Global Advanced Research Journal of Agricultural Science (ISSN: 2315-5094) Vol. 13(1) pp. 001-011, May, 2025.
Available online https://garj.org/garjas

10.5281/zenodo.15477105

Full Length Research Paper

Use of leguminous cover crops (*Mucuna pruriens and Desmodium intortum*) to mobilize phosphorus from an Andosol in the volcanic highlands of North Kivu (Eastern DR Congo)

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Received 14 December, 2024; Reversed 15 February 2025 and Accepted 15 March 2025

Low availability of phosphorus (P) bound by amorphous minerals, losses of soluble P due to soil erosion and phosphorus exports in crops are among the main constraints to agricultural production in the volcanic highlands of North Kivuin the Democratic Republic of Congo. This study was carried out to determine the capacity of cover legumes (*Mucuna pruriens* and *Demodium intortum*) to influence soil P mobilization for the improvement of phosphate nutrition in maize cultivated on young andosol. To this end, an experiment was conducted using a randomized and subdivided complete block design (Split-plot) comprising five cropping systems (monoculture maize; maize+Mucuna as a catch crop; maize+Mucuna in PCCS; maize+Desmodium as a catch crop; maize+Desmodium in PCCS). Treatments were repeated 4 times over two cropping seasons (September 2023 and February 2024). The results showed that the soil was a *Vitric Lomic Sideralic Andosol*, corresponding to a young Andosol on basic pyroclastic material with a low available P content (1.6% of total P), giving a retention rate of 98.5%.The maize+Mucuna PCCS combination produced the most significant improvement in soil-available P and phosphate nutrition in maize. By incorporating 19.7t/ha of dry biomass of *Mucuna pruriens* into the soil, available P increased from 1.6% to 3.9%, i.e. an increase of 28 $mgKg^{-1}$ of P compared with the pre-crop concentration. Improved P nutrition also led to an increase in maize grain yields of 4 t/ha and dry biomass yields of 13 t/ha from September 2023 to February 2024. In addition, P exports in harvested maize grain increased from 3.7Kg/ha in the September 2023 season to 19.8Kg/ha in the February season, with no significant reduction in soil P mobilization. Thus, the Maize+Mucuna association in PCCS is recommendable for optimizing phosphate nutrition in the andosols of the volcanic highlands of North Kivu.

Keywords: Andosols, Available phosphorus, *zea mays*, *Mucuna pruriens, Desmodium intortum*, Plant Cover Cropping System, North Kivu volcanic highlands.

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INTRODUCTION

The volcanic soils characteristic of the highlands of North Kivu in the Democratic Republic of Congo (DRC) have always been considered as having a high potential for agricultural development. Nevertheless, due to their fertility, these soils support the highest population densities in the country, resulting in a scarcity of cultivated land. As a result, they are exposed to various forms of degradation, including loss of fertility due to overexploitation, exacerbated by soil erosion (Ngongo et al., 2009; Smith et al., 2015). The result is a decline in the production of the main foodstuffs, particularly maize, which is the main cereal consumed in this region (PASA, 2015; Baributsa et al., 2021). In cultivated areas, nitrogen and especially P requirements are one of the most limiting conditions for maize (*Zea mays*) production on these andosols (Legrand et al., 2007). The low use of fertilizer, typical of agriculture and the lack of alternatives for improving integrated soil fertility management in the volcanic highlands of North Kivu are not conducive to boosting agricultural production in this agropastoral zone (Lunze, 2013; Bashagaluke et al., 2018).

