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N-P-K FERTILISATION OF TEAK (*TECTONA GRANDIS*) PLANTATIONS: A CASE STUDY IN COSTA RICA

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Despite the international importance of teak (*Tectona grandis*) plantations, very few studies have been published on fertilisation, generally with inconsistent conclusions. To evaluate the effect of N-P-K fertilisation on teak stands of different ages and related factors, four N-P-K fertilisation trials were analysed over an 11-year chronosequence (1, 3, 6 and 10 year-old plantations) in northern lowlands of Costa Rica. The site has a humid climate (with 3 dry months) and low fertility clayey acidic red soils (typic hapludults). ANOVA and Tukey-LSD mean differences tests ($\alpha = 0.05$) were conducted to determine the best fertilisation treatment at each age. No evidence of growth improvement, related to fertilisation, was observed in the 3 and 10-year-old plantations, while a positive (but low) effect of fertilisation was recorded in the 1 and 6-year-old plantations. The present study highlighted the need for further research with greater scope, both spatial and temporal, to gain a clearer understanding of the fertilisation requirements of teak, an important pantropical species.

Keywords: Planted forests, forest nutrition, Central America, soil fertility, forest soils

INTRODUCTION

The global importance of short rotation, intensively managed planted forests has increased over recent years due to the growing need for timber and other goods. In this kind of system, nutrient management is a key issue and fertilisation plays a double role: a) improving productivity and b) compensating nutrient output in order to attain sustainability and maintain productivity for further rotations. The need to replace nutrients, taken up by the growing forest or removed during timber extraction, has long been recognised (Rennie 1955). However, Fölster & Khanna (1997) stated that conventional forest management has shown a general lack of concern with regard to this problem. Several authors have recommended the application of fertiliser to sustain productivity in short-cycle plantations (FSC 2004, Rennie 1955, Gonçalves et al. 1997, Worrel & Hampson 1997). This is especially important in tropical forests where nutrient dynamics and tree growth take place more rapidly than temperate zones.

Teak (*Tectona grandis*) is an important species worldwide in the quality tropical hardwood sector, with a total planted area of 4.3×10^6 ha, of which 132,780 ha are in Central America and 31,500 ha in Costa Rica (Kollert & Cherubini 2012). Teak nutrition in Central America should pay special attention to N, K and Ca, as these three nutrients are the most absorbed by teak, although P, Zn, B and Mg may also limit productivity in planted teak forest (Fernández-Moya et al. 2013, 2015, Zhou et al. 2016). Teak is a species with high nutrient requirements. Deep, well-drained soils with high chemical fertility (especially Ca), and acidity saturation values lower than 3% are required for the successful growth of this species (Montero 1999, Oliveira 2003, Alvarado & Fallas 2004, Mollinedo et al. 2005, Kumar 2011, Alvarado 2012, Zhou et al. 2012). Although site selection is a key issue in teak plantation management, subsequent fertilisation is also necessary. Such treatments are aimed at satisfying the high nutrient demand of teak trees, thereby maintaining the high nutrient concentrations (Drechsel & Zech 1991, Fernández-Moya et al. 2013, Zhou et al. 2016).

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Despite the international importance of teak plantations, very few nutritional and fertilisation studies have been published in Asia and Latin America, generally with inconsistent conclusions (Kumar 2011, Alvarado 2012). However, the application of fertiliser, usually N-P-K formulas, is a common practice in teak plantations both in Asia (until intermediate ages) and in Central America (at establishment). The present study aims to further the understanding of fertilisation, providing valuable information from four N-P-K fertilisation trials over an 11-year chronosequence in teak plantations, in the Northern lowlands of Costa Rica.

MATERIALS AND METHODS

Study area

The study area is located in the Northern Atlantic lowlands of Costa Rica, San Carlos region. Four sites were selected within the Expomaderas teak plantations (10.75–10.95 °N, 84.50–84.70 °W, 35–60 m asl). According to Holdridge's life zones, the area is classified as tropical wet forest with a humid climate, characterised by mean annual rainfall of 2500–3100 mm, with three dry months, when the potential evapotranspiration is higher than the precipitation. The study site has low fertility clayey acidic red soils (typic hapludults). Due to the absence of data from the experimental plots, information of the topsoil (0–20 cm) and foliage nutrient concentration from nearby plots were used as a reference to estimate the nutritional deficiencies of the plantations (Tables 1 and 2). Fernández-Moya et al. (2013) further reported on soil and foliage nutrient concentration. Laboratory results for soil analysis used cmol(+) L^{-1} units for Ca, Mg and K availability, the effective cation exchange capacity (ECEC) and acidity, which are commonly used units. The results were converted to International System Units [cmol(+) kg^{-1}] using a mean reference bulk density value (1.03 mg m^{-3}) for ultisols and alfisols topsoil in Costa Rica (Alvarado & Forsythe 2005).

