



RESEARCH ARTICLE

Biomass amendment effects on soil nutrients and microbial phosphorus under different land uses in a tropical dryland

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Abstract

Dryland agriculture is constrained by limited water availability, low organic matter and increasing erosion. In sloping dryland areas of eastern Indonesia, slash-and-burn land preparation can reduce soil fertility. This study examined the effects of five biomass amendments (control, rice husk charcoal (RHC), wood charcoal (WC), rice husk (RH) and wood leaves (WL), each at 20 t ha⁻¹) on soil chemical properties and microbial phosphorus (microbial P) in two land-use systems, intensive cultivation (IC) and non-intensive cultivation (NIC), sampled at two sites (Netpala and Kualeu, Indonesia) and incubated for 30 and 60 days. Using a randomised complete block design (RCBD) with site as the blocking factor, biomass treatment significantly increased total nitrogen (N), phosphorus pentoxide (P₂O₅) and potassium oxide (K₂O) in IC soils ($p < 0.05$), whereas effects in NIC soils and effects on pH, organic carbon (C) and microbial P in either soil type, were not statistically significant at the achieved replication. Intensive cultivation soils showed larger numerical gains relative to their own controls than NIC soils, which maintained higher absolute nutrient levels throughout; wood leaves produced the largest gains in N and K₂O, while charcoal amendments produced the largest gains in P₂O₅ and organic C. These findings, based on a high, non-field-representative rate and two-site incubation, indicate that biomass amendments can improve short-term soil chemical status in degraded tropical dryland soils, most clearly under intensive cultivation; field trials at realistic rates with greater replication are needed to confirm their practical value for restoring soil quality and reducing degradation from slash-and-burn practices.

Keywords: dryland; microbial phosphorus; nitrogen; organic carbon; phosphorus; potassium

Introduction

Dryland ecosystems play a critical role in global food production but are highly vulnerable to land degradation due to water scarcity, low soil organic matter and increasing climate variability (1). In semi-arid regions of Indonesia, particularly Nusa Tenggara Timur (NTT), drylands dominate the landscape and support smallholder agriculture under challenging biophysical conditions, including erratic rainfall, prolonged dry seasons and inherently low soil fertility (2). These constraints limit biomass production, accelerate soil degradation and threaten the sustainability of agricultural systems.

Recent studies emphasise that soil quality, as reflected by soil organic carbon (C-org), nutrient availability, pH balance and microbial activity, is a key determinant of ecosystem functioning and resilience in dryland environments (3–5). Organic amendments such as crop residues and biochar have gained increasing attention over the last decade as effective strategies for restoring degraded soils by improving C stabilisation, nutrient retention and soil physical properties (6, 7). In parallel, advances in soil microbiology have drawn attention to microbial-mediated phosphorus (P) cycling as a sensitive indicator of soil functional recovery and long-term fertility improvement (8).

In NTT, agricultural land management is commonly characterised by two different systems: intensive cultivation (IC), involving continuous cropping with limited organic inputs and non-intensive cultivation (NIC), typically based on traditional slash and burn practices on sloping lands. Although NIC systems may temporarily benefit from ash-derived nutrients, repeated burning has been shown to reduce SOC stocks, degrade soil structure and alter soil microbial communities, thereby impairing nutrient cycling and long-term productivity (9–13). Despite growing global interest in sustainable dryland management, comparative studies evaluating soil chemical and microbial responses to organic amendments under IC and NIC systems in tropical semi-arid regions remain scarce.

Organic amendments offer a promising approach for restoring degraded dryland soils. Biomass additions can increase SOC, improve nutrient retention and stimulate microbial biomass, particularly when applied consistently or combined with mineral inputs (14). Soil microbial communities respond rapidly to both land-use intensity and organic matter inputs and changes in microbial P pools serve as sensitive indicators of soil functional recovery (11).

The significance of this study lies in its integrated assessment of soil chemical properties and microbial P dynamics in response to different biomass amendments under different land-use intensities. Understanding how various biomass types, such as rice husk charcoal, wood charcoal and fresh plant residues, affect soil fertility and microbial functioning is essential for designing locally appropriate and climate-resilient soil management strategies (15).

Therefore, the objective of this research was to evaluate the short-term effects of multiple biomass additions, applied at a high (20 t ha⁻¹) laboratory rate, on soil chemical properties (SOC, N, P, K and pH) and microbial P dynamics under IC and NIC systems in semi-arid NTT, Indonesia. The results are intended to provide proof of concept evidence to inform biomass-based soil restoration research and to identify priorities for subsequent field scale validation in tropical semi-arid environments.

