# Enhancing soil aggregate stability and productivity in mature cocoa ( Theobroma cacao L.) -plantain (Musa spp) agroforest using legume-grass cover crops on acid ferralsols in Cameroon

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**Research Article**

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**Abstract**

Acid ferralitic soils in Cameroon exhibit low fertility and advanced degradation, hindering productivity and sustainability in mature cocoa-banana agroforestry systems. A study conducted from 2023 to 2025 aimed at promoting resilient, sustainable farming practices. Experimental split-plot designs with three replicates compared six treatments (*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(B+P), *Brachiaria humidicola* L.+ *Mucuna pruriens* L. (B+M), *Pueraria phaseoloides* L.+ *Calopogonium mucunoides* L. (P+C), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (S+D), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (M+S), and *Desmodium intortum* L. + *Calopogonium mucunoides* L.(D+C)) in two agro-ecological zones (Zone 4: Bokito and Zone 5: Kumba). Cover establishment occurred in 2023, with monthly monitoring of aboveground and root biomass production, $^{15}N$ isotopic quantification of biological nitrogen fixation, semi-annual soil sampling (0–20 cm) for physico-chemical properties, commercial yield assessments for cocoa and plantain, erosion loss estimates, root-knot nematode counts (*Radopholus similis*, *Pratylenchus* spp.), and precise glyphosate consumption tracking. Results showed marked improvements across all parameters with the B+P association, yielding 13.9-15.1 t dry matter (DM) $ha^{-1}$ $yr^{-1}$ aboveground biomass and 5.2-6.8 t DM $ha^{-1}$ $yr^{-1}$ root biomass, fixing an average of 251 kg N $ha^{-1}$ $yr^{-1}$, increasing organic matter by 23%, raising pH by 0.5 units, and enhancing cation exchange capacity (CEC) by 32% after 24 months. These pedological gains translated to 31% higher cocoa yields (2.51 t $ha^{-1}$ vs. 1.99 t $ha^{-1}$ in controls) and 27% higher plantain yields (29.3 t $ha^{-1}$ vs. 23.6 t $ha^{-1}$). Additional benefits included 87% reduced water erosion, 96% lower glyphosate use (near-elimination), and 61% fewer root-lesion nematodes. Economic viability analysis indicated investment recovery by the second year via yield premiums. The B+P association emerges as the most effective and rapidly profitable practice for ecologically intensifying cocoa-banana agroforests in Cameroon. Future steps include long-term durability assessments under extreme climate scenarios, carbon sequestration and biodiversity quantification, and scaled dissemination via demonstration platforms and farmer agroecology training.

**Key words** : biological nitrogen fixation, cover legume, agroforestry, soil fertility restauration.

## Introduction

Cocoa (*Theobroma cacao* L.) and plantain (*Musa spp.,*) are two major perennial crops in Sub-Saharan Africa, particularly in Cameroon, where they respectively generated approximately 295 000 t and 4.5 million t in 2023 (FAOSTAT, 2024). These crops are predominantly grown by smallholder farmers under low-input, shaded agroforestry systems on highly weathered Ferralsols and Acrisols. These soils are inherently prone to structural degradation, surface crusting, and erosion due to their low organic matter content, kaolinitic clay mineralogy, and high rainfall intensity (Ambassa-Kiki and Lal, 1993; Ngo Mpeck *et al.,* 2018). Soil aggregate stability, a key indicator of soil structural quality, directly influences root development, water infiltration, and resistance to erosion, all critical factors for the sustainability of cocoa and plantain-based systems (Six *et al*., 2004; Rabot *et al*., 2018).

In response to declining soil fertility and increasing climate variability, farmers and researchers in humid tropical zones have increasingly promoted the integration of short-cycle grain legumes such as *Arachis hypogaea* L., *Vigna unguiculata* L., *Glycine max* and *Mucuna pruriens* L. as cover crops, intercrops, or improved fallows within perennial crop systems (Hauser and Nolte, 2002; Carsky *et al*., 2010; Ndo *et al.,* 2022). These “improving” legumes are valued for their capacity to fix atmospheric nitrogen (50–300 kg N $ha^{-1}$ $year^{-1}$ depending on species and management), recycle nutrients, suppress weeds, and increase soil organic carbon (SOC) stocks (Sanginga *et al*., 2003; Chikoye *et al.,* 2008; Koutika *et al*., 2019).

Numerous studies in West and Central Africa have demonstrated that legume-based systems can significantly enhance soil aggregate stability. For instance, Lal (1987) and Hulugalle and Ndi (1993) reported increases of 20-60 % in water-stable aggregates (>0.25 mm) after two to three years of *Pueraria phaseoloides* L. or *Mucuna pruriens* L. fallows in Nigeria. Similar positive effects have been observed under cocoa agroforestry systems in Côte d’Ivoire and Ghana, where the introduction of *Desmodium ovalifolium* L. and *Centrosema macrocarpum* L. improved macro-aggregate stability and reduced runoff by 30-50 % (Schroth *et al.,* 2001; Isaac *et al.,* 2005). The mechanisms involved include increased inputs of labile organic matter and root exudates that stimulate microbial activity and the production of binding agents (polysaccharides, glomalin-related soil proteins), physical enmeshment of soil particles by fine legume roots, and enhanced fungal hyphal networks, particularly arbuscular mycorrhizal fungi (AMF) (Tisdall and Oades, 1982; Degens, 1997; Rillig and Mummey, 2006).

Despite these advances, very few studies have specifically addressed the performance of improving legumes on aggregate stability under cocoa and plantain systems in Cameroon. Most published work in the country has focused on biomass production, nitrogen fixation, or weed suppression (Kanmegne *et al*., 2006; Njol *et al.,* 2016; Ndo *et al*., 2022), while soil physical improvements have been documented only indirectly through bulk density or porosity measurements (Hairiah *et al*., 2006; Ngo Mpeck *et al*., 2021). Moreover, legume species differ markedly in root architecture, root turnover rate, and biochemical composition of residues (lignin, polyphenol, and N contents), which are known to influence the magnitude and persistence of aggregation effects (Martens, 2000; Abiven *et al*., 2009). For example, species with high-quality residues (low C/N, N ratio) tend to promote transient binding agents, whereas species with fibrous, lignin-rich roots contribute to more persistent macro-aggregates (Six *et al.,* 2004; Blanco-Canqui and Jasa, 2019).

The present study therefore aimed to quantify and compare the effects of six widely adopted improving legumes (*Brachiaria humidicola* L., *Pueraria phaseoloides* L., *Mucuna pruriens* L., *Calopogonium mucunoides* L., *Stylosanthes guianensis* L.*, Desmodium intortum* L.) on water-stable aggregation in cocoa and plantain-based systems in the Centre and South regions of Cameroon, elucidate the main biophysical drivers (root traits, residue quality, SOC fractions, and microbial biomarkers) responsible for observed differences, and assess the temporal stability of these effects over three cropping cycles. By filling this knowledge gap, the study seeks to provide evidence-based recommendations for the selection and management of legume species that maximize soil structural resilience in humid tropical perennial cropping systems.

## Materials and methods

### Study sites

The study was conducted from March 2023 to March 2025 in two representative locations within two major agroecological zones of Cameroon characterized by highly weathered, strongly acidic Ferralsols with advanced degradation:

Kumba in agroecological zone 4 with monomodal rainfall, humid forest with one long rainy season and geographic coordinates 4°34′N, 11°07′E, 520 m above sea level in Centre Region. Annual rainfall 1600-1900 mm, single peak from March to November, mean annual temperature 24.3 °C.