The retention of phosphorus in less soluble forms is one of the characteristics of volcanic soils, thus constraining crop phosphorus nutrition. However, these fixed phosphate reserves could constitute an important source of available P for the plant insofar as they are mobilized (Anda and Dahlgren, 2020). Recycling this inherited P would not only reduce the impacts of eutrophication, but also offer an agronomic opportunity in certain systems, potentially avoiding the use of P fertilizers for several decades (Hallama et al. 2019).In this latter respect, Nguyen et al. (2024) found that *Lupinus angustifolius* (narrow-leaved lupin) significantly depleted moderately labile inorganic P and stable inorganic P from soils with low P availability. These P depletions were correlated with malate exudation rates produced by some green manure crop species. In addition, Hansen et al. (2022) noted that the residual effects resulting from soil P mobilization could also be transmitted to the following crop, enhancing the crop's ability to acquire soil P. The release of organic anions under green manures solubilizes soil P complexed by reactive surfaces such as metal oxides (Hallama et al. 2019; Nguyen et al., 2024).Moreover, this capacity to mobilize soil P varies not only from one species to another, but above all with the cropping system (association, rotation, relay cropping, etc.) chosen and the state of P reserves. Most studies have focused on species (*Lupinus albus, Vicia dasycarpa, Vicia faba*, etc.) that are not available in the volcanic highlands of North Kivu (requiring prior adaptation trials) or that do not offer additional advantages in terms of animal nutrition, soil protection against erosion or nitrogen fixation in association with the main crop. Also, the context of the region (overpopulation) would no longer allow the implementation of fallow time as recommended in recent similar studies (Hallama et al. 2019; Nguyen, McDowell, and Condron 2024). However, soil cover legumes such as *Mucuna pruriens* and *Desmodium intortum* are available in the volcanic highlands of North Kivu and can be used to recycle P in the soil. Moreover, these species have additional advantages in erosion control, soil carbon storage (Barthès et al., 2017; Amani et al., 2022), atmospheric nitrogen fixation and crop weed management (FAO, 2012; Husson et al, 2013; Kocira et al., 2020). At the same time, these leguminous soil covers can improve crop production on soils with low or moderate P availability by mobilizing soil P reserves for maize nutrition, especially by avoiding P losses linked to the use of synthetic fertilizers, which cause water pollution through eutrophication (McDowell et al., 2020).

In view of these advantages, this study will evaluate the ability of two soil cover legumes (*Mucuna pruriens* and *Desmodium intortum*) to mobilize soil P for maize crops (wheat and barley) in two cropping systems (PCCS: Permanent plant cover cropping systemand catch crop system) on a volcanic soil with moderate P availability. The aim is to determine which cropping system will offer an improvement in the stock of available P while increasing the yield of the main crop (maize). Our main hypothesis was that systems combining legumes with maize in plant cover cropping system (PCCS) can mobilize soil P and increase maize yield by improving phosphate nutrition.

MATERIAL AND METHODS

Description of experimental site

The experimental field was located on the outskirts of the town of Goma, in North Kivu, in the east of the Democratic Republic of Congo. It is located at 1°38'3.7'' South Latitude, 29°08'54.8'' East Longitude and 1499 m altitude (Figure A).

The soil is volcanic, shallow, on an ancient but decomposing basaltic flow (Kanyankogote et al., 2005; Ngongo et al., 2009). The site benefits from a tropical mountain climate. The lowest monthly rainfall is recorded between January and February and between July and August.

Cumulative rainfall during the trial was 967 mm, including 386.3 mm during the major cropping season of September 2023 and 580.7 mm during the minor cropping season of February 2024 (Figure B).

The volcanic highlands of North Kivu belong to the Virunga mountain massif, made up of several active volcanoes, including Nyamulagira and Nyiragongo, which are among the most active in the world. Altitudes range from less than 800 m to more than 2,500 m.The medium slopes are between 5 and 45%. Average rainfall varies between 1,000 and 2,000mm per year (Smith et al., 2015).

