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ARTICLE

A review of nutrient, water and organic matter dynamics of tropical acacias on mineral soils for improved management in Southeast Asia

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ABSTRACT

More than 3 000 000 ha of tropical acacias have been established in recent decades, mostly grown on short rotations of 4–7 years, by a range of growers, from smallholders in Vietnam with less than 5 ha to large industrial growers in Sumatra managing hundreds of thousands of hectares. While the acacia estate is declining in some areas due to disease susceptibility, it is still expanding in other areas, and acacias would probably be the preferred species in many areas if the disease issues can be overcome. To date, many of the silvicultural management practices have largely been based on operational trial and error rather than backed by scientific evidence. To ensure sustained production, a deeper understanding of the mechanism for the response of acacias to management and environment is required. The objective of this paper is to review recent advances in our knowledge of the nutrient, water and organic matter dynamics of acacia plantations on mineral soils in Southeast Asia. We show that water availability is a key factor influencing productivity in many locations, but also that there are options for new approaches to management, including regional and site selection (or choice to plant or not on any given plot of land), and an understanding of nutritional requirements will help managers to adopt best practices in their plantations. While many plantations show significant responses to nutrients, particularly phosphorus (P, e.g. up to 200% stem volume increase at age one year); initial large responses to P fertiliser are reported to diminish over time, such that the response tends to be non-significant at many sites by harvest age. Only small quantities are recommended at establishment (equivalent to around 10 kg P ha^{-1}) to maximise productivity. Large quantities of site nutrient pools are held in harvesting debris or slash. Slash should be considered a valuable resource for sustaining productivity into the future, and its role in relation to fertiliser application needs further study.

Introduction

Tropical acacias have become one of the mainstays of the global forest plantation resource, occupying an area of more than 3 000 000 ha in Southeast Asia, mainly in Indonesia, Vietnam, Malaysia and China (Harwood & Nambiar 2014; Nambiar et al. 2018) with smaller areas in other parts of the world, including in Brazil and India (Griffin et al. 2011). Three key acacia species, *Acacia mangium* Willd., *Acacia crassicarpa* A.Cunn. ex Benth., *Acacia auriculiformis* A.Cunn. ex Benth., and the interspecific hybrid between *A. mangium* and *A. auriculiformis* are the main commercially planted species, and these four phyllodenous taxa are the focus of this review (hereafter referred to as the commercial tropical acacias). These acacias contribute to a resource of fast-growing short rotation plantations that is set to expand as countries aim to increase rural wealth by further developing these plantations and encouraging downstream processing. For example, Indonesia's long-term plan has been to increase the industrial timber plantation area to 14 700 000 ha by 2025 (Obidzinski & Dermawan 2012), and Vietnam intends to value add to its plantation resource by converting a proportion of its existing acacia estate from export pulpwood to being able to provide material for the local processing industries (MARD Directive 774, 18 April 2014).

Commercial tropical acacias are widely grown because of their high tolerance to a range of site types, excellent growth rates, and capacity to produce timber for a range of end-uses. The largest consumer of acacia wood in Southeast Asia is the pulp and paper sector (Griffin et al. 2011), replacing wood sourced from natural forest resources (Clay 2004), with rotation lengths of 4–6 years. Larger diameter acacia logs, typically from plantations on a 5–8-year rotation, and sometimes up to ten years, are used to produce sawlogs in Vietnam (Harwood et al. 2015) and Malaysia (Lim et al. 2011) among other places. Most growers prefer to have shorter rotation lengths and do not tend to grow specifically for solid wood through extending the rotation or employing thinning operations.

Currently, commercial tropical acacias are grown in a range of soils, including around 700 000 ha of *A. crassicarpa* on peat in Sumatra and Kalimantan (Nambiar & Harwood 2014), 1 100 000 ha of *A. mangium* on mineral soils in Indonesia and Vietnam, and 400 000 ha of acacia hybrid (*A. mangium* × *A. auriculiformis*) on mineral soils in Vietnam (Nambiar & Harwood 2014). Both the peat and mineral soils that acacias are grown in tend to be relatively low in fertility with high acidity. Mineral soils typical of acacia growing areas tend to be highly phosphorus (P)-fixing Ferralsols (FAO 1998) or Acrisols (FAO 1998) with high clay content, such as those in South Sumatra (Nurudin et al. 2013) and West Kalimantan (Tyynelä et al. 2003). In Vietnam, acacias are grown on a wide range of soils, including Acrisols (FAO 1998) in central Vietnam (Nambiar et al. 2015; Harwood et al. 2017), reddish-yellow Ferralsols (FAO 1998) in the north and centre (Nambiar et al. 2015), and on

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some Acrisols (FAO 1998), silicious sands and acid sulphate soils in southern Vietnam. Many acacias growing on mineral soils are on undulating topography, which can be eroded and stony, especially in Vietnam (Nambiar et al. 2015). Typical operational mean annual increments for *A. mangium* were reported by Harwood and Nambiar (2014) to be between 22.4 m^3 ha^{-1} y^{-1} and 35 m^3 ha^{-1} y^{-1} in Sumatra, an average of 11.3 m^3 ha^{-1} y^{-1} in Northern and Central Vietnam, while acacia hybrid reportedly had productivity levels between 11 m^3 ha^{-1} y^{-1} and 28.6 m^3 ha^{-1} y^{-1} across all regions in Vietnam. Harwood and Nambiar (2014) also report that typical stockings at establishment range between 1100 stems ha^{-1} and 1600 stems ha^{-1} (and are not different to those for eucalypts).

Science-based sustainable management practices need to be communicated to and adopted by managers to achieve impact. Large areas of acacia plantations are managed by industrial companies in Malaysia, Sumatra and Kalimantan, while in Vietnam independent smallholders with 5 ha or less manage around 46% of the acacia estate, and the balance by small and medium size companies (Nambiar et al. 2015). Similarly, in Java, acacia plantations tend to be grown more by smallholder farmers. To maintain sustainable profitability and site quality of both large and small growers, it is important to ensure that acacia plantations are both sustainable and productive into the future.