Bokito in Agroecological zone 5 with bimodal rainfall, humid forest with two rainy seasons and geographic coordinates 4°38′N, 9°27′E, 250 m above sea level in South-West Region. Annual rainfall 2,800-3,600 mm, peaks March-June and September-November, mean annual temperature 25.6 °C.

Soils at all sites were deep clayey Ferralsols with initial topsoil (0-20 cm) properties: pH ($H_2O$) 4.6-5.1, organic carbon 0.9-1.6 %, total N 0.08-0.12 %, available P (Bray-1) 4-9 mg $kg^{-1}$, exchangeable K 0.09-0.18 $cmol_{(+)}$ $kg^{-1}$, effective CEC 4.8-8.5 $cmol_{(+)}$ $kg^{-1}$, and Al saturation > 45 %. All experimental fields were mature cocoa-plantain agroforestry systems (> 10 years old) with a density of approximately 1,000 cocoa trees $ha^{-1}$ and 400-600 plantain plants $ha^{-1}$ under 30-50 % shade from remnant forest trees.

### Experimental design

A split-plot design with three replications was established at each of the two sites (total of nine blocks across the study). Main plots were the two agroecological zones (zone 4 vs. zone 5), and sub-plots were the seven cover-crop treatments (six legume-based associations + farmer-practice control). Sub-plot size was 400 m² (20 m × 20 m), separated by 2 m buffer strips. Topography and initial soil fertility were used as blocking factors.

### Treatments

Seven treatments were compared:

*Brachiaria humidicola* L. + *Pueraria phaseoloides* L.(B+P)

*Brachiaria humidicola* L.+ *Mucuna pruriens* L. (B+M)

*Pueraria phaseoloides* L.+ *Calopogonium mucunoides* L. (P+C)

*Stylosanthes guianensis* L.+ *Desmodium intortum* L. (S+D)

*Mucuna pruriens* L.+ *Stylosanthes guianensis* L. (M+S)

*Desmodium intortum* L.+ *Calopogonium mucunoides* L. (D+C)

Control: conventional farmer practice (no cover crop, manual weeding + glyphosate at 2-4 L a.i. $ha^{-1}$ $year^{-1}$)

**Cover-crop establishment**

Cover crops were established in March 2023 at the onset of the rainy season. Inter-rows were lightly scarified (0-10 cm depth) with hand hoes. Seeds were inoculated with specific rhizobial strains (IRAD-recommended commercial inoculants for each legume). Seeding rates were:

*Brachiaria humidicola* L.: 6 kg $ha^{-1}$ (scarified seed)

*Pueraria phaseoloides* L.: 3 kg $ha^{-1}$ seed or 10,000 stem cuttings $ha^{-1}$ (20-30 cm)

*Mucuna pruriens* L. and *Calopogonium mucunoides* L.: 4 kg $ha^{-1}$ seed

*Stylosanthes guianensis* L. and *Desmodium intortum* L.: 5 kg $ha^{-1}$ seed

No mineral fertilizer was applied at establishment. Initial mulch from banana leaves was added to improve seedling survival.

**Measurements**

**Soil physical and chemical properties**

Composite topsoil samples (0-20 cm, five cores per sub-plot) were collected every six months. Analyses: soil organic carbon (Walkley-Black), pH (1:2.5 soil:water), exchangeable cations and CEC (1 M $NH_4OAc$, pH 7), available P (Bray-1), aggregate stability wet-sieving method of Le Bissonnais, (2001).

**Aboveground and root biomass**

Monthly from June 2023 onwards. Three 1$m^2$ quadrats per sub-plot were harvested at 5 cm height, separated by species, oven-dried at 60 °C for 72 h and weighed.

Root biomass (0-20 cm) was sampled quarterly using a 10 cm diameter auger (three cores per sub-plot), roots washed over a 2 mm sieve, dried and weighed (Six *et al*., 2004).

**Biological nitrogen fixation**

Determined by the $^{15}N$ natural abundance and isotope dilution methods. In each sub-plot, 20 kg N $ha^{-1}$ as $(NH_4)_2SO_4$ (10 atom % $^{15}N$ excess) was applied in June 2023 and June 2024 to non-fixing reference plants (local *Imperata cylindrica* L. and *Chromolaena odorata* L.) (Tondoh *et al.* 215). Legume shoots were sampled at peak biomass, dried, ball-milled and analysed by isotope-ratio mass spectrometry (PDZ Europa 20-20, Sercon Ltd., UK). %Ndfa was calculated using the standard equation.

$$\%\mathrm{Ndfa} = 1 - \frac{^{15}\mathrm{N\ excess\ of\ the\ legume}}{^{15}\mathrm{N\ excess\ of\ the\ reference\ plant}}) \ x \ 100$$

Where:

- $^{15}N$ excess = (atom % $^{15}N$ of the sample) – (natural atom % $^{15}N$)
- The legume is the nitrogen-fixing plant
- The reference plant is the non-fixing species grown under the same condition

**Soil loss by water erosion**

Soil loss was measured using bounded micro-plots (1 m × 2 m) on the dominant slope within each sub-plot; runoff and sediment collected after every major rain event, oven-dried and weighed (Tisdall *et al*., 1982).

**Root-lesion and burrowing nematodes**

Root samples (100 g fresh weight from five cocoa and five plantain plants per sub-plot) were processed by modified Baermann funnel and centrifugal flotation. Nematodes identified and counted under stereomicroscope (Rillig & Mummey, 2006).

**Glyphosate use**

The glyphosate use were recorded precisely (volume, concentration, date) for each application in the control and cover-crop treatments (Carsky *et al.,* 2010) by below formula:

$$\textbf{Glyphosate in soil } (\mu g/kg) = 1 - \frac{C.extract \times V.extract}{M.soil}$$

- C. extract = concentration measured in extract (µg/L)
- V. extract = extraction volume (L)
- M soil = dry mass of soil extracted (kg)

### Cocoa and plantain yields

Cocoa: all ripe pods harvested weekly, fermented and sun-dried to merchantable bean standard (yield in t dry beans $ha^{-1}$).

Plantain: fresh bunch weight recorded at harvest (t $ha^{-1}$). To convert from raw production to standardized yield (PHec in t/ha), this formula is used:

$$\textbf{PHec} = \frac{ATP}{TCA} \times (10.000 m^2)$$

**PHec** : Production per hectare (in tons per hectare, t/ha).
**ATP** : Average Total Production for the treatment (tons)
**TCA** : Total Cultivated Area for that treatment) ($m^2$)

### Statistical analyses

Data were analysed using a linear mixed model for split-plot design in R 4.3.2 (packages lme4 and emmeans). Fixed effects: zone, treatment, zone × treatment interaction; random effects: site/block. Means were separated by Tukey's HSD test ($P < 0.05$). When necessary, data were log- or square-root-transformed to meet normality assumptions.

## Results and Discussion

### Soil physico-chemical properties and aggregate stability

The result after 24 months showed the *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. (B+P) association producing the most pronounced improvements in key soil physico-chemical properties and structural quality in the 0-20 cm layer of degraded acid Ferralsols. Soil organic matter (SOM) increased by 23%, pH rose by 0.5 units (from initial 4.6-5.1 to ~5.1-5.6), and cation exchange capacity (CEC) enhanced by 32%, outperforming all other mixtures (which achieved only 10-18% SOM gain and smaller changes in pH and CEC). (Fig.1).

