017). Eucalypt plantations have been shown to respond to both N and P applied at planting (Judd et al. 1996; Xu et al. 2001; Melo et al. 2016) and acacias to P applied at planting (Beadle et al. 2013; Huong et al. 2015; Mendham et al. 2017). However, responses can vary across sites depending on soil fertility and tree requirements (Sankaran et al. 2007; Mendham et al. 2017). As acacias are N-fixing, they are generally considered to have an increased requirement for P compared with non-leguminous species (Ingestad 1980). However, responses to high rates of P at planting have also been found in eucalypt plantations (Judd et al. 1996), especially in soils with low levels of extractable P (Xu et al. 2001; Melo et al. 2016). Thus, high rates of P may need to be applied at planting of both acacia and eucalypt plantations to maintain and improve productivity, especially in northern Vietnam where most soils have low levels of extractable P that are considered to limit growth (Sam and Binh 2001).

On steep slopes, forest plantation productivity has also been shown to be influenced by slope position (Qingshan et al. 1998; Omary 2011). For example, in central Vietnam, Harwood et al. (2017) found that stem volume of an *Acacia* hybrid (*A. mangium* × *A. auriculiformis*), grown on a moderate slope, was significantly lower at the top than in the middle and bottom of the hill. This was attributable to differences in soil moisture, nutrient status and topsoil quality (De et al. 2008; Hardie et al. 2018), as well as incident solar radiation (Auslander et al. 2003), between slope positions. Hence, understanding the impact of slope and its position on tree growth could provide useful information for sustaining productivity of acacia and eucalypt plantations managed on steep slopes.

The productivity of eucalypt and acacia plantations worldwide is also increasingly threatened by insect pests and pathogens (Wingfield et al. 2015; Crous et al. 2017). Growth rates of *Acacia mangium* have been reduced from 23.5 to less than 15 m^3 ha^{-1} y^{-1} as a result of fungal diseases (*Ganoderma philippii* and *Ceratocystis manginecans*) in Sumatra, Indonesia (Harwood and Nambiar 2014). Among the most serious pests of eucalypts in Asia is the gall wasp *Leptocybe invasa* (Dell et al. 2012; Thu 2016; Tong et al. 2016), which caused a 20% reduction in productivity of eucalypts (*E. tereticornis*, *E. camaldulensis* and *E. saligna*) in Tanzania (Kurganova et al. 2018). In Brazil, volumetric growth of *Eucalyptus urophylla* and its hybrid (*E. urophylla* × *E. grandis*) has been found to be reduced by up to 82% after 30 months infection by *Ralstonia solanacearum* (Ferreira et al. 2018). Tropical acacias and eucalypts are also affected by termites (Calderon and Constantino 2007; Ngoc et al. 2011), with up to 30% of seedlings being infested in many young acacia and eucalypt plantations across Vietnam (Ngoc et al. 2011). However, there has been limited studies linking plantation health to silvicultural practices (Jactel et al. 2009). In Australia, Pinkard et al. (2006) found that fertiliser application as N or N + P improved crown health and productivity of a three-year-old *E. globulus* plantation that suffered attack from the eucalypt weevil (*Gonipterus scutellatus*). Residue management has been found to influence community structure of invertebrate pests in wattle (*Acacia mearnsii*) plantations in South Africa with a greater infestation of soil invertebrate pests on sites where the plantation residue was windrowed–burnt–weeded or 'broadcast' (20.34%) than in the other treatments (windrowed–burnt–ripped or fallow; 2.36%) (Govender 2014). Hence, the effect of silvicultural treatments to be trialled on potential biotic damage should be taken into account in any experimental design.

This study examined whether residue retention and higher levels of P fertiliser application at planting can be used to arrest any yield decline on a steeply sloping sites and provide a pathway for sustaining higher yields in acacias and eucalypts planted in Vietnam in the longer term. We examined the effects of burning harvest residues (current practice) compared with residue retention, and the interactions between harvest residue management and P fertiliser application (current practice vs a higher rate) on the productivity of *Acacia mangium* and a *Eucalyptus* hybrid (*E. urophylla* × *E. pellita*).

Materials and methods

Study site

The study site was located 170 km north of Hanoi at latitude 21°51′ N, longitude 105° 00′ E, and altitude 100 m in a commercial forest area in Yen Bai province, Vietnam. The mean annual temperature is 22.9 °C, relative humidity is commonly >75% and mean annual rainfall is 1 808 mm (range 1 396–2 140 mm), most falling from May to September (Figure 1).

The site had slopes ranging from 5–10° (at the top of the hill) to 25–30° (in the middle) and 30–40° (at the bottom). The soils at the site are classified as ferric (Ferralic) Acrisols (FAO 1988) and had mean soil pH (1:5; H_20) of 3.8 and Bray extractable P of 3.5 mg kg^{-1} (Table 1).

Land-use history, stand harvest and site preparation

Historically, the site was converted from secondary forest (degraded natural forest) to plantation *Styrax tonkinensis*

(Pierre) Craib in the 1980s, followed by two rotations of *A. mangium* planted in 2000 and 2008. Site preparation on each occasion involved the burning of post-harvest residues and, at planting, the application of small amounts of inorganic fertiliser.

The previous stand of *A. mangium* was clear-felled in January 2015. The detailed measurements, analyses and descriptions of the stand were presented in Bich et al. (2018). In brief, at harvesting the stand had a mean height of 14.5 m, stem diameter (DBH) of 13.2 cm, mean annual increment (MAI) of 13.3 m^3 ha^{-1} y^{-1} and aboveground stand biomass of 60.8 Mg ha^{-1}. Stemwood, without bark, of commercial size (diameter > 3 cm over bark) was removed from the site. The other stand components (estimated to be 18.1 Mg ha^{-1}), including bark (8.9 Mg ha^{-1}), branches (<3 cm in diameter, 6.6 Mg ha^{-1}), leaves (2.5 Mg ha^{-1}) and forest floor, including litter (5.8 Mg ha^{-1}) and understorey vegetation (3.3 Mg ha^{-1}), were retained on the site. The total initial nutrient contents in all residues maintained on the site were estimated to be 440, 15, 61, 185 and 20 kg ha^{-1} of N, P, K, Ca and magnesium, respectively. The residue was distributed evenly prior to the imposition of treatments. The site then was planted with the *Eucalyptus* hybrid experiment in March–April 2015 and the *A. mangium* experiment in June 2015.

Experimental design and treatments

A randomised complete block experiment with five replications was applied to both the *A. mangium* and *Eucalyptus* hybrid experiments. Replicate blocks were located so as to account for slope effects, with the plots in each block having a similar slope range (5–10°, 20–30° and 30–40° at the top, middle and bottom position of the hill, respectively). Availability of the land area dictated that there was one replication at the top, two in the middle and two at the bottom of the hill for the *Eucalyptus* hybrid, whereas for the *A. mangium* experiment there was sufficient space for two replications at the top, two in the middle, and one at the bottom. Four treatments were imposed: a factorial combination of residue management (burning vs retention) and P fertiliser application (current practice vs a higher level of P fertiliser). Details of the treatment combinations are given below.

The two residue management treatments were:

(1) S0: Residues burnt: harvest residues evenly distributed, and then all residues subsequently burnt 60 d after clear-cutting and two weeks before planting
(2) S1: Residues retained: harvest residues evenly distributed and no burning.

The plantation soils are dominated by acidic and leached Acrisols with low available soil P (Sam and Binh 2001; Phuong et al. 2012; Sang et al. 2013; Hung et al. 2017) and P at planting is a critical requirement for growth (Hai et al. 2005; Son et al. 2006). A zero P treatment therefore was not applied and the two P fertiliser treatments were:

(1) P15: Current fertiliser practice: 17 kg ha^{-1} of N, 15 kg ha^{-1} of P and 8 kg ha^{-1} of K, applied as N:P:K 5:10:3 fertiliser.
(2) P100: High P fertiliser: as for P15 plus 85 kg ha^{-1} of P, applied as superphosphate (16% P_2O_5), thus a total of 100 kg ha^{-1} of P.