While the expansion of this acacia estate has been rapid, there are now emerging risks to its productivity, including rapid spread of fungal pathogens (Nambiar et al. 2018), and inappropriate management of site and soil resources at harvest (Harwood & Nambiar 2014). Over 600 000 ha of *A. mangium* plantations on mineral soils have been replaced by eucalypt plantations since 2012 due to disease-induced mortality (Nambiar et al. 2018). However, there is no systematic evidence of decline in site potential productivity providing that sound management practices are employed, and managers are prepared to adapt their approaches to new challenges (Harwood & Nambiar 2014). If disease resistance can be introduced via breeding and deployment (the subject of current research, Trang et al. 2018), it is likely that acacias will return to many planting sites because of their higher productivity and lower requirement for management inputs (Nambiar et al. 2018).

Research into site and soil management of tropical acacias has not kept pace with the level of their genetic advancement and deployment. Consequently, there is paucity of scientific data to support sustainable management and a risk that the benefits of the large investment in domestication and genetic improvement are not being fully realised. It is always prudent to consider management of nutrients and water together. Proposed plantation expansion and climate change will also necessitate a greater understanding of the effects of water on productivity and survival in existing and new plantations. This paper reviews the available research on water and nutrient dynamics in tropical acacia plantations on mineral soils and explores how the information can be used to ensure best practice management for sustainable production.

Water

Knowledge of the interactions of trees with water resources is derived from two largely separate research endeavours.

First, the effects of soil and internal tree water deficits on growth processes, productivity and tree survival has been an active area of forest research since the early 1960s and the subject of numerous reviews including one with a focus on *Eucalyptus* in plantations (Whitehead & Beadle 2004). In the last decade, reported increases in the size and frequency of forest mortality (Allen et al. 1998; Adams et al. 2009) and has resulted in renewed activity with a focus on understanding the relative role of carbon (C) and water balance in drought mortality (McDowell & Sevanto 2010; Zeppel et al. 2011; Anderegg et al. 2015). A second area of work with an equally long history has addressed the effect of plantation establishment on the availability of water for other users (Brown et al. 2005; Van Dijk & Keenan 2007). Although the interactions of forests with water have been extensively studied from the leaf to the catchment scale, very little work has been done on *Acacia* species and even less on the tropical acacias that are grown in Southeast Asia. In this section we aim to place the limited amount of research on the water relations of tropical acacias in the context of the large amount of work in other systems to develop strategies for managing plantations of acacias to make efficient use of water resources. The water use strategies of fast-growing acacias and eucalypts are similar, so many of the findings from studies in eucalypts will be broadly applicable to acacia systems (Hardie et al. 2018).

Plantation water use (evapotranspiration) includes transpiration by crop trees, canopy interception, soil evaporation and understorey transpiration. A whole-of-system approach is required that accounts for the importance of the timing of management and its impact on growth and all water fluxes including transpiration. Plantation forests are perennial systems that use water during the dry season. This creates a trade-off between productivity and drought risk in seasonally dry climates (White et al. 2009).

As detailed in White et al. (2016), plantation water productivity (PWP_{wood}, g wood kg^{-1} H_2O) can be expressed as the product of the transpiration efficiency of dry matter accumulation (TE_{DM}, expressed in g DM kg^{-1} H_2O), the partitioning of dry matter to wood (harvest index (HI), g g^{-1}), and the components of evapotranspiration; transpiration (T, kg H_2O), evaporation from the soil (S) and canopy interception (I) (Equation 1).

$$PWP_{wood} = \frac{TE_{DM}HI}{1 + \left(\frac{S+I}{T}\right)} \qquad (1)$$

There are therefore three primary drivers of plantation water productivity for wood producers. Plantation water productivity is positively correlated with both the transpiration efficiency of dry matter accumulation, and the proportion of this dry matter allocated to harvestable stem wood (HI) and is inversely proportional to the ratio of evaporative losses (soil evaporation, interception, weed or understorey transpiration) to transpiration (water extracted from the soil by tree roots and transpired from the leaf surface via the conducting tissues in branches and stems; White et al. 2016, adapted from Passioura 1977). It is important to note that HI and transpiration efficiency of dry matter accumulation are not independent and are typically negatively correlated in water-limited plantations, so that increased transpiration efficiency of dry matter accumulation, which is driven by stomatal closure during water

stress, is often associated with reduced proportional allocation to stem wood (Hubbard et al. 2010). Unfortunately, in plantation systems around the world there is a strong emphasis on quantifying variation between genotypes (species, families and clones) in transpiration efficiency in isolation from stand management, including establishment, silviculture and forest nutrition (Pita & Pardos 2001; Monclus et al. 2006). This contrasts with a trend in agriculture towards a whole of system approach to making more effective use of water in production (Blum 2009; Passioura & Angus 2010). The use of transpiration efficient material may result in marginal gains in productivity during dry years, but this will not compensate for reduced productivity in wetter years (Passioura & Angus 2010). Transpiration efficiency equates to drought avoidance and it is our view that planting of this material will almost certainly reduce the risk of mortality but at the cost of reduced productivity. The ultimate effect on system productivity will play out at the stand scale and be the result of a range of complex feedbacks amongst response, water use and growth processes. This is an important area for new research and for application of process-based modelling.

A series of studies in tropical and sub-tropical regions in Brazil, have found positive relationships between water productivity and growth rate and between water productivity and water use (Stape et al. 2004a; Stape et al. 2004b; Stape et al. 2010; Hubbard et al. 2010); more intensively managed planted forests yield more wood and also convert water to wood more efficiently. There are two main mechanisms for this effect. Fast-growing plantations occupy the site more quickly, limiting weed transpiration and soil evaporation so that the denominator in Equation 1 is closer to unity. The second is concerned with the timing of water use relative to seasonal variation in the air saturation deficit. In a series of experiments in south-western Australia, fertilised stands of Eucalyptus globulus Labill. had significantly higher PWP$_{wood}$ compared to unfertilised stands (White et al. 2016). Closer examination of seasonal patterns showed that the faster growing fertilised plots, which had a higher leaf area index (White et al. 2010), used more water than the unfertilised plots during the early dry season when the air saturation was moderate (maximum values of 3 kPa) and the converse was true later in the year when the air saturation deficit was more severe (maximum values of 6 kPa). The fertilised plots also experienced more severe water stress (White et al. 2009) but had higher water productivity than the unfertilised trees. In water-limited environments, an increased yield will improve water productivity but will also increase drought risk. Strategies must therefore be developed to manage that risk without compromising production (White et al. 2009). It should be noted that the environment in which White et al. (2009) conducted their experiments was in a Mediterranean climate region with a strongly winter dominant rainfall out of phase with evaporation. Tropical environments generally have a summer dominant rainfall that coincides with the high evaporation period. In these environments it is possible that transpiration efficiency is better correlated with stand scale production than appears to be the case in temperate environments (e.g. Xu et al. 2000)

