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Phil. Trans. R. Soc. Lond. B 1999 **354**, 1825-1829
doi: 10.1098/rstb.1999.0524

THE ROYAL SOCIETY

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Effects of nitrogen and phosphorus fertilization in a lowland evergreen rainforest

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A nutrient addition experiment was set up in August 1993 in a species-rich primary lowland dipterocarp forest in Barito Ulu, Central Kalimantan, Indonesia. The following treatments were applied: control, +N, +P and +NP. There were five blocks of four 50 m × 50 m plots with a separate treatment for each plot. Fine litterfall was measured on all the plots from 1 May 1994 for 12 months. Litterfall mass and phosphorus concentrations were significantly higher in all the fertilizer treatments compared with the controls. All trees (⩾ 10 cm dbh) were measured in August 1993 and in August 1998, and there was no significant girth increment response to fertilization in dipterocarps or non-dipterocarps. Dipterocarps of the red meranti group showed a doubling of girth increment in the +NP treatment, however, the difference from the control fell short of significance.

Keywords: rainforest; fertilization; litterfall; girth increment; dipterocarps; Borneo

1. INTRODUCTION

It is still often assumed that most soils under primary tropical lowland evergreen rainforests are poor in nutrients to an extent that limits the production of the forest. However, the evidence for such limitation is not strong (Proctor 1992), and direct experiments involving fertilizer additions have largely been made in montane rainforests.

In Hawaii, combined fertilizer (N, P, K, Mg, S, B, Cu and Zn) addition increased trunk diameter compared with unfertilized controls after two years (Gerrish & Bridges 1984). Vitousek *et al.* (1987), also in montane Hawaii, reported that added N increased the trunk growth of trees in younger soils. Tanner *et al.* (1990) found that two to three years after N or P addition to a Jamaican montane forest, there was increased trunk growth and inferred increased leaf production. More recently, experiments have been made on the effects of N and P on production in a Venezuelan montane forest (Tanner *et al.* 1992). Their results showed that the rates of trunk growth in both N- and P-fertilized plots were faster than in the unfertilized plots. However, there were no significant increases in rates of litterfall among treatments except in the fourth year after fertilization. In addition, there were no significant increases in litterfall N concentrations in both N- and P-fertilized plots, but litterfall P concentrations were increased after 2.5 years by P fertilization. Walker *et al.* (1996) compared responses to fertilization of hurricane-damaged lowland and lower montane rainforest in Puerto Rico. They found increased leaf litter production in both forests but no effect on tree diameter increment. Fertilization greatly increased the density of the pioneer tree *Cecropia schreiberiana* in the lowland forest and the density of the graminoids in both forests. Similar work appears not to have been attempted in South-East Asia and this paper reports an experiment on litterfall production and girth increment in a primary lowland evergreen rainforest at Barito Ulu, Central Kalimantan. We tested three hypotheses: (i) that +N, +P and +NP fertilization increases the production of litterfall; (ii) that fertilization influences the quantity of N and P in litterfall; and (iii) that fertilization increases the rate of trunk growth.

2. SITE AND METHODS

(a) *Physical environment*

The Barito Ulu study site is at 113°56′ E and 0°6′ S. It lies about 150 m above sea level near Muara Joloi village and about 250 km north of Palangkaraya, the capital city of Central Kalimantan. The vegetation is mainly primary lowland evergreen rainforest.

Climate data have been recorded since 1989. In general, the climate is wet and falls within the perhumid type of Schmidt & Ferguson's (1951) classification. However, there have been three substantial droughts of about three months in 1991, 1994 and 1997. (The last two droughts occurred during the present experiment.) Annual rainfall during 1989–1998 was about 3600 mm, of which the driest year was 1997 (2780 mm) and the wettest was 1990 (4005 mm). The months June to October are often dry. The wettest month was January 1995 with 659 mm and the driest was September 1994 with 2.5 mm. Conditions are generally warm and humid throughout the year, with a daily mean maximum temperature of 32 °C and a mean minimum of 23 °C.

The area is based on a Tertiary sedimentary formation, which has given rise to yellow sandy soils low in nutrients (table 1). The topography is rugged with some slopes in excess of 30°.