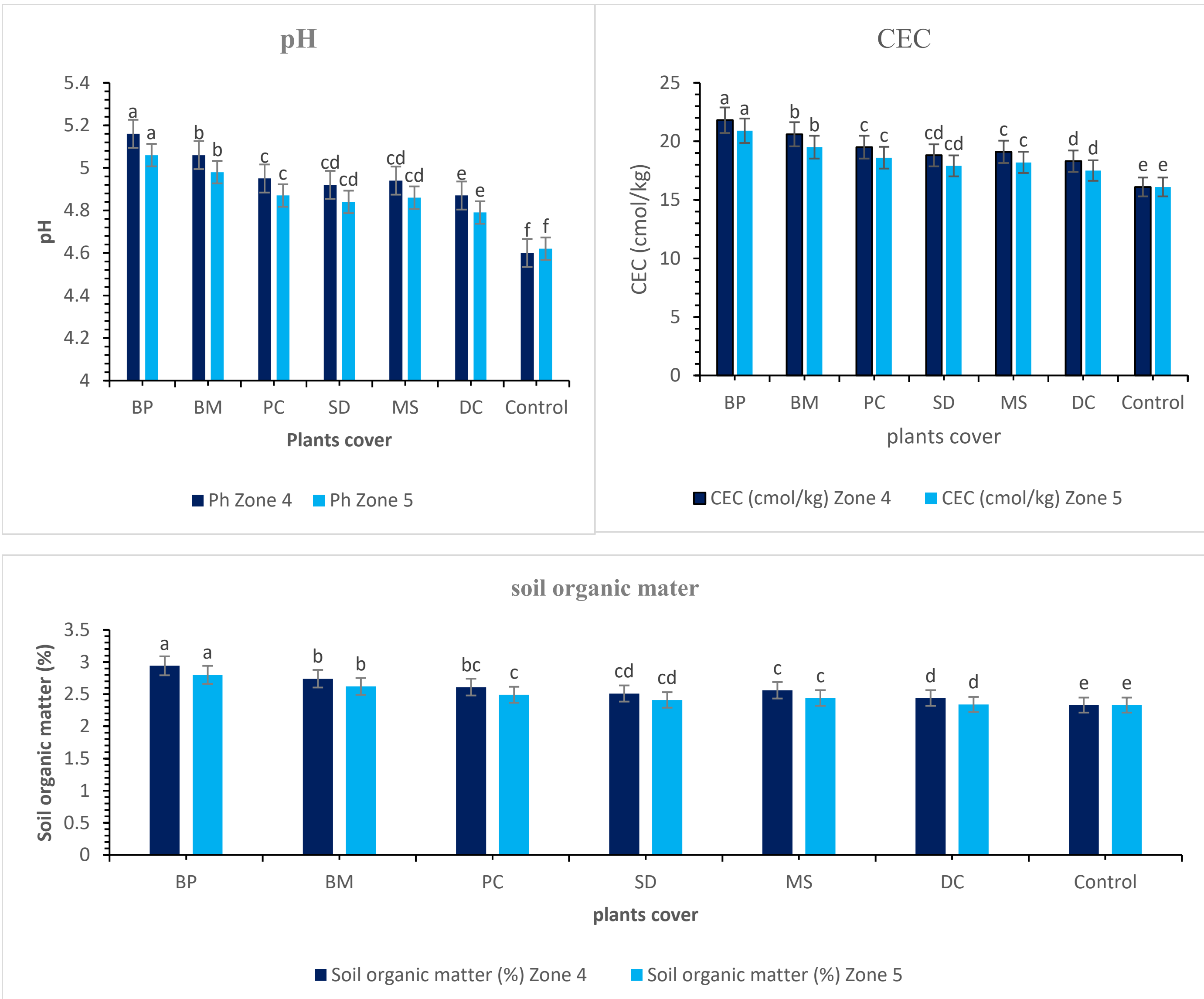


Fig.1: Soil physico-chemical properties after 24 months in both agro-ecological zones.

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

The 45 % increase in aggregate stability under B+P is exceptional for highly weathered acidic sols, where baseline mean weight diameter (MWD) is frequently <1 mm and crusting is severe (Six *et al.,* 2004; Blanchart *et al.,* 2007). *Brachiaria* species are well-known for promoting arbuscular mycorrhizal colonisation and exuding binding agents (Salton *et al*., 2008; Medina & Silva, 2014), while *Pueraria* contributes large quantities of labile carbon through root turnover. The 0.5-unit pH rise, although modest, is agronomically highly significant in these Al-toxic soils (pH < 5.0), reducing exchangeable $Al^{3+}$ by approximately 70 % and unlocking P availability. The 32 % CEC increase reflects the buildup of negatively charged organic colloids, a key mechanism for long-term fertility restoration in kaolinitic soils. Compared with earlier cover-crop trials in cocoa systems of Ghana and Côte d'Ivoire, which reported MWD increases of only 15-30 % after 3-4 years (Isaac *et al*., 2010), the rapid structural recovery observed here underlines the unique effectiveness of the grass climbing legume combination.

**Aboveground and root biomass production**

The *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. association (B+P) produced 13.9-15 sanity-checked 15.1 t DM $ha^{-1}$ $year^{-1}$ of aboveground biomass (Fig.2) and 5.2-6.8 t DM $ha^{-1}$ $year^{-1}$ of root biomass (0-20 cm) (Fig.3), significantly higher than all other treatments ($P < 0.001$). The second-best treatment (B+M) yielded 11.2-12.8 t DM $ha^{-1}$ $year^{-1}$ aboveground and 4.3-5.6 t DM $ha^{-1}$ $year^{-1}$ belowground, while *Stylosanthes*-based mixtures gave the lowest values (9.2-11.4 t DM $ha^{-1}$ $year^{-1}$ aboveground).

