

Residual Effects of Moroccan Rock Phosphate and Triple Superphosphate on Chemical Properties of Acid Rice Soils in Côte d'Ivoire: A Comparison Between Lowland and Upland Ecologies

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DOI: <https://doi.org/10.36347/sajb.2026.v14i04.001>

| Received: 17.02.2026 | Accepted: 26.03.2026 | Published: 01.04.2026

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Abstract

Original Research Article

This study was carried out in Côte d'Ivoire, where acid rice soils are characterized by chronic phosphorus (P) deficiency and low chemical fertility that constrain productivity. The use of Morocco rock phosphate (RP) as an alternative amendment to triple superphosphate (TSP), represents a promising option; however, its medium-term effects on soil chemical properties across contrasting rice-growing ecologies remain insufficiently documented. The present study assessed the residual effects of six PR/TSP combinations (ranging from 100% RP to 100% TSP at a total application rate of 300 kg ha⁻¹) on soil chemical properties after two successive cropping cycles in lowland (hydromorphic sandy soils, pH 5.6) and upland (argilo-sandy Ferralsols, pH 5.2) ecologies in the Man zone, Côte d'Ivoire. A randomized complete block design with four replicates and eight treatments was used. Before establishment, both soils showed degraded chemical characteristics: very low available phosphorus (P initial: 5 mg kg⁻¹ in upland, 2.1 mg kg⁻¹ in lowland), low CEC (8.5 and 3.4 cmol⁺ kg⁻¹ respectively) and low organic carbon. After two cycles, results show that phosphate amendment significantly increased total nitrogen, available phosphorus, organic matter and cation exchange capacity (CEC) in both ecologies. In lowland, CEC reached 116.75 cmol⁺ kg⁻¹ under T0 at the second cycle, and organic matter increased strongly (up to 92,269 mg kg⁻¹ under T6). Treatment T3 (80% PR + 20% TSP) showed the highest available P content in lowland (14 mg kg⁻¹) and upland (2 mg kg⁻¹). The C/N ratio revealed rapid mineralization under T4 in lowland (C/N = 6.4 at cycle 2), while the upland showed normal to slow mineralization (C/N between 11 and 13). Lowland ecology responds more strongly to phosphate amendment, due to more intense biological activity and favorable redox conditions. These results confirm the importance of differentiated phosphate fertilization management according to rice ecologies.

Keywords: Natural phosphate, soil fertility; organic matter; Côte d'Ivoire.

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1. INTRODUCTION

The decline in soil fertility is one of the major constraints on rice production in sub-Saharan Africa (Koulibaly, 2011). In Côte d'Ivoire, nearly two-thirds of rice-growing areas are located on acidified soils (pH < 5.5), characterized by low cation exchange capacity (CEC), a deficiency in essential minerals (P, K, Ca, Mg), and significant phosphorus retrogradation by the metal cations Al³⁺ and Fe²⁺ (Sahrawat *et al.*, 2001; Akassimadou *et al.*, 2017). Under these conditions,

phosphorus (P) deficiency is the primary limiting factor for rice productivity (Razafinimpiasa *et al.*, 2022).

Given the high cost of soluble phosphate fertilizers such as triple superphosphate (TSP), Moroccan phosphate rock (MPR) emerges as a potentially accessible alternative for rice-growing systems. Its dissolution is enhanced in acidic conditions, and its chemical reactivity allows it to act both as a sustained-release source of phosphorus and as a calcium amendment (Adou *et al.*, 2025). While its effects on crop

yields have been documented (Bado *et al.*, 1997; Lompo *et al.*, 2007; Boueunan *et al.*, 2024; Kouakou *et al.*, 2024), its medium-term impacts on soil chemical properties—particularly the dynamics of available phosphorus, organic matter, cation exchange capacity (CEC), and the C/N ratio—remain poorly studied across the various rice-growing contexts in Côte d’Ivoire (Kpan *et al.*, 2023). The decline in soil fertility is one of the major constraints; lowland and upland soils exhibit marked differences in texture, water regime, and biological activity, which may influence the response to phosphate amendment (Haefele, 2001; Pouya *et al.*, 2023). A better understanding of these interactions appears essential for adapting fertilization strategies to the country’s main rice-growing systems. This study thus aims to evaluate the residual effect of six combinations

(PR/TSP) on the main chemical properties of soils after two successive cropping cycles in the lowland and on the Man upland. The hypothesis is that treatments with a high proportion of PR improve soil chemical fertility, with a response that varies depending on the cropping ecology.