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Table 1. *Mean soil chemical properties (with ranges in parentheses) for five blocks of four plots (each with ten samples 0–10 cm depth) sampled before the fertilization at Barito Ulu and from three plots (each with four samples 5–10 cm depth) at Danum Valley (Green 1992)*

	Barito Ulu		Danum Valley	
chemical property	mean	range	mean	range
pH_{H_2O}	3.8	(3.6–4.1)	4.3	(4.1–4.6)
pH_{CaCl_2}	3.5	(3.3–3.8)	3.7	(3.6–3.8)
loss on ignition (%)	6.2	(3.5–8.2)	4.8	(2.9–7.7)
N_{total} (%)	0.23	(0.15–0.32)	0.08	(0.02–0.14)
P_{total} ($\mu g\ g^{-1}$)	80	(30–150)	237	(174–296)
$P_{extr.}$ ($\mu g\ g^{-1}$)[a]	1.3	(0.4–2.8)	0.25	(0.15–0.39)
K^+ (milliequivalents 100 g^{-1})	0.04	(0.03–0.06)	0.17	(0.11–0.25)
Na^+ (milliequivalents 100 g^{-1})	0.01	(0.00–0.01)	0.04	(0.02–0.18)
Ca^{2+} (milliequivalents 100 g^{-1})	0.10	(0.01–0.16)	0.20	(0.05–1.07)
Mg^{2+} (milliequivalents 100 g^{-1})	0.14	(0.09–0.27)	0.24	(0.10–0.49)
H^++Al^{3+} (milliequivalents 100 g^{-1})	7.0	(3.5–11.5)	11.0	(7.6–13.9)
CEC (milliequivalents 100 g^{-1})	7.3	3.8–11.5	11.7	8.2–14.8
base saturation (%)	4.4	(1.8–9.0)	5.7	3.3–12.6

[a] 0.5 M acetic acid extractant.

(b) *Plot selection*

Five blocks of four 50 m × 50 m permanent plots were set up within primary lowland evergreen rainforest in sites which offered relatively flat terrain within an area of about 4 km^2. The distance between the plots in each block was at least 50 m; their exact location is shown in Mirmanto (1996). Each plot was divided into 25 subplots of 10 m × 10 m.

(c) *Forest structure*

Within each subplot, the position of all trees and lianas (⩾ 10 cm diameter at breast height, dbh) was measured in August or September 1993, and each was marked with an aluminium tag at 140 cm from the ground. Girth was measured 10 cm below the tag for unbuttressed trees, or, in the case of trees with buttresses (>1 m high) or with prop roots or distorted trunks, the dbh was measured at least 30 cm above any protrusion that affected the breast height measurement.

(d) *Soil sampling and analysis*

Samples (0–10 cm depth) were collected at a random point in each of ten subplots (10 m × 10 m), which were selected in a stratified random way in each plot. The samples were air-dried, ground and sieved through a 2 mm mesh before analysis in Stirling. pH_{H_2O} was measured on 10 g subsamples, to each of which 20 ml of deionized water were added and which were stirred and left to equilibrate for 1 h. pH_{CaCl_2} measurements were made similarly but with 20 ml of 0.01 M $CaCl_2$. The moisture content of air-dried soil was determined by heating 5 g subsamples to 105 °C for 24 h. The same subsamples were used to measure loss on ignition at 375 °C for 16 h. Total N and P were determined on 0.3 g subsamples of soil digested in a mixture of 4.4 ml of H_2SO_4, H_2O_2 and a Se catalyst (Allen 1989). N and P were measured colorimetrically on an autoanalyser with the gas diffusion method for NH_4–N and the $SnCl_2$–$NH_4Mo_7O_{24}$ method for P. For extractable P, 5 g soil were shaken in 0.5 M acetic acid for 30 min. Exchangeable bases were leached from 5 g subsamples by five successive additions of 20 ml 1 M NH_4COOCH_3 solution. K and Na were measured by flame emission and Ca and Mg by atomic absorption spectrophotometry. An air–acetylene flame was used for K and Na and a nitrous oxide–acetylene flame for Ca and Mg. For exchangeable Al and H, 5 g subsamples were leached with five successive additions of 20 ml 1 M KCl solution. A 5 ml extract was titrated against 2.5 mM NaOH in the presence of phenolphthalein indicator to determine total acidity. Al was measured by back titration with 5 mM HCl after the addition of 10 ml 1 M NaF. H was estimated by subtraction. The sum of exchangeable cations plus total acidity was used to determine the cation-exchange capacity (CEC).