Materials and Methods

Study area and soil sampling

The study was conducted at two sites in Timor Tengah Selatan (TTS) District, Nusa Tenggara Timur, Indonesia: Netpala village (Kecamatan Molo utara): -9.742675°, 124.258717° Kualeu village (Kecamatan Molo Tengah): -9.750358°, 124.296048° both within the Mollo highland dryland complex and characterised by seasonal rainfall and prolonged dry periods. At each site, soil samples were collected from two different land-use systems: IC and NIC. Intensive cultivation soils were obtained from lowland fields cultivated continuously throughout the year, whereas NIC soils were collected from sloping lands managed using a traditional slash and burn system and cultivated once annually. Approximately 5 kg of surface soil (0–20 cm) was collected from each site x land-use combination, homogenised, air-dried and sieved to 2 mm prior to analysis. Based on the measured particle-size distribution, pH and organic C content (Table 1), together with the soil-forming conditions reported for semi-arid drylands elsewhere in West Timor (5), the NIC soils are classified as Inceptisols, while the IC soils are classified as Alfisols of the Ustalf suborder, consistent with a tropical wet dry (ustic) moisture regime.

Experimental design and biomass treatments

The experiment followed a randomised complete block design (RCBD) with the two sites (Netpala and Kualeu) serving as blocks, five biomass treatments and two land-use systems (IC and NIC), sampled destructively at 30 and 60 days of incubation. This gives, for each land-use system and sampling time, five treatments x two site-blocks = 10 experimental units (40 units in total across both land-use

systems and both sampling times). Each experimental unit consisted of approximately 1 kg of air-dried soil in a sealed 1 L plastic container. Because site (block) rather than within site subsampling was the primary source of replication, treatment comparisons should be interpreted as having modest statistical power (error degrees of freedom = 4 per ANOVA); this is discussed further in the Limitations section. The treatments consisted of: (i) control (no amendment), (ii) rice husk charcoal (RHC, 20 t ha⁻¹), (iii) wood charcoal (WC, 20 t ha⁻¹), (iv) rice husk (RH, 20 t ha⁻¹) and (v) wood leaves (WL, 20 t ha⁻¹).

Biomass materials were air dried prior to application. Charcoal materials were produced through local traditional carbonisation under limited oxygen (O) conditions. All biomass amendments were thoroughly mixed with soil on a weight basis to ensure homogeneity. The carbon-to-nitrogen (C: N) ratio and total C content of each biomass material is relevant to interpreting the treatment responses reported below. Based on published characterisations of comparable materials, fresh RH and wood leaves typically have moderate C: N ratios (roughly 40–80 and 40–100, respectively), whereas carbonisation markedly narrows the pool of readily available N relative to C, so RH and WC typically show substantially higher C: N ratios than their uncharred counterparts (16). These are literature-typical ranges for comparable feedstocks, not values measured for the specific batches used in this study; the true values will depend on the specific feedstock and the temperature and duration of the traditional carbonisation process used here.

The 20 t ha⁻¹ application rate used for all biomass treatments was selected to produce a clearly detectable short-term signal in soil chemical and microbial responses within the 30–60 day incubation window used here, rather than to represent an agronomically realistic field practice. Assuming a bulk density of approximately 1.3 g cm⁻³, typical of the sandy loam and sandy-clay loam textures reported in Table 1 for these soils and an incorporation depth of 0–20 cm, field biochar 20 t ha⁻¹ (commonly 5–20 t ha⁻¹), underscoring that the tested rate characterises the upper bound of short-term soil response under controlled laboratory conditions rather than a field-applicable recommendation; its implications for field applicability are discussed further in the limitations section.

Treated soils were incubated in the dark under controlled conditions at 25 ± 2 °C, with destructive subsampling at 30 and 60 days to capture short term temporal dynamics. Soils were held in closed but vented containers to minimise moisture loss while allowing gas exchange. Soil moisture was adjusted to and maintained at approximately 60 % of the maximum water-holding

Table 1. Initial (day-30 control) soil properties of intensively cultivated (IC) and non-intensively cultivated (NIC) soils, averaged across the two study sites (Netpala and Kualeu)

Soil property	NIC (mean, range)	IC (mean, range)
N (%)	0.71 (0.53–0.89)	0.34 (0.30–0.37)
P ₂ O ₅ (mg 100 g ⁻¹)	22.4 (16.6–28.3)	17.3 (16.6–18.1)
K ₂ O (mg 100 g ⁻¹)	58.7 (44.1–73.3)	28.8 (26.3–31.2)
Microbial P (10 ⁻¹⁴)	0.017 (0.010–0.024)	0.038 (0.000–0.075)
pH	6.35 (6.1–6.6)	6.25 (5.8–6.7)
C-org (%)	2.73 (1.36–4.10)	0.84 (0.42–1.25)
Sand (%)	73	60.59
Silt (%)	10	8.65
Clay (%)	17	30.76
Soil texture	Sandy loam	Sandy-clay loam