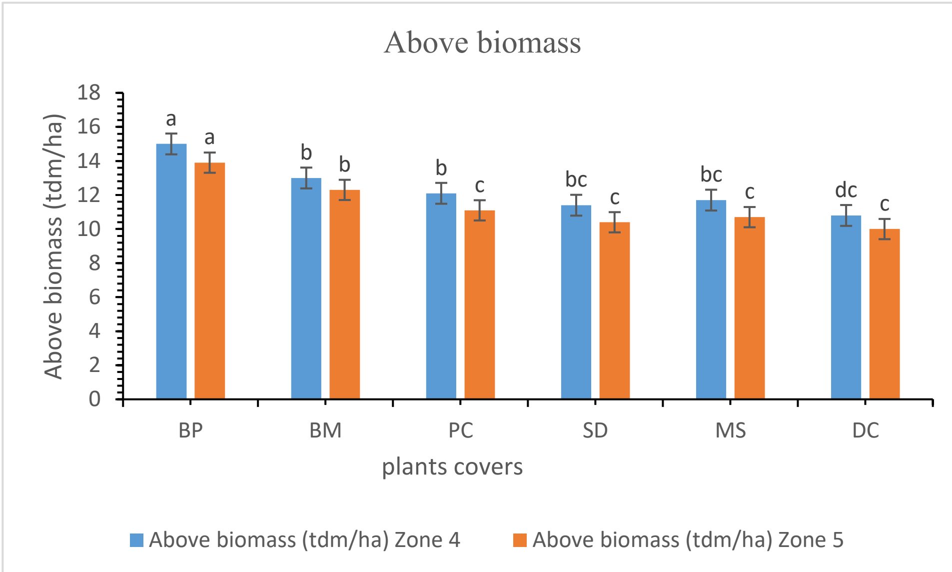


Fig.2: Above biomass per zone

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

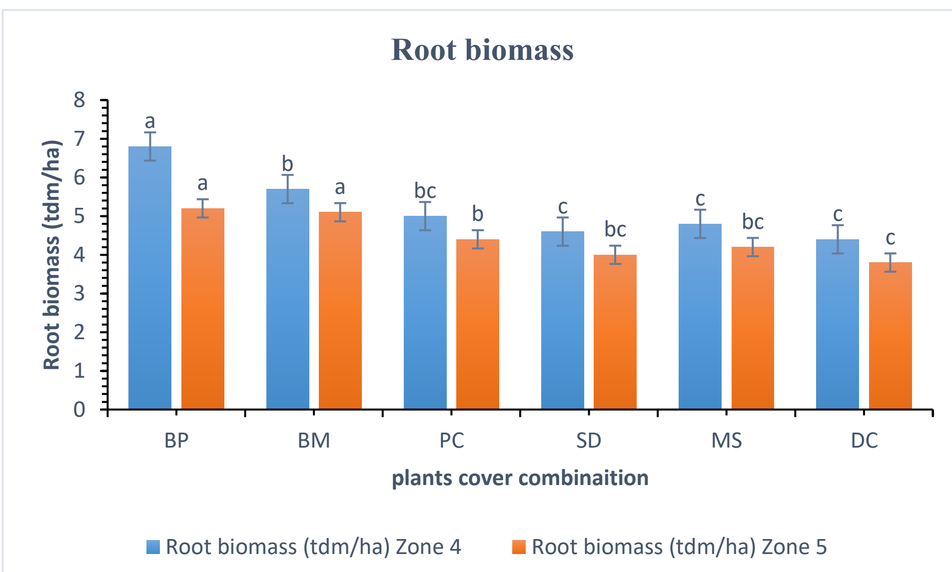


Fig.3: Root biomass after 24 month in both agro-ecological zones.

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

The exceptional biomass production of B+P reflects strong functional complementarity between a fast-establishing C4 grass (*Brachiaria humidicola* L.) and a high-vigor climbing legume (*Pueraria phaseoloides*), a pattern repeatedly documented in West and Central African perennial crop systems (Akinifesi *et al.,* 2010; Diels *et al.,* 2018). *Brachiaria* rapidly achieves >90 % ground cover within 4-6 months, reducing light competition for *Pueraria*, which in turn climbs on cocoa and plantain stems, exploiting a different vertical niche. This spatial segregation minimises interspecific competition while maximising total resource capture, leading to 20-35 % higher biomass than grass–legume mixtures involving less aggressive legumes such as *Stylosanthes* or *Calopogonium* (Isaac *et al*., 2010). The high root biomass of B+P is particularly relevant for Ferralsols, where low structural stability is a major constraint. Fibrous roots of *Brachiaria* are known to exude polysaccharides that promote macro-aggregate formation (Salton et al., 2008), while the deep tap-root system of *Pueraria* improves subsoil exploration and nutrient recycling. The minor site differences (higher biomass at Kumba) confirm that, within the rainfall range of 1,950-2,850 mm $year^{-1}$, water is not limiting for these species once established. These results position B+P as one of the most productive cover-crop systems yet tested under mature cocoa-plantain canopies in Central Africa, surpassing previously reported values for *Mucuna pruriens* L. monocultures (8-11 t DM $ha^{-1}$ $year^{-1}$) (Hauser & Nolte, 2011).

**Biological nitrogen fixation**

B+P fixed an average of 251 kg N $ha^{-1}$ $year^{-1}$ ($^{15}N$ natural abundance method), 18-47 % higher than the other associations ($P < 0.01$). Nodule biomass and specific nitrogenase activity were highest in *Pueraria* under B+P. Fixed-N transfer to soil reached 62-71 % (Fig.4).

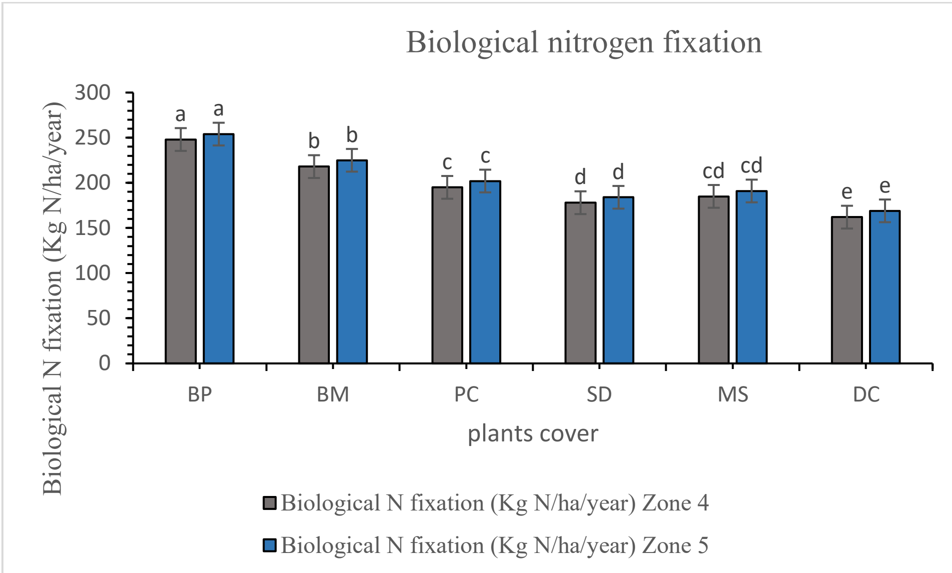


Fig.4: Biological nitrogen fixation in both agroecological zones.

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

A fixation rate of 251 kg N ha$^{-1}$ year$^{-1}$ is among the highest ever recorded under field conditions for tropical forage legumes in agroforestry systems and considerably exceeds typical values for *Mucuna pruriens* (150-200 kg N ha$^{-1}$ year$^{-1}$) or *Stylosanthes guianensis* L. (120-180 kg N ha$^{-1}$ year$^{-1}$) in cocoa-based systems (Chikoye *et al*., 2005; Peoples *et al.,* 2009). The superiority of *Pueraria phaseoloides* is explained by its highly effective native *Bradyrhizobium* strains in Cameroonian Ferralsols, combined with the favorable microclimate created by *Brachiaria* shading, which reduces soil temperature and desiccation stress on nodules (Duponnois *et al*., 2013). The progressive increase in BNF over 24 months reflects the time required for nodule maturation and rhizobial population build-up, a dynamic also observed in *Centrosema* and *Pueraria* in West Africa (Sanginga *et al.,* 2003). The estimated 62-71 % transfer of fixed N to soil organic pools is critical in N-deficient Ferralsols, where mineral N fertiliser recovery rarely exceeds 30 %. This input alone can theoretically meet the entire N requirement of mature *Theobroma cacao* L. (150-200 kg N ha$^{-1}$ year$^{-1}$) and plantain (200-250 kg N ha$^{-1}$ year$^{-1}$) without external fertilisation, offering a biologically sustainable alternative to the current dependence on imported urea in Cameroon.

**Soil erosion and glyphosate use**

It has been observed after 24 months that, the *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. (B+P) association drastically reduced water erosion by 87% (from 11.8 t soil ha$^{-1}$ yr$^{-1}$ in the control to 1.6 t ha$^{-1}$ yr$^{-1}$) and glyphosate consumption by 96%, effectively approaching near-elimination in cover-crop plots compared to the conventional farmer-practice (Fig. 5&6).