Water availability is determined by the amount, intensity and timing of rainfall, additional water inputs (due to, e.g.

topography, irrigation, or access to fresh groundwater), the capacity of the soil to store rainfall, and the rate of evapotranspiration. Plantation growth can be limited by the availability of water wherever potential evaporation exceeds rainfall, even if only for short period during the late dry season. Stored soil water buffers the plantation during periods when potential evaporation exceeds rainfall. Indeed, the dryness of a site can be quantified as the sum of the difference between potential evaporation and rainfall in months where potential evaporation exceeds rainfall, less the maximum water storage capacity of the soil. The capacity of a soil to store water that is available for plantations depends on its depth (or the depth that tree roots have access to), texture (sand, silt, clay content), organic matter content, bulk density, porosity, and coarse fragments (Gupta & Larson 1979), and on the rooting characteristics of the species planted. For example, a study by Nurudin et al. (2013) found that the typical maximum rooting depth of A. mangium appears to be around 1 m or less for acidic Acrisols and Plinthisols in South Sumatra, with a plinthite layer being associated with the maximum rooting depth. As many soils in tropical areas have a clay or clay-loam texture, a soil available water-holding capacity of around 140 mm m^{-1} would be typical (Gupta & Larson 1979). Clay soils tend to release water more slowly than sandy soils, but for the purposes of a simple water balance, we can assume that a tropical humid region tends to have a potential evapotranspiration (PET) rate of 80–120 mm month^{-1}, so a 1 m deep soil with a storage capacity of 140 mm m^{-1} could store sufficient water to buffer the plantation for more than one month without further rainfall. Note that these are generic soil water storage estimates, and root access to the stored water is dependent on both soil chemistry and physical characteristics being amenable for root exploration.

Even in locations with an average annual rainfall of more than 1100 mm (where commercial tropical acacias are typically from and grown, Booth et al. 2014), fast-growing plantations can be vulnerable to collapse in unusually dry years (White et al. 1996; White et al. 2009), especially on shallow soils. Commercial tropical acacias are relatively shallow rooted so that their water use and growth may become 'water-limited' after even one week without rain. Hardie et al. (2018) found that water use of tropical acacias and eucalypts grown in Sumatra were broadly comparable, although the current commercial distribution of commercial acacias in the tropics (which has resulted from extensive species introduction and testing, Doran & Turnbull 1997), suggests that they will be more drought sensitive than tropical Eucalyptus species. Given the likelihood of increases in extremes of wet and dry in the region, the planning of future planting of these species could benefit from a better understanding of the physiological basis for observed variation in performance in field tests.

In large areas of Sumatra, Malaysia, Kalimantan, and West Java where tropical acacias are planted, there are very few (or no) months where average PET is greater than average rainfall or precipitation (PPT, Fig. 1). Thus, it would be rare for these areas to become severely water limited unless the soils are extremely shallow, or during times of drought (note that drought is a relative term and in wet climates drought occurs in years that are dry relative to the median rainfall). Even where PET > PPT, the soil needs to only store enough
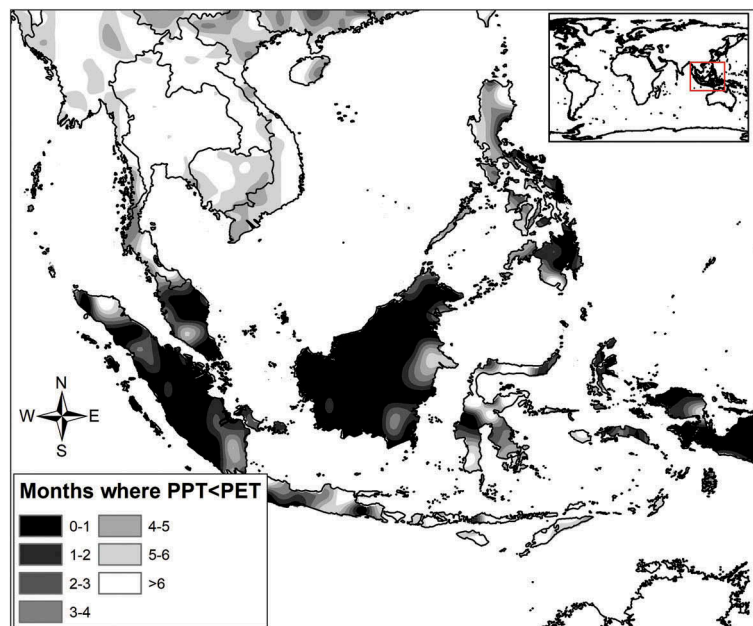
Figure 1. Map of Southeast Asia showing the average number of months per year where rainfall (or precipitation (PPT) is less than potential evapotranspiration (PET) for the month. Climate data sourced from LocClim (Grieser et al. 2006)

water to maintain plant hydration through to the next rainfall.