N: nitrogen; P₂O₅: phosphorus pentoxide; K₂O: potassium oxide; P: phosphorus; C-org: soil organic carbon; IC: intensively cultivated; NIC: non-intensively cultivated.

capacity (WHC), determined gravimetrically for each soil type prior to incubation and was checked gravimetrically every 3–4 days and replenished with distilled water to the target level as needed. At each sampling time, soil samples were re-homogenised and subsampled for chemical and microbial analyses.

Soil chemical and microbial analyses

Soil pH was measured in a soil-to-water suspension (1: 2.5, w/v) using a calibrated glass electrode. Soil organic carbon (C-org) was determined using the Walkley-Black wet oxidation method, while total N was measured using the Kjeldahl digestion method.

Available phosphorus (P_2O_5) was extracted using the Bray or Olsen method, depending on soil pH and quantified colorimetrically. Exchangeable potassium (K_2O) was extracted using 1 M ammonium acetate (pH 7.0) and determined by flame photometry.

Microbial P was quantified using the chloroform fumigation-extraction method, which estimates biologically immobilised P by comparing fumigated and non-fumigated soil extracts (11). All chemical and microbial analyses were performed in triplicate to ensure analytical precision. Microbial P was the only microbial indicator measured in this study; this scope is discussed further in the limitations section.

Statistical analysis

Data were analysed using two way analysis of variance (ANOVA) for a RCBD, with biomass treatment as the factor of interest and site (Netpala, Kualeu) as the blocking factor, performed separately for each land-use system (IC, NIC), each sampling time (30, 60 days) and each response variable, using Type II sums of squares (treatment df = 4, error df = 4, except K_2O at 60 days in NIC soils where one value was missing, giving error df = 3). Treatment effects were considered statistically significant at $p < 0.05$. Because replication was limited to two site-blocks, statistical power was modest and formal post-hoc mean separation (e.g., Tukey's HSD) was not performed; treatment means are instead reported descriptively alongside the ANOVA outcome for each variable (Table 2).

Results

Initial soil properties

Baseline properties (control treatment, day 30) depicted in Table 1 confirmed that NIC soils had higher fertility than IC soils at both sites. Averaged across Netpala and Kualeu, NIC soils had higher total N (0.71 %, range 0.53–0.89 %), P_2O_5 (22.4, range 16.6–28.3 mg 100 g⁻¹), K_2O (58.7, range 44.1–73.3 mg 100 g⁻¹), pH (6.35, range 6.1–6.6) and C-org (2.73 %, range 1.36–4.10 %) than IC soils (N 0.34 %, range 0.30–0.37 %; P_2O_5 17.3, range 16.6–18.1 mg 100 g⁻¹; K_2O 28.8, range 26.3–31.2 mg 100 g⁻¹; pH 6.25, range 5.8–6.7; C-org 0.84 %, range 0.42–1.25 %). Microbial P was low at both sites and in both land-use systems at baseline, with no consistent land-use pattern. Non-intensive cultivation soils were classified as sandy loam and IC soils as sandy-clay loam based on particle-size analysis (Table 1).

Effects of biomass addition on soil macronutrients

Two-way ANOVA (biomass treatment blocked by site) showed that treatment produced statistically significant effects on total N and K_2O in IC soils at both sampling times (N: $F_{4,4} = 7.37$, $p = 0.039$ at 30 days; $F_{4,4} = 22.84$, $p = 0.005$ at 60 days; K_2O : $F_{4,4} = 6.78$, $p = 0.045$ at 30 days; $F_{4,4} = 6.56$, $p = 0.048$ at 60 days) and on P_2O_5 at 60 days ($F_{4,4} = 15.76$, $p = 0.010$) though not at 30 days ($F_{4,4} = 3.64$, $p = 0.119$) (Fig. 1,

Table 2). In IC soils, K_2O increased most under WC at both times (mean + 60 % at 30 days, + 115 % at 60 days, relative to control), N increased most under WC at 30 days (+ 67 %) and under WL at 60 days (+ 100 %) and P_2O_5 increased most under RHC at both times (+ 251 % at 30 days, though highly variable between sites; + 149 % at 60 days). By contrast, treatment effects on N, P_2O_5 and K_2O in NIC soils did not reach statistical significance at either sampling time (all $p > 0.12$) (Fig. 1, Table 2), despite numerically higher values under WL and the biochar treatments relative to the NIC control.