2. MATERIALS AND METHODS

2.1. Study site, experimental design, and treatments

The study was conducted at the National Center for Agricultural Research (CNRA) station in Man, in two contrasting ecosystems: hydromorphic lowland (N 07°21'12"; W 07°36'19") and a ferrallitic upland (N 07°20'57"; W 07°36'19").

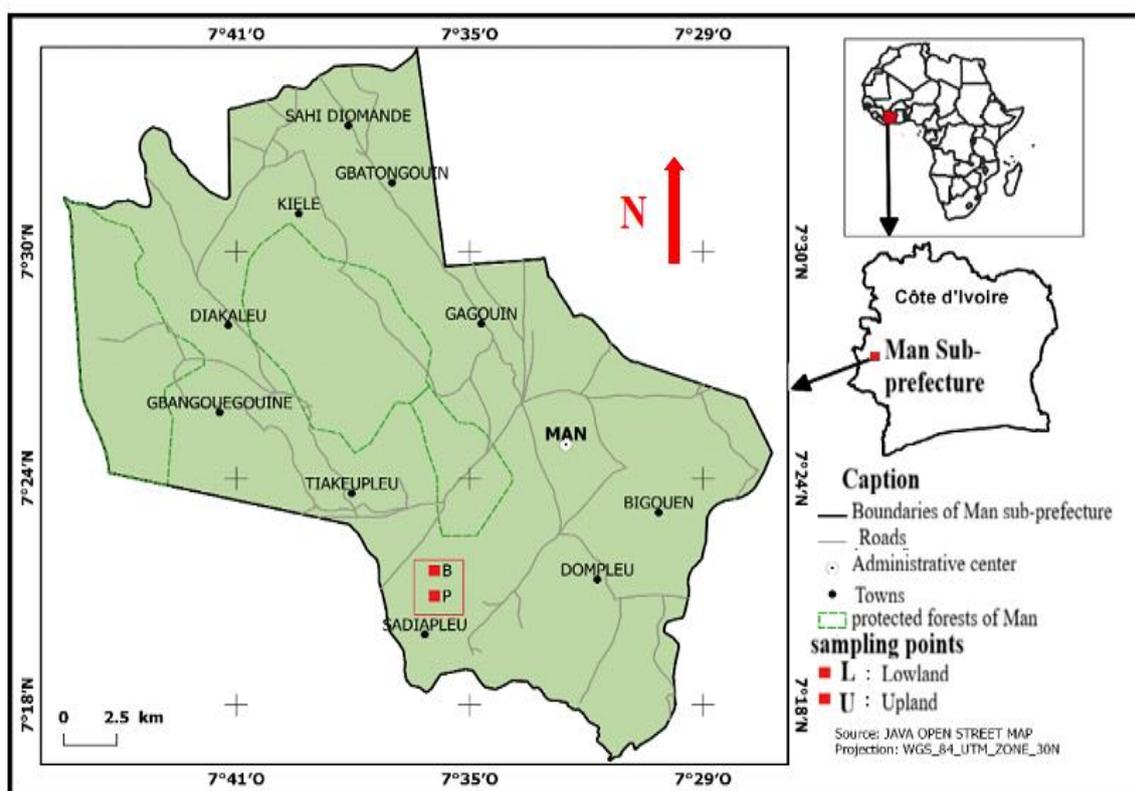


Figure 1: Location of the study site on the map of the Man sub-prefecture

The experimental design was a completely randomized block design with five replicates and eight treatments, described in detail by Kpan *et al.* (2023) and Kouakou *et al.* (2024): two control treatments (T0a: unfertilizer; T0: NPK + urea only) and six combinations (PR/TSP) applied at a total dose of 300 kg ha⁻¹ of P₂O₅ (90 kg P₂O₅ ha⁻¹): T1 (100% PR), T2 (90% PR + 10% TSP), T3 (80% PR + 20% TSP), T4 (60% PR + 40% TSP), T5 (20% PR + 80% TSP), and T6 (100% TSP). The Moroccan PR (OCP-Africa) contained 30% P₂O₅ and 49.54% CaO. All treated plots received a basal application of NPK 15-15-15 (200 kg ha⁻¹) supplemented with 46% N urea (100 kg ha⁻¹). Phosphate

amendment and TSP were incorporated to a depth of 20 cm prior to the first cycle only; the second cycle was conducted without additional phosphate application in order to evaluate the residual effect.