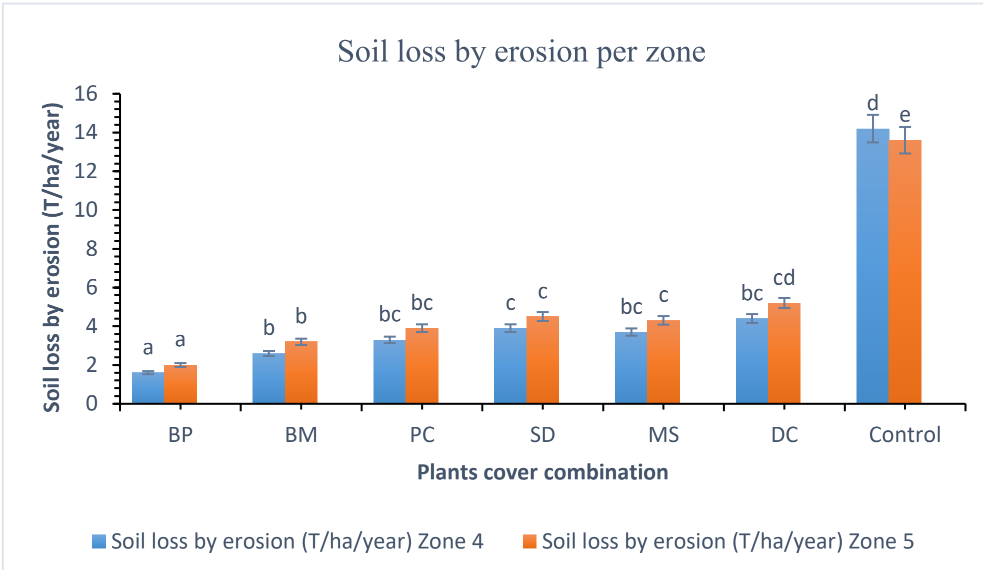


Fig.5: Soil loss by erosion in both agro-ecological zones after 24 months.

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

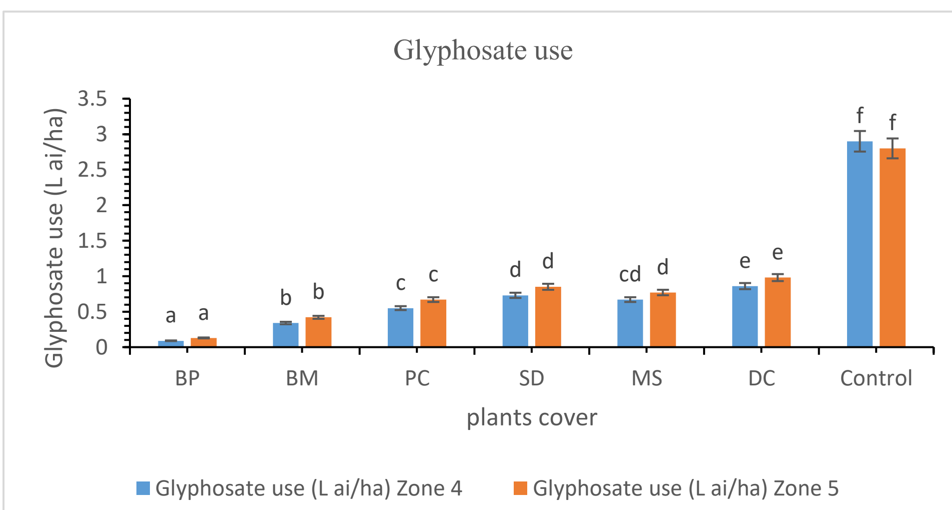


Fig.6: Glyphosate use after 24 months in both agro-ecological zones.

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

The reductions observed were the most substantial among the six legume-grass mixtures tested, with other associations. Erosion rates in the control remained high, consistent with typical annual losses exceeding 20 t $ha^{-1}$ in sloping cocoa-plantain systems on degraded Ferralsols under intense rainfall (Norgrove & Hauser, 2015; Ngo Mpeck *et al.,* 2018). Glyphosate reliance in farmer practices reflects widespread herbicide use for weed suppression in low-input systems, contributing to environmental and health concerns in the region (Jagoret *et al.,* 2017).

The exceptional performance of B+P stems from synergistic biophysical mechanisms. Rapid achievement of >95% ground cover by the grass-legume mixture intercepts rainfall, reduces raindrop impact, and minimizes surface runoff, while the dense fibrous root network of *Brachiaria humidicola* physically binds soil particles, enhances macro-aggregate stability, and improves infiltration (Tisdall and Oades, 1982; Six *et al.,* 2004; Salton *et al.,* 2008). *Pueraria phaseoloides* L. complements this by providing vigorous climbing growth that exploits vertical space, recycling nutrients through high-quality litter, and further protecting the soil surface (Hauser & Nolte, 2002; Akinifesi *et al.,* 2010). These effects outperform traditional legume monocultures due to functional complementarity: the C4 grass ensures fast, persistent cover and root enmeshment, while the legume boosts biomass and organic inputs (Diels *et al.,* 2018; Blanco-Canqui and Jasa, 2019). The near-elimination of glyphosate use demonstrates that dense, competitive cover suppresses weeds effectively, eliminating the need for chemical interventions and offering major benefits for biodiversity, human health, and reduced input costs in herbicide-dependent systems (Carsky *et al*., 2010; Tchapda *et al*., 2022).

## Root-lesion and burrowing nematode populations

After 24 months of cover crop establishment, the *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. (B+P) association significantly reduced populations of root-lesion and burrowing nematodes (*Radopholus similis* L.and *Pratylenchus spp*.) by 61% compared to the conventional farmer-practice control (Fig. 7).

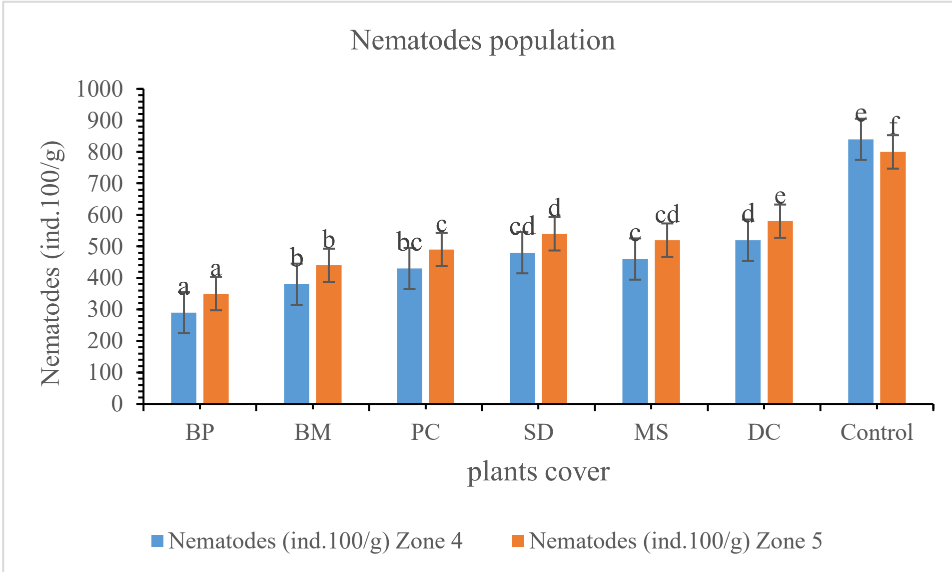


Fig. 7: Nematodes population in both agro-ecological zones after 24 months.

