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Micro-scale Nutrient Gradients in a Low-Input Cacao Agroforestry System

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Shade trees and nutrient cycling

Cacao agroforestry systems combine cacao (*Theobroma cacao*) with shade trees and are considered a biodiversity-friendly, climate-resilient alternative to monocultures (Niether et al., 2018). Shade trees govern far more than light: they set litter input, litter quality and root distribution, and with them the nutrient cycles of the soil (Isaac & Borden, 2019). In low-input systems this weighs twice as heavily – with little external fertilisation, productivity rests on internal recycling through litter decomposition, soil organic matter and biological nutrient mobilisation (Asitoakor et al., 2022). Species differ in exactly these traits, which makes the choice of shade tree an agronomic decision, not only a structural one (Tscharntke et al., 2011).

Aim of the study

In tropical ecosystems P limits biomass growth, especially on highly weathered and volcanic ash soils (Cunha et al., 2022). In Andosols total P is high, but plant-available P is not: P is bound to amorphous Al- and Fe-oxides and to organo-mineral complexes (Takamoto et al., 2021). What matters is therefore not how much P is stored, but how it is bound and whether it can be mobilised. We ask whether shade trees create micro-scale P hotspots – and whether *Erythrina* and *Cedrelinga* create different ones.

Study system & experimental design

The site is a cacao agroforestry system established in 2020 at Universidad Regional Amazónica IKIAM in Tena, Ecuador – humid tropical climate, high year-round rainfall, volcanically influenced Andosol. Two shade-tree species with contrasting functional roles were compared: *Erythrina amazonica*, a genus associated with high litter production, rapid nutrient cycling and positive effects on soil fertility (Aleixo et al., 2017), and *Cedrelinga cateniformis*, a valuable Amazonian timber species whose influence on P dynamics has received little attention (Tinoco-Jaramillo et al., 2024).

Eight plots per species were established, of which seven (*Erythrina*) and six (*Cedrelinga*) could be sampled. Each plot comprises one shade tree and two adjacent cacao trees; five standardised positions were sampled along the connecting line at 0–10 and 10–20 cm depth (Fig. 2), following a common transect approach for temperate agroforestry systems (Minarsch et al., 2025).

Fig. 1: Cacao agroforestry system with the investigated shade-tree species, left: *E. amazonica*, right: *C. cateniformis* (own photographs).

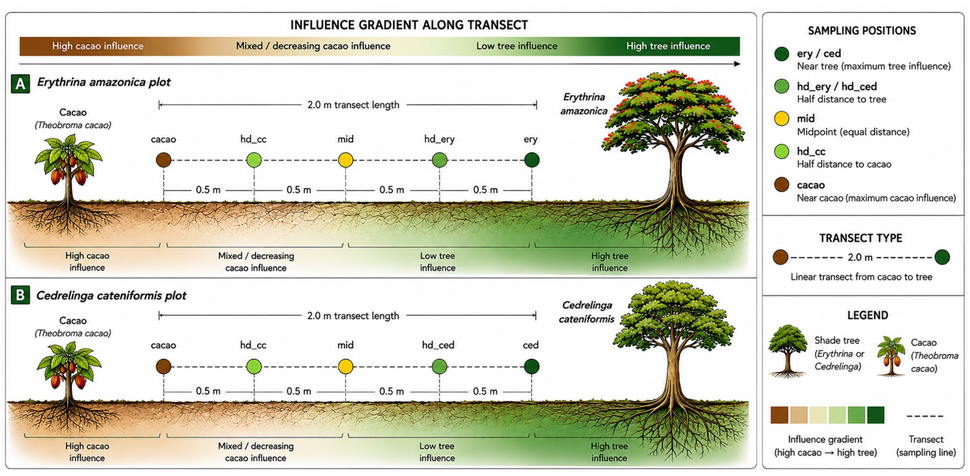

Fig. 2: Scheme of the transects with the sampling positions inside the plots for *E. amazonica* and *C. cateniformis*.

Analysis & Results

Soil from 0–10 and 10–20 cm was analysed for total C, N, P and K, a sequential Hedley P fractionation and plant-available P (Mehlich-3). Litterbags were incubated in situ at each position; mass loss after 15, 30 and 60 days gave the decomposition constant *k*. Effects were tested with linear mixed models (plot as random effect) and ordered contrasts along the transect.

Depth governs the stocks, species do not. C, N and total P are 1.3–1.7 times higher in the topsoil, while the two species differ in none of the total stocks (Tab. 1). Across both depths 59–69 % of total P is bound in organic forms.

The steepest micro-scale gradient sits at the cacao stem. NaOH-P_i falls from 295 to 176 mg kg^{-1} between the cacao stem and mid-transect in *both* species ($p < 0.001$), and with it the inorganic share of total P, from 32 % to 22 %, and the composition of the P pools shifts significantly along the transect (PERMANOVA, $p = 0.005$; Fig. 4). Soil C and the C:P ratio show the mirror image.