The average cumulative annual climatic water deficit (Fig. 2, calculated for all months where PET > PPT) can be approximately equated to the depth of soil required to store the average monthly difference between potential evaporation and rainfall, where 1 cm soil depth can store approximately 1–1.4 mm of water; thus 50 cm rooting depth stores at least 50 mm of plant available water. This again shows that in much of Indonesia and Malaysia, plantations only need relatively shallow soils to store sufficient rainfall to buffer against short dry periods. Northern Australia, where seasonal climatic water deficits can be more than 800 mm in an 'average' year, is at the opposite extreme, and acacia plantations are subjected to high levels

of water stress for long periods. The Indo-China region is intermediate, and deep soils are required to ensure that acacia plantations do not become significantly water stressed. Supporting this for tropical acacias, Hung et al. (2016) found that soil water deficit was strongly related to the growth of *Acacia* hybrid plantations in Vietnam, and Huong et al. (2016) demonstrated a highly seasonal growth pattern of *A. auriculiformis* in southern Vietnam, with no diameter increment occurring later in the dry season when the soil water storage was low. Observationally, *A. mangium* can be more sensitive to seasonal soil water deficit than *A. auriculiformis* or *A. crassicarpa*, with very slow growth rates during the dry season in northern Australia, and loss of apical dominance, resulting in trees with very poor form. This is consistent with our overall understanding of the

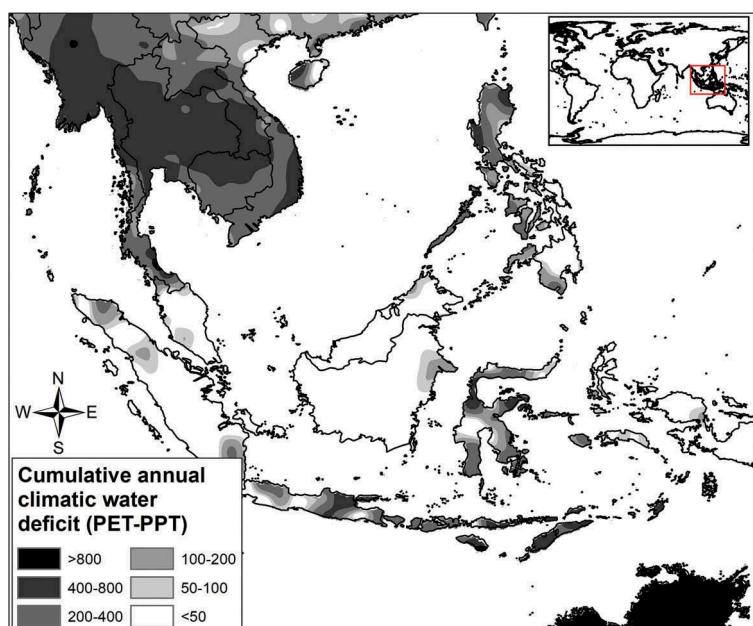**Figure 2.** Average cumulative annual climatic water deficit for Southeast Asia. This is the sum of potential evapotranspiration-precipitation (PET-PPT) for all months where PET exceeds PPT. Climate data sourced from LocClim (Grieser et al. 2006)

relationship between productivity, drought sensitivity and drought risk (White et al. 2003). It is also worth noting that climate change is likely to result in changes in climatic suitability of many planting sites over time, with Booth et al. (2014) suggesting that much of the current land area that is suitable for acacias may become hotter than the current ranges for those species, especially by 2080, even if it is also wetter than at present.

Water availability to trees can also be influenced by management, including site-genotype matching, weed control and stocking/thinning. White et al. (2009) found that early thinning of *E. globulus* from 1250 stems ha^{-1} to 600 or 300 stems ha^{-1} in south-western Australia resulted in no differences in the final standing volume of the stands at age ten years, but that the thinning treatments reduced the risk of mortality due to drought. This is consistent with earlier work in *Pinus pinaster* Aiton (Butcher 1977) and more recent work in *Pinus radiata* D. Don (Stone et al. 2012) that highlight the importance of timely thinning for mitigating drought risk. This also decreased the harvesting costs due to the greater wood volume per stem and is likely to be an important management strategy where seasonal water deficits are high (darker coloured areas in Fig 2). The benefits of thinning for reducing drought risk in acacias may need to be considered in partnership with the additional risks, including the possibility of increasing wind damage (Locatelli & Nicoll 2017).

Other management such as early weed control has been shown to be important in *A. auriculiformis* in Vietnam (Huong et al. 2008) as well as in eucalypts and acacias in both South Africa (Du Toit et al. 2010) and Indonesia (Turvey 1996). The mechanisms of weed competition varies between sites, and can be through competition for light, water, nutrients, or a combination of these resources (Balandier et al. 2006). Some weeds also have allelopathic as well as direct competitive effects (Bais et al. 2006). Whatever the source of the impact of weeds on growth, it is clear that weed control is an important management strategy for ensuring optimal productivity of plantation species, as long as detrimental practices, such as repeated ploughing are avoided (Nambiar & Harwood 2014).

Water can also present a problem where it is in excess. If the water table is too shallow and/or drainage is insufficient, this can reduce the effective rooting depth. Nurudin et al. (2013) found that *A. mangium* productivity in South Sumatra was related to the depth of the soil to plinthite, which is a mineral formed during the anaerobic conditions of waterlogging. Mound ploughing of shallower soils (or soils with shallow water table) may improve productivity by increasing the effective depth of soil for rooting, as has been practiced in other environments for some time (Casson 1947), but this needs further research before widescale adoption to ensure that it does not impact on the wind stability of acacias.

Nutrients

Of the 16 nutrient elements known to be essential for plant growth (Clarkson & Hanson 1980) tree crops are typically responsive only to a limited number of nutrients, in particular nitrogen (N), P, potassium (K), magnesium (Mg) and calcium (Ca), as well as boron (B). Other micronutrient deficiencies do exist (Dell et al. 2001) but are typically restricted to specific situations.