Effects on soil pH and organic carbon

Treatment effects on soil pH and C-org were not statistically significant in either soil type at either sampling time (all $p > 0.10$) (Fig. 2, Table 2), reflecting substantial variability between the two sites. Descriptively, C-org increased most under WC and WL, exceeding a 2–6-fold increase relative to the control in some site x treatment combinations by day 60, while pH shifted only modestly, remaining within about one pH unit of the control under all treatments in both soil types.

Effects on microbial phosphorus

Treatment effects on microbial P were not statistically significant in either soil type at either sampling time (all $p > 0.50$) (Fig. 2, Table 2). Microbial P was generally low under all treatments at 30 days in both soil types and remained highly variable at 60 days; the largest numerical values at 60 days occurred under the control and RH/RHC treatments in NIC soils, but not consistent, statistically supported treatment effect on microbial P could be established at the achieved replication (two site-blocks).

Multivariate response pattern

Hierarchical clustering of the treatment mean responses (Fig. 3) grouped N and K_2O together, both showing their strongest response under WL, whereas P_2O_5 and C-org clustered separately and showed their strongest response under the biochar treatments (RHC and WC), broadly consistent with the treatment patterns described above. This clustering reflects descriptive similarity in treatment response profiles rather than formal statistical testing; the full ANOVA outcomes for each variable, land-use system and sampling time are given in Table 2 and, as reported, statistical significance was confined to N, K_2O and P_2O_5 in IC soils.

Discussion

Nutrient dynamics under biomass amendment

The statistically significant treatment effects on total N, K_2O (both sampling times) and P_2O_5 (60 days) in IC soils (Table 2) can be explained by two complementary mechanisms operating differently across the tested materials. Wood leaves (WL), as a fresh, labile organic material, likely decomposed progressively over the 30–60 day incubation, releasing mineral N and K through ammonification and cation exchange, consistent with WL producing among the largest N and K_2O responses in IC soils, particularly by day 60 (17). In contrast, the biochar materials (RHC and WC) are expected to be dominated by more aromatic, recalcitrant C with comparatively high surface area and cation/anion exchange capacity; under this assumption, their pronounced effect on P_2O_5 and K_2O in IC soils is consistent with the recognised capacity of biochar to reduce phosphate sorption on iron (Fe) and aluminium oxide (Al_2O_3) surfaces and to supply exchangeable base cations (6, 16). Because this study did not directly characterise the pH, total C, or ash content of the RHC