(e) *Litterfall sampling and analysis*

Litterfall was collected in ten traps arranged in a stratified random way in each plot. The traps were 0.7 m × 0.7 m and made with a plastic net (mesh 0.1 cm), which was framed with four pieces of wood and supported on four 1 m legs. The traps were put in place between 27 and 30 April 1994, and litterfall was collected from them at 14-day intervals until 30 April 1995. At each collection the contents were placed in cloth bags and air-dried for at least two days. After drying, the contents of each bag were sorted into four fractions following Proctor (1983): (1) leaves; (2) branches (<2 cm diameter); (3) flowers and fruits; and (4) miscellaneous. The fractions were weighed and combined to give bulked litterfall for each fraction for each plot. They were oven-dried at 80 °C and subsamples reweighed to give a moisture correction factor.

Chemical analyses were made of the four fractions for six collections from each of the 20 plots: 25–28 May (day 28), 23–26 June (day 56), 21–24 July (day 84), 15–18 November (day 196), 13–16 December (day 224) and 12–15 January (day 252). These dates were chosen to give samples before and after the second fertilizer application on 7–11 August 1994 (see below).

Before analyses the samples were ground. A subsample of 0.2 g dry weight was digested in a mixture of 4.4 ml of H_2SO_4, H_2O_2 and a Se catalyst (Allen 1989). N and P were measured colorimetrically on an autoanalyser with the gas diffusion method for NH_4–N and the $SnCl_2$–$NH_4Mo_7O_{24}$ method for P. K and Na were measured by flame emission and Ca and Mg by atomic absorption spectrophotometry. An air–acetylene flame was used for K and Na and a nitrous oxide–acetylene flame for Ca and Mg. Analyses were checked against foliar controls.

(f) *Fertilizer addition*

Fertilizers were applied to each block of four of the 50 m × 50 m plots described earlier. There were four treatments: (1) unfertilized controls; (2) +N, 56.25 kg/plot N (as urea); +P, 18.75 kg/plot P (as triple super phosphate); and (4) +N and +P. The treatments were applied from 28 August–16 September 1993, from 7–11 August 1994, 18–23 August 1995 and 12–17 November 1996. Where possible the treatments were assigned randomly within each block, but in two instances the random location of control plots was swapped with those of fertilizer treatments upslope to avoid contamination. D. M. Newbery (personal communication) has pointed out that the addition of the large amounts of fertilizer may cause a severe, albeit temporary, perturbation to the forest. This is accepted but there was no evidence of any damage and in any case, the remoteness of the site precluded the addition of nutrients in smaller and more frequently applied quantities.

(g) *Girth increments*

An analysis of the 1993 girth data showed that there were differences among the plots assigned to the different treatments. To account for possible effects of initial size on increment the analyses were made on the 1998 data by using the 1993 data as covariates.

An analysis of variance on the plot mean girth at breast height (gbh) values showed no overall treatment effects. Species were then grouped into Dipterocarpaceae and non-Dipterocarpaceae and a second analysis of variance was carried out. Finally, the Dipterocarpaceae were analysed separately after splitting them into red meranti (*Shorea* Sect. *Brachyptera*, *Mutica* and *Ovalis*; Whitmore *et al.* 1990) and other dipterocarps.

The model used was $X_{ijkl} = \mu + A_i + B(A)_{j(i)} + C_k + AC_{ik} + CB(A)_{kj(i)} + e_{1(ijk)}$, where X_{ijkl} represents the annual growth increment in the species group k in block j of treatment i. A_i, C_k and $B_{j(i)}$ represent the effects of treatments A (fertilizer), C (species group) and block B in treatment A; μ is the overall mean and $e_{1(ijk)}$ the error.