Nitrogen

Nitrogen is a key nutrient that needs to be managed in many plantation systems. Acacias are an N-fixing species, and so require less N fertiliser than non-N-fixing species, and in many cases do not respond to N fertiliser. Mendham et al. (2011) reported no response to basal fertiliser application (including N) at two sites in South Sumatra to age two years, and Turvey (1996) showed no significant response to N and K addition over and above P application at age 30 months in South Kalimantan. However, other studies have reported responses of tropical acacias to N fertiliser in some situations. For example, Dang (2011) found that the addition of 17 kg of N ha^{-1} significantly increased the height and diameter of *A. mangium* at two of three sites in Northern Australia (Melville Island) at age one year, but no further gains were obtained with higher N application. Similarly, Ryan et al. (1991) found a small but consistent height response to N fertiliser at age 11 months across six acacia species in Queensland. Reports of responses to N fertiliser at establishment are mixed, but lower fertility sites may require some starter N fertiliser (Mead & Miller 1991). Few studies have explored responses to N application later in the rotation, but Majid and Paudyal (1999) found no significant increase with application of N fertiliser on diameter increment at two *A. mangium* sites in Malaysia (3.5 and 5 years old). They did, however, report a significant response in height increment at one of the two sites. Additionally, Inagaki et al. (2009) found indirect evidence of N deficiency through fine root growth responses to N fertiliser in older *A. mangium* (>20 years old) in Malaysia. Mid-rotation N fertiliser responses appear to warrant further exploration where tropical acacias are grown for an extended time, but most acacia plantations are grown on a much shorter rotation than would justify follow-up N fertiliser application. Biologically, N fixation comes at the cost of C, with around 8–12 kg C required per kg of N fixed (depending on soil temperature, Fisher et al. 2010). In practice this C cost is relatively low, compared to the benefits obtained by the trees, as the N concentration in tissues is also low (typically 0.5–2.5%), and the trees utilise soil-sourced as well as fixed N (e.g. Wibisono et al. 2015).

The N-fixation capacity of acacias is mediated through a symbiotic relationship with bacterial species of *Rhizobium* and *Bradyrhizobium*; the actual species may be important for determining this capacity and the growth of the trees. Galiana et al. (1998) and Galiana et al. (2002) found large differences in N-fixation capacity between different strains of *Rhizobium/Bradyrhizobium* in glasshouse experiments. In addition, persistence of inoculated strains in field environments also appeared to be dependent on the strain of N-fixing bacterium and its interaction with the specific tree species (Burdon et al. 1999; Galiana et al. 2002; Le Roux et al. 2009). For example, Le Roux et al. (2009) found that *A. auriculiformis* × *A. mangium* hybrid plantations in Malaysia were more commonly associated with *Bradyrhizobium japonicum*, whereas both of the hybrid parental trees tended to be more associated with *Bradyrhizobium elkanii*. In addition, the seedling roots of each tree species could be re-inoculated with any of the *Bradyrhizobium* species and strains that they tested, but *Bradyrhizobium* strains (within a species) were associated with higher nodulation and conveyed greater growth benefits when re-inoculated back to their original host.

Rhizobium selection and species matching has provided significant gains in other systems (Dilworth et al. 2008).

Nitrogen-fixation rates of acacia plantations have been reported to be moderate compared to other N-fixing species, with Brockwell et al. (2005) summarising the literature to that time and finding reported N-fixation rates in a range of acacia species typically between 50 kg ha^{-1} y^{-1} and 100 kg ha^{-1} y^{-1}, and possibly up to 200 kg ha^{-1} y^{-1} in an *A. mearnsii* plantation. They also noted that higher rates were likely where soil conditions were most favourable, including adequate soil moisture, aeration and nutrition of the host species, though Galiana et al. (2002) found that the proportion of N derived from the atmosphere increased on sites with lower fertility. Bouillet et al. (2008) also reported relatively low N-fixation rates by *A. mangium*, with up to 66 kg ha^{-1} fixed up to age 30 months (representing 10–59% of the total N in the plant), but they noted that this was in conditions that were suboptimal for *A. mangium* productivity, with a long dry season (four months) and low winter temperatures. Similarly, Paula et al. (2018) found 35–39 kg ha^{-1} of fixed N in 18-month-old *A. mangium* in Brazil. Recent studies in tropical plantations in Southeast Asia, where soil moisture and nutrient conditions promote high growth rates of *A. mangium*, found higher rates of N fixation than most reported above. For example, Wibisono et al. (2015) found rates during the first 18 months of an *A. mangium* plantation in field conditions in South Sumatra to be greater than 200 kg N ha^{-1} in treatments receiving high levels of P fertiliser (representing 14–45% of the plant N). Similarly, Huong et al. (2015) found increases of around 700 kg N ha^{-1} in the 0–10 cm soil depth range under a second rotation *A. auriculiformis* plantation in Vietnam (average 177 kg ha^{-1} y^{-1}), with most of this accumulation occurring between around 12 months and four years of age. It is recognised that this increase may not all be associated with N fixation, as some N may have been uplifted from deeper horizons via plant uptake and litter cycling.

In summary, because of their N-fixation capacity, plantations of acacia will not respond strongly to N fertiliser in environments with good water availability and adequate supply of other key nutrients. There does, however, seem to be an interaction between P availability and N fixation suggesting that P and N must be managed so that P availability does not limit the fixation and supply of N. This issue is considered in more detail in the next section.

Phosphorus and nitrogen fixation

Phosphorus availability can affect N fixation because it is critical for nitrogenase activity in *Rhizobium* and *Bradyrhizobium* nodules (Israel 1987). This was also supported by a study with *A. mangium* (Ribet & Drevon 1996), where seedlings in solution culture without exogenous N (i.e. they were reliant on N fixation) were more dependent on P than when they were supplied with urea. However, Ribet and Drevon (1996) also found that this effect was only minor and concluded that *A. mangium* had a high efficiency of utilisation of internal P compared to other N-fixing legumes. In addition, Vadez et al. (1995) found significant variation in N fixation between seedlots of *A. mangium* at different levels of P in solution culture: one seedlot had increasing nodulation activity with increased solution P concentration, a second increased nodulation activity up to a P concentration of 500 μM, and two others showed high nodulation activity even at low solution P concentration. Wibisono et al. (2015) explored the interactions between *A. mangium* genotype and N fixation in the field in South Sumatra and found that genetic material selected for high growth rates in their study had less dependence on fertiliser P for high N fixation than slower-growing genetic material. This suggests that the capacity of certain genotypes to utilise low levels of P in association with their N-fixing organisms may be one of the underlying biophysical mechanisms that tree breeders are incidentally selecting for when they choose higher performing genotypes.