2.2. Soil sampling and analysis

Soil samples were collected prior to the start of the experiment (initial condition) and at harvest for each crop cycle, from the 0–20 cm layer on the upland and the 0–10 cm layer in the lowland (due to hydromorphic conditions). For each experimental plot, a composite sample was prepared from three cores collected at the yield squares using the diagonal sampling method. After air-drying and sieving to 2 mm, physicochemical

analysis were conducted at the OCP (Office Chérifien des Phosphates) laboratory in Abidjan. The parameters analyzed were: (i) particle size distribution using the Robinson-Köln pipette densimetric method (Robinson, 1992); (ii) water pH (soil/water ratio = 1/2.5, WTW inoLab pH 7110 pH meter) and KCl pH (1 M KCl solution); (iii) organic carbon (Walkley and Black, 1934) and organic matter (OM = C × 1.724; Baize, 2000); (iv) total nitrogen by the Kjeldahl method (Bremner, 1996); (v) available phosphorus (P_{av}) according to the Olsen-Dabin method (Olsen and Sommers, 1982); (vi) exchangeable bases (K⁺, Na⁺, Ca²⁺, Mg²⁺) extracted with 1 M ammonium acetate at pH 7 and determined by atomic absorption spectrophotometry (Ca, Mg) and flame spectrophotometry (K); (vii) cation exchange capacity (CEC) using the Metson method (1956).

2.3. Statistical Analysis

The data were subjected to an analysis of variance (ANOVA) using XLSTAT 2014.5.03 software at a 5% significance level. Mean comparisons were performed using the Student-Newman-Keuls (SNK) test (p < 0.05). Pearson correlations were calculated between soil chemical properties and grain yields to characterize the relationships between soil fertility and production.

3. RESULTS

3.1. Initial physicochemical characteristics of the soils

The soil on upland had a sandy-clay texture (29% clay, 55% sand), while the soil in the lowland was predominantly sandy (6% clay, 81% sand). Chemically, both soils were acidic (soil pH: 5.2 on upland; 5.6 in the lowland) and chemically depleted: very low levels of available phosphorus (5 mg kg⁻¹ on upland; 2.1 mg kg⁻¹ in the lowland), total nitrogen (13 and 7 mg kg⁻¹ respectively), and low cation exchange capacity (CEC) (8.5 and 3.4 cmol⁺ kg⁻¹). The initial C/N ratios (11 on upland ; 9.8 in the lowland) indicated slow to normal organic matter decomposition. The base saturation rate was low in the lowland), total nitrogen (13 and 7 mg kg⁻¹ respectively), and low cation exchange capacity (CEC) (8.5 and 3.4 cmol⁺ kg⁻¹). The initial C/N ratios (11 on the plateau; 9.8 in the lowland) indicated slow to normal organic matter decomposition. The base saturation rate was low in both ecosystems (15.66% on upland ; 10.27% in lowland), confirming the oligotrophic status of these soils (Table 1).