Table 1 Topsoil (0–20 cm) attributes of three teak (*Tectona grandis*) plantations with fertilisation trials in San Carlos region, North of Costa Rica

	Escaleras 8*	Banderas 1*	Banderas 3*	Critical values	
	1 yr	6 yr	10 yr	Published***	Experience of the authors
pH	4.39**	4.90**	5.20**	5.5	5.5
OM [%]	2.6	5.1	3.4		
Sand [%]	26	33	17		
Silt [%]	16	16	18		
Clay [%]	58	51	65		
Acidity [cmol (+) kg^{-1}]	1,12	1,45	0,43	0,49	0,49
Ca [cmol (+) kg^{-1}]	5,11	2,33	3,84	3,88	9,71
Mg [cmol (+) kg^{-1}]	3,18	0,74	1,32	0,97	2,91
K [cmol (+) kg^{-1}]	0,54	0,06	0,07	0,19	0,19
ECEC [cmol (+) kg^{-1}]	9,94	4,57	5,66	4,85	14,56
AS [%]	11.23**	31.63**	7.55**	3	3
P [mg L^{-1}]	12	2**	2**	10	5
Zn [mg L^{-1}]	6	1**	1**	3	3
Cu [mg L^{-1}]	6	7	10	1	1
Fe [mg L^{-1}]	200	202	123	10	
Mn [mg L^{-1}]	263	8	16	5	

OM = organic matter, ECEC = effective cation exchange capacity [ECEC = acidity + Ca + Mg + K], AS = acidity saturation [AS = acidity/ECEC]; *information was obtained from Fernández-Moya et al. (2013) from nearby plots of the same plantations, ** values marked in bold type are higher or lower to references considered as adequate, *** critical values as reference levels to evaluate soil fertility in Costa Rica, as reported by Bertsch (1998) for general crops and by Alvarado and Fallas (2004) for AS in teak plantations

Table 2 Foliar nutrient concentration of trees at three teak (*Tectona grandis*) plantations with fertilisation trials in San Carlos region, North of Costa Rica

Stand	Escaleras 8**		Banderas 1**		Banderas 3**		References from literature***
Age (years)	0.8	2.5	6.3	7.3	10.5	12.0	
N [%]	2.53	2.12*	1.92*	2.18	1.57*	1.89*	1.52–2.78
Ca [%]	1.40	1.12*	0.94*	1.51	0.90*	1.28*	0.72–2.20
K [%]	0.95	0.87*	0.44*	0.64*	0.83*	0.84*	0.80–2.32
Mg [%]	0.13*	0.19*	0.21*	0.24*	0.36	0.42	0.20–0.37
P [mg kg^{-1}]	0.15	0.12*	0.14	0.12*	0.11*	0.11*	0.14–0.25
S [mg kg^{-1}]	0.08*	0.13	0.08*	0.13	0.08*	0.11*	0.11–0.23
Fe [mg kg^{-1}]	71*	140	70*	69*	116*	96*	58–390
Mn [mg kg^{-1}]	78	54	43	56	71	48	50–112
Cu [mg kg^{-1}]	17	12	14	10*	8*	11	10–25
Zn [mg kg^{-1}]	31*	23*	23*	25*	27*	35	20–50
B [mg kg^{-1}]	25	16*	19	17*	16*	19	15–45

* Values marked in bold type are higher or lower to references considered as adequate (Fernández-Moya et al., 2013) for their respective ages for plantations in Central America, ** information was obtained from Fernández-Moya et al. (2013) from nearby plots of the same plantations, *** adapted from Drechsel and Zech (1991) and Alvarado (2012)

The studied plantations were representatives of company-managed teak plantations in the region. Management of these plantations involves continuous silvicultural activities, such as land preparation, fertilisation and liming during establishment (at variable dosages and formulas), weed control, pruning and thinning, approximately from 816–1111 trees ha^{-1} to 150–200 trees ha^{-1} at final felling. An expected commercial volume of 100–150 m^3 is expected, when harvested at the end of the 20–25 year rotation.

Experimental design and field measurements

The same experimental design was replicated over an 11-year chronosequence in four independent trials at four sites, i.e. Escaleras 8 (1-year-old), Escaleras 3 (3-year-old), Banderas 1 (6-year-old) and Banderas 3 (10-year-old). The experimental design established at each site consisted of four replicates of all 12 treatments, defined in Table 3. Ammonium nitrate (NH_4NO_3) was used as N fertiliser (33.5% N), triple super phosphate ($Ca(H_2PO_4)_2{\cdot}H_2O$) was used as P fertiliser (45% P_2O_5) and potassium chloride (KCl) was used as K fertiliser (60% K_2O). Fertiliser was applied on the soil surface in a circle, around the selected trees. Due to their high mobility, the dosages of N and K were split into two applications, half at the beginning of the wet period and the other half at the peak of the rainy season.

The study plot size was: a) 324 m^2 (9 × 36 m) with 36 trees (3 × 12) and an effective plot (without the border effect) of 10 trees (1 × 10) in the 1-year-old trial, b) 432 m^2 (9 × 48 m) with 48 trees (3 × 16) and an effective plot of around 10 trees, taking into account the thinning, in the 3 and 6-year-old trials, and c) 540 m^2 (9 × 60 m) with 60 trees (3 × 20) and an effective plot of around 10 trees, taking into account the thinning, in the 10-year-old trial. In the present study, only measurements from the effective plots were used for the analyses.