3. RESULTS

(a) *Forest structure*

The mean density of trees and lianas ($\geqslant$ 10 cm dbh) in the 20 plots combined was 630 ha^{-1} ranging among blocks from 565 ha^{-1} to 721 ha^{-1}. The mean basal area was 31.9 $m^2\,ha^{-1}$ ranging among blocks from 25.0 $m^2\,ha^{-1}$ to 36.5 $m^2\,ha^{-1}$. The total number of tree ($\geqslant$ 10 cm dbh) species in the 5 ha was 480 (ranging from 183–224 ha^{-1} for the blocks). The identification for families was nearly 100% but that for individual species was only 50% although the species richness values include recognized but unidentified taxa. The Dipterocarpaceae were the family with the highest density of individuals (25.2% over all the plots) and had the highest basal area (45.1%).

(b) *Soils*

The soils were acid and low in nutrients in all the plots (table 1).

(c) *Litterfall*

The mean total fine litterfall in the control plots was 7.1 t $ha^{-1}\,yr^{-1}$. Both control and fertilized plots showed a similar seasonal pattern (figure 1) and total litterfall over the measurement period was significantly higher in the fertilizer treatments than in the control (table 2). The N

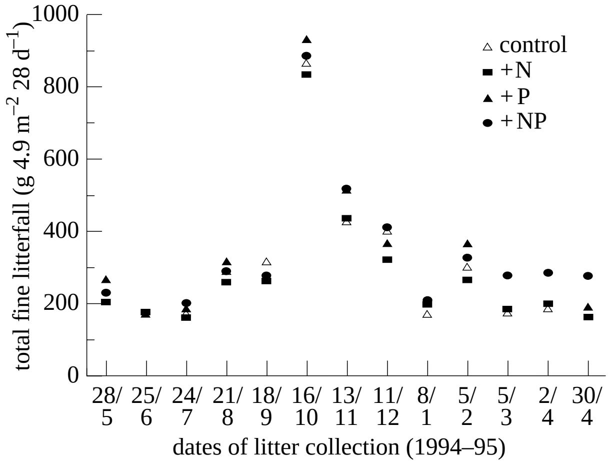

Figure 1. The mean mass of total fine litterfall on plots at Barito Ulu with four different fertilizer treatments. There were five replicate plots per treatment.

concentrations and accession in the total fine litterfall were higher (+N and +NP for concentrations; +N, +P and +NP for accession) than in the control, but not significantly so. The P concentrations and accession were significantly higher than the control in all the fertilizer treatments (table 2).

(d) *Girth increment*

The Dipterocarpaceae had significantly higher girth increment than the non-dipterocarps in all four treatments (table 2). The red meranti group of fast growing *Shorea* spp. in the +NP treatment had a twofold larger girth increment than the other dipterocarps, but this result was not significant.

4. DISCUSSION

(a) *Forest structure and physical environment*

The forest structure and the dominance of the Dipterocarpaceae have many similarities with those in the Danum Valley, Sabah (Newbery *et al.* 1992), but the rainfall and frequency of droughts are higher at Barito Ulu (Walsh & Newbery, this issue). There are general similarities with the Danum Valley soils analysed by Green (1992) although the comparisons are limited because of the different sample depths (table 1).

(b) *Litterfall*

The mass of fine litterfall is considerably smaller at Barito Ulu than it is in the Danum Valley (7.1 t $ha^{-1}\,yr^{-1}$ versus 11.1 t $ha^{-1}\,yr^{-1}$) as are the accession rates of N (58.4 versus 158 kg $ha^{-1}\,yr^{-1}$) and P (1.6 versus 5 kg $ha^{-1}\,yr^{-1}$) (Burghouts 1993). In fact, the Barito Ulu N and particularly P concentrations and contents are low for lowland tropical forests in general (Vitousek 1982; Proctor 1984).

In the experiment, the production of litterfall during April–July 1994 (11 months after the first fertilization) showed no significant differences among the treatments. This is similar to the results from a rainforest in Venezuela during the first year of fertilization (Tanner *et al.* 1992). During February–April 1995, the production of litterfall in all the fertilized plots was higher than in the

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Table 2. *Mean ± s.e. annual total fine litterfall mass, N and P concentrations, N and P accession and gbh increment on the control and fertilized plots, in 1994–1995*

(Asterisks indicate the level of significant difference from the controls compared by using Dunnett's test after ANOVAs (* $p<0.05$; ** $p<0.01$; *** $p<0.001$).)