Table 1: Initial physicochemical characteristics of rice paddy soils in Man (before trial establishment)

Plots	P H ₂ O	P H KCl	P _{ass}	C	N	OM	C/N	CEC	C a ²⁺	K ⁺	S/T
Upland	5,2	3,6	5,0	143	13	246	11,0	8,5	4,96	0,96	15,66
Lowland	5,6	4,3	2,1	69	7	119	9,8	3,4	2,47	0,22	10,27

P_{ass}: available phosphorus (Olsen-Dabin method), OM: organic matter, CEC: cation exchange capacity, BSS: base saturation. Unity of physicochemical characteristics : P_{ass}: mg kg⁻¹; C : mg kg⁻¹; N : mg kg⁻¹; OM : mg kg⁻¹; CEC : cmol⁺ kg⁻¹; ST : %

3.2. Residual effect of phosphate amendment on soil total nitrogen

After two growing cycles, soil nitrogen levels increased in both ecosystems compared to baseline values (upland: 13 mg kg⁻¹; lowland: 7 mg kg⁻¹), regardless of the treatment (Table 2). In the lowland, significant differences between treatments were observed in both crop cycles (p < 0.05), unlike on the upland, where treatments did not differ significantly. In the first cycle, N levels in the lowland ranged from 800

mg kg⁻¹ (T3, T6) to 1,250 mg kg⁻¹ (T4, T5), with treatments T0, T4, and T5 showing the highest values. In the second cycle, treatments T0 (NPK + urea, 3,450 mg kg⁻¹) and T6 (100% SPT, 3,000 mg kg⁻¹) stood out in the low-lying areas, while T2 had the lowest levels (1,675 mg kg⁻¹). On the plateau, concentrations in the second cycle ranged from 825 mg kg⁻¹ (T3) to 950 mg kg⁻¹ (T6), with no significant difference between treatments.

Table 2: Mean total nitrogen content in rice paddy soils in Man, before and after two crop cycles

Treatments	Upland: initial	Upland : harvest C1	Upland : harvest C2	Lowland : initial	Lowland : harvest C1	Lowland : harvest C2
T0a	13 ^a	1 000 ± 100 ^{ab}	875 ± 100 ^a	7 ^a	1 000 ± 150 ^{ab}	2 200 ± 139 ^{bc}
T0	13 ^a	1 050 ± 182 ^{ab}	850 ± 96 ^a	7 ^a	1 225 ± 182 ^a	3 450 ± 365 ^a
T1	13 ^a	1 125 ± 150 ^a	900 ± 164 ^a	7 ^a	900 ± 258 ^b	1 875 ± 427 ^c
T2	13 ^a	1 050 ± 208 ^{ab}	900 ± 163 ^a	7 ^a	900 ± 258 ^b	1 675 ± 665 ^c
T3	13 ^a	1 000 ± 163 ^{ab}	825 ± 170 ^a	7 ^a	800 ± 282 ^b	2 125 ± 441 ^{bc}
T4	13a	1 075 ± 95 ^{ab}	925 ± 125 ^a	7 ^a	1 225 ± 95 ^a	2 225 ± 442 ^{bc}
T5	13 ^a	900 ± 81 ^c	875 ± 95 ^a	7 ^a	1 250 ± 238 ^a	1 975 ± 95 ^c
T6	13 ^a	933 ± 115 ^{ab}	950 ± 191 ^a	7 ^a	800 ± 216 ^b	3 000 ± 513 ^{ab}

T0a : unfertilized, T0 : NPK + Urea, T1 : 100 % PR, T2 : 90 % PR + 10 % TSP, T3 : 80 % PR + 20 % TSP, T4 : 60 % PR + 40 % TSP, T5 : 20 % PR + 80 % TSP, T6 : 100 % TSP.

Values followed by the same letter in a column are not significantly different (SNK test, $p < 0.05$). NS: not significant. C1: cycle 1, C2: cycle 2.

3.3 Residual effect of phosphate amendment on soil available phosphorus

Available P levels increased in both ecosystems following the application of phosphate amendment, compared to initial levels (Table 3). In the lowland area, the increases were substantial and significant in both cycles ($p < 0.05$): concentrations in the first cycle ranged from 12.5 mg kg⁻¹ (T6) to 27.6 mg kg⁻¹ (T5), followed by a moderate decrease in the second cycle (8.8 to 14 mg kg⁻¹), with concentrations nevertheless remaining higher

than the initial level (2.1 mg kg⁻¹). Treatment T3 (80% RP) had the highest value in the second cycle at the low point (14 mg kg⁻¹), while T5 (20% RP) recorded the lowest value (8.8 mg kg⁻¹). On the plateau, variations between treatments were not significant, and concentrations after two cycles (1.77 to 2 mg kg⁻¹) remained lower than the initial state (5 mg kg⁻¹), indicating strong P retention in this acidic sandy loam soil. The slight upward trend observed between cycle 1 and cycle 2 at the plateau may reflect a gradual mobilization of P from PR particles that had not yet dissolved.