Plot establishment and first fertilisation were carried out between March and April 2007. Tree growth measurements were taken in June–July 2007 and one year later in August 2008, to evaluate the effects of the fertilisation after one year. Diameter at breast height (DBH) and tree height (H) were measured, and tree volume was estimated using the formula developed by Expomaderas. Based on the field data, mean annual increment (MAI) and current annual increment (CAI) were calculated. Growth data from nearby permanent plots (PP) were used

Table 3 Fertiliser dosage (g tree^{-1}) for each treatment at the fertilisation trial established in teak (*Tectona grandis*) plantations of 1, 3, 6 and 10-year-old in San Carlos region, North of Costa Rica

Treatments	$CaCO_3$*	Fertiliser			Nutrient		
		NH_4NO_3	$Ca(H_2PO_4)2{\cdot}H_2O$	KCl	N	P_2O_5	K_2O
N0	1	0	300	220	0	135	132
N1	1	80	300	220	26.8	135	132
N2	1	160	300	220	53.6	135	132
N3	1	220	300	220	73.7	135	132
P0	1	220	0	220	73.7	0	132
P1	1	220	100	220	73.7	45	132
P2	1	220	200	220	73.7	90	132
P3	1	220	300	220	73.7	135	132
K0	1	220	300	0	73.7	135	0
K1	1	220	300	80	73.7	135	48
K2	1	220	300	160	73.7	135	96
K3	1	220	300	220	73.7	135	132

*Lime dosage was 1 kg tree^{-1} at younger trees (1 and 3-year-old) and 1 mg ha^{-1} in older trees (6 and 10-year-old); N0, N1, N2 and N3 are fertilisation treatments with different dosages of nitrogen (N); P0, P1, P2 and P3 are fertilisation treatments with different dosages of phosphorus (P); and K0, K1, K2 and K3 are fertilisation treatments with different dosages of potassium (K)

as a control, to compare data from the best fertilisation treatment with that of non-fertilised, regular plantation practice.

One and 3-year-old plantations were limed (85–95% $CaCO_3$) (1 kg lime tree^{-1}) and fertilised at establishment, while 6 and 10-year-old plantations were limed (1 kg lime ha^{-1}) and fertilised in 2006, one year before the establishment of the fertilisation trials. It is not known whether the latter plantations received any fertilisation or liming prior to 2006. These operations were carried out before the trials were established and were also applied to the PP, which were used as a control.

Statistical analysis

Increments in DBH, H and volume between June–July 2007 and August 2008 were calculated. A total of 12 ANOVA tests were performed to analyse the effect of the treatments on the increment in DBH, H and commercial volume (three response variables), in four independent trials at different ages (Table 3). When the ANOVA tests were significant, a Tukey-LSD mean differences test was conducted to determine the best fertilisation treatment at each age. All statistical analyses were performed using R, with a significant value of $\alpha = 0.05$.

RESULTS

Fertilisation trial in 1-year-old plantation

Fertilisation treatment in 1-year-old plantation showed significant increment in DBH ($F_{11,455}$ = 3.06, $p < 0.001$) and H ($F_{11,455}$ = 2.84, $p = 0.001$). The best treatment, in both cases, was those highest in K (K3), showing slight differences from other treatments (Figure 1). The H or volume data were not available for nearby PP, to be compared with the fertilised plots, although K3 treatment plots showed slightly higher DBH compared with unfertilised ones in PP (Figure 2), which means a higher MAI DBH (Figure 3) and CAI DBH (Figure 4).

Fertilisation trial in 3-year-old plantation

Fertilisation treatment in 3-year-old plantation showed significant increment in DBH ($F_{11,699}$ = 9.87, $p < 0.001$) and volume ($F_{11,699}$ = 3.73, $p < 0.001$). In this trial, the best treatment, in both cases, were those with the highest N dosages (N1, N2 and N3 for DBH and N3 for volume), although without large differences from the other treatments (Figure 1). The treatments also had an effect on H increment ($F_{11,699}$ = 1.99, $p = 0.027$), although there were no noticeable