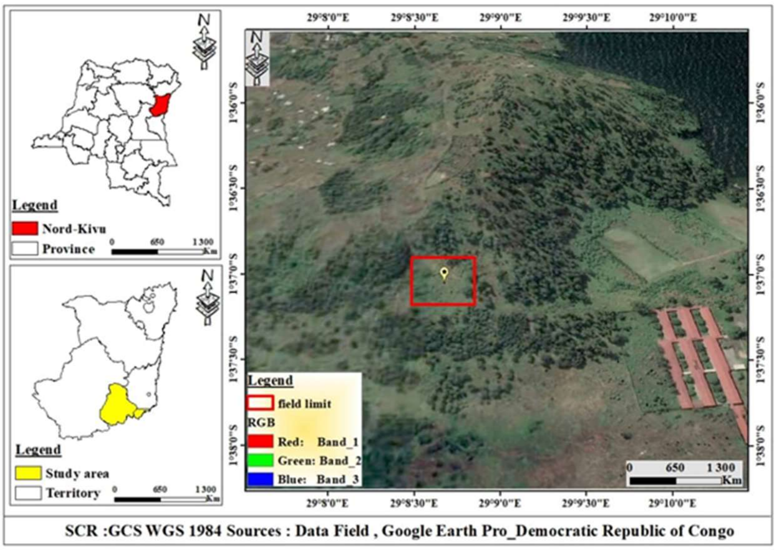

Figure A. Geolocation map of the experimental site in the philosophic major seminary concession at Buhimba

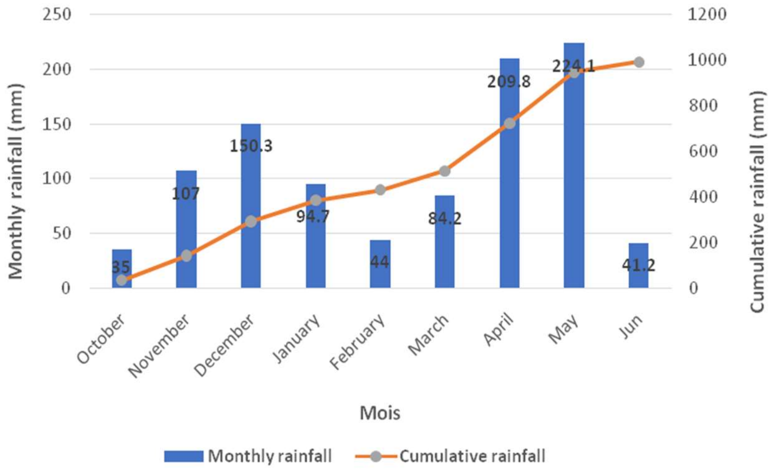

Figure B. Rainfall distribution over the experimental period

Ash layers alternate with basalt layers (Ngongo et al., 2009). The sandy fraction of the ashes consists mainly of volcanic glass, olivine augite, albite, muscovite and biotite. The clay fraction consists mainly of alumino-silicic gels: allophanes and imogolites (Kanyankogote et al., 2005). The vegetation is formed by the mountain rainforests that dominate the Virunga Park. The population of the area is estimated at 6,665,000, giving an average density of 111 inhabitants/km2 (compared with 30 inhabitants/km^2 for the DRC). The population is predominantly rural (60%), with agriculture their main activity (Ngongo et al., 2009).

Field management and experimentation

Experimental set-up

The experimental field was set up according to a randomized and subdivided complete block design (Split-plot) with two factors studied. The first was the type of cover crop, with two variants (*Mucuna pruriens* and *Desmodium intortum*), and the second was the maize cropping system, with three variants: cover cropping (PCCS), catch cropping (Der) and monoculture maize.

Thus, five treatments comprising the following combinations: Maize+*Mucuna pruriens* relay (Muc-Der), maize+*Mucuna pruriens* PCCS (Muc-PCCS), maize+*Desmodium intortum* relay (Desmo-Der), maize+*Desmodium intortum* PCCS (Desmo-PCCS) and monoculture maize (MP). These treatments were randomly distributed in each of four blocks set up perpendicular to the direction of the slope. Each block comprised 5 experimental units, making a total of 20 experimental units for the whole field trial.

This experiment was carried out in the major cropping season of September 2023, then repeated in the minor cropping season of February 2024. An improved fallow of cover legumes (*M. pruriens* and *D. intortum*) preceded the first cropping season with the aim of eliminating heterogeneities linked to the previous crop and producing initial plant biomass (Husson et al., 2013). Each experimental unit was an individual 5 m X 2 m plot bounded upstream by a drainage channel 30 cm wide and 30 cm deep (Bashagaluke et al., 2018).