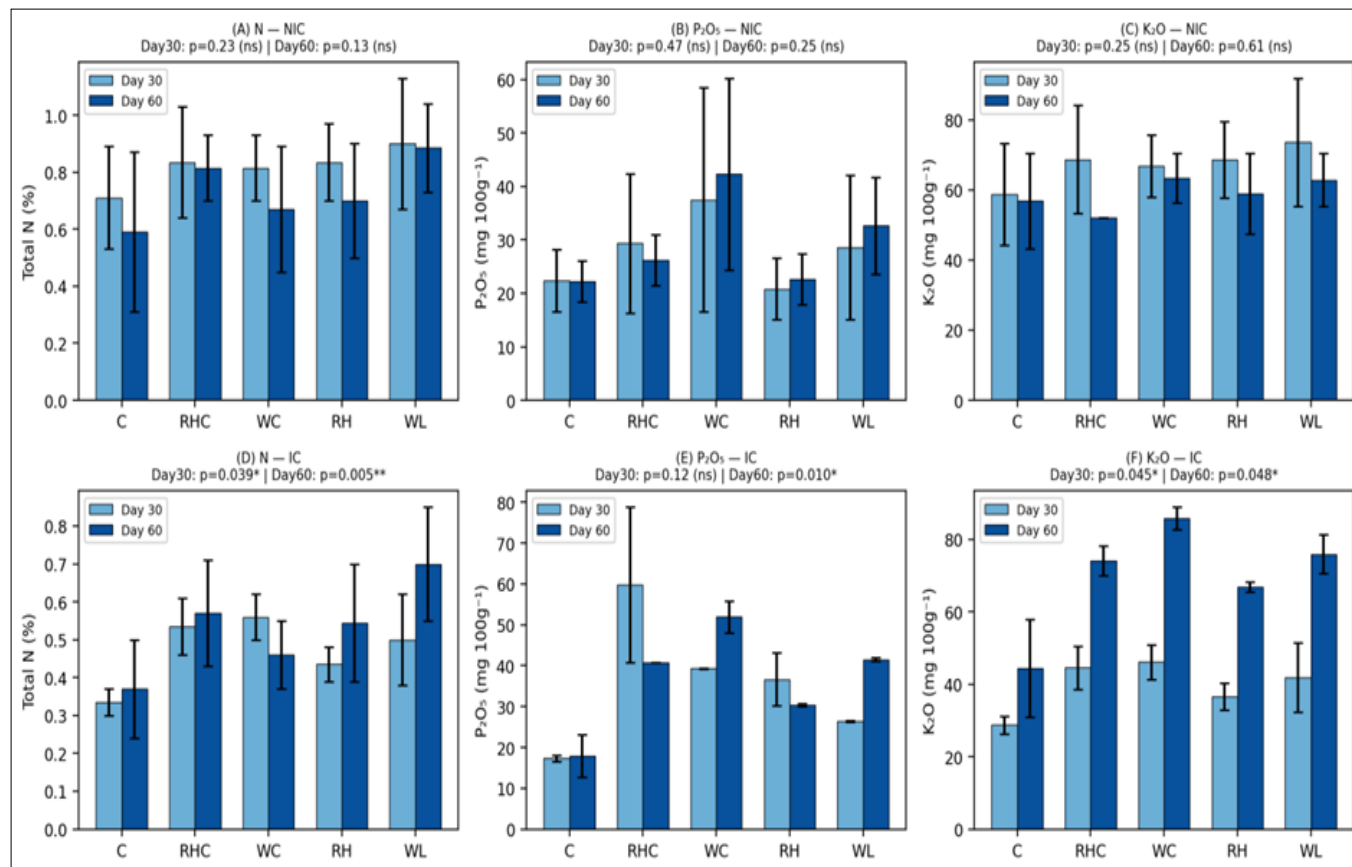


Fig. 1. Effects of biomass addition on soil macronutrients at 30 and 60 days of incubation, by land-use system. (A–C) NIC soils: total N, P₂O₅ and K₂O by biomass treatment (C, RHC, WC, RH, WL). (D–F) IC soils: total N, P₂O₅ and K₂O by biomass treatment. Bars show the mean across the two sites (Netpala, Kualeu); error bars span the site minimum-maximum range. Panel subtitles give the two-way ANOVA (treatment blocked by site) result for each sampling time (*p < 0.05, **p < 0.01, ns = not significant) (Table 2). Treatment effects were statistically significant only in IC soils.

Table 2. Two-way analysis of variance (ANOVA) summary (biomass treatment, blocked by site) for each land use system, sampling time and response variable

Land use	Day	Variable	F	df (trt, error)	p	Sig.
NIC	30	Total N	2.21	4, 4	0.230	ns
NIC	30	P ₂ O ₅	1.09	4, 4	0.468	ns
NIC	30	K ₂ O	2.09	4, 4	0.247	ns
NIC	30	Microbial P	0.47	4, 4	0.756	ns
NIC	30	pH	2.59	4, 4	0.190	ns
NIC	30	C-org	2.55	4, 4	0.194	ns
NIC	30	SWC	0.92	4, 4	0.531	ns
NIC	60	Total N	3.49	4, 4	0.127	ns
NIC	60	P ₂ O ₅	2.05	4, 4	0.252	ns
NIC	60	K ₂ O	0.77	4, 3	0.609	ns
NIC	60	Microbial P	0.93	4, 4	0.528	ns
NIC	60	pH	0.43	4, 4	0.784	ns
NIC	60	C-org	2.96	4, 4	0.159	ns
NIC	60	SWC	1.28	4, 4	0.407	ns
IC	30	Total N	7.37	4, 4	0.039	*
IC	30	P ₂ O ₅	3.64	4, 4	0.119	ns
IC	30	K ₂ O	6.78	4, 4	0.045	*
IC	30	Microbial P	0.90	4, 4	0.538	ns
IC	30	pH	1.17	4, 4	0.440	ns
IC	30	C-org	2.58	4, 4	0.191	ns
IC	30	SWC	0.63	4, 4	0.666	ns
IC	60	Total N	22.84	4, 4	0.005	**
IC	60	P ₂ O ₅	15.76	4, 4	0.010	*
IC	60	K ₂ O	6.56	4, 4	0.048	*
IC	60	Microbial P	1.00	4, 4	0.500	ns
IC	60	pH	1.00	4, 4	0.500	ns
IC	60	C-org	3.85	4, 4	0.110	ns
IC	60	SWC	4.59	4, 4	0.084	ns