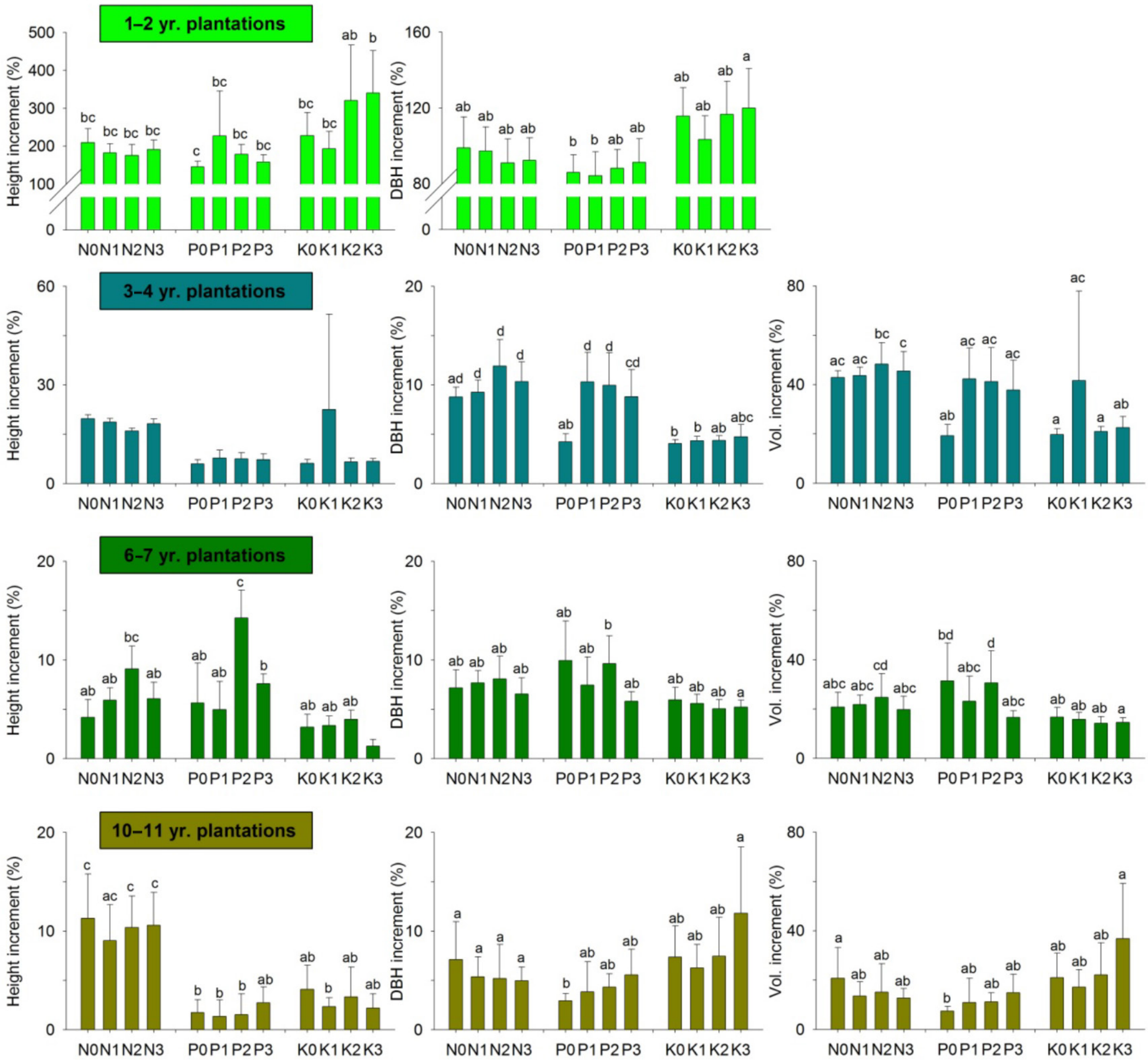

Figure 1 Effects of the fertilisation treatments established in teak (*Tectona grandis*) plantations of 1, 3, 6 and 10-year-old in San Carlos region (North of Costa Rica) on the increment of height, diameter at breast height (DBH) and volume over one year of growth (i.e. at 2, 4, 7 and 11 years old respectively); data is expressed as study variables mean with confidence interval ($\alpha = 0.05$); different letters indicate treatments with significant difference, using Tukey test for mean differences analysis ($\alpha = 0.05$); ammonium nitrate fertiliser, P = triple super phosphate fertiliser, K = potassium chloride fertiliser N0, N1, N2 and N3 are fertilisation treatments with different dosages of nitrogen (N); P0, P1, P2 and P3 are fertilisation treatments with different dosages of phosphorus (P); and K0, K1, K2 and K3 are fertilisation treatments with different dosages of potassium (K)

differences between means (Figure 1). The H, DBH and volume of plots with fertilisation were higher than PP (Figure 2). The larger size of the fertilised trees (prior to fertilisation) is probably the reason for their lower growth compared with unfertilised ones in PP (Figures 2, 3 & 4), as tree growth is usually lower in larger and older trees.

Fertilisation trial in 6-year-old plantation

The fertilisation treatments in 6 year old plantations showed significant increament in DBH ($F_{11,441} = 2.56$, $p = 0.004$), H ($F_{11,441} = 7.18$, $p < 0.001$) and volume ($F_{11,441} = 6.87$, $p < 0.001$). The P2 treatment gave best results, although