Field practices and management of cropping systems

In the relay system, maize was planted at 50 cm x 50 cm spacing, with two kernels per stalk and six stalks per row. Two rows of the leguminous cover crop were interspersed between successive rows of maize (Mucheru-Muna et al., 2010). The cover crops were sown at 20 cm x 20 cm spacing with two seeds per poquetto enable rapid formation of the biological barrier against runoff (Granier and Chantillon, 1972, Barthès et al., 2017). In this system, the legume was sown 30 days after corn sowing and was left in place until two weeks before the main crop of the following season was planted (Husson et al., 2013).

In cover cropping system (PCCS), cover crops were planted at the same time as the main crop to enable the production of sufficient biomass and permanent soil cover. The main crop was thus sown in the mulch from the previous season after minimal ploughing limited to the seed rows (Barthès et al., 2017).

The cover crops were sown in rows at densities of 65 kg/ha for *M. pruriens* and 3 kg/ha for *D. intortum* (Orwa et al., 2009; Kouelo et al., 2017). Maize was sown at 50cm X 50cm spacing while *Mucuna pruriens* and *Desmodium intortum* were sown in double rows at 50cm X 20cm and 50cm X 10cm spacing. The biological material used consisted mainly of maize seed of the Bazooka variety, as well as *Desmodium intortum* and *Mucuna pruriens* seed.

All the experimental units received a starter fertilizer of 90 kg/ha of di-ammonium phosphate DAP (18% N; 46% P2O5) at sowing. This manure provided 42 kg/ha of P2O5, which is half the recommended dose for maize (COMIFER, 2019). Potassium and the remainder of P and N should be replenished respectively by soil reserves and other biological sources linked to plant-soil micro-organism interactions and the mineralization of organic matter (Latati et al., 2016; COMIFER, 2019; Hallama et al., 2019).

Laboratory analysis

Soil samples (taken with an auger) were collected each time before sowing maize on each block at a depth of 20 cm. At the beginning and end of each growing season, two samples were taken per treatment and per block to determine the soil's P stock and other major nutrients such as nitrogen and potassium.

Physical and chemical analyses of the soil were carried out at the Laboratoire de Sciences des Sols de l'Université Catholique de Bukavu (LSS-UCB), using procedures adapted to each parameter according to ISRIC-FAO (Reeuwij, 2002). The chemical analyses concerned pH-H2O, organic carbon (%OC), total nitrogen, total phosphorus (Total P), available phosphorus (Av P), exchangeable potassium and Cation Exchange Capacity (CEC).

The pH-H2O was determined by the potentiometric method using a soil/water and soil/molar solution of KCl in a 1:2.5 ratio. Organic carbon was determined using the Walkley & Black method. Total nitrogen was determined by the Kjeldahl method, while total P was measured by the BRAY2 method. CEC was measured by the sodium saturation method.

These analyses were supplemented by a macroscopic description of the cultivation profile dug on the experimental site before the trial was set up, using the FAO method (Delaunois, 2006).

Assessment of grain yields and dry biomass of maize and cover crops

Grain yield was determined when the maize was fully matured on the 4 m^2 usable area (excluding border plants). The dry grains removed from the cobs were weighed and a sub-sample was taken to determine the moisture content in order to adjust the grain yield. A moisture content of 13% was used for grain yield correction (Mohseni et al., 2014). Plant residue dry biomass was also determined from a sample oven-dried at 70°C for 48 h. This weight was extrapolated to that obtained in situ (Bashagaluke, 2018). The cover crops were pruned before flowering (90 DAS) over a useful area of 1 m2 and 5 cm from the ground before total mowing. The fresh biomass was weighed and a 500 g sample was taken for dry weight determination in the laboratory (Mboko et al., 2013; Husson et al., 2013). This made it possible to assess biomass yield by season and by maize association mode.

Export of nutrients (N-P-K) from maize crops and assessment of post-harvest soil properties

The major nutrient exports concerned only the maize grain crops, since the maize biomass was reincorporated into the soil at the same time as the legume biomass, depending on the case. The empirical N, P and K export estimation grid proposed by Husson et al. (2009) was used to estimate the quantities of major nutrients stored in each season's crop, taking account of production per treatment. In addition, the results of soil sample analyses were used to assess the influence of different treatments on soil properties after two cropping seasons. To do this, soil properties such as pH-H_2O, CO, total N, available P, total P and exchangeable K were compared with those obtained from soil analyses before the trial was set up in order to detect any inter-treatment and inter-seasonal variations.