The total treatment area for the 40 plots (20 plots of 20 m × 30 m for the *Eucalyptus* hybrid, and 20 plots of 25 m × 30 m for *A. mangium*) was 2.7 ha, i.e. 1.2 ha for the *Eucalyptus* hybrid and 1.5 ha for *A. mangium*. The seedlings were sourced from a national seed orchard in Ba Vi established by the Forest Tree Improvement and Biotechnology Research Institute, Vietnamese Academy of Forest Sciences, Hanoi. Seedlings were planted in 30 cm × 30 cm × 30 cm planting holes with spacing between plants of 2 m × 3 m (1 666 trees ha^{-1}) in the *Eucalyptus* hybrid trial, and 2.5 m × 3 m (1 333 trees ha^{-1}) in the *A. mangium* trial. To minimise loss of P as a result of the high P-fixing capacity of the Acrisols soil (Sam and Binh 2001), fertiliser was applied in the base of the planting hole without mixing through the soil and covered by a soil layer before planting the trees. Weed control was applied to the whole area across all treatments, using a wood-handle machete, at six-monthly intervals following planting and until canopy closure. The tree measurements were made on net plots (a sampling area within the treatment area) of six rows of six trees to provide plot areas of 216 m^2 and 270 m^2 in the *Eucalyptus* hybrid and *A. mangium*, respectively. Each net plot was surrounded by two rows of buffer trees on all sides.

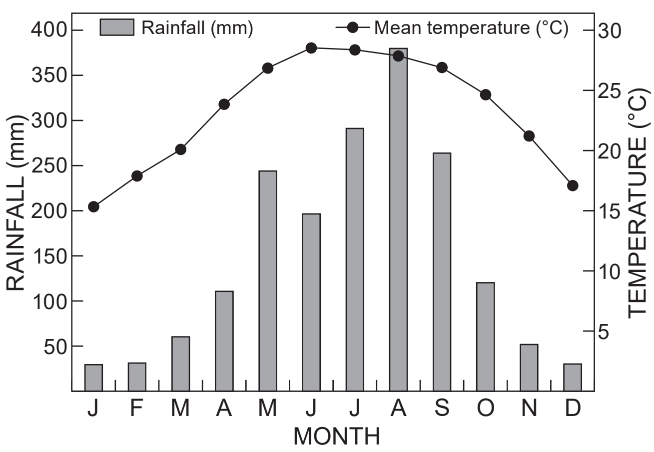

Figure 1: Mean monthly temperatures (continuous line) and rainfall (vertical bars) during the experimental period in northern Vietnam

Table 1: Soil chemical properties at 0–10 cm soil depth sampled immediately before establishment of the *Eucalyptus* hybrid and *Acacia mangium* trials in northern Vietnam (n = 5). Soil sampling and analysis were based on the method of Hung et al. (2016)

Soil chemical property	*Eucalyptus* hybrid		*A. mangium*	
	Mean	SE	Mean	SE
pH_{H_2O} (1:5 water)	3.79	0.04	3.79	0.03
Total C (g kg^{-1})	27.51	2.70	29.10	2.60
Total N (g kg^{-1})	2.30	0.10	2.10	0.10
Total P (g kg^{-1})	0.08	0.00	0.09	0.00
Bray extractable P (mg kg^{-1})	2.94	0.41	4.04	0.51
Exchangeable K (cmol kg^{-1})	0.10	0.01	0.12	0.01
Exchangeable Ca (cmol kg^{-1})	0.21	0.01	0.70	0.11
CEC (cmol kg^{-1})	10.83	0.63	7.81	0.74

Experimental measurements and calculations

Tree growth

Tree size was measured at 6, 12, 18 and 24 months after planting. Diameter (DBH; cm) at breast height (1.3 m) was measured, as was total tree height (*H*; m). Numbers of dead trees were recorded in each plot. Stem volume (*V*) of *A. mangium* and *Eucalyptus* hybrid was calculated using Equations 1 and 2 (MARD 2001), respectively:

$$V = \pi/4 \times \mathrm{DBH}^2 \times H \times 0.490 \quad (1)$$

where 0.490 is the stem form factor and

$$V = 0.3256 \times (\mathrm{DBH}^2 \times H)^{0.9106} \quad (2)$$

Standing volume was calculated as the sum of the individual stem volumes per plot, and expressed per hectare.

In addition to the tree growth measurements, geographic location and slope angle of each plot were determined with a GPS (Garmin 60CSx; Garmin Ltd, Olathe, KS, USA) and Abney hand level (CST/berger 5.25″ 17-640), respectively. Furthermore, three soil pits per slope position (a total of nine pits, representing three slope positions, i.e. top, middle and bottom) for each species were dug to measure soil profile and soil depth.

Leaf area index

Leaf area index (LAI) was determined at age 6, 12, 18 and 24 months after planting using a destructive harvesting method (du Toit and Dovey 2005). Ten trees representing the range of diameter classes of each species were destructively sampled from the buffer rows of the experimental plots at each assessment time. After felling the trees, DBH and *H* of the trees was assessed, and fresh mass of leaves of each tree was determined in the field. A sample of 20 representative fresh leaves per tree was selected. The sample leaves were scanned with a Canon scanner (Canon Scanner Lide 210) and leaf area was determined using LIA32 V0.377e software (Yamamoto 2004). All samples were then oven dried to constant mass at 65 °C and then weighed for conversion of fresh sample mass to oven-dry mass and calculation of specific leaf area (the ratio of leaf area to leaf dry weight; m^2 kg^{-1}) of each sample tree. Leaf area of each sample tree was determined by multiplication of the leaf dry mass and its specific leaf area. Leaf area of the destructive sample trees was regressed against the tree diameter (DBH) and height (*H*), and the models explaining the largest portion of the variation were used to estimate leaf area of individual trees in plots (for *Eucalyptus* hybrid: leaf area = 0.8421 × $\mathrm{DBH}^{1.5228}$, $R^2 = 0.88$, $p < 0.001$; and for *A. mangium*: leaf area = 3.5965 × DBH − 0.7609, $R^2 = 0.90$, $p < 0.001$). Total leaf area per plot was calculated as the sum of the leaf area of individual trees in the plot. The LAI was determined as the total leaf area of the plot divided by the plot area.

Tree form

Tree form was assessed at age 12 months. The number of competing leaders per tree and the number of large branches > 10 mm in diameter from the main stem (or stem with the largest diameter if not single-stemmed) were measured (Medhurst et al. 2003; Beadle et al. 2007). As the preferred form for harvesting is single stems (Beadle et al. 2007), more competing leaders or large branches per tree are associated with poorer tree form.

Crown damage index

Crown damage was assessed at age 12 months using the methodology developed for young eucalypts by Stone et al. (2003).

Crowns of each tree were divided vertically into thirds based on tree height, and a separate assessment done for each third. Three types of leaf damage were assessed: defoliation (damage from chewing insects), necrosis and discolouration. Crown condition of both species was expressed as the crown damage index (CDI):

$$\mathrm{CDI} = \frac{D_s \times D_i}{100} + \frac{N_s \times N_i}{100} + \frac{C_s \times C_i}{100} \quad (3)$$

where *D* denotes defoliation, *N* denotes necrosis and *C* denotes foliage discolouration. The subscript *i* is incidence, estimated as the percentage of leaves in the crown affected by the specified type of damage relative to the crown of an undamaged tree on that site, and *s* is severity, estimated as the average percentage area of leaf with the specified type of damage. The CDIs for each third of the tree were summed to calculate the CDI per sampled tree.

Visual standards for *D*, *N* and *C* for the *Eucalyptus* hybrid were based on Stone et al. (2003). Using on-site material, a visual standard was developed for *A. mangium* (details are given in Supplementary Figure S1) based on the range of leaf areas showing each type of damage. In both species, a time limit was not set for each evaluation, but assessors were asked to walk around the tree and assess damage looking away from the sun (Smith et al. 2005). Prior to the assessments, all assessors were trained in the method and tested for consistency in their assessments.

Foliar sampling and analysis

Foliage was sampled at ages one and two years after planting (in March 2015 and 2016 for the *Eucalyptus* hybrid, and June 2015 and 2016 for *A. mangium*). Foliar sampling and analysis procedures were based on those of Judd et al. (1996). In brief, a single bulked sample of 40 fully expanded leaves was sampled from the outer branch position of the upper third of the crown of five dominant and co-dominant trees in the inner rows of each plot (total of 20 samples per species per collection time).