		control	+N	+P	+NP	
litterfall mass	($t\ ha^{-1} yr^{-1}$)	7.1 ± 0.8	9.1 ± 0.3**	8.9 ± 0.5*	9.5 ± 0.3**	$F=6.1$; d.f = 3, 12
litterfall concentration						
N	($mg\ g^{-1}$ dry wt)	8.1 ± 0.7	9.3 ± 0.5	7.7 ± 1.0	8.2 ± 0.5	$F=1.4$; d.f. = 3,12
P	($mg\ g^{-1}$ dry wt)	0.2 ± 0.02	0.3 ± 0.01**	0.4 ± 0.03***	0.3 ± 0.03**	$F=13.6$; d.f. = 3,12
litterfall accession						
N	($kg\ ha^{-1}$)	58.4 ± 10.2	84.7 ± 5.0	69.7 ± 13.5	77.5 ± 4.4	$F=2.7$; d.f. = 3,12
P	($kg\ ha^{-1}$)	1.6 ± 0.3	2.8 ± 0.1**	3.4 ± 0.5***	2.9 ± 0.2**	$F=11.8$; d.f. = 3,12
dipterocarp versus (non-dipterocarp) gbh	($cm\ yr^{-1}$)	0.74 (0.40)	0.73 (0.46)	0.84 (0.52)	0.86 (0.45)	$F=38.4$; d.f. = 1,16
red meranti gbh	($cm\ yr^{-1}$)	0.71	1.15	0.93	1.86	$F=3.0$; d.f. = 1,11

control plots, although significantly so only for the +NP treatment. The total fine litter production during this period was 41% higher in the +NP plots than in the control plots. By comparison, litterfall was 32–34% higher than the controls during the second and third year of the Venezuelan experiment (Tanner *et al.* 1992). A faster response might have been expected at Barito Ulu since the temperatures were higher than in the montane forests.

The changes in litterfall mass and chemical composition are a demonstration that the added nutrients are reaching the trees and not being entirely leached or bound in insoluble compounds in the soil.

(c) *Girth increment*

The annual girth increment values were similar to those reported from the Philippines (Brown 1919) and lower than those reported from Pasoh, Malaysia (Condit *et al.*, this issue). There was no overall treatment effect on the growth of trees in the experimental plots. The concurrent increased fine litterfall production in the fertilizer treatments may explain the lack of an overall trunk growth response. In montane forests, a trunk girth increment response to fertilization has been found to predate a litterfall increase (Tanner *et al.* 1990, 1992). One speculative explanation of this could be that montane forests may be relatively more nutrient limited than lowland forests and adaptive traits in montane forest species may include higher leaf longevity.

5. CONCLUSIONS

Three hypotheses were tested: (i) that +N, +P and +NP fertilization increases the production of litterfall; (ii) that fertilization influences the quantity of N and P in litterfall; and (iii) that fertilization increases the rate of trunk growth. The data support the first two hypotheses. The third hypothesis may hold for the fast-growing 'red meranti' group of dipterocarps in the +NP treatment where, although falling short of significance, a doubling of girth increment occurred (table 2). There was no evidence for a similar response for any other group of trees, although statistical comparisons were impossible for most because of the high species richness and hence poor replication.

In view of the low soil nutrients and low litterfall N and P, it would be expected that the addition of N and P might increase tree growth at this site. The fact that there is no statistically significant girth increment response to added nutrients at Barito Ulu suggests that forests with higher amounts of nutrients in circulation would also not respond to fertilization. The experiment was not aimed at investigating potential application of fertilizer to increase commercial timber production in dipterocarp forests. Their low growth rates (N. Brown, personal communication) make nutrient addition uneconomic. Further work is necessary, and in particular, the possible response of flower and fruit production to nutrient addition in mast fruiting and non-mast fruiting species should be investigated.

We thank Dr S. Wirjoatmodjo and Dr J. P. Mogea of the Research and Development Centre for Biology, the Indonesian Institute of Sciences, and Mr S. R. G. Ridgeway for their support. Andi, Francis Brearley, Joannis Kalopissis, Kursani, Laura MacMillan, Mulyadi, Nurdin, Rahmadi, Sain, Gillian Telford, Angela Tucker and Carol Waters helped with the measurements and remeasurements. The work was funded by the Royal Society and the British Council.

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