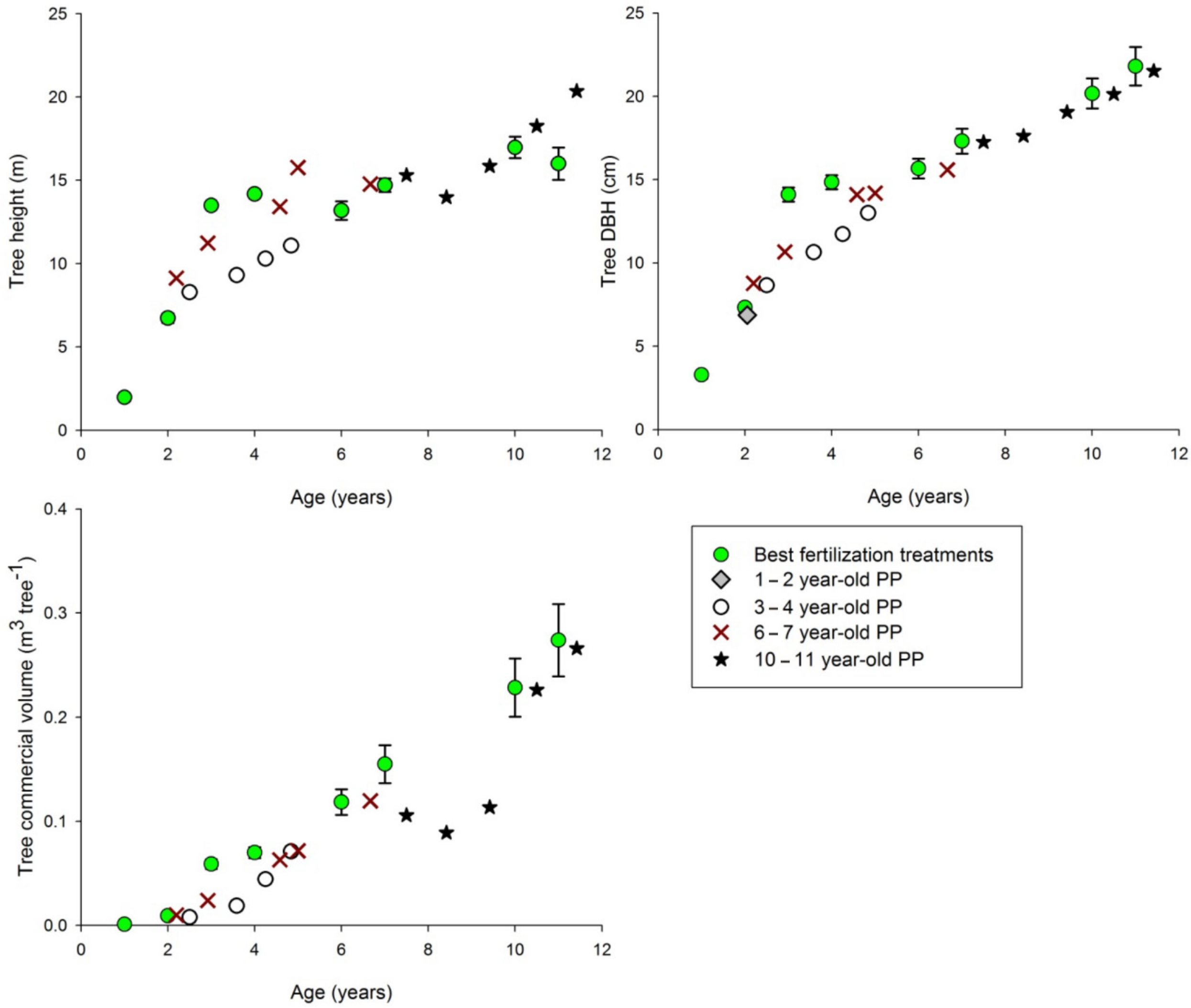

Figure 2 Comparisons of tree height (m), diameter at breast height (DBH) (cm) and commercial volume (m^3) between permanent plots (PP, as control) and the best fertilisation treatments established in teak (*Tectona grandis*) plantations of 1, 3, 6 and 10-year-old in San Carlos region (North of Costa Rica); data is expressed as study variables mean with confidence interval ($\alpha = 0.05$) for best fertilisation treatments: K3 at age 1–2, N3 at age 2–3, P2 at age 6–7 and K3 at age 10–11

without great differences from the others (Figure 1). The plots with fertilisation had lower H and similar DBH and commercial volume to PP (Figure 2). After the application of fertiliser, in P2 treatment, tree height increased to that of PP, and both DBH and commercial volume exhibited greater increments than the unfertilised plots (Figure 2). This response to fertilisation can also be observed in the higher MAI DBH and MAI commercial volume than the unfertilised plots (Figure 3), and in the higher CAI H, CAI DBH and CAI volume exhibited by the fertilised plots compared with the unfertilised ones in PP (Figure 4).

Fertilisation trial in 10-year-old plantation

Fertilisation treatment in 10-year-old plantation showed significant increment in DBH ($F_{11,285} = 1.84$, $p = 0.047$), H ($F_{11,284} = 8.37$, $p < 0.001$) and volume ($F_{11,285} = 2.72$, $p = 0.002$). The treatments, N0, N2 and N3, showed the highest H increment, K3 showed the highest DBH increment and N0 and K3 showed the highest volume increment, although the differences between treatments were low (Figure 1). The plots with fertilisation had similar or slightly higher H, DBH and volume compared with the PP, although no important effect of fertilisation was noticed one year after