The samples were dried to a constant weight at 65 °C and then ground to pass through a 2 mm mesh sieve. The ground material was redried (65 °C overnight) prior to digestion in concentrated sulphuric acid and 30% hydrogen peroxide and all nutrients were measured from that digest. Total N was analysed by Automatic Kjeldahl distillation (UDK 149; PLT Scientific Sdn Bhd, Puchong, Selangor Darul Ehsan, Malaysia), P by spectrophotometry (Jasco 7800 spectrophotometer; JASCO International Co. Ltd, Tokyo, Japan), K by flame photometry (Model 410 Flame Photometer Range; Sherwood Scientific Ltd, Cambridge, UK), and Ca and magnesium by atomic absorption spectroscopy (Berry and Johnson 1966).

Statistical analysis

The effect of treatment on survival, growth (DBH, *H* and *V*), LAI, form (the number of competing leaders and the number of branches > 10 mm), CDI and foliage nutrient concentration was investigated using two-way analysis of variance of two levels of P fertiliser and two types of residue management in five topographically arranged blocks. The effects of slope (which was used as a surrogate for position in the landscape) on the tree growth parameters, LAI, form and CDI were explored using regression analysis. Statistical tests were conducted with SPSS for Windows version 22.0 (IBM Corporation, Armonk, NY, USA, 2013).

Results

Survival

Survival of trees to age 24 months was consistently high in all treatments in the *Eucalyptus* hybrid trial (95%–96%) but was variable in the *A. mangium* (82%–93%) trial (Table 2). A lower survival rate in the *A. mangium* plots was observed when residue was retained rather than burned ($p < 0.05$; Table 2, also see Supplementary Table S1 for summary of statistical analysis). Rate of P fertiliser application did not significantly affect survival of either *A. mangium* or the *Eucalyptus* hybrid in either trial, nor did residue management in the *Eucalyptus* hybrid trial.

Regression analysis showed that slope had no significant effect on survival in either the *Eucalyptus* hybrid or the *A. mangium* trial for the duration of the study period ($p > 0.10$; data not shown).

Growth

There was no significant interaction between residue management and rate of P fertiliser application on measures of tree growth (DBH, *H* and *V*) for either species ($p > 0.05$). Therefore, only the main effects are presented.

The standing volume (*V*) of *A. mangium* at age 24 months after planting was significantly higher when residue was burned than when residue was retained ($p < 0.05$; Table 3, Supplementary Table S1). Neither stem diameter (DBH) nor tree height (*H*) of *A. mangium* responded significantly to the residue management treatments at age 6, 12, 18 or 24 months after planting ($p > 0.05$; Table 3). The higher levels of competition in the residue-retained treatments might have masked other growth responses to treatments if weeds were not adequately controlled. Residue management had no effect on tree growth in the *Eucalyptus* hybrid trial ($p > 0.05$; Table 3).

In the *Eucalyptus* hybrid trial, DBH and *H* responded significantly to the higher level of P application at ages 6 and 12 months; however, there were no significant differences between treatments at age 18 and 24 months (Table 4). There were no significant differences at 24 months between the fertiliser treatments as measured by DBH and *H* of *A. mangium* and in standing volume of either *A. mangium* or *Eucalyptus* hybrid at 24 months ($p > 0.05$; Table 4).

Negative relationships between tree growth (DBH, *H* and *V*) were observed with slope early in stand development in *A. mangium*, but disappeared with time (data not shown). There was no effect ($p > 0.05$) of slope on the growth (DBH, *H* and *V*) of the *Eucalyptus* hybrid (data not shown).

Leaf area index

Mean values of LAI at ages 6, 12, 18 and 24 months after planting for the *Eucalyptus* hybrid were 1.2, 2.2, 2.3 and 2.9 $m^2\ m^{-2}$, respectively, and for *A. mangium* were 0.3, 1.4, 2.9 and 3.5 $m^2\ m^{-2}$, respectively. There was no significant effect of residue management, or interaction

Table 2: Mean survival (%) of trees at 6, 12, 18 and 24 months (mo) after planting according to the residue management or fertiliser treatments in an *Eucalyptus* hybrid and *Acacia mangium* residue management and fertilisation trial in northern Vietnam. Means within a column sharing the same superscript letter are not significantly different ($P < 0.05$). The full analysis is shown in Supplementary Table S1

Treatment		*Eucalyptus* hybrid				*Acacia mangium*			
		6 mo	12 mo	18 mo	24 mo	6 mo	12 mo	18 mo	24 mo
Residue management[1]	S0	98^a	97^a	97^a	96^a	96^a	95^a	93^a	93^a
	S1	96^a	95^a	95^a	95^a	91^b	88^b	83^b	82^b
Fertiliser application[2]	P15	98^a	97^a	96^a	96^a	92^a	90^a	86^a	86^a
	P100	97^a	96^a	96^a	95^a	95^a	94^a	89^a	88^a

[1] S0 and S1 are burning and retention of residue, respectively
[2] P15 is low (15 kg ha^{-1}) and P100 is high (100 kg ha^{-1}) rates of phosphorus fertiliser

Table 3: Mean stem diameter (DBH), tree height (*H*) and standing volume (*V*) of the *Eucalyptus* hybrid and *Acacia mangium* in response to residue management treatments (burning vs retention) at 6, 12, 18 and 24 months (mo) after planting in northern Vietnam. Standing volume was not calculated at age 6 months. Means within a column sharing the same superscript letter within each growth attribute are not significantly different ($P < 0.05$). The full analysis is shown in Supplementary Table S1

Tree growth	Treatment	*Eucalyptus* hybrid				*Acacia mangium*			
		6 mo	12 mo	18 mo	24 mo	6 mo	12 mo	18 mo	24 mo
Stem diameter at 1.3 m (cm)	Burning	2.9^a	5.1^a	6.7^a	7.5^a	1.4^a	3.4^a	6.1^a	7.0^a
	Retention	2.8^a	5.1^a	6.8^a	7.7^a	1.3^a	3.2^a	5.9^a	6.7^a
Tree height (m)	Burning	4.0^a	6.7^a	9.7^a	10.2^a	2.2^a	3.5^a	6.1^a	6.8^a
	Retention	4.1^a	6.9^a	9.9^a	10.5^a	2.1^a	3.4^a	6.0^a	6.5^a
Standing volume ($m^3\ ha^{-1}$)	Burning	–	5.8^a	13.0^a	39.5^a	–	2.5^a	14.4^a	21.7^a
	Residue	–	6.0^a	13.4^a	42.0^a	–	1.8^b	11.5^a	17.0^b

Table 4: Mean stem diameter (DBH), tree height (*H*) and standing volume (*V*) of the *Eucalyptus* hybrid and *Acacia mangium* in northern Vietnam at ages 6, 12, 18 and 24 months (mo) in response to fertiliser treatments applied at planting. Standing volume was not calculated at 6 months. Means within a column sharing the same superscript letter within each growth attribute were not significantly different ($P < 0.05$). The full analysis is shown in Supplementary Table S1

Tree growth	Treatment[1]	*Eucalyptus* hybrid				*A. mangium*			
		6 mo	12 mo	18 mo	24 mo	6 mo	12 mo	18 mo	24 mo
Stem diameter at 1.3 m (cm)	P15	2.7^{a}	5.0^{a}	6.7^{a}	7.5^{a}	1.3^{a}	3.3^{a}	6.1^{a}	7.0^{a}
	P100	3.0^{b}	5.2^{b}	6.9^{a}	7.7^{a}	1.4^{a}	3.3^{a}	5.9^{a}	6.7^{a}
Tree height (m)	P15	3.9^{a}	6.6^{a}	9.7^{a}	10.2^{a}	2.1^{a}	3.4^{a}	6.1^{a}	6.7^{a}
	P100	4.2^{b}	7.0^{b}	9.9^{a}	10.5^{a}	2.2^{a}	3.5^{a}	6.0^{a}	6.5^{a}
Standing volume (m^3 ha^{-1})	P15	–	5.6^{a}	12.8^{a}	40.2^{a}	–	2.1^{a}	13.7^{a}	20.4^{a}
	P100	–	6.2^{a}	13.6^{a}	41.3^{a}	–	2.2^{a}	12.2^{a}	18.2^{a}

[1] P15 and P100 are low (15 kg ha^{-1}) and high (100 kg ha^{-1}) rates of phosphorus fertiliser

between residue management and fertiliser, on LAI for the *Eucalyptus* hybrid ($p > 0.05$; Figure 2a), but burning resulted in a significantly increased LAI of *A. mangium* at age 12, 18 and 24 months ($p < 0.05$; Figure 2b, Supplementary Table S1).