Several studies have explored the use of acacias in mixtures with eucalypts, to improve the N status of the *Eucalyptus* plantations (e.g. Laclau et al. 2008; Santos et al. 2016), with promising results, including the observation that the eucalypts in a 50/50 mix of eucalypts and acacias did not stagnate in their growth like they did in other treatments, probably because of the increased supply of N. The eucalypts in the 50/50 mixture also accumulated similar levels of nutrients as those in a pure *Eucalyptus* stand (Santos et al. 2017), suggesting that the acacias were reducing the N deficiency that was experienced in the eucalypt-only treatment, and increasing the efficiency of use of other nutrients in the production of wood. Santos et al. (2017) also noted that mixed acacia and eucalypt plantings synergistically improved biogeochemical cycling, utilising P derived from *Eucalyptus* litter and N derived from acacia litter at their Planosol site in Brazil.

Responses to phosphorus fertiliser

Acacia plantations are often highly responsive to application of P fertiliser (Jasper et al. 1989; Turvey 1996; Mendham et al. 2011; Beadle et al. 2013) applied at, or soon after, establishment. The early stages of growth are the most important for nutrition of short rotation acacia plantations, with stand nutrient demand at its highest between planting and canopy closure, to meet the requirements for growth and accumulation of foliage and fine branches (Miller 1995). At canopy closure, typically within 1–2 years in fast-growing tropical acacias, internal (retranslocation) and external (litter turnover) recycling of nutrients reduces, but does not eliminate, the demand on soil reserves. At age 3.8 years, an *A. mangium* plantation in Sabah, Malaysia had accumulated around 60–70% of the N, P, Ca and Mg in biomass that was present at age ten years (Nykvist & Sim 2009). Similarly, in an *A. mangium* plantation in South Sumatra the rate of uptake of P, K and Mg was most rapid in the first year, and declined thereafter; annual uptake after Year 4 was only 32–37% of the uptake observed in Year 1 (Hardiyanto & Nambiar 2014).

Although plantations of acacia may respond to P early in the rotation, this effect may not persist to the end of the rotation. Harwood et al. (2017) found that P fertiliser significantly increased the diameter at breast height of acacia hybrid plantations in central Vietnam, and while the absolute difference between fertilised and unfertilised stems remained similar, the significance of the difference declined such that after about Year 5 the treatments were not significantly different.

Mendham et al. (2011) found that *A. mangium* responded to P applied at establishment at every one of 12 sites in South Sumatra, standing volume was 50–200% more in

P-fertilised treatments compared to non-P-fertilised controls at age one year. This equated to an absolute volume gain at age one year in the P-fertilised treatments of 10–40 m^3 ha^{-1}. Although this volume gain tended to increase over time, the proportional response was diminished because the overall standing volume increased at a greater rate. Interestingly, the P fertiliser requirement (calculated as the amount of P required to reach 90% of the maximum productivity) was less than 10 kg ha^{-1} P at every site (Mendham et al. 2017), so a universal dose of 10 kg ha^{-1} P was recommended to be sufficient across all planting sites within the study region of South Sumatra. It was further recommended that further refinement of diagnostics of P fertiliser requirement would not be cost effective within that region. Huong et al. (2015) with *A. auriculiformis* in Vietnam and Hardiyanto and Nambiar (2014) with *A. mangium* in South Sumatra both found that available soil P declined over the course of the rotation (6–7 years), suggesting that the level of P required for maximum productivity may need to be adjusted over successive rotations.

Phosphorus fertiliser can also have marked impacts on tree form. This is an important consideration for growers where form is important, such as in plantations managed for sawlog production. Bon and Harwood (2016) found that P fertiliser applied at 50 kg ha^{-1} P to *A. auriculiformis* × *A. mangium* hybrids resulted in high growth rates, but could also be associated with heavy branching, and even after a number of form-pruning operations had been conducted. The P-fertilised trees also had significantly greater stem kinking and a greater proportion of trees with broken stems at age four years compared to the non-fertilised trees. Pruning of large branches can also result in increasing the risk of disease entry and incidence of heart rot in the treated plantations.

There are few published reports on the impact of late rotation application of P fertiliser in tropical acacias, but early work in temperate *A. mearnsii* in South Africa found that application of P up to six months after establishment had a much bigger impact on productivity than later applications (reported in Herbert & Schönau 1989). Similarly, Harwood et al. (2017) found a response to fertiliser applied to acacia hybrid at establishment in central Vietnam, but there was no additional response to fertiliser applied at 12 months. Anecdotally, operational experiments with tropical acacias have shown little response to P applied post canopy closure. This has also been observed in other species (Smethurst & Wang 1998) and is likely to be due to the efficient internal cycling of acacias, high affinity of root systems for P, and the extensive development of mycorrhizal associations with the tree roots (Barrow 1977). For example, Michelsen and Rosendahl (1990) found that the growth promoting effect of vesicular arbuscular mycorrhizal fungi was similar to that of P nutrition after about 12 weeks in a glasshouse experiment with *Acacia nilotica* (L.) Willd. ex Delile and *Leucaena leucocephala* (Lam.) De Wit. The opportunity for management of mycorrhizal associations to improve nutrient uptake efficiency has shown promise (Vance 2001), but there are few reports of situations where management of mycorrhizae has been able to improve productivity in the field, because local mycorrhizal species tend to outcompete any introduced species. While inoculation of specific fungal strains may be challenging in the soil environment, it has been demonstrated that the species

composition and diversity can be modified through changes in the species, with mixed species plantings showing much higher diversity of fungal species compared to monocultures (Rachid et al. 2015).

As noted above, another factor reducing the requirements of acacias for external P may be their high capacity for internal cycling, with Inagaki et al. 2011) showing that *A. mangium* had a very high internal P retranslocation capacity, with litter P concentrations only 12–22% of two other species under investigation. The lower deposition of P in litter (also observed by Kaye et al. 2000; Santos et al. 2018) may be contributing to the observation of declining soil P availability (Hardiyanto & Nambiar 2014; Huong et al. 2015), and suggests that P-fertiliser management over multiple rotations may need to be given more attention.