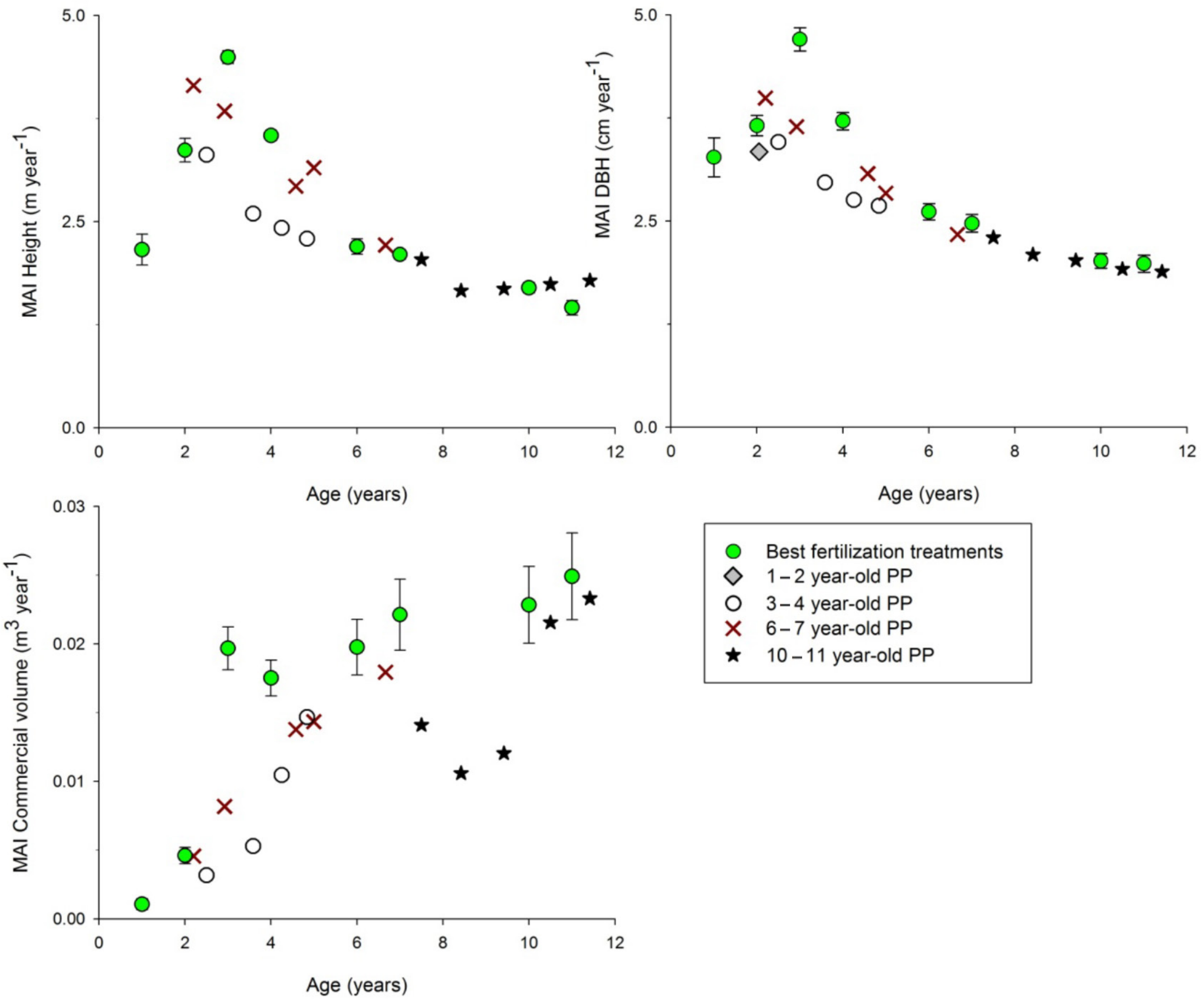

Figure 3 Comparisons of tree Mean Annual Increment of height (m), diameter at breast height (DBH) (cm) and commercial volume (m^3) between permanent plots (PP, as control) and the best fertilisation treatments established in teak (*Tectona grandis*) plantations of 1, 3, 6 and 10-year-old in San Carlos region (North of Costa Rica); data is expressed as study variables mean with confidence interval (α = 0.05) for best fertilisation treatments: K3 at age 1–2, N3 at age 2–3, P2 at age 6–7, and K3 at age 10–11

the experiment (Figure 2). DBH and volume increments were similar between fertilised and unfertilised plots, whereas tree height seem to decrease after fertilisation, although this is probably an indirect effect of thinning (Figures 2, 3 and 4).

DISCUSSION

A general positive effect of liming and fertilisation was observed in 1 and 6-year-old plantations, contrasting with the lack of effect in 3 and 10-year-old plantations (Figures 2, 3 and 4). The positive effect of fertilisation on the 1-year-old teak plantation is probably more associated to a residual effect of liming carried out at establishment than to the fertilisation itself, because although the soils show some acidity problems, soil nutrient availability is adequate (Table 1). On the other hand, the foliar nutrient content of a nearby, unfertilised 1-year-old plantation showed deficiencies in Mg, P, S, Fe and Zn, while a 2.5-year-old plantation in the same area showed deficiencies in N, Ca, K and B (Table 2). The response of young teak plantations to liming and fertilisation have been reported previously (Alvarado & Fallas 2004, Kumar 2011, Alvarado 2012, Balám-Che et al. 2015), including studies under nursery conditions (Zhou et al. 2012). The positive effect of liming and fertilisation in