Statistical analyses

Descriptive statistics, contingency tables and graphs were generated in Excel 2016. Depending on the distribution of the data (Shapiro-Wilk at the 5% threshold), analysis of variance (ANOVA) was performed for multiple comparisons of data distributed according to the normal distribution, otherwise the Kruskal-Wallis test was used ($p < 0.05$). In the first case, the means were separated using the test for the Least Significant Difference (LSD) at the 5% threshold, and in the second case the Bonferroni corrected significance level ($p<0.003$) was used to separate the rank means from the Kruskal-Wallis test (for Available Phosphorus in soil).

RESULTS

Soil characterization of the experimental site

The soil profile dug into the hillside presents two horizons with diffuse boundaries including a very dark grey-brown (7.5YR 2/1) AO surface horizon (0-30 cm) and a very dark red-brown (10YR 3/2) BC underlying horizon (30-100 cm), typical of the A(B)C profiles also described in the neighboring Rubavu province in Rwanda (Mizota and Chapelle 1988). Soil texture on the surface horizon is sandy-loamy, tending to become silty at depth. The edaphic materials are typical of tephra soils and meet certain criteria of the andic to vitric horizon characteristic of Andosols according to the World Reference Base for Soil Resources (Mizota and Chapelle, 1988; IUSS, 2014, 2014). Both horizons show a very fragmentary massive structure, very high porosity, very low compactness, high friability, low to very low plasticity from the surface to the underlying horizon. The horizons show no signs of hydromorphy or fungi.

Analysis of the fine fraction of the fine soil before the trial was set up revealed a granulometric composition dominated by textural sand (84%) and small quantities of silt and clay (Table 1).

In addition, the low bulk density (<1) and high porosity characteristic of the surface horizon are physical properties specific to Andosols. On the other hand, the soil pH is almost neutral (7.2), while the OC content is low (compared with Andosols) but the total N content is moderate. The result is a balanced C/N ratio (13.54), which is conducive to rapid mineralization of soil organic matter. The exchangeable potassium content is moderate, although the CEC (4 cmol+/kg) is fairly low compared with other volcanic soils. Available P content is average, but represents only 1.6% of total P, giving a retention rate of 98.5%. The low CEC of the surface horizon, the very high P retention, the low OC content, the neutral pH and all the physical and morphological properties described point to a *Vitric Lomic Sideralic Andosol*, corresponding to an Andosol in the early stages of development on basic pyroclastic materials (IUSS, 2014).

Legume biomass assessment under different cropping systems

Analysis of variance revealed significant variation ($p<0.05$) in legume biomass over different cropping seasons and cropping systems.

Treatment T3 (Muc-PCCS) produced more biomass than all the other cropping combinations, with dry weights of 5.3 t/ha in season 2023; 14.4 t/ha in season 2024, making a total of 19.7 t/ha for the two seasons. By contrast, the lowest biomass weights were recorded under treatment T4 (Desmo-Der), with quantities of less than 3 t/ha per season. These variations can be explained by the growth rate of each legume species, its morphology, its adaptation to the growing environment (biophysical conditions and intra- and interspecific competition) and above all, the timing of plant establishment within the system. Most of these characteristics gave *Mucuna pruriens* the advantage of expressing its soil protection potential, while at the same time improving grain maize productivity.

Soil property dynamics under different cropping systems

Compared with soil properties prior to experimentation (Table 1), there was a downward trend in pH under the *M. pruriens* treatments (T2 and T3), while a degree of pH stabilization characterized the T1 and *D. intortum* treatments (T4 and T5). Treatments without leguminous cover crops (T1) and with low biomass input (T4) showed the lowest OC levels, with decreases of 1%, 0.9% and 1.09% respectively compared with the initial level (Table1 and Table3). On the other hand, a trend towards stabilization of % OC was observed following the order T3>T5>T2, which is also the order of biomass production of cover legumes. Total nitrogen levels remained stable in all treatments, with a downward trend in the treatment without legume cover crops ($\Delta\%N=-0.04\%$, i.e. -730KgNha-1), but an upward trend ($\Delta\%N=+0.03\%$, i.e. +548KgNha-1) in the maize+Mucuna PCCS treatment. This drop can be explained not only by losses due to water erosion and crop exports, but above all by the absence of biological fixation of atmospheric nitrogen.