While acacia plantations are responsive to P, the maximum effect can be achieved with relatively low rates (<10 kg ha^{-1}), particularly in short rotation plantations managed for pulpwood production. In plantations managed for sawlog production, care should be taken to avoid excessive application of P as this may have a negative effect on tree form. Early responses to P may not carry through to the end of the rotation in a statistically significant way in many plantations, though absolute differences in standing volume may remain and provide a good return on the initial investment. Rotation length field experiments into P fertilisation effects on acacia are still lacking, and further work on defining the responses to P are required to improve confidence in growers about management of P in acacias.

Cations

Cations are taken up by acacia stands in relatively large quantities. Hardiyanto and Nambiar (2014) reported cations in the above-ground biomass of a seven-year-old *A. mangium* plantation in South Sumatra of 208, 581 and 58 kg ha^{-1} of K, Ca and Mg. This equated to 98%, 133% and 42% of the exchangeable soil pools, respectively, to 40 cm depth. Similarly, Nykvist and Sim (2009) showed that the biomass of a ten-year-old *A. mangium* plantation in Sabah had around 149%, 236% and 57% of the initial soil exchangeable pools of K, Ca and Mg, respectively, to 50 cm depth. These authors also found that the exchangeable pools of Ca and Mg to this depth slightly increased over the ten years the stand had been growing, and that exchangeable K declined. Conversely, Hardiyanto and Nambiar (2014) demonstrated a decline in exchangeable Ca and Mg in the 0–10 cm depth range, but that exchangeable K levels were not different between ages zero and seven years of the plantation. These conflicting results suggest two mechanisms for cation dynamics in plantation systems: (1) uplift from deeper horizons and cycling through litter (Jobbágy & Jackson 2004) and/or (2) poor relationships between current methods used to assess exchangeable cations and actual soil cation availability to trees, especially in acidic soils, where plantations are typically planted (Smethurst et al. 2007; Ross et al. 2008). It is likely that these two mechanisms are co-occurring, and their relative importance at any site will be soil dependent. Irrespective of the mechanism to explain the observed cation dynamics, it is clear that high foliar levels of some cations (notably Ca and Mg) are due to 'luxury uptake' because they are taken up with mass flow of soil solution into the roots and,

especially for Ca, cannot be easily remobilised in the plant (Clarkson & Hanson 1980). Dell et al. (2001) noted that the critical concentrations marking deficiency of Ca and Mg in several species of eucalypts were low and unknown, and this is likely to be similar for acacias. Responses to Mg or Ca (Hardiyanto & Wicaksono 2008; Huong et al. 2008) have not been reported in acacia plantations. However, continued export of large quantities of cations over successive rotations will induce deficiency at some stage in the future unless there is some supplementation. Potassium may be more important to manage before Ca and Mg at many sites, as other plantation systems have been found to be responsive to K addition. Barros and Novais (1996) reported that eucalypt plantations on low fertility soils in Brazil are responsive to K, and that K deficiency became exacerbated over multiple rotations (JL de M et al. 2004). No responses to K have been reported in acacias as yet. For example, Harwood et al. (2017) found no response to 14 kg ha^{-1} of K in *Acacia* hybrid in central Vietnam, and Hardiyanto and Wicaksono (2008) also found no response to K addition in *A. mangium* in South Sumatra. Potassium deficiency may start to manifest more after several rotations if the harvest residues are removed after harvest, and then it might become interesting to explore the substitutability between K and Na in tropical acacias (Battie-Laclau et al. 2014).

Another concern has been raised specifically around the possibility of soil acidification due to removal of cations from soil in the large uptake by the trees and leaching of cations with nitrate when there is excess N in the system (Binkley & Giardina 1997). Two main approaches to exploring this issue have been reported in the literature: paired sites with adjacent alternative land uses and long-term studies at the same sites. Paired studies have the advantage of allowing relatively rapid comparisons for assessing the effect of land-use change, but also have the problem that they require good matching of soil, landform and landuse history between the pairs. Even if these attributes are well-matched, soils are notoriously heterogeneous over short distances, so large numbers of paired sites are required to reduce the error associated this heterogeneity. Using the paired site approach, Yamashita et al. (2008) found that soil pH (in water) was around one unit lower under both *A. mangium* and secondary forest in South Sumatra compared to adjacent *Imperata* grasslands. The observation that this was the case under secondary forest as well as *A. mangium* plantations, suggested that the soil pH may have actually increased under grassland rather than decreased under forest, and may have been attributable to the influx of cations associated with logging and slash burning of the original natural forest. Similarly, Dong et al. (2014) reported slightly higher pH (by about 0.2 units) in abandoned land compared to adjacent second and third rotation *Acacia* hybrid plantations in Vietnam. Detailed studies which have assessed changes in soil pH at the same site over the duration of an *A. mangium* rotation (Hardiyanto & Nambiar 2014), and *A. auriculiformis* rotation (Huong et al. 2015) have not revealed any significant changes in pH by rotation end. Another study by Koutika et al. (2014) found that soil pH under acacias was around 0.3 units lower than under eucalypts at age seven years in a sandy soil in Congo. Thus, it is likely that there is a slight reduction in soil pH within the first rotation of an acacia plantation, probably mainly driven by the uptake of

cations by the plantation, and/or by the production of H + ions through the biological N-fixation process (Raven et al. 1990). However, this effect is usually minor, and it does not appear to represent a continuing trend in pH change over multiple rotations.

Water and nutrient interactions

Management of both nutrients and water must be considered together, as they cannot be managed in isolation. At times when water is available for growth, the nutrient supply must also be able to match the capacity of the trees to respond. For example, Huong et al. (2016) demonstrated that acacia hybrid tree diameter increment in the dry season declined to 0 mm month^{-1}, and there were no treatment effects on growth, but when water was available, growth increments were high (1–4 mm month^{-1}), and treatment effects were significant and pronounced. Where water is less limiting and productive potential is high, the demand on soil nutrients is commensurately higher too. In South Sumatra, higher productivity of *A. mangium* was associated with greater nutrient demand (Mendham et al. 2011).