Application of 100 kg ha^{-1} of P fertiliser at planting of the *Eucalyptus* hybrid resulted in a higher LAI than the lower rate at age 6 months ($p < 0.05$), but the effect was no longer significant at age 12, 18 and 24 months ($p > 0.05$; Figure 3a). Application of the higher rate of P had no effect on the LAI of *A. mangium* ($p > 0.05$; Figure 3b, Supplementary Table S1).

At 24 months, there was no effect of position on the landscape on LAI of both the *Eucalyptus* hybrid and *A. mangium* plantations (data not shown).

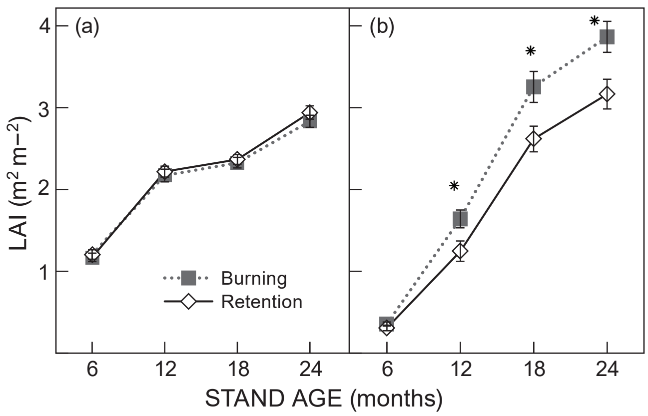

Figure 2: Leaf area index of the *Eucalyptus* hybrid (a) and *Acacia mangium* (b) according to residue management treatments at 6, 12, 18 and 24 months after planting in northern Vietnam. The asterisk denotes a statistically significant difference between treatments ($P < 0.05$). Error bars represent the SE

Form

Twelve months after planting, the percentage of the trees that had less than two large branches (>10 mm) was 80% and 25% in the *Eucalyptus* hybrid and *A. mangium* trials, respectively. The percentage of the trees with a single leader was >90% and >70% in the *Eucalyptus* hybrid and *A. mangium* trials, respectively. There was no effect of residue management and fertiliser on tree form for either species ($p > 0.05$).

The residue-management treatment had no effect on either the number of large branches or competing leaders per tree for the *Eucalyptus* hybrid ($p > 0.05$; data not shown). In contrast, residue management had a significant effect on the number of large branches ($p < 0.05$), but not on the number of competing leaders per tree ($p > 0.05$) for *A. mangium*, with a lower percentage of trees having less than two large branches per tree and a higher percentage of trees having ≥8 large branches per tree when residue was burned compared with it being retained ($p < 0.05$; Figure 4).

Fertiliser treatment had no significant effect on either the number of large branches or number of competing leaders for both *A. mangium* and *Eucalyptus* hybrid at 12 months after planting ($p > 0.05$; data not shown).

Regression analysis showed that slope had no significant effect ($p > 0.05$) on the form of the *Eucalyptus* hybrid (data not shown). A higher slope significantly increased the number of large branches per tree in *A. mangium* ($p < 0.05$), but there was no effect on the number of competing leaders per tree ($p > 0.05$; data not shown).

Crown damage index

Mean CDI at age 12 months across the treatments of both species was 5.2%. The mean score of each component of the CDI (defoliation damage from chewing insects, necrosis or discolouration) of both species was <3%. The major contribution to the CDI of the *Eucalyptus* hybrid was fungal diseases, whereas the CDI of *A. mangium* was mostly attributable to insect pests.

Burning residue after harvesting had no effect on CDI of the *Eucalyptus* hybrid ($p > 0.05$; Figure 5a), but it did significantly increase the CDI of *A. mangium* ($p < 0.05$; Figure 5b). Conversely, higher fertiliser application significantly increased the CDI of the *Eucalyptus* hybrid ($p < 0.05$; Figure 5a), but not that of *A. mangium* ($p > 0.05$; Figure 5b, Supplementary Table S1).

Regression analysis showed that higher slope significantly decreased the CDI of both species ($p < 0.001$; Figure 6).

Foliar nutrient concentration

Harvest residue management and P fertiliser application treatments had no effect on foliar nutrient concentration of either the *Eucalyptus* hybrid or *A. mangium* at ages one and two years after establishment ($p > 0.05$). Therefore, only the average values are presented (see Supplementary Table S2).

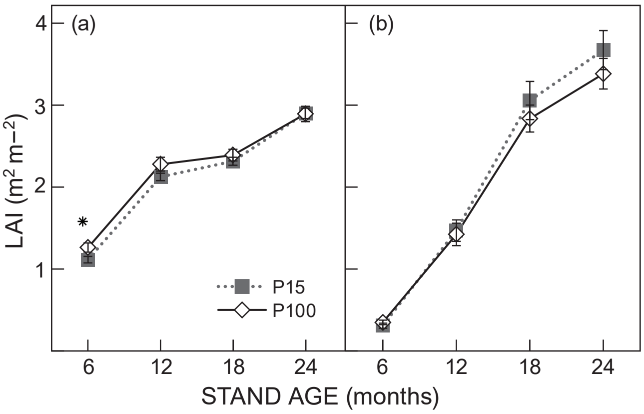

Figure 3: Leaf area index of the *Eucalyptus* hybrid (a) and *Acacia mangium* (b) according to the amount of P fertiliser applied (P15 = 15 kg ha^{-1}, P100 = 100 kg ha^{-1}) 6, 12, 18 and 24 months after planting in northern Vietnam. The asterisk denotes a statistically significant difference between treatments ($p < 0.05$). Error bars represent the SE

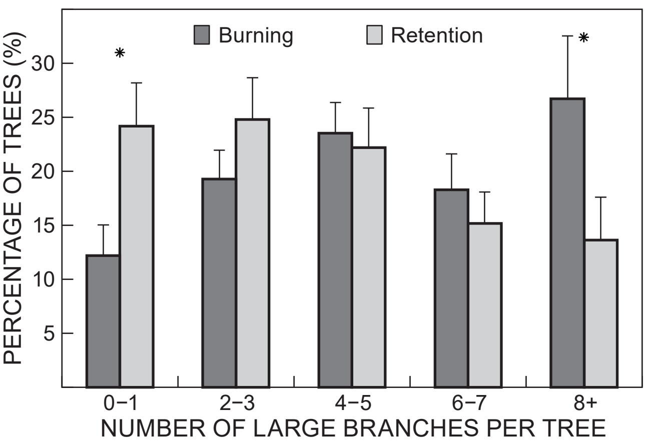

Figure 4: Effect of residue management treatment on the number of large branches > 10 mm per tree 12 months after planting in *Acacia mangium* plantations in northern Vietnam. The asterisk indicates a significant difference ($p < 0.05$). Error bars represent the SE

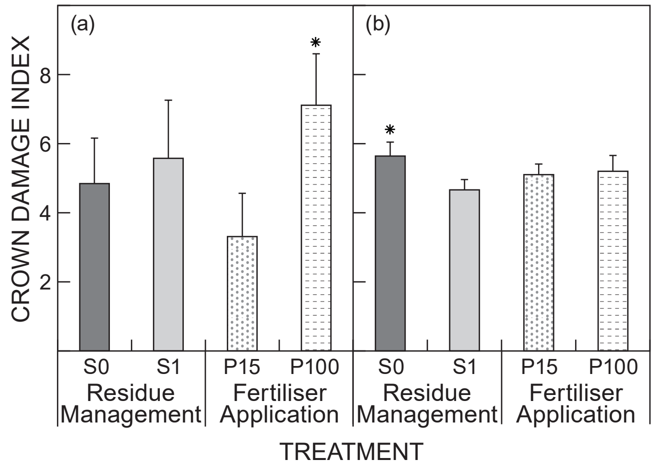

Figure 5: Crown damage index of the *Eucalyptus* hybrid (a) and *Acacia mangium* (b) with residue management treatment (S0 = burning, S1 = retention) and amount of P fertiliser applied at planting (P15 = 15 kg ha^{-1}, P100 = 100 kg ha^{-1}) 12 months after planting in northern Vietnam. The asterisk indicates a significant main effect of treatment ($p < 0.05$). Error bars represent the SE

Discussion

This study investigated the influence of high P fertiliser applied at planting and the inter-rotational practice of residue burning or retention on tree growth, LAI, form and CDI. While these silvicultural treatments have previously been explored in acacia and eucalypt forestry in South-east Asia and elsewhere, this study focused on a plantation established on a steeply sloping site that is typical of many in Vietnam and other South-east Asian countries. The results demonstrated that the current practice of applying 15 kg ha^{-1} of P (P15) was adequate to address any P deficiency in the first 2 years after planting. Residue management treatments had no effect on DBH and *H* of either *A. mangium* or the *Eucalyptus* hybrid; however, retention of harvest residue improved tree form and crown health of *A. mangium* compared with that of *A. mangium* in the burning treatment.