Table 3: Mean available phosphorus content in rice paddy soils in Man, before and after two crop cycles

Treatments	Upland: initial	Upland: harvest C1	Upland: harvest C2	Lowland: initial	Lowland: harvest C1	Lowland: harvest C2
T0a	5 ^a	1,60 ± 0,23 ^a	1,87 ± 0,17 ^a	2,1 ^a	17,1 ± 5,0 ^{abc}	13,5 ± 4,3 ^a
T0	5 ^a	1,65 ± 0,15 ^a	1,85 ± 0,17 ^a	2,1 ^a	26,4 ± 7,2 ^{ab}	13,4 ± 4,3 ^a
T1	5 ^a	1,47 ± 0,30 ^a	1,77 ± 0,20 ^a	2,1 ^a	21,0 ± 9,8 ^{abc}	12,7 ± 8,8 ^a
T2	5 ^a	1,60 ± 0,05 ^a	2,00 ± 0,12 ^a	2,1 ^a	16,7 ± 5,1 ^{bc}	10,2 ± 5,7 ^a
T3	5 ^a	1,50 ± 0,10 ^a	2,00 ± 0,31 ^a	2,1 ^a	19,2 ± 8,4 ^{abc}	14,0 ± 6,3 ^a
T4	5 ^a	1,50 ± 0,30 ^a	1,90 ± 0,30 ^a	2,1 ^a	17,1 ± 6,2 ^{bc}	12,4 ± 6,2 ^a
T5	5 ^a	1,60 ± 0,20 ^b	2,00 ± 0,28 ^b	2,1 ^a	27,6 ± 9,8 ^a	8,8 ± 1,1 ^a
T6	5 ^a	1,40 ± 0,08 ^a	1,80 ± 0,26 ^a	2,1 ^a	12,5 ± 2,5 ^c	9,1 ± 1,2 ^a

T0a : Unfertilized, T0 : NPK + Urea, T1 : 100 % PR, T2 : 90 % PR + 10 % TSP, T3 : 80 % PR + 20 % TSP, T4 : 60 % PR + 40 % TSP, T5 : 20 % PR + 80 % TSP, T6 : 100 % TSP.

Values followed by the same letter in a column indicate no significant difference (SNK test, $p < 0.05$). NS: not significant in the plateau for all cycles. C1 : Cycle1; C1 : cycle 1.

3.4. Changes in exchangeable potassium

There were no significant differences in exchangeable potassium (K⁺) concentrations between treatments in either ecosystem (Table 4). In the shallow water, levels in cycle 1 (0.10–0.14 cmol⁺ kg⁻¹) and then

in cycle 2 (0.13–0.18 cmol⁺ kg⁻¹) remained below the initial values (0.22 cmol⁺ kg⁻¹), despite a slight increase between the two cycles. On the plateau, an increase was observed in cycle 1 under all treatments compared to the initial state (0.96 cmol⁺ kg⁻¹), followed by a sharp drop in cycle 2 (0.06–0.077 cmol⁺ kg⁻¹). T1 (100% RP) exhibited the highest levels at the plateau in the second cycle (0.077 cmol⁺ kg⁻¹), while T0 and T6 showed the lowest values (0.06 cmol⁺ kg⁻¹).

Table 4: Mean exchangeable potassium content in rice paddy soils in Man, before and after two crop cycles