Treatment df = 4 (5 treatments - 1); error df = 4 in most cases (one missing K₂O value at NIC Day 60 reduces error df to 3). Sig: *p < 0.05, **p < 0.01, ***p < 0.001, ns = not significant. Site (block) effects, not shown here, were frequently significant, reflecting genuine baseline differences between Netpala and Kualeu that justify the blocked design. N: nitrogen; P₂O₅: phosphorus pentoxide; K₂O: potassium oxide; P: phosphorus; C-org: soil organic carbon; IC: intensively cultivated; NIC: non-intensively cultivated; SWC: soil water content

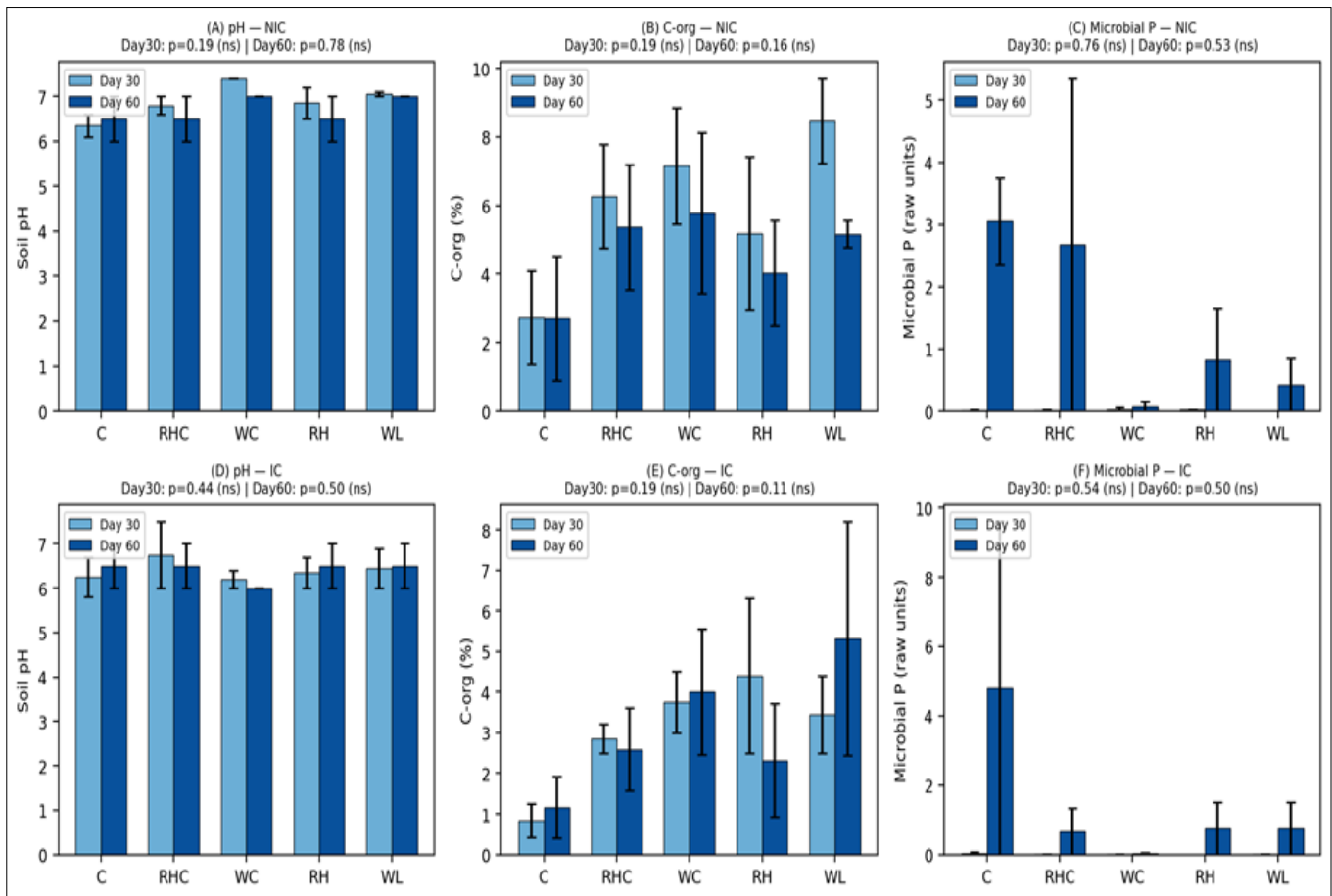


Fig. 2. Effects of biomass addition on soil pH, organic carbon (C-org) and microbial phosphorus at 30 and 60 days of incubation, by land-use system. (A-C) NIC soils: pH, C-org and microbial P (raw units as recorded; see Table 1 footnote) by biomass treatment. (D-F) IC soils: pH, C-org and microbial P by biomass treatment. Bars show the mean across the two sites (Netpala, Kualeu); error bars span the site minimum-maximum range. Panel subtitles give the two-way ANOVA result for each sampling time (Table 2); none of these treatment effects reached statistical significance at the achieved replication.