Residue treatment had no significant effect on DBH, *H*, *V* or LAI of the *Eucalyptus* hybrid at age 24 months. Burning of residues after harvesting has been shown to increase tree diameter and height in the short term because of the release of nutrients from ash and the higher rates of mineralisation (Deleporte et al. 2008; Gonçalves et al. 2008), though the growth response can be dependent on site fertility. For example, Mendham et al. (2008) found that there were no differences in the growth of *E. globulus* between treatments where residue was retained or burnt on a highly productive red earth site in south-western Australia; however, on a low productivity grey sand site there was a growth response to residue retention (Mendham et al. 2008). Soil total C and N ranges in the present study were 27.5–29.1 g kg^{-1} and 2.1–2.3 g kg^{-1}, respectively. These are high values for Vietnam (Dong et al. 2014; Hung et al. 2017) and at least average for a range of tropical forest soils (Tiarks and Ranger 2008). This suggests that the Yen Bai site has at least moderate inherent fertility that may have masked any increase in the nutrient supply following burning. That the standing volume of the *Eucalyptus* hybrid at 24 months (39.5–42.0 m^3 ha^{-1}) was high for this environment in Vietnam (Nghia et al. 2010; Thinh et al. 2015) supports this assertion. The relatively low mass of residues (27 Mg ha^{-1}) compared with that in other studies in the tropics of 38–135 Mg ha^{-1} (Hardiyanto and Nambiar 2014; Huong et al. 2015) may also have been insufficient to significantly change the supply at this site. In *E. grandis* and *E. tereticornis* in India, lack of response of tree growth (DBH, *H* and *V*) to residue management treatments was due to the low amount of harvest residue retained at the sites, such as Punnala and Surianelli, or being masked by high inherent soil fertility in the Vattavada site (Sankaran et al. 2007). Thus it appears that, in the eucalypt in this study, the low amount of harvest residue and high site fertility

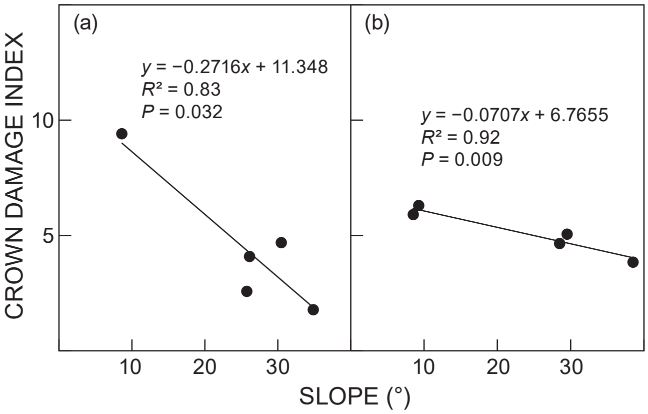

Figure 6: Relationship between slope within trial site and crown damage index of *Eucalyptus* hybrid (a) and *Acacia mangium* (b) 12 months after planting in northern Vietnam

resulted in the absence of growth response to the residue management treatments.

In contrast, burning led to higher *V* and LAI at 24 months in *A. mangium*; *V* was 28% greater (21.7 vs 17.0 m^3 ha^{-1}) and LAI was 22% greater (3.9 vs 3.2 m^2 m^{-2}) than where residue was retained. However, this difference can be largely attributed to the 13% higher survival rates of trees in the burning treatment at that age. The higher rates of survival were most likely due to lower termite damage in the burnt treatment (Hoang Van Thanh, Vietnamese Academy of Forest Sciences, pers. comm., 2017).

Compared with 15 kg ha^{-1}, application of 100 kg ha^{-1} of P fertiliser significantly increased the DBH and *H* of the *Eucalyptus* hybrid at ages 6 and 12 months, but this benefit disappeared at the later ages. Early growth responses of eucalypts to P fertiliser at planting can be dependent on the underlying soil P concentration (Xu et al. 2001; Melo et al. 2016). For eucalyptus hybrids (*E. grandis* × *E. urophylla* and *E. urophylla* × *E. globulus*) planted in Brazil at a site with resin-extractable soil P of 1.4 mg kg^{-1}, stand volume responded positively as P fertiliser application at planting increased from 13 to 40 kg ha^{-1}; however, there was no response to P fertiliser when resin-extractable soil P was 8.7 mg kg^{-1} (Melo et al. 2016). At sites in China, DBH and *H* of *E. urophylla* and *E. globulus* also responded positively up to age 3 years to P fertiliser applied at planting; the optimum rates of application for *V* production at that age were 200 and 40 kg P ha^{-1}, respectively, where soil Bray extractable P was 1.5 mg kg^{-1} and 8.7 mg kg^{-1} (Xu et al. 2001). For *E. globulus* at several sites in Australia where Bray extractable P ranged from 7.1 to 26.7 mg kg^{-1}, applications of P up to 50 kg ha^{-1} to age 9 months led to volume gains up to age 26 months (Judd et al. 1996). In the current study, soil Bray extractable P was 2.9 mg kg^{-1}, at the lower end of the range of P in the sites reported above, and high P also accelerated early growth. By 18 months, however, there were no longer any growth responses to the high P fertiliser at planting treatment.

Demand for P by eucalypts declines with time, a finding that is supported by a decreasing growth response to P fertiliser at later stages of stand development (Melo et al. 2016); for example, the annual demand for P in a short-rotation *E. grandis* plantation in Brazil was greatest in the first year (Leite et al. 2011). Early growth requires a high uptake of nutrients to support rapidly developing root and leaf biomass (Miller 1995). As a tree ages its root system (and associated mycorrhizae) extends and accesses increasing amounts of resident soil P (Harrison et al. 1988; Miller 1995; Gonçalves et al. 2004). Crown development leads to an increase in LAI (Smethurst et al. 2003), which results in the faster development of intraspecific competition in higher P treatments because of the greater retranslocation of P within the tree (Miller 1995; Gonçalves et al. 2004; Niederberger et al. 2017). Thus, high P applied at planting can be used to stimulate more rapid early establishment and may bring forward the harvest age at some sites, but its relative effect compared with a lower application of P is likely to decline with stand age and, as with the present study, it can disappear entirely.

In contrast to the *Eucalyptus* hybrid, the higher level of P had no significant effect on DBH, *H*, *V* or LAI of *A. mangium*. While tropical acacias can respond to P fertiliser applied at planting, the quantity required for optimum response has generally been low (Hardiyanto and Nambiar 2014; Huong et al. 2015). Mendham et al. (2017) applied four rates of P fertiliser (0, 10, 20 and 100 kg ha^{-1}) at planting to *A. mangium* across 11 sites in South Sumatra, Indonesia. At 10 of these sites there were significant responses of *V* to P, and at nine sites *V* was more than double that in the zero P-fertiliser treatment up to age 3 years. However, the quantity of P fertiliser required to achieve this level of response was generally low and it declined over time, with an average across sites of 23, 5.1 and 2.7 kg ha^{-1} of P at establishment able to provide 90% of maximum growth at ages 1, 1.5 and 3 years, respectively (Mendham et al. 2017). In some cases, the lack of a growth response to high P application may be due to induced nutrient imbalances, such as N:P ratio (Güsewell 2004). In the current study, foliar concentration of N, P and N:P ratios of *A. mangium* ranged from 2.8%–3.0%, 0.15%–0.17% and 17–19, respectively, during 12 and 24 months following planting and these are within the range observed for *A. mangium* in tropical plantations (Majid and Paudyal 1999; Hardiyanto et al. 2004), suggesting that neither N nor P were limiting tree growth (Paudyal and Majid 2000). Thus, the current practice of applying 15 kg P ha^{-1} in northern Vietnam (P15) should remain adequate to address any P deficiency in the first 2 years after planting.