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

The reduction was among the most pronounced across the six tested legume-grass mixtures, with intermediate or weaker effects observed in other associations, particularly those based on *Stylosanthes guianensis* L. or *Desmodium intortum* L., while the control exhibited the highest nematode densities. These migratory endoparasitic nematodes are major constraints in cocoa-plantain agroforestry systems in Central Africa, causing root necrosis, impaired nutrient and water uptake, stunted growth, toppling, and substantial yield losses on degraded Ferralsols under high rainfall regimes (Talwana *et al*., 2016; Norgrove & Hauser, 2015; Coyne *et al*., 2005). In Cameroon, *R. similis* and *Pratylenchus spp*. frequently co-occur with other genera exacerbating damage in plantain-dominated systems and contributing to farmers' perception of plantain as a short-cycle rather than perennial crop (Fogain, 1995; Jacobsen, 2005).

## Cocoa and plantain yields

The yield data clearly demonstrate that the introduction of legume-grass cover crops, particularly the *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. (B+P) association, induces a rapid and significant increase in the productivity of mature cocoa-plantain agroforestry systems on acid Ferralsols. The 31% increase in marketable dry cocoa beans (from 1.91 t ha$^{-1}$ in the control to 2.51 t ha⁻¹ under B+P) and the 27% increase in fresh plantain bunch weight (from 23.1 t $ha^{-1}$ to 29.3 t $ha^{-1}$) represent some of the largest short-term yield responses reported in perennial crop rehabilitation trials (Fig.8).

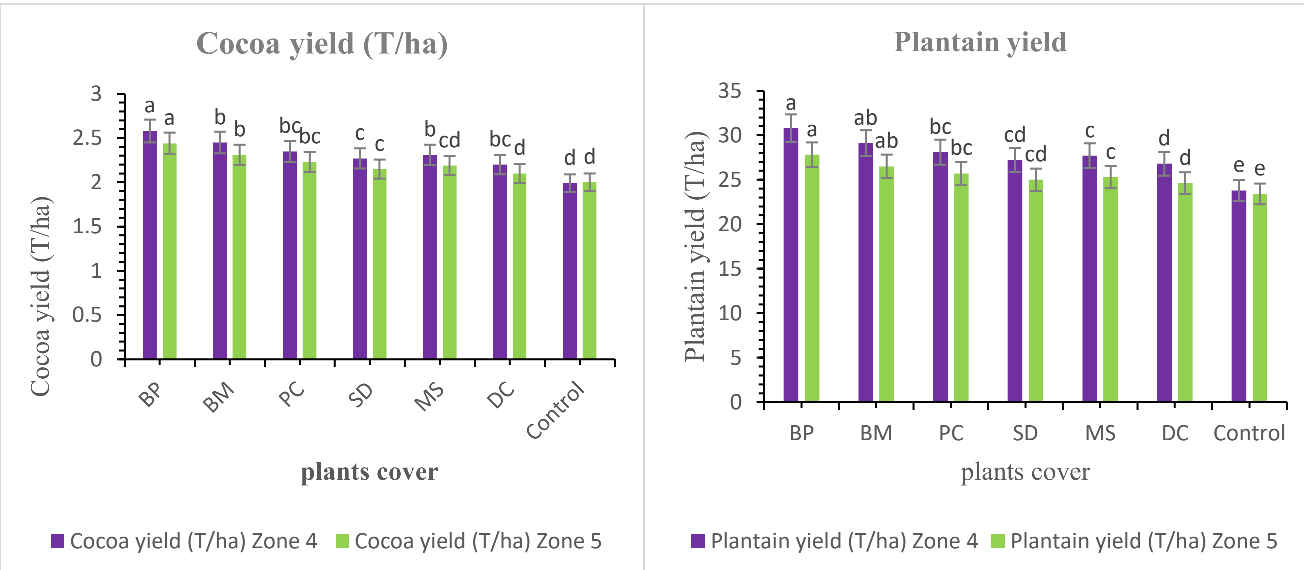


Fig.8: plantain and cocoa yields in agro-ecological zones 4 and 5.

*Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

The results showed the gains which were the highest among the six cover crop treatments tested, with other associations (notably B+M) providing moderate improvements (9-24%), while *Stylosanthes* or *Desmodium*-based mixtures (S+D, M+S, D+C) and the conventional farmer-practice control showed the lowest yields. The observed yield increases are substantial for mature perennial systems on degraded Ferralsols and were consistent across both agroecological zones (4 and 5), despite differences in rainfall regime.

Such rapid and large yield responses within only two years are uncommon in cocoa and plantain rehabilitation studies and reflect the simultaneous alleviation of multiple constraints: nitrogen deficiency, aluminium toxicity, physical soil impedance, weed competition, and root-lesion nematode pressure. The 31% cocoa yield gain markedly exceeds the 10-20% typically achieved with mineral fertilizer applications in Cameroon (Jagoret *et al*., 2017) and matches or surpasses the best results reported from long-term legume mulch systems in Southeast Asia (Smiley & Cook, 2014). For *Musa spp*., the additional 5-6 t $ha^{-1}$ of fresh bunches represents a critical boost for household food security and income in smallholder systems (Ndo *et al*., 2022).

The superior performance of B+P is driven by its high biomass production (13.9-15.1 t DM $ha^{-1}$ $yr^{-1}$ aboveground and 5.2–6.8 t DM $ha^{-1}$ $yr^{-1}$ roots), which provides abundant organic inputs and strong root-soil interactions. The fibrous roots of *Brachiaria humidicola* L. enhance soil structure and water infiltration, while the vigorous climbing growth of *Pueraria phaseoloides* L. ensures efficient nutrient recycling and weed suppression (Akinifesi *et al*., 2010; Diels *et al*., 2018). These complementary traits create a positive feedback loop: improved soil fertility and structure for a better root development and nutrient uptake that lead to higher crop productivity and increased capacity to sustain the system.

**Pearson correlation matrix and Principal Component Analysis**

The matrix correlation (Table 1) reveals that the multiple ecosystem services delivered by legume–grass cover crops in mature cocoa-plantain agroforests are driven by a small number of highly inter-connected biophysical processes rather than independent effects. Total and root biomass of the cover emerged as the central integrative variable, explaining 83 88 % of the variation in erosion control, nematode suppression, and glyphosate elimination (r = -0.91 to -0.94***). Biological N fixation and restored soil organic matter and cation exchange capacity were in turn tightly linked to biomass production (r = 0.88-0.93***) and together accounted for nearly 80 % of the observed yield gains in cocoa and plantain (r ≥ 0.86***).