Treatments	Upland: initial	Upland: C1	Upland: C2	Lowland: initial	Lowland: C1	Lowland: C2
T0a	0,96 ^a	0,14 ± 0,009 ^a	0,070 ± 0,05 ^a	0,22 ^a	0,12 ± 0,01 ^a	0,16 ± 0,04 ^a
T0	0,96 ^a	0,12 ± 0,02 ^a	0,060 ± 0,01 ^a	0,22 ^a	0,14 ± 0,04 ^a	0,16 ± 0,05 ^a
T1	0,96 ^a	0,13 ± 0,01 ^a	0,077 ± 0,005 ^a	0,22 ^a	0,13 ± 0,03 ^a	0,15 ± 0,04 ^a
T2	0,96 ^a	0,11 ± 0,008 ^a	0,070 ± 0,005 ^a	0,22 ^a	0,11 ± 0,02 ^a	0,13 ± 0,03 ^a
T3	0,96 ^a	0,10 ± 0,009 ^a	0,070 ± 0,01 ^a	0,22 ^a	0,10 ± 0,01 ^a	0,16 ± 0,02 ^a
T4	0,96 ^a	0,12 ± 0,009 ^a	0,070 ± 0,01 ^a	0,22 ^a	0,12 ± 0,08 ^a	0,17 ± 0,08 ^a
T5	0,96 ^a	0,11 ± 0,009 ^a	0,070 ± 0,005 ^a	0,22 ^a	0,11 ± 0,02 ^a	0,15 ± 0,03 ^a
T6	0,96 ^a	0,10 ± 0,02 ^a	0,060 ± 0,009 ^a	0,22 ^a	0,10 ± 0,02 ^a	0,18 ± 0,04 ^a

T0a : unfertilized, T0 : NPK + Urea, T1 : 100 % PR, T2 : 90 % PR + 10 % TSP, C1: cycle 1, T3 : 80 % PR + 20 % TSP, T4 : 60 % PR + 40 % TSP, T5 : 20 % PR + 80 % TSP, T6 : 100 % TSP.

No significant differences among treatments were observed in either ecosystem (NS, SNK test, $p < 0.05$). C1: cycle 1; C2: cycle 2.

3.5. Changes in organic matter, C/N ratio, and cation exchange capacity

After two growing cycles, a marked improvement in organic matter (OM) was observed compared to the initial levels on the upland (246 mg kg⁻¹) and in the lowland (119 mg kg⁻¹). On the upland, concentrations reached 12,373 mg kg⁻¹ in cycle 1 (T2), representing a 9,550% increase. In the second cycle, a

slight decrease was observed (19,780 mg kg⁻¹), but levels remain well above the baseline, representing a 7,940% increase. In the lowland area, OM accumulation was even more pronounced and continued between cycles. Concentrations from 34,539 mg kg⁻¹ in cycle 1 (+28,900%) to 92,269 mg kg⁻¹ in cycle 2 (+77,400%) compared to initial values. The highest levels were observed under T6 (100% TSP).

The C/N ratio remained relatively stable at the plateau (11-13), indicating normal to slightly slowed mineralization of organic matter. In the shallow water, two dynamics were distinguished: C/N ratios < 9 (T4 and

T0) indicated rapid mineralization, while C/N ratios (9–13) under the other treatments were characteristic of a more balanced mineralization regime. At the bottom, it increased from 3.4 cmol⁺ kg⁻¹ to 35.75 cmol⁺ kg⁻¹ in cycle 1 (+950%), then to 116.75 cmol⁺ kg⁻¹ in cycle 2 (+3,330%). At the plateau, CEC increased from 8.5 cmol⁺ kg⁻¹ to 24.75 cmol⁺ kg⁻¹ in cycle 1 (+191%), before stabilizing at 16.25 cmol⁺ kg⁻¹ in cycle 2, representing a residual increase of +121% compared to the initial state. The concordance of OM and CEC dynamics confirms the structuring role of organic matter in improving the adsorbent complex of the studied rice-growing soils. Detailed results are presented in Figure 2.