Phosphorus fertiliser and residue management treatments had no effect on the number of large branches and leaders per tree of the *Eucalyptus* hybrid or the number of leaders per tree of *A. mangium*. Fertiliser application can increase branch size and/or numbers of competing leaders (Neilsen 1996; Wiseman et al. 2006; Bon and Harwood 2016). In *Eucalyptus nitens* and *E. regnans* in Australia, greater branch size and numbers of competing leaders were found on trees that received 151, 74 and 186 kg ha^{-1} of N, P and K, respectively, between two to eight months after planting compared with no fertiliser (Neilsen 1996). Similarly, application at planting of 18, 50 and 9 kg ha^{-1} of N, P and K, respectively, resulted in greater branch size in an *Acacia* hybrid in southern Vietnam compared with a no-fertiliser treatment

(Bon and Harwood 2016). However, in these same studies, there was a 72% increase in DBH and 22% increase in *H* at age 12 months in the *E. nitens* and *Acacia* hybrid (*Acacia mangium* × *A. auriculiformis*), respectively. In the current study the growth difference between the 100 and 15 kg ha^{-1} P-fertiliser treatments, although significant in the *Eucalyptus* hybrid at age 12 months, was only 4% and 6% in DBH and *H*, respectively. Although P fertiliser did not influence tree form in *A. mangium*, burning did lead to a significantly greater number of large branches, but not competing leaders, in this species. In Malaysia, there were greater numbers of competing leaders in *A. mangium* following a burning treatment compared with a residue-retention treatment; branch size was not measured (Eldoma et al. 2015). Compared with the burnt treatment, the more rapid development of weeds in the current study where residue was retained, particularly between ages 6 and 12 months (Hoang Van Thanh, pers. comm.), may have resulted in more competing vegetation, which can suppress branch size (Petersen et al. 2008).

There have been limited studies linking plantation health to silvicultural practices in tropical eucalypts and acacias. In the present study, a higher CDI was observed in the higher P treatment at planting in the *Eucalyptus* hybrid, and in the burning treatment compared with residue retention in *A. mangium*. Damage from insect pests and diseases is often linked to a wide range of biotic and abiotic factors (Pinkard et al. 2010; Dell et al. 2012). One factor is the nutritional status of the host. Actively growing plants can rapidly develop canopies and regular flushes of new succulent leaves with a nutritional status favouring pest infestation (de Bruyn et al. 2002; Rashid et al. 2017). The CDIs decreased from the top to the bottom position on the slope for both species, which might be explained by differences along the slope in host vigour (de Bruyn et al. 2002) and/or access to the canopy by wind-disseminated insect pests and fungal spores (Hardwick 2002). Although the average level of CDI across species and treatments was low and the effects on productivity are likely to have been small (Pinkard et al. 2006), it can be seen that there was an influence of different silvicultural treatments on the levels of pest damage and disease.

Conclusions

We concluded that the application of a high level of P fertiliser (100 kg ha^{-1} at planting) had little benefit on the growth of both *Eucalyptus* hybrid and *A. mangium* compared with the standard dose (15 kg ha^{-1}). The low amount of harvest residue and reasonably high fertility levels at the experimental site may have masked the response of tree growth to the residue-retention treatments. Poorer form in *A. mangium* following burning residue could increase production costs in plantations managed for sawlogs if more singling (removing multiple stems from trees to leave a single stem) and pruning is required. Harvest residue retention with adequate weed and termite control may be preferential to burning on a steep slope because the residue can reduce the speed of water run-off and soil erosion (Edeso et al. 1999; Oyarzun and Peña 1995; Costantini and Lcoh 2002).

Acknowledgements — This study was funded by the Ministry of Agriculture and Rural Development of Vietnam under the research project ‘Management of multi-rotation plantations of *Acacia mangium*, *Acacia auriculiformis* and *Eucalyptus* hybrids for saw-log production in Vietnam’ and the Department of Foreign Affairs and Trade (formerly AusAID) in the form of an Australian Award Scholarship to the senior author. We thank colleagues from the Silviculture Research Institute and Thac Ba Forest Enterprise for assistance with data collection, sampling and maintenance of the field experiment, Dr David Ratkowsky for statistical advice, Dr Chris Beadle for editing the manuscript, Chris Harwood and two anonymous reviewers for their review of the manuscript.

ORCID

Katherine Evans https://orcid.org/0000-0003-2189-5870
Tran Lam Dong https://orcid.org/0000-0002-3862-6039
Caroline Mohammed https://orcid.org/0000-0002-2878-1094

References

Auslander M, Nevo E, Inbar M. 2003. The effects of slope orientation on plant growth, developmental instability and susceptibility to herbivores. *Journal of Arid Environments* 55: 405–416.

Beadle C, Barry K, Hardiyanto E, Irianto R, Junarto, Mohammed C, Rimbawanto A. 2007. Effect of pruning *Acacia mangium* on growth, form and heart rot. *Forest Ecology and Management* 238: 261–267.

Beadle C, Ottenschlaeger M, Dung PT, Mohammed C. 2013. *Optimising silvicultural management and productivity of high-quality acacia plantations, especially for sawlogs*. Project Report FST/2006/087. Canberra: Australian Centre for International Agricultural Research.

Berry WL, Johnson CM. 1966. Determination of calcium and magnesium in plant material and culture solutions, using atomic-absorption spectroscopy. *Applied Spectroscopy* 20: 209–211.

Bich NV, Eyles A, Mendham D, Dong TL, Ratkowsky D, Evans K, Hai VD, Thanh HV, Thinh NV, Mohammed C. 2018. Contribution of harvest residues to nutrient cycling in a tropical *Acacia mangium* Willd. plantation. *Forests* 9: 577.

Bon PV, Harwood CE. 2016. Effects of stock plant age and fertiliser application at planting on growth and form of clonal *Acacia* hybrid. *Journal of Tropical Forest Science* 28: 182–189.

Calderon RA, Constantino R. 2007. A survey of the termite fauna (Isoptera) of an eucalypt plantation in central Brazil. *Neotropical Entomology* 36: 391–395.

Cao TT, Son HL. 2014. *Status of growing commercial plantations in Vietnam*. Hanoi: Vietnamese Academy of Forest Sciences.

Costantini A, Lcoh RJ. 2002. Effects of site preparation on runoff, erosion, and nutrient losses from *Pinus* plantations established on the coastal lowlands of south-east Queensland, Australia. *Australian Journal of Soil Research* 40: 1287–1302.

Crous CJ, Burgess TI, Le Roux JJ, Richardson DM, Slippers B, Wingfield MJ. 2017. Ecological disequilibrium drives insect pest and pathogen accumulation in non-native trees. *AoB Plants* 9: plw081.

De NV, Douglas I, McMorrow J, Lindley S, Binh DKNT, Van TT, Thanh LH, Tho N. 2008. Erosion and nutrient loss on sloping land under intense cultivation in southern Vietnam. *Geographical Research* 46: 4–16.

de Bruyn L, Scheirs J, Verhagen R. 2002. Nutrient stress, host plant quality and herbivore performance of a leaf-mining fly on grass. *Oecologia* 130: 594–599.

Deleporte P, Laclau JP, Nzila JD, Kazotti JG, Marien JN, Bouillet JP, Szwarc M, D’Annunzio R, Ranger J. 2008. Effects of slash and litter management practices on soil chemical properties and growth of second rotation eucalypts in the Congo. In: Nambiar EKS (ed.), *Site management and productivity in tropical plantation forests: proceedings of workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 6-9 November 2006.* Bogor: Center for International Forestry Research. pp 5–22.

Dell B, Xu D, Thu P. 2012. Managing threats to the health of tree plantations in Asia. In: Bandani A (ed.), *New perspectives in plant protection* no. 4. Rijeka: InTech. pp 63–92.

Dong TL, Doyle R, Beadle CL, Corkrey R, Quat NX. 2014. Impact of short-rotation *Acacia* hybrid plantations on soil properties of degraded lands in central Vietnam. *Soil Research* 52: 271–281.

Dung PT, Dat KT, Quang LT, Bon PV, Huong VD. 2012. Reseach on technical measures to protect and improve soil fertility for enhancing productivity of eucalypt and acacia plantations in successive rotations. Project report. Hanoi: Vietnam Academy of Forest Science.

Dung PT, Tung PV, Ngoc NV. 2005. Productivity of commercial *Acacia* hybrid in south-eastern Vietnam: main concerns about site management practices. Inventory report. Hanoi: Vietnamese Academy of Forest Sciences.

du Toit B, Dovey SB. 2005. Effect of site management on leaf area, early biomass development, and stand growth efficiency of a *Eucalyptus grandis* plantation in South Africa. *Canadian Journal of Forest Research* 35: 891–900.