Shade-tree identity changes availability, not stocks. Mehlich-3 P is 28 % higher under *E. amazonica* ($p = 0.008$), whereas total C, N, P and K are indistinguishable.

Only *Erythrina* builds a subsoil hotspot at its own stem: +35 % soil C and +70 mg kg^{-1} NaOH-P_o at 10–20 cm, accompanied by 57 % faster litter decomposition there, while *Cedrelinga* stays flat ($p = 0.034$; Fig. 3).

Tab. 1: Soil chemical properties under the two shade-tree species at 0–10 and 10–20 cm depth. Values are means ± SD; p-values from LMM with plot as random effect.

	E. amazonica		*C. cateniformis*		p-value	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm	depth	species
Total C (Mg ha^{-1})	75.9 ± 6.3	43.8 ± 8.1	72.8 ± 8.0	41.9 ± 8.1	< 0.001	0.44
Total N (Mg ha^{-1})	7.0 ± 0.5	4.2 ± 0.7	6.8 ± 0.7	4.1 ± 0.9	< 0.001	0.47
C/N ratio	10.8 ± 0.3	10.3 ± 0.5	10.8 ± 0.2	10.3 ± 0.3	< 0.001	0.91
Total P (mg kg^{-1})	1342 ± 150	1027 ± 125	1301 ± 199	930 ± 100	< 0.001	0.17
Total K (mg kg^{-1})	677 ± 96	799 ± 159	709 ± 219	680 ± 90	0.01	0.16
Mehlich-3 P (mg kg^{-1})	11.1 ± 4.2	5.1 ± 1.7	8.7 ± 1.0	4.1 ± 0.7	< 0.001	0.008

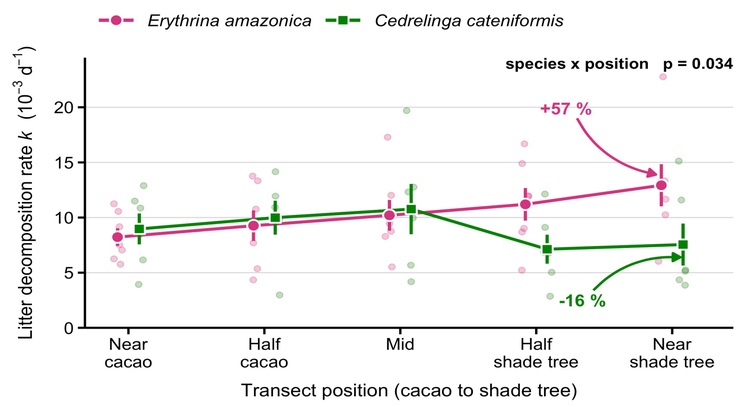

Fig. 3: Litter decomposition rate *k* along the transect from the cacao stem to the shade-tree stem, estimated from single exponential decay. Symbols show the mean per position ± SE, faint points the individual plots.

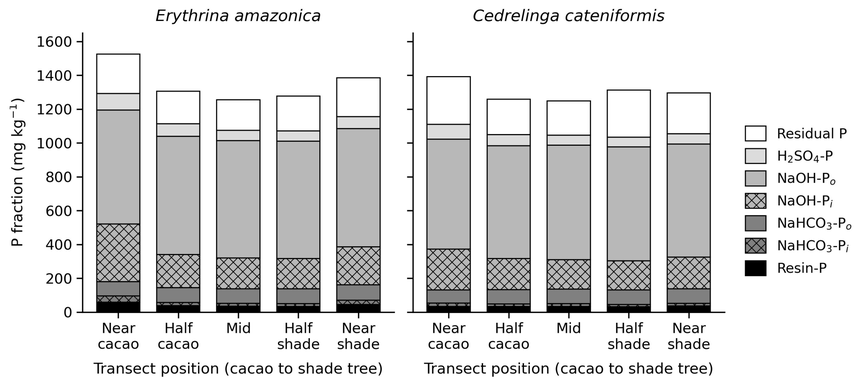

Fig. 4: Sequential P fractionation of the topsoil (0–10 cm) along the transect. Bars show mean fraction contents per position; total bar height corresponds to total P.

Conclusion & next steps

Shade trees shape the P economy of this system through availability rather than stocks – and the strongest spatial signal belongs to the cacao itself. Whether the higher availability under *Erythrina* reflects true P mobilisation cannot be decided from pools alone. Litter C, N and P, oxalate-extractable Al and Fe, root traits and phosphatase activity will close the gap between pool and process.

The sharpest phosphorus gradient in this cacao agroforest is centred on the **cacao stem — not on the shade tree**. Shade-tree identity changes how much P is *plant-available*, not how much P is there.

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