Post-harvest residue management and soil carbon stocks

Management of organic matter, particularly between rotations, is one of the key options that managers have to influence sustainable production (Mendham et al. 2014; Nambiar & Harwood 2014; Nambiar et al. 2015). Organic matter, both above- and below-ground is one of the main pools of plant essential nutrients at many plantation sites; cycling of organic matter is critical for nutrient turnover and availability of these nutrients to growing tree crops (Tiessen et al. 1994). The harvest residues, typically comprising the foliage, branches and bark, contain high concentrations of nutrients compared to the stem wood, so while they represent a smaller proportion of the overall standing biomass, they contain a larger share of the nutrients. The bark, branches, unmerchantable stem wood (<8 cm), and foliage were 32% of the harvested above-ground live-tree biomass of an *A. mangium* plantation in South Sumatra, but contained 65%, 51%, 71%, 69%, and 79% of the N, P, K, Ca and Mg, respectively (Hardiyanto & Nambiar 2014). Similarly, in Vietnam, Huong et al. (2015) found that these residue components (bark, branches, leaves) of a productive *A. auriculiformis* plantation comprised around 73%, 40%, 52% and 77% of the total above-ground content of N, P, K and Ca, respectively, but only 30% of the biomass (average of second and third rotations). It is critical that plantation managers account for the effect of their method of harvest residue management, either burning, retention or manual removal, on site productivity in the medium and longer term.

Retention of residues on site allows for the return of nutrients to the system as the residues decompose. In tropical systems, leaf litter can decompose within 18 months (Sankaran 1993), and the half-lives of acacia leaves, bark and twigs in harvest residues in northern Vietnam were 0.47, 1.29 and 3.09 years, respectively (Nguyen et al. 2018). Thus, the release of nutrients from decomposing harvest residues tends to be aligned with the period of high demand associated with the growth of a new canopy in the next rotation.

Burning of the harvest residues will result in loss of a proportion of most nutrients, through a combination of volatilisation and emissions in particulate matter. Raison et al. (1985) found that the prescribed low-intensity burning of three *Eucalyptus* forests resulted in an average loss of 62%, 42%, 51%, 32% and 34%, respectively, for N, P, K, Ca and Mg, in the understorey. It is likely that burning conditions in Southeast Asia will tend to have a lower intensity than the prescribed burning of Raison et al. (1985), so elemental transfer rates may be less than these reported values, as hotter fires tended to result in greater site losses of these nutrients from the site. Mackensen et al. (2003) estimated the average nutrient losses due to burning of slash in two *A. mangium* plantations (8 years old) in East Kalimantan at 349, 122, 67 and 21 kg ha^{-1} of N, K, Ca and Mg, respectively.

The utilisation of plantation residues as a feedstock for bioenergy and/or biofuel production is under strong consideration by plantation growers around the world and this trend is likely to increase in the immediate future. The nutritional value of these residues, however, needs to be thoroughly accounted for, with Mackensen and Fölster (2000) estimating nutrient replacement costs alone for second rotation *A. mangium* to be approximately 9–16% of the total growing costs, compared to expenditure on nutrients of around 4% in the first rotation in East Kalimantan. The comparative economic returns from plantation systems with harvest residue retention or removal for bioenergy production can be estimated using current knowledge but this is based on fertiliser responses measured mostly in first rotation plantations. A crucial gap in our knowledge is the response of second rotation plantations to fertiliser and the interactions with harvest residue manipulation. We recommend that those considering harvest residue removal should conduct second rotation fertiliser trials on the alternative management options as a basis for a rigorous economic analysis of the options.

In contrast to many other non-N-fixing plantation species, acacias have the capacity to markedly increase soil N and organic matter content (Johnson & Curtis 2001). In a second rotation *A. auriculiformis* plantation in southern Vietnam, Huong et al. (2015) found that soil organic matter in the 0–10 cm depth range increased from 23 Mg ha^{-1} at the start to 27 (residues removed) to 32 (residues retained) Mg ha^{-1} at age six years. Similarly, Koutika et al. (2014) found that soil under *A. mangium* and mixtures of *A. mangium* and *E. urophylla* S.T.Blake × *E. grandis* W.Hill hybrid in Congo had higher C than under eucalypts only. Both Resh et al. (2002) and Kaye et al. (2000) found that C sequestration across eight tropical sites in Hawaii and Puerto Rico was the result of a combination of greater retention of the older existing soil C (55%, in the case of Resh et al. 2002) as well as greater accretion of new organic C. The retention of older soil organic C may have been associated with an inhibition of lignocellulosic decomposers, thus slower decomposition of the more recalcitrant forms of soil organic matter (Resh et al. 2002). The increase in soil C under acacias is not universal, though, and appears to be site dependent. For example, Hardiyanto and Nambiar (2014) found no significant increase in soil C under a highly productive *A. mangium* stand in South Sumatra, and Voigtlaender et al. (2012) found that C stocks in the soil under *A. mangium* were also unchanged, but forest floor C declined by 44%. Further research is required to elucidate the factors influencing C and N accumulation under acacias at different sites.

Conclusions

Past work on species and genotype testing have largely resulted in the establishment of large areas of commercial plantations of acacias in the wet tropical areas of Malaysia, Northern Vietnam and Indonesia, to which they are well-suited. Further expansion of the plantation estate will require ongoing field testing of genotypes in existing, new and proposed plantation regions. While the risk of mortality due to drought has been managed it is likely that short-term water deficits reduce productivity and the accuracy and precision of yield prediction is limited by a poor understanding of soil depth in the region.

Acacias can fix substantial quantities of atmospheric N which can build up the N status of the site and negate the need for addition of N fertilisers. Phosphorus fertiliser is critical for establishment of acacia plantations, but only in small quantities; excessive quantities may cause problems with tree form. Potassium is a key nutrient that is not yet requiring management in many plantations, but it could require closer attention in the future as multiple rotations are harvested and removal of K from the sites happens. Magnesium and Ca may also require more attention in the future too, for similar reasons. It is also becoming apparent that acacia plantations have potential to substantially improve the site through increasing the soil N and organic C capital, but this does not occur at all sites, and further research is required to ascertain the mechanism for this in relation to fertilisation.

A strong, linked, network of experimentation across the production areas of Southeast Asia would help to better understand and manage the water, nutrient and C dynamics of these systems, as has been conducted in Brazil, through the Brazil Eucalyptus Potential Productivity Project (Stape et al. 2010).

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