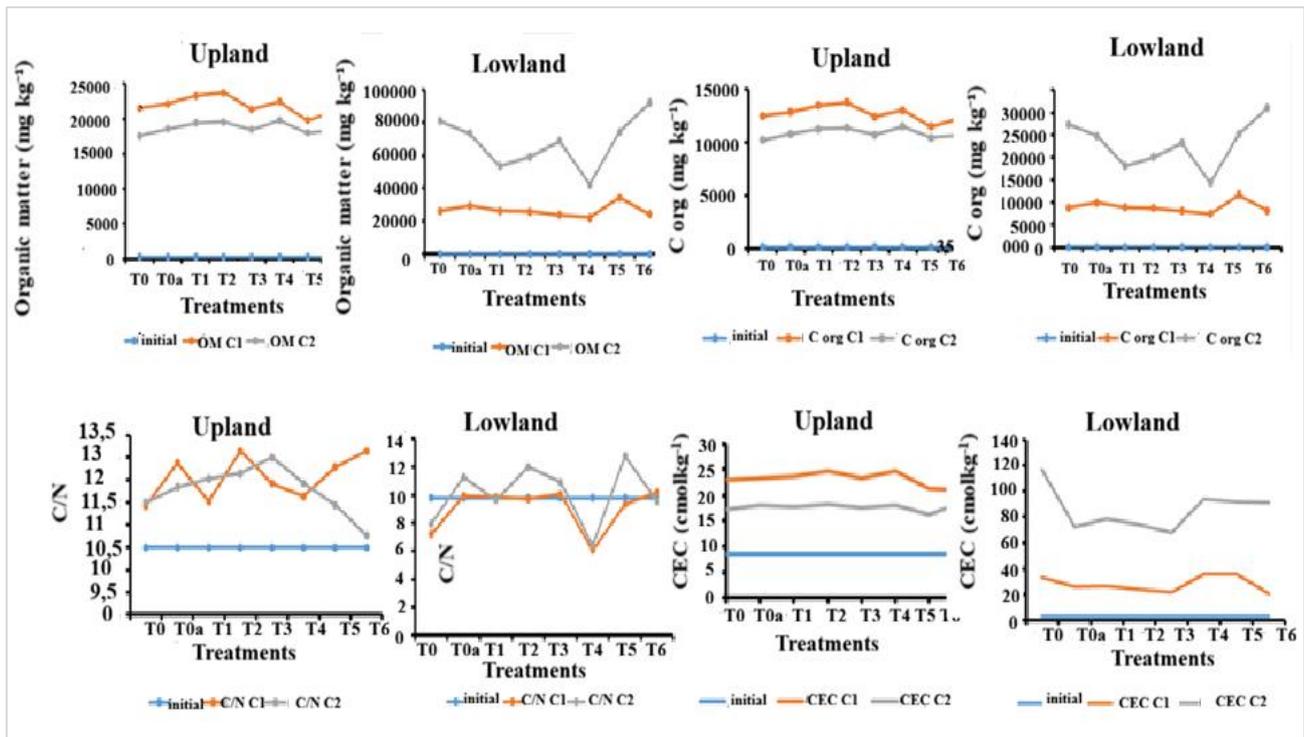


Figure 2: Evolution in organic matter and organic carbon, the C/N ratio, and cation exchange capacity in soils under different phosphate treatments after two crop cycles in upland and lowland ecosystems in the Man region T0= NPK; T0a= sans NPK; T1= 100 % RP; T2=90 % RP + 10% SPT; T3= 80 % RP + 20% SPT; T4 =60 % RP + 40% SPT; T5= 20 % RP + 80% SPT; T6= 100% SPT, C1: cycle 1, C1: cycle 2

4. DISCUSSION

4.1. Dynamics of Nitrogen and Available Phosphorus in Rice-Growing Soils

The increase in soil nitrogen levels, which exceeded initial values in both ecological systems, indicates positive interactions between phosphate amendments and nitrogen dynamics. On acidic soils, phosphate fertilizers stimulate the activity of microorganisms involved in organic matter mineralization and nitrification, promoting nitrate accumulation (Kotchi, 2010). The superiority of T0 (NPK) in the lowland during the second cycle for nitrogen is explained by the direct availability of mineral nitrogen in the form of urea, whose uptake by roots is facilitated by the water conditions in the lowland. The lower accumulation of N under amended treatments (T2, T3) is consistent with the observations of Kam (2016)