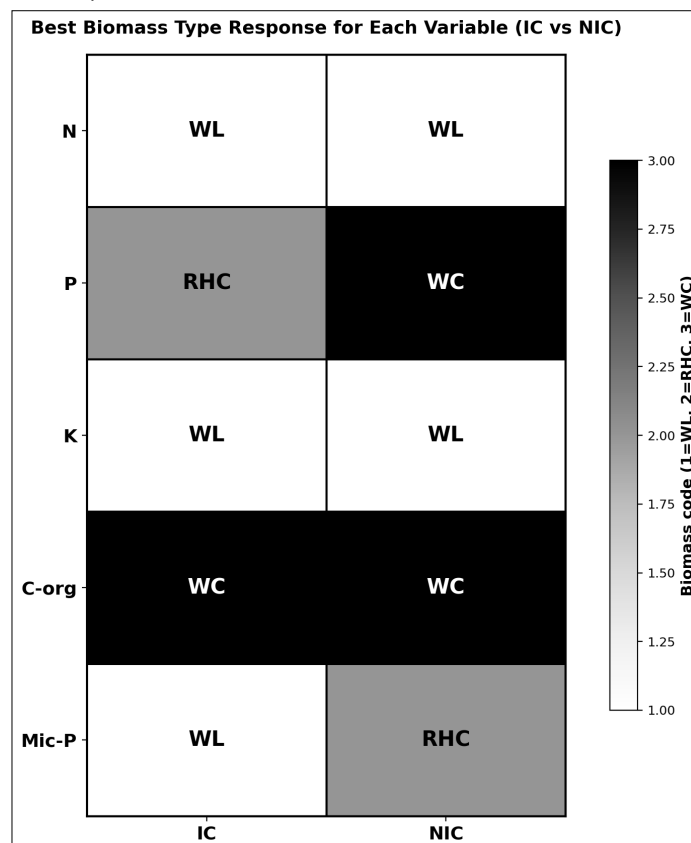


Fig. 3. Hierarchical clustering (heatmap) of soil response variables. The heatmap groups response variables linked to short-term nutrient release (N, K) with the WL treatment, while variables associated with structural soil improvement and longer-term stability (P, C-org) cluster with the biochar treatments (RHC, WC), illustrating two distinct pathways of soil response to biomass amendment.

and WC materials used, these explanations should be read as consistent with, rather than directly confirmed by the observed responses; future work should report basic biochar characterisation data (pH, total C, ash content) alongside soil response data to more rigorously support this mechanistic interpretation.

That treatment effects reached statistical significance in IC soils but not in NIC soils (Table 2) is consistent with nutrient cycling theory: soils with depleted internal nutrient reserves, such as the continuously cropped IC soils in this study, which had markedly lower and more consistent (less variable between sites) baseline N, P_2O_5 and K_2O than NIC soils (Table 1), tend to show a clearer, more detectable response to a given quantity of external organic input than soils that already maintain relatively higher and more heterogeneous internal nutrient cycling through intermittent fallow and ash deposition, as in the NIC system (2). The comparatively high between-site variability observed in NIC soils and in C-org and microbial P in both soil types, likely reflects genuine differences in fallow history, ash deposition and microclimate between Netpala and Kualeu; with only two site-blocks, this heterogeneity limited the statistical power available to detect treatment effects for these variables, even where the underlying numerical differences were often as large as or larger than those found to be significant in IC soils. The higher clay content of IC soils (30.8 % clay vs. 17 % in NIC) (Table 1) may also have contributed to greater P sorption capacity in the untreated control, amplifying the apparent relative benefit of biochar-mediated P desorption once RHC or WC was applied.

Soil pH, organic carbon and microbial phosphorus responses

Although treatment effects on soil pH and C-org did not reach statistical significance at the achieved replication (Table 2), the descriptive pattern, with the charcoal amendments, particularly WC, producing the largest numerical increases in both soil types, is consistent with expected biochar mechanisms: the base cations (e.g., Ca^{2+} , Mg^{2+} , K^+) typically present in ash-derived charcoal residues can raise pH, while the recalcitrant aromatic C structures in charcoal persist in soil and accumulate as C-org (7). The lack of statistical significance for C-org, despite some site $\times$ treatment combinations showing more than a five-fold increase relative to the control, reflects the high variability between Netpala and Kualeu in this variable; direct measurement of soil aggregate stability and a larger number of site replicates would help clarify whether this reflects genuine site-dependent C stabilisation or simply limited statistical power.