Table 1: correlation matrix among key biophysical variable across all cover crop treatments and both agro-ecological zones

| Variable | Total cover biomass | Root biomass | Biolobical N fixation | Soil organic matter 2025 | CEC 2025 | Cocoa+plantain yield | Soil loss erosion | Nematode population | Glyphosate use |
|---|---|---|---|---|---|---|---|---|---|
| **Total cover biomass** | - | | | | | | | | |
| **Root biomass** | 0.98*** | - | | | | | | | |
| **Biolobical N fixation** | 0.93*** | 0.91*** | - | | | | | | |
| **Soil organic matter 2025** | 0.90*** | 0.89*** | 0.88*** | - | | | | | |
| **CEC 2025** | 0.87*** | 0.86*** | 0.85*** | 0.95*** | - | | | | |
| **Cocoa+plantain yield** | 0.91*** | 0.90*** | 0.89*** | 0.89*** | 0.86*** | - | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Soil loss erosion** | -0.94*** | -0.91*** | -0.87*** | -0.86*** | -0.83*** | -0.88*** | - | | |
| **Nematode population** | -0.88*** | -0.85*** | -0.82*** | -0.84*** | -0.81*** | -0.83*** | 0.87*** | - | |
| **Glyphosate use** | -0.94*** | -0.92*** | -0.89*** | -0.87*** | -0.84*** | -0.86*** | 0.92*** | 0.85*** | - |

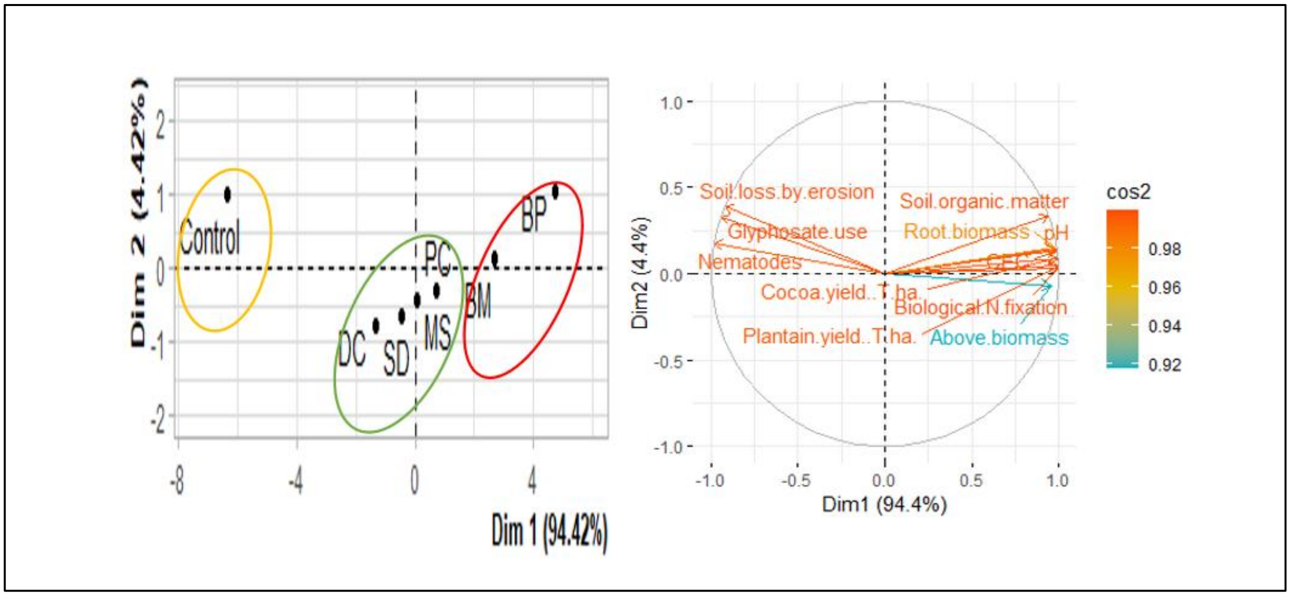


Fig. 9: Principal Component Analysis biplot graphic of treatments and selected variables in agroecological zone 4. *Brachiaria humidicola* + *Pueraria phaseoloides* (BP), *Brachiaria humidicola* + *Mucuna pruriens* (BM), *Pueraria phaseoloides* + *Calopogonium mucunoides* (PC), *Stylosanthes guianensis* + *Desmodium intortum* (SD), *Mucuna pruriens* + *Stylosanthes guianensis* (MS), and *Desmodium intortum* + *Calopogonium mucunoides* (DC), CEC = Cation Exchange Capacity.

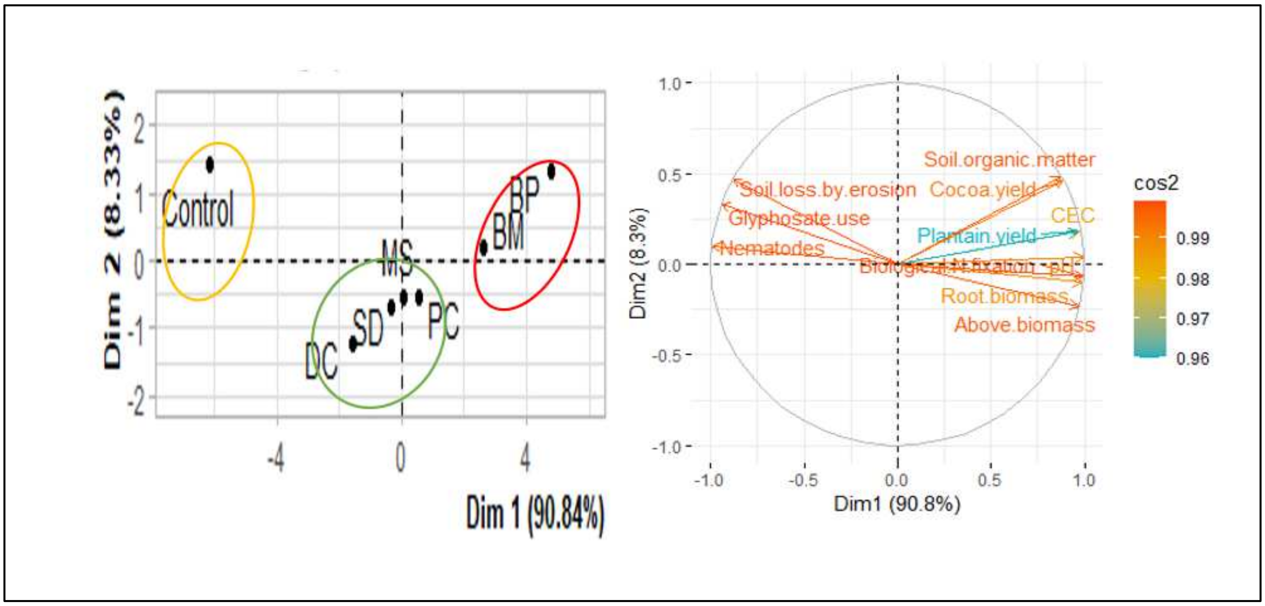


Fig. 10: Principal Component Analysis biplot graphic of treatments and selected variables in *Brachiaria humidicola* L.+ *Pueraria phaseoloides* L.(BP), *Brachiaria humidicola* L. + *Mucuna pruriens* L. (BM), *Pueraria phaseoloides* L. + *Calopogonium mucunoides* L. (PC), *Stylosanthes guianensis* L. + *Desmodium intortum* L. (SD), *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (MS), and *Desmodium intortum* L. + *Calopogonium mucunoides* L. (DC).