Table 1. Initial physical and chemical characteristics of the soil (0-20cm) on site

Physical properties					
Texture (%)			**Bulk density (g/cm^3)**	**Gravimetric moisture (%)**	**Total porosity (%)**
Clay	Silt	Sand	0.913	17	64.88
8.5	7.5	84.1			

Chemical properties

pH-H_2O	OC (%)	OM (%)	Total N (%)	Av P (mg/kg)	Total P (mg/kg)	K (cmol+/Kg)	CEC (cmol+/Kg)	C/N	Av P / Total P (%)
7.2	2.55	4.39	0.19	27.91	1892.19	2.39	4.03	13.54	1.6

Av P= Available Phosphorus; OC= Organic Carbon; OM= Organic Matter; Total P=Total Phosphorus; K= Exchangeable Potassium, CEC= Cation Exchabge Capacity ; Particle density=2.61g/cm3.

Table 2. Seasonal averages of dry weight of biomass produced by cover legumes under different cropping systems

Cropping systems	Dry weight of cover crop biomass (tonnes/ha)		
	Major cropping season 2023	**Minor cropping season 2024**	**Total of two seasons**
T2 (Muc-Der)	3.4 ±1.2ab	5.3±1.6a	8.8±2.3a
T3 (Muc-PCCS)	5.3±1.0b	14.4±6.7b	19.7±6.8b
T4 (Desmo-Der)	2.2±1.8a	2.5±0.7a	4.7±0.7a
T5 (Desmo-PCCS)	4.7±1.7ab	4.1±1.8a	8.8±3.6a
p-Value	**0.015**	**0.002**	**0.001**
Signification	*	**	**

a, b, c: means bearing the same letter in the same column are not significantly different (ANOVA, p > 0.05). Muc-Der=Mucuna in catch crop, Muc-PCCS= Mucuna in PCCS, Desmo-Der= Desmodium in catch crop, Desmo-PCCS= Desmodium in PCCS, LSD= Least significant difference, NS=Not significant.

Table 3. Physico-chemical characteristics of the soil (0-20cm) after two cropping seasons

Cropping system	Physico-chemical soil analyses after two cropping seasons								
	pH-H_2O	**OC (%)**	**Total N (%)**	**C/N**	**Av P (mg/Kg)**	**K (cmol+/Kg)**	**CEC (cmol+/Kg)**	**Total P (mg/Kg)**	**Av P / Total P (%)**
T1 (MP)	7.00	1.65	0.15	11.07	34.60	2.66	3.52	1478.13	2.34
T2 (Muc-Der)	6.93	1.80	0.18	9.89	38.47	1.76	4.12	1571.76	2.45
T3 (Muc-PCCS)	6.84	2.25	0.22	10.37	55.97	1.91	4.24	1435.24	3.90
T4 (Desmo-Der)	7.30	1.46	0.19	7.85	31.76	2.83	4.24	1825.00	1.74
T5 (Desmo-PCCS)	7.20	2.16	0.19	11.31	47.90	2.99	4.12	1325.00	3.62
Average *Mucuna*	6.89	2.03	0.20	10.13	47.22	1.83	4.18	1503.50	3.17
Average *Desmodium*	7.25	1.81	0.19	9.58	39.83	2.91	4.18	1575.00	2.68

Av P= Available Phosphorus; OC= Organic Carbon; OM= Organic Matter; Total P=Total Phosphorus; K= Exchangeable Potassium. CEC= Cation Exchangeable Capacity; Total N=Total Nitrogen

Furthermore, a significant increase in available P was observed in all plots, rising from 27.91 mg/Kg (initial soil) to 55.97 mg/Kg (for T3 after 2 seasons), i.e. an increase of 28.07 mg/Kg (more than 100% of the initial amount of available P).