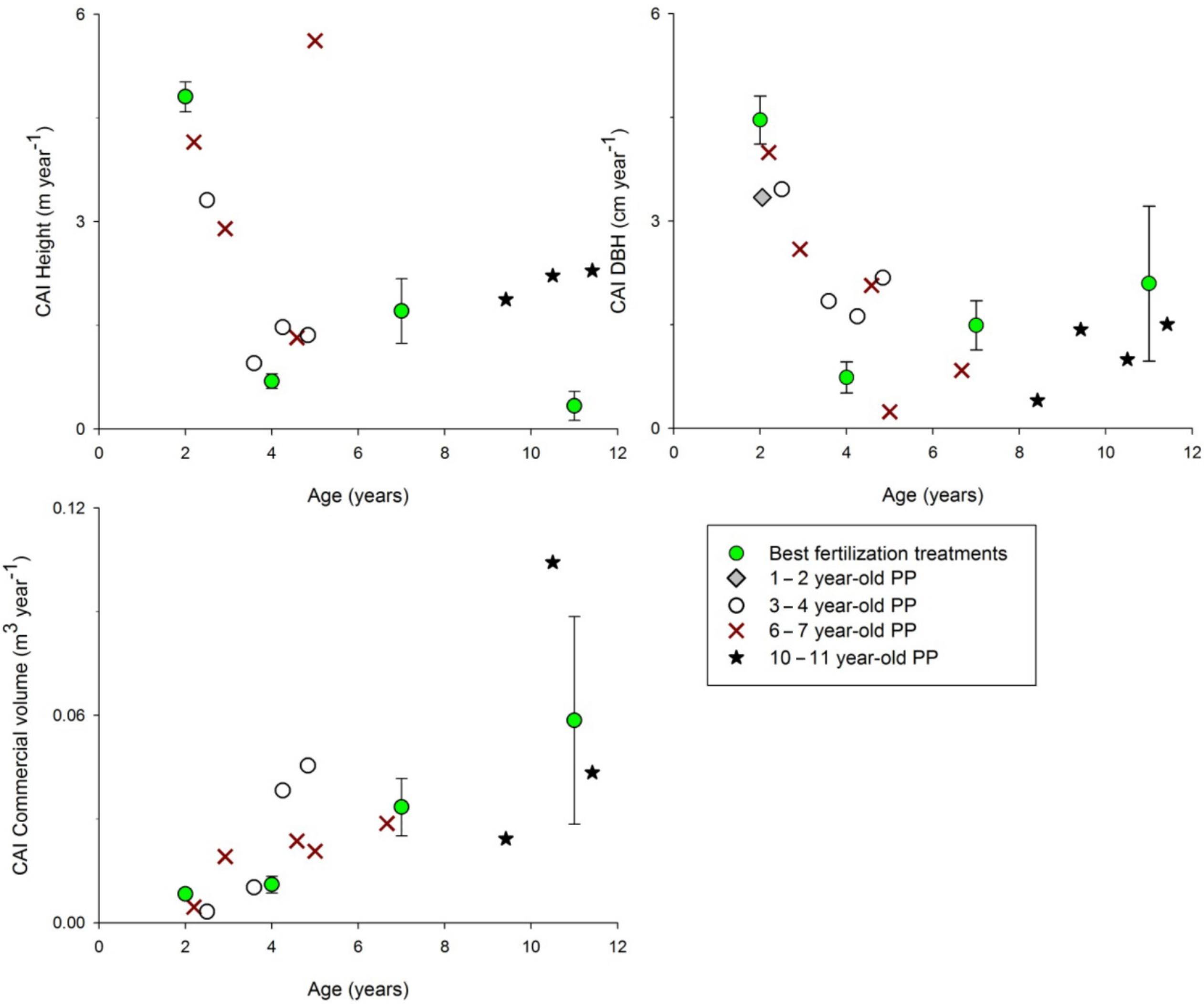

Figure 4 Comparisons of tree current annual increment (CAI) of height (m), diameter at breast height (DBH) (cm) and commercial volume (m^3) between permanent plots (PP, as control) and the best fertilisation treatments established in teak (*Tectona grandis*) plantations of 1, 3, 6 and 10 year-old in San Carlos region (North of Costa Rica); data is expressed as study variables mean with confidence interval ($\alpha = 0.05$) for best fertilisation treatments: K3 at age 1–2, N3 at age 2–3, P2 at age 6–7, and K3 at age 10–11

6-year-old plantations might also be explained by the generally low soil fertility observed, with deficiencies of Ca, Mg, K, P and Zn (Table 1) and low values of foliar nutrient content (Table 2). A positive effect of fertilisation on teak growth was also reported by other authors for plantations of intermediate ages, slightly younger or older than the 6-year-old plantation (Prasad et al. 1986, Montero 1995, Alvarado 2012).

The lack of fertilisation effect in 3 and 10-year-old plantations was unexpected. Soil and foliar data revealed important deficiencies in the 10-year-old plantation (Tables 1 and 2). Although there was no available data for the 3-year-old plantation, some deficiencies existed, at least with respect to soil acidity and P, common to all the sites (Tables 1 and 2). The lack of effect in the 3-year-old plantation could be explained by the larger size of the trees in the plots compared to the PP (Figure 2). In the case of the 10-year-old plantation, it is possible that one year is insufficient to detect any difference in growth between fertilised and unfertilised plots, and that a period of at least two years would be necessary. This two-year response lag has previously been observed in other fertilisation studies, and is associated with the Steenberg effect (Blinn & Buckner 1989). Another plausible explanation could be that the nutritional requirements of trees at this age exceed the dosage of fertiliser used in the trial (Fernández-Moya et al. 2013, 2015). Contrary to the results of the present study, Prasad et al. (1986) found a positive response to fertilisation in 10-year-old plantations.

In addition to this unexpected absence of response to fertilisation in the 3 and 10-year-old plantations, the effect on the 1 and 6-year-old plantations, although positive, was much lower than expected, considering the very low soil fertility and generalised nutrient deficiencies (Tables 1 and 2). As discussed below, several factors could be influencing this null or low response to fertilisation. If the nutrient status of the stand is not the limiting factor to growth, no fertilisation effect is likely to be observed.