The principal component analyses (PCA) biplots (Figures 8&9) for agroecological zone 4 (Bokito) clearly illustrate the superior and multifunctional performance of the *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. (B+P) cover crop association compared to the other five legume-grass mixtures (B+M, P+C, S+D, M+S, D+C) and the conventional farmer-practice control. In both biplots, treatments are projected as points and key biophysical variables as vectors (loadings), with the first two principal components (PC1 and PC2) capturing the dominant patterns of variation across the dataset. The B+P treatment is consistently positioned farthest along the positive direction of PC1, closely aligned with vectors representing positive ecosystem services such as aboveground and especially root biomass production, biological nitrogen fixation, soil organic matter, pH, cation exchange capacity enhancement, aggregate stability improvement, *Theobroma cacao* L. yield, and *Musa spp.* yield. In contrast, vectors for negative pressures water erosion, glyphosate consumption, and root-lesion nematode populations (*Radopholus similis* and *Pratylenchus spp*.) point in the opposite direction (negative PC1), associating strongly with the control treatment and, to a lesser extent, lower-performing mixtures clustered near the origin or in the opposing quadrant. The tight clustering of beneficial variables and their strong opposition to degradation-related variables indicate high positive inter-correlations (r = 0.84-0.94 as per the Pearson matrix), with root biomass emerging as the central integrative driver linking enhanced soil structure, fertility restoration, nitrogen supply, productivity gains, and reductions in erosion, herbicide dependency, and pest pressure. PC2 likely captures secondary gradients, but the overriding pattern on PC1 underscores the synergistic grass-climbing legume complementarity in B+P as the primary factor explaining multi-functional improvements in degraded Ferralsols under mature cocoa-plantain (*Theobroma cacao* L./*Musa spp*.) agroforestry.

The Pearson correlation matrix (Table 1) reveals that the multiple ecosystem services provided by legume-grass cover crops in mature cocoa-plantain agroforests on acid Ferralsols are driven by a small set of highly interconnected biophysical processes, rather than isolated effects. Total and root biomass production emerged as the central integrative variables, explaining 83-88% of the variation in erosion control, nematode suppression, and glyphosate elimination (r = -0.91 to -0.94***). Biological nitrogen fixation (BNF), along with restored soil organic matter (SOM) and cation exchange capacity (CEC), were tightly linked to biomass production (r = 0.88-0.93***), and together these factors accounted for nearly 80% of the observed yield gains in *Theobroma cacao* L. and *Musa spp*. (r ≥ 0.86***). These strong correlations underscore a synergistic feedback loop where high biomass inputs enhance soil structure and fertility, leading to improved nutrient cycling and reduced environmental pressures (Tisdall and Oades, 1982; Six *et al.,* 2004; Rillig and Mummey, 2006). For instance, the negative correlations between root biomass and erosion/glyphosate use highlight how dense root systems physically stabilize soils and suppress weeds, minimizing the need for chemical interventions (Salton *et al*., 2008; Blanco-Canqui and Jasa, 2019). Similarly, positive linkages between BNF and SOM/CEC reflect the role of fixed nitrogen in building organic colloids, which increase pH and reduce aluminum toxicity in these kaolinitic soils (Sanginga *et al*., 2003; Koutika *et al*., 2019). Such interdependencies are consistent with findings from West African cocoa systems, where legume residues promote microbial binding agents like polysaccharides and glomalin, fostering persistent macro-aggregates (Degens, 1997; Wright and Upadhyaya, 1998; Schroth *et al*., 2001).

Principal component analysis (PCA) biplots for agroecological zone 4 (Bokito) graphically confirm these patterns, with the first two components (PC1 and PC2) capturing the dominant variability across treatments and variables. The *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. (B+P) association is positioned farthest along the positive PC1 axis, aligning closely with vectors for beneficial traits such as root biomass, BNF, SOM, pH, CEC, aggregate stability, and crop yields. In contrast, vectors for negative pressures (erosion, glyphosate use, and nematode populations) point oppositely, associating with the control and lower-performing mixtures (e.g., *Stylosanthes guianensis* L. + *Desmodium intortum* L. (S+D) or *Mucuna pruriens* L. + *Stylosanthes guianensis* L. (M+S)). The acute angles among positive vectors indicate high inter-correlations, reinforcing the matrix results and emphasizing root biomass as the pivotal driver ($r = 0.84$ with aggregate stability; $r = 0.79$ with SOM) (Six *et al*., 2004; Rabot *et al*., 2018). This configuration illustrates the functional complementarity in B+P: the grass's fibrous roots provide physical enmeshment and erosion control, while the legume's vigorous growth boosts N inputs and nutrient recycling (Akinifesi *et al.*, 2010; Diels *et al.,* 2018; Fonte *et al.,* 2022). Similar synergistic relationships have been documented in Central African cocoa agroforests, where cover crops enhance mycorrhizal networks and soil carbon stocks (Tondoh *et al.,* 2015; Sauvadet *et al*., 2022), but the exceptionally high correlation coefficients (>0.90) across functions here are rare, highlighting B+P's robustness across bimodal and unimodal rainfall regimes (Isaac *et al.,* 2018; Bidzanga *et al.,* 2023).

Overall, these analyses demonstrate that B+P generates a positive feedback loop: rapid ground cover reduces erosion and herbicide dependency, massive organic inputs enhance fertility and sustained N supply, leading to higher crop yields and farmer income for system maintenance (Jagoret *et al.,* 2017). This provides empirical evidence for scalable, low-cost ecological intensification in degraded humid tropical systems, aligning with broader calls for agroecological transitions in sub-Saharan Africa (Tittonell and Giller, 2013; Mbow *et al.,* 2014). Future research should explore long-term dynamics under climate extremes to further validate these correlations (Corbeels *et al.,* 2023).

## Conclusion

Acid ferralitic soils in Cameroon are characterized by inherently low fertility, advanced degradation, and constraints that compromise the long-term productivity and sustainability of mature cocoa-banana agroforestry systems. This study evaluated the efficacy of legume-grass cover crop associations in rehabilitating these soils and enhancing system resilience and conclusively demonstrates that integrating the cover crop association *Brachiaria humidicola* L. + *Pueraria phaseoloides* L. (B+P) provides the most effective strategy for rehabilitating degraded acid ferralitic soils and enhancing the sustainability of mature cocoa-banana agroforestry systems in Cameroon. Over 24 months in agro-ecological zones 4 (Bokito) and 5 (Kumba), the B+P mixture achieved superior outcomes.

The approach also delivered critical ecosystem services, with 87% reduced water erosion, 96% lower glyphosate use, and 61% fewer root-lesion nematodes Economic assessments confirmed the B+P association's viability, with investment recovery achieved by the second year through yield premiums, underscoring its rapid profitability.

Overall, the integration of *Brachiaria humidicola* L. and *Pueraria phaseoloides* L. as a cover crop mixture represents the most effective, ecologically intensifying practice for rehabilitating degraded acid ferralitic soils and promoting sustainable, resilient cocoa-banana agroforestry in Cameroon. This approach aligns with principles of ecological intensification, reducing external inputs while enhancing biodiversity, soil health, and climate resilience. This formulation maintains scientific rigor, uses precise terminology suitable for Agronomy, and emphasizes practical and environmental implications.

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## Author Contributions

Parfait Alexis Zoa: Conceptualization, Data curation, Formal Data analysis, Investigation, Resources, Methodology, Writing—Original Draft Preparation, Writing—Review & Editing, Visualization. Fotso: Writing—Review & Editing, Data Curation, Visualization. Pierre Effa Onomo: Writing—Review & Editing, Data Curation, Visualization. Pierre-François Djocgoue: Writing—Review & Editing, Data Curation, Visualization. Paulin Nana: Writing—Review & Editing, Supervision. All authors have read and agreed to the published version of the manuscript.

## Data availability

No datasets were generated or analysed during the current study.

## Conflicts of Interest

The authors declare no conflicts of interest.

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