and Traoré (2015), who reported increased losses due to volatilization and leaching under combined fertilization. The sharp increase in available phosphorus in the bottom layer during the first cycle, followed by a moderate decline during the second cycle, reflects two opposing processes well documented in the literature: the rapid release of soluble phosphorus (SPT, SPT fraction of the mixtures) followed by its gradual immobilization through adsorption onto iron and aluminum oxides (Fardeau, 1993; Mihoub, 2012). The superiority of the lowland over the plateau in terms of P availability stems from the combined effect of a more favorable pH (5.6 vs. 5.2), more intense biological activity that mobilizes organic P, and redox conditions associated with periodic waterlogging that reduce Fe³⁺ oxides to less adsorbent Fe²⁺ (Haefele, 2001; Frossard and Sinaj, 1997). These results confirm those of Lompo *et al.* (2007) regarding

the gradual solubilization of natural phosphates in the Lixisols of Burkina Faso. The slight increase in available P observed between C1 and C2 clearly reflects the effect of the gradual release of RP in an acidic environment (Prakash and Badrinath, 1995). The dramatic increase in CEC in the topsoil (from 3.4 to over 100 $\text{cmol}^+ \text{kg}^{-1}$ in cycle 2) is directly linked to the accumulation of organic matter, the primary determinant of CEC in sandy soils with low mineral content (Koull and Halilat, 2016; Amonmide, 2019). This relationship between OM and CEC, observed in both ecosystems, is fundamental to the long-term fertility of these soils: increased CEC improves the retention of nutrient cations (Ca^{2+} , Mg^{2+} , K^+) and reduces the risk of leaching. The more moderate effect on the plateau can be explained by the sandy-clay texture (29% clay), which contributes more to the baseline CEC, thereby limiting the relative variation following amendment.

4.1. Dynamics of organic matter, C/N ratio, and CEC

The significant increase in organic matter in both ecosystems after two crop cycles is remarkable given the very low initial values. This is mainly due to the accumulation of root biomass and crop residues (rice straw) in the plots, amplified by the application of phosphate fertilizers, which improved plant productivity and thus organic matter returns to the soil. The more pronounced increase in the lowland area results from the additional supply of organic matter via runoff and a slowing of decomposition under hydromorphic conditions, a phenomenon well documented in irrigated rice fields (Menzies, 2003). Analysis of the C/N ratio reveals differing mineralization dynamics depending on the ecological context and treatment. On the plateau, C/N ratios maintained between 11 and 13 reflect moderate biological activity and gradual humification, consistent with the observations of Koulibaly *et al.* (2015) on Ivorian Ferralsols. In the lowland, C/N ratios below 9 observed under T4 in both cycles indicate rapid mineralization of organic matter, which promotes the release of nutrients and is consistent with the high rice productivity observed under this treatment in the companion article. This dynamic is explained by the combination of more intense biological activity and the application of P in a mixed form, which stimulates decomposing microorganisms (Assémien, 2018; Soltner, 2000).

5. CONCLUSION

This study highlights the significant long-term effect of combined applications of Moroccan phosphate rock and triple superphosphate, in conjunction with basic mineral fertilization, on change in the chemical properties of acidic rice-growing soils in the Man region after two crop cycles. Treatment T3 stood out for having the highest levels of available phosphorus in both ecological zones, reaching 14 mg kg^{-1} in the lowlands and 2 mg kg^{-1} on the plateau. This result confirms the ability of phosphate rock to ensure, as a partial substitute for triple superphosphate, a sustainable maintenance of

phosphorus availability, thus reflecting a favorable residual effect in the medium term.

Furthermore, the after-effect of phosphate amendments resulted in a marked improvement in organic matter and cation exchange capacity, particularly in the lowland. The hydromorphic conditions there favored biomass accumulation and carbon stabilization. The C/N ratio observed under T4 in the lowland indicates rapid mineralization dynamics, contributing to nutrient mobilization and the agronomic utilization of residual phosphorus.

Overall, lowland soils showed greater sensitivity to the after-effect of phosphate applications, due to physicochemical conditions more favorable to the dissolution and mobilization of phosphorus from the RP. These results support a differentiated approach to phosphorus fertilization management based on rice-growing ecosystems. They also confirm that Moroccan phosphate rock is a sustainable alternative to SPT for the gradual improvement of the chemical fertility of acidic soils in western Côte d'Ivoire. However, longer-term investigations (three to five growing seasons) would be necessary to clarify the kinetics of phosphorus release and the stabilization of CEC gains in these contrasting soil systems.

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