Kumar (2011) highlighted several possible causes which could explain the lack of fertilisation response: a) promoting growth of competing understory, b) enhanced palatability and herbivore pressure and c) original high fertility of the sites. None of these explanations tie in with the observations of this study, as weed control was carried out properly, no herbivores were present in the area and soil fertility was generally low (Table 1). Montes et al. (2012) pointed out the importance of water in determining a response to fertilisation in forest plantations, as water stress may be more limiting than nutrient deficit. However, the climate in the study area is characterised by high rainfall and the soils are relatively deep, with good physical properties which retain enough water, hence, a slight water deficit is not likely to make a big difference. Nevertheless, detailed information on climate and physical soil properties in the study area is lacking and should be taken into account, both in forest nutrition management and in further research work.

Another factor which could be affecting the response of teak to fertilisation at different ages in the chronosequence of the thinning regime (Binkley 1986). As observed in other species, competition, rather than tree nutrition, can become the limiting factor, and excessive competition can mask tree response to fertilisation. If the plantation is thinned, the plants are released from competition and are able to use the extra nutrients from the fertilisation to grow (Fôlster & Khanna 1997, Kumar 2011). The 3-year-old plantation, where fertilisation trial was conducted, was unthinned (1111 trees ha^{-1}), while the density of PP was 865 and 855 trees ha^{-1} at ages of 3 and 4 years respectively, which may explain the absence of fertilisation response. However, the 10-year-old plantation with fertilisation had been thinned to a similar density as the control PP.

The previous application of lime and fertiliser, only one year before in the 1, 6 and 10-year-old plantations and three years before in the 3-year-old plantation, could also affect tree response to fertilisation. This application of lime and fertiliser in previous years was also performed in PP, which may have been sufficient to amend the nutritional deficiencies of the plantations, hence the 10-year-old plantation did not respond to fertilisation. However, the 1 and 6-year-old plantations responded to fertilisation one year after the previous liming and fertilisation operations. Possible explanations for this observations are: a) the nutritional deficiencies at these sites were so great that the treatments applied were insufficient, b) the dosages applied in these operations were inadequate or the plants were not able to use the extra fertilisation (problems related to the time, form of application or high stocking level), c) the growth rates of the plantations are so high that the plants are able to use the extra nutrient or d) the observed response is mainly a residual effect of the previous operations.

Finally, the selection of fertiliser is another factor affecting the fertilisation response. The application of N-P-K alone may be insufficient to address the nutrient deficit, since other nutrients such as Mg, Zn and B may be limiting tree growth. These nutrients are generally deficient (Tables 1 and 2) and have been identified as important nutrients for teak nutrition (Fernández-Moya et al. 2013, 2015). However, Balám-Che et al. (2015) did not find a positive effect of fertilisation with micronutrients in a trial in South East Mexico.
The P nutrition, even though commonly deficit in many soils worldwide, it is often not caused by the low content, but by the low availability caused by immobilisation in organic form or precipitation as Ca phosphates, formed at high soil pH, or Fe and Al phosphates in highly weathered acidic soils (Gyaneshwar et al. 2002, Khan et al. 2007). Hence, it has been observed that the addition of P chemical fertilisers is an ineffective practice (Balám-Che et al. 2015) because it does not solve the soil P deficiency, which is rapidly immobilised or precipitated. Conversely, it has been found

that the application of biofertilisers is far more effective, although not tested for teak, because it solubilises and mineralises the immobilised P, hence increasing P availability and higher plant growth (Gyaneshwar et al. 2002, Khan et al. 2007). Corryanti et al. (2007) described how mycorrhizal activity promotes phosphatase in rhizosphere and root of teak seedlings, resulting in higher growth. Similarly, Alvarado et al. (2004) collected mycorrhizae throughout teak plantations in Costa Rica and proposed the inoculation of seedlings, as a way to improve P uptake and enhance productivity, particularly in acid soils.

The results from fertilisation studies in teak plantations in Latin America (Alvarado 2012) are similarly inconsistent compared with literature revision undertaken by Kumar (2011), which mainly focuses on Asiatic and African plantations. Several authors found a positive effect of fertilisation in Panama, Venezuela and Mexico, even though it was also lower than expected in some cases (Mothes et al. 1991, Torres et al. 1993, Montero 1995, Balám-Che et al. 2015), while Hernández et al. (1990) found no effect in El Salvador. Despite this lack of consistency in the fertilisation trials in teak plantations, fertiliser application is usually recommended and generally applied (Kumar 2011, Alvarado 2012). The application of fertiliser, without taking into account the environmental and silvicultural factors, or the application of an inadequate product, would be of little or no benefit to plantation growth.

CONCLUSIONS

A positive, though weak, effect of N-P-K fertilisation was observed in 1 and 6-year-old plantations, while no response was observed in the 3 and 10-year-old plantations. This low or null response to fertilisation contrasted with expectations, given the very low soil fertility and generalised nutrient deficiencies in the studied plantations. The inconsistent results from fertilisation trials in the present study revealed that the commonly used N-P-K fertilisation is not always useful to improve teak growth, even in low fertility soils. The present study highlighted the need for further research with greater scope, both spatial and temporal, to gain a clearer understanding of fertilisation requirements for teak, an important pantropical species. Environmental and silvicultural factors should be carefully taken into consideration, both in the design of fertilisation strategies and in future research, in order to avoid pointless investment and pollution.

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