Edeso JM, Merino A, González MJ, Marauri P. 1999. Soil erosion under different harvesting managements in steep forestlands from northern Spain. *Land Degradation and Development* 10: 79–88.

Eldoma AMA, Kumar SM, Shukor NAA. 2015. Effects of site burning on multiple leader formation and growth performance of selected *Acacia* genotypes. *American Journal of Plant Sciences* 6: 777–784.

FAO/UNESCO/ISRIC. 1988. *FAO–UNESCO soil map of the world. Revised legend. World Soil Resources Report* 60. Rome: FAO.

Ferreira MA, Mafia RG, Alfenas AC. 2018. *Ralstonia solanacearum* decreases volumetric growth of trees and yield of kraft cellulose of *Eucalyptus* spp. *Forest Pathology* 48: e12376.

Gonçalves JLM, Alvares CA, Higa AR, Silva LD, Alfenas AC, Stahl J, Ferraz SFB, Lima WP, Brancalion PHS, Hubner A, Bouillet J-PD, Laclau J-P, Nouvellon Y, Epron D. 2013. Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. *Forest Ecology and Management* 301: 6–27.

Gonçalves JLM, Stape JL, Laclau JP, Bouillet JP, Ranger J. 2008. Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. *Southern Forests* 70: 105–118.

Gonçalves JLM, Stape JL, Laclau J-P, Smethurst P, Gava JL. 2004. Silvicultural effects on the productivity and wood quality of eucalypt plantations. *Forest Ecology and Management* 193: 45–61.

Gonçalves JLM, Wichert MCP, Gava JL, Masetto AV, Junior JCA, Serrano MIP, Mello SLM. 2007. Soil fertility and growth of *Eucalyptus grandis* in Brazil under different residue management practices. *Southern Hemisphere Forestry Journal* 69: 95–102.

Govender P. 2014. Effects of plantation residue management on the community structure of wattle regeneration invertebrate pests in South Africa. *Southern Forests* 76: 229–236.

Güsewell S. 2004. N : P ratios in terrestrial plants: variation and functional significance. *New Phytologist* 164: 243–266.

Hai PH, Harwood C, Beadle C, Huong VD, Trieu DT. 2005. Genetic materials and silvicultural techniques in plantation grown acacias for sawn timber products. Technical report. Canberra: Commonwealth Scientific and Industrial Research Organisation.

Hardie M, Akhmad N, Mohammed C, Mendham D, Corkrey R, Gafur A, Siregar S. 2018. Role of site in the mortality and production of *Acacia mangium* plantations in Indonesia. *Southern Forests* 80: 37–50.

Hardiyanto E, Anshori S, Sulistyono D. 2004. Early results of site management in *Acacia mangium* plantations at PT Musi Hutan Persada, South Sumatra, Indonesia. In: Nambiar EKS, Ranger J, Tiarks A, Toma T (eds), *Site management and productivity in tropical plantation forests: proceedings of workshops in Congo July 2001 and China February 2003.* Bogor: Center for International Forestry Research. pp 93–108.

Hardiyanto E, Nambiar SE. 2014. Productivity of successive rotations of *Acacia mangium* plantations in Sumatra, Indonesia: impacts of harvest and inter-rotation site management. *New Forests* 45: 557–575.

Hardwick NV. 2002. Weather and plant diseases. *Weather* 57: 184–190.

Harrison AF, Miles J, Howard DM. 1988. Phosphorus uptake by birch from various depths in the soil. *Forestry* 61: 349–358.

Harwood CE, Nambiar EKS. 2014. Productivity of acacia and eucalypt plantations in Southeast Asia. 2. Trends and variations. *International Forestry Review* 16: 249–260.

Harwood CE, Nambiar EKS, Dinh PX, Toan LX, Quang LT. 2017. Managing wood production from small grower *Acacia* hybrid plantations on eroded soils in central Vietnam. *Australian Forestry* 80: 286–293.

Hung TT, Almeida AC, Eyles A, Mohammed C. 2016. Predicting productivity of *Acacia* hybrid plantations for a range of climates and soils in Vietnam. *Forest Ecology and Management* 367: 97–111.

Hung TT, Doyle R, Eyles A, Mohammed C. 2017. Comparison of soil properties under tropical *Acacia* hybrid plantation and shifting cultivation land use in northern Vietnam. *Southern Forests* 79: 9–18.

Huong VD, Nambiar ES, Quang LT, Mendham DS, Dung PT. 2015. Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in South Vietnam. *Southern Forests* 77: 51–58.

Ingestad T. 1980. Growth, nutrition, and nitrogen-fixation in grey alder at varied rate of nitrogen addition. *Physiologia Plantarum* 50: 353–364.

Jactel H, Nicoll BC, Branco M, Gonzalez-Olabarria JR, Grodzki W, Långström B, Moreira F, Netherer S, Orazio C, Piou D, Santos H, Schelhaas MJ, Tojic K, Vodde F. 2009. The influences of forest stand management on biotic and abiotic risks of damage. *Annals of Forest Science* 66: 701.

Judd TS, Bennett LT, Weston CJ, Attiwill PM, Whiteman PH. 1996. The response of growth and foliar nutrients to fertilizers in young *Eucalyptus globulus* (Labill.) plantations in Gippsland, southeastern Australia. *Forest Ecology and Management* 82: 87–101.

Khan M, Gong Y, Hu T, Lal R, Zheng J, Justine M, Azhar M, Che M, Zhang H. 2016. Effect of slope, rainfall intensity and mulch on erosion and infiltration under simulated rain on purple soil of south-western Sichuan province, China. *Water* 8: 528.

Khiet NV. 2014. Research and evaluation of the current situation and proposed solutions to improve efficiency of forest planting production in the northern mountainous areas of Vietnam. *Vietnam Journal of Forest Science* 2014: 3557–3570 [in Vietnamese with English abstract].

Kurganova I, de Gerenyu VL, Galibina N, Kapitsa E, Shorohova E. 2018. Coupled effect of temperature and mineral additions facilitates decay of aspen bark. *Geoderma* 316: 27–37.

Leite FP, Silva IR, Novais RF, Barros NF, Neves JCL, Villani EMA. 2011. Nutrient relations during an *Eucalyptus* cycle at different population densities. *Revista Brasileira de Ciência do Solo* 35: 949–959.

Majid NM, Paudyal BK. 1999. Growth response of *Acacia mangium* plantation to N, P, K fertilisation in Kemasul and Kerling, Peninsular Malaysia. *Journal of Tropical Forest Science* 11: 356–367.

MARD (Ministry of Agriculture and Rural Development). 2001. Volume and yield tables for *Acacia mangium* and *Eucalyptus urophylla*. Hanoi: Agricultural Publishing House [in Vietnamese].

MARD. 2014. The National Forest Status. Decision no. 3322/QD-BNN-TCLN dated July 28, 2014. Hanoi: MARD.

Medhurst JL, Pinkard EA, Beadle CL, Worledge D. 2003. Growth and stem form responses of plantation-grown *Acacia melanoxylon* (R. Br.) to form pruning and nurse-crop thinning. *Forest Ecology and Management* 179: 183–193.

Melo EASC, Gonçalves JLM, Rocha JHT, Hakamada RE, Bazani JH, Wenzel AVA, Arthur JC Jr, Borges JS, Malheiros R, Lemos CCZ, Ferreira EVO, Ferraz AV. 2016. Responses of clonal eucalypt plantations to N, P and K fertilizer application in different edaphoclimatic conditions. *Forests* 7: 2.

Mendham DS, Grove TS, O'Connell AM, Rance SJ. 2008. Impacts of inter-rotation site management on soil nutrients and plantation productivity in *Eucalyptus globulus* plantation in south-western Australia. In: Nambiar EKS (ed.), *Site management and productivity in tropical plantation forests: proceedings of workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 6-9 November 2006*. Bogor: Center for International Forestry Research. pp 79–92.

Mendham DS, Hardiyanto EB, Wicaksono A, Nurudin M. 2017. Nutrient management of contrasting *Acacia mangium* genotypes and weed management strategies in South Sumatra, Indonesia. *Australian Forestry* 80: 127–134.

Mendham DS, Sankaran KV, O'Connell AM, Grove TS. 2002. *Eucalyptus globulus* harvest residue management effects on soil carbon and microbial biomass at 1 and 5 years after plantation establishment. *Soil Biology and Biochemistry* 34: 1903–1912.