Microbial P did not show a statistically significant treatment effect in either soil type at either sampling time (Table 2), in contrast to the clearer chemical responses observed for N, P_2O_5 and K_2O in IC soils. This may reflect genuinely weaker or more variable microbial responses to a single 20 t ha^{-1} biomass pulse over 30–60 days, particularly given that microbial P integrates both substrate availability and the pre-existing microbial community, which is itself likely to vary between sites independently of biomass treatment. The numerically larger, though not statistically confirmed, increases in microbial P under RH and RHC in NIC soils by day 60 are broadly consistent with the general expectation that fresh, labile organic inputs and porous biochar substrates can support microbial colonisation over time (17, 18); confirming this pattern would require greater replication and ideally additional microbial indicators beyond microbial P.

Differential responses between intensive cultivation (IC) and non-intensive cultivation (NIC) soils and implications for dryland management

Across the response variables with statistically significant treatment effects, N, P_2O_5 and K_2O in IC soils, biomass type and land-use history jointly determined the magnitude of soil response. Wood leaves was among the most effective amendments for N and K_2O enrichment in IC soils by day 60, reflecting its highly labile organic fractions, which decompose and mineralise progressively and are therefore well suited to supporting nutrient demand in the more degraded IC soils. Phosphorus and K responses were dominated by the biochar amendments: RHC produced the strongest P_2O_5 increase and WC the strongest K_2O increase in IC soils, plausibly reflecting greater P and cation sorption in the more clay-rich, more acidic IC soil (Table 1) that biochar mediated surface modification can more readily counteract. For C-org and microbial P and for all variables in NIC soils, treatment differences were numerically present but did not reach statistical significance at the achieved replication, so these patterns should be regarded as descriptive rather than confirmed.

Taken together, these patterns suggest that biomass amendment is most reliably beneficial, at the tested 20 t ha^{-1} rate, for improving N, P and K availability in IC-type soils, which are more chemically degraded and less variable in their baseline condition; effects on NIC-type soils and on pH, C-org and microbial P in either soil type were not statistically distinguishable from no effect in this study, given the limited replication. For dryland soils in TTS, which are predominantly sandy loam to sandy-clay loam with generally low C-org (Table 1), this indicates that fresh, labile materials such as WL and charcoal-type amendments such as RHC and WC both have a role to play in intensively cultivated soils, with WL more relevant for short-term N and K replenishment and the biochars more relevant for P and K availability. Whether these benefits extend to non-intensively cultivated (fallow based) soils and whether they translate into detectable changes in C-org or microbial P, remains to be confirmed with greater site replication.

Conclusion

This two-site, two timepoint incubation study found that biomass amendment significantly improved total N, K_2O and P_2O_5 (60 days) in intensively cultivated (IC) dryland soils ($p < 0.05$), while effects in non-intensively cultivated (NIC) soils and on pH, organic carbon (C) and microbial P in either soil type, were not statistically significant at the achieved replication (two site blocks). Intensively cultivated soils, starting from a lower and less variable baseline, showed the clearest responses; wood leaves (WL) were most effective for N and K_2O and the biochar amendments (rice husk charcoal (RHC), wood charcoal (WC)) for P_2O_5 and K_2O . These results are bounded by a high (20 t ha^{-1}), non-field representative application rate, a 30–60-day laboratory window, modest statistical power and microbial P as the sole microbial indicator. Within this scope, biomass amendment, particularly with wood leaves or biochar, shows promise for improving short term soil chemical status in degraded, intensively cultivated tropical dryland soils. Confirming this for field use and for NIC soils, organic C and microbial P, will require field trials with greater replication, realistic application rates and longer observation periods.

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Authors' contributions

MRS M led the overall research program, including hypothesis formulation, conceptual and methodological design of the field experiment and integration of soil–plant–climate interactions within a semi-arid agroecosystem framework. MRS M also coordinated and supervised field implementation and laboratory analyses, ensured data quality, performed advanced statistical analyses, interpreted and synthesised the results and led manuscript structuring, scientific writing, critical revision and response to peer review. MRS M also served as the guarantor of the study's scientific integrity and managed correspondence with the journal. WB contributed to the experimental setup and management, data processing, statistical validation and improvement of the overall scientific clarity. SV contributed to laboratory analysis and interpretation of the results. AAGMT contributed to interpretation and drafting paper. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 5.2 (OpenAI) in order to enhance the clarity of the writing. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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