Miller HG. 1995. The influence of stand development on nutrient demand, growth and allocation. *Plant and Soil* 168: 225–232.

Nambiar EKS, Harwood CE, Kien ND. 2015. *Acacia* plantations in Vietnam: research and knowledge application to secure a sustainable future. *Southern Forests* 77: 1–10.

Neilsen WA. 1996. Response of *Eucalyptus nitens* and *Eucalyptus regnans* seedlings to application of various fertilisers at planting or soon after planting. *New Zealand Journal of Forestry Science* 26: 355–369.

Nghia N, Thu P, Chien N, Ha N, Quang D, Trang T, Binh L, Chi N, Quynh D, Dinh V, et al. 2010. Selection of high yield and disease resistant of *Acacia* and *Eucalyptus* clonals for commercial plantation forests in Vietnam. Hanoi: Vietnamese Academy of Forest Sciences.

Ngoc NTB, Khue ND, Thuy BT. 2011. The termite species composision (Isoptera) and their harmful effect on *Eucalyptus urophylla*, *Acacia* hybryd plantations in Vietnam. *Vietnam Journal of Forest Science* 2011: 1745–1751 [in Vietnamese with English abstract].

Niederberger J, Kohler M, Bauhus J. 2017. The relevance of different soil phosphorus fractions for short-term tree nutrition: results from a mesocosm bioassay. *Forestry* 90: 258–267.

Nzila JD, Bouillet JP, Laclau JP, Ranger J. 2002. The effects of slash management on nutrient cycling and tree growth in *Eucalyptus* plantations in the Congo. *Forest Ecology and Management* 171: 209–221.

O'Connell AM, Grove TS, Mendham DS, Rance SJ. 2004. Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in south western Australia. *Soil Biology and Biochemistry* 36: 39–48.

Omary A. 2011. Effects of aspect and slope position on growth and nutritional status of planted Aleppo pine (*Pinus halepensis* Mill.) in a degraded land semi-arid areas of Jordan. *New Forests* 42: 285–300.

Oyarzun CE, Peña L. 1995. Soil erosion and overland flow in forested areas with pine plantations at Coastal Mountain Range, central Chile. *Hydrological Processes* 9: 111–118.

Paudyal BK, Majid NM. 2000. The relationship between growth and foliar nutrient concentrations in *Acacia mangium* seedlings. *Journal of Tropical Forest Science* 12: 62–76.

Petersen KS, Ares A, Terry TA, Harrison RB. 2008. Vegetation competition effects on aboveground biomass and macronutrients, leaf area, and crown structure in 5-year old Douglas-fir. *New Forests* 35: 299–311.

Phuong V, Anh H, Lung N, Sam D, Ky N, Lien T. 2012. *Forest ecological stratification in Vietnam*. Hanoi: Techniques and Science Publishing House.

Pinkard EA, Baillie C, Patel V, Mohammed CL. 2006. Effects of fertilising with nitrogen and phosphorus on growth and crown condition of *Eucalyptus globulus* Labill. experiencing insect defoliation. *Forest Ecology and Management* 231: 131–137.

Pinkard EA, Battaglia M, Bruce J, Leriche A, Kriticos DJ. 2010. Process-based modelling of the severity and impact of foliar pest attack on eucalypt plantation productivity under current and future climates. *Forest Ecology and Management* 259: 839–847.

Qingshan R, Yixin C, Jingsheng W. 1998. Effect of slope on growth of three hard broadleaved tree species in Northeast China. *Journal of Forestry Research* 9: 27–30.

Rashid MM, Jahan M, Islam KS. 2017. Effects of nitrogen, phosphorous and potassium on host-choice behavior of Brown Planthopper, *Nilaparvata lugens* (Stal) on rice cultivar. *Journal of Insect Behavior* 30: 1.

Rocha JHT, Gonçalves JLM, Gava JL, Godinho TD, Melo EASC, Bazani JH, Hubner A, Arthur Junior JC, Wichert MP. 2016. Forest residue maintenance increased the wood productivity of a *Eucalyptus* plantation over two short rotations. *Forest Ecology and Management* 379: 1–10.

Sam DD, Binh NN. 2001. *Assessment of productivity of forest lands in Vietnam*. Hanoi: Statistical Publishing House.

Sang PM, Lamb D, Bonner M, Schmidt S. 2013. Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. *Plant and Soil* 362: 187–200.

Sankaran KV, Mendham DS, Chacko KC, Pandalai RC, Grove TS, O'Connell AM. 2007. Increasing and sustaining productivity of tropical eucalypt plantations over multiple rotations. *Journal of Sustainable Forestry* 24: 109–121.

Sidle RC, Ziegler AD, Negishi JN, Nik AR, Siew R, Turkelboom F. 2006. Erosion processes in steep terrain—truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecology and Management* 224: 199–225.

Smethurst P, Baillie C, Cherry M, Holz G. 2003. Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. *Forest Ecology and Management* 176: 531–542.

Smith AH, Pinkard EA, Stone C, Battaglia M, Mohammed CL. 2005. Precision and accuracy of pest and pathogen damage assessment in young eucalypt plantations. *Environmental Monitoring and Assessment* 111: 243–256.

Son NH, Quat NX, Nam DH. 2006. *Planting techniques of tree species for raw materials*. Hanoi: Statistical Publishing House.

Stone C, Matsuki M, Carnegie A. 2003. *Pest and disease assessment in young eucalypt plantations: field manual for using the crown damage index*. Parsons M (ed.). Canberra: National Forest Inventory, Bureau of Rural Sciences.

Thinh HH, Kien ND, Son DH, Lan CT, Chi N, Quang HT, Chinh NV, Kien MT, Dinh PX, Bien TH. 2015. Progress in the genetic improvement for some main commercial planting tree species in Vietnam: duration 2011–2015. Project report. Hanoi: Vietnamese Academy of Forest Sciences.

Thu P. 2016. Results of a survey of insect pests and diseases of the main forest plantation species in Vietnam. *Vietnam Journal of Forest Science* 2016: 4257–4264 [in Vietnamese with English abstract].

Thu PQ, Qynh DN, Dell B. 2012. *Ceratocystis sp.* causes crown wilt of *Acacia* spp. planted in some ecological zones of Vietnam. In: Mohammed C, Beadle C, Roux J, Rahayu S (eds), *Proceedings of the International Conference on the Impacts of Climate Change to Forest Pests and Diseases in the Tropics, 8–10 October 2012, Yogyakarta, Indonesia.* Yogyakarta: Universitas Gadjah Mada. pp 38–44.

Tiarks A, Ranger J. 2008. Soil properties in tropical plantation forests: Evaluation and effects of site management: a summary. In: Nambiar EKS (ed.), *Site management and productivity in tropical plantation forests: proceedings of workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 6-9 November 2006*. Bogor: Center for International Forestry Research. pp 191–204.

Tong Y-G, Ding X-X, Zhang K-C, Yang X, Huang W. 2016. Effect of the gall wasp *Leptocybe invasa* on hydraulic architecture in *Eucalyptus camaldulensis* plants. *Frontiers in Plant Science* 7: 130.

Tran DV, Osawa A, Nguyen TT. 2011. Recovery of vegetation structure and species diversity after shifting cultivation in northwestern Vietnam, with special reference to commercially valuable tree species. *ISRN Ecology* 2011: Art. ID 751472.

Wingfield MJ, Brockerhoff EG, Wingfield BD, Slippers B. 2015. Planted forest health: the need for a global strategy. *Science* 349: 832–836.

Wiseman D, Smethurst P, Pinkard L, Wardlaw T, Beadle C, Hall M, Baillie C, Mohammed C. 2006. Pruning and fertiliser effects on branch size and decay in two *Eucalyptus nitens* plantations. *Forest Ecology and Management* 225: 123–133.

Xu D, Dell B, Malajczuk N, Gong M. 2001. Effects of P fertilisation and ectomycorrhizal fungal inoculation on early growth of eucalypt plantations in southern China. *Plant and Soil* 233: 47–57.

Yamamoto K. 2004. LIA for Win32 (LIA32). Laboratory of Forest Environment and Resources, Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya, Japan. Available at http://www.agr.nagoya-u.ac.jp/~shinkan/LIA32/index-e.html [accessed 20 February 2017].

Received 10 June 2018, revised 29 October 2018, accepted 4 November 2018