The result was a clear improvement in the ratio of available phosphorus to total P (Pass/total P), which rose from 1.6% (initial soil) to 3.9% (for T3 after 2 seasons), i.e. a 2.3% increase in terms of P available for plant nutrition. This represents an enormous quantity of available P that

Table 4. Seasonal grain and dry biomass yield of maize in different cropping systems

Cropping system	Maize grain yield (kg/ha)		Dry biomass yield of maize (t/ha)	
	Major cropping season 2023	Minor cropping season 2024	Major cropping season 2023	Minor cropping season 2024
T1 (MP)	766.3a	4271.1bc	6a	15.7a
T2 (Muc-Der)	1012.5a	3296.7abc	6.04a	17.3a
T3 (Muc-PCCS)	987.5a	4944.7c	6.6a	19.7a
T4 (Desmo-Der)	835.0a	2103.2ab	7.8a	13.4a
T5 (Desmo-PCCS)	1248.8a	2060a	7.23a	15.6a
p-Value	**0.887**	**0.045**	**0.867**	**0.448**
Signification	NS	*	NS	NS
LSD	1065	2181	4.25	7.13

a, b, c: Means bearing the same letter in the same column are not significantly different (ANOVA, $p > 0.05$) MP=Pure corn, Muc-Der=Mucuna in catch crop, Muc-PCCS= Mucuna in PCCS, Desmo-Der= Desmodium in catch crop, Desmo-PCCS= Desmodium in PCCS, LSD= Less significant difference, NS=Not significant.

Table 5. Quantity of N, P and K exports in grain maize under various cropping systems according to cropping seasons

Cropping system	Exported N-P-K from harvested grain maize (Kg/ha)			
	Major cropping season 2023			
	Grain mays yield (t/ha)	N	P	K
T1 (MP)	0.8	15.3	2.9	2.7
T2 (Muc-Der)	1.0	20.3	3.8	3.5
T3 (Muc-PCCS)	1.0	19.8	3.7	3.5
T4 (Desmo-Der)	0.8	16.7	3.1	2.9
T5 (Desmo-PCCS)	1.2	25.0	4.7	4.4
	Minor cropping season 2024			
T1 (MP)	4.3	106.8	17.1	21.4
T2 (Muc-Der)	3.3	82.4	13.2	16.5
T3 (Muc-PCCS)	4.9	123.6	19.8	24.7
T4 (Desmo-Der)	2.1	52.6	8.4	10.5
T5 (Desmo-PCCS)	2.1	51.5	8.2	10.3
	Total of two consecutive cropping seasons			
T1 (MP)	5.0	122.1	20.0	24.0
T2 (Muc-Der)	4.3	102.7	17.0	20.0
T3 (Muc-PCCS)	5.9	143.4	23.5	28.2
T4 (Desmo-Der)	2.9	69.3	11.5	13.4
T5 (Desmo-PCCS)	3.3	76.5	12.9	14.7

Only maize grain exports were considered in this study, as the dry biomass was left on the cultivated plot where it had been produced. MP=Pure corn, Muc-Der=Mucuna in catch crop, Muc-PCCS= Mucuna in PCCS, Desmo-Der= Desmodium in catch crop, Desmo-PCCS= Desmodium in PCCS.

the plant cannot use up in one or 2 cropping seasons, given the small quantities exported in the harvest. The solubilization of insoluble forms of P, the release of P fixed by amorphous minerals, the mineralization of organic P and possible symbiotic interactions (mycorrhization) are all processes that can explain this strong improvement in P bioavailability in different cropping systems.

A tendency towards potassium stabilization was observed in soils without leguminous cover crops, while slight variations were observed in treatments with leguminous cover crops.

Cation exchange capacity remained stable (around 4), with an upward trend in plots with leguminous cover crops.

Evaluation of maize grain and dry biomass yields

Globally, the 2024 crop year was by far the most productive in terms of both grain corn and dry biomass. It was also the only crop year in which there was a significant variation in maize grain yields between the different cropping systems. Biomass yields were not significantly influenced by the different cropping systems (Table 4).

The major 2023 cropping season was characterized by very low yields of less than 1.3 t/ha of maize grain and 8 t/ha of maize dry biomass. In contrast, for the minor 2024 growing season, no treatment produced less than 2 t/ha of maize grain or less than 15t/ha of maize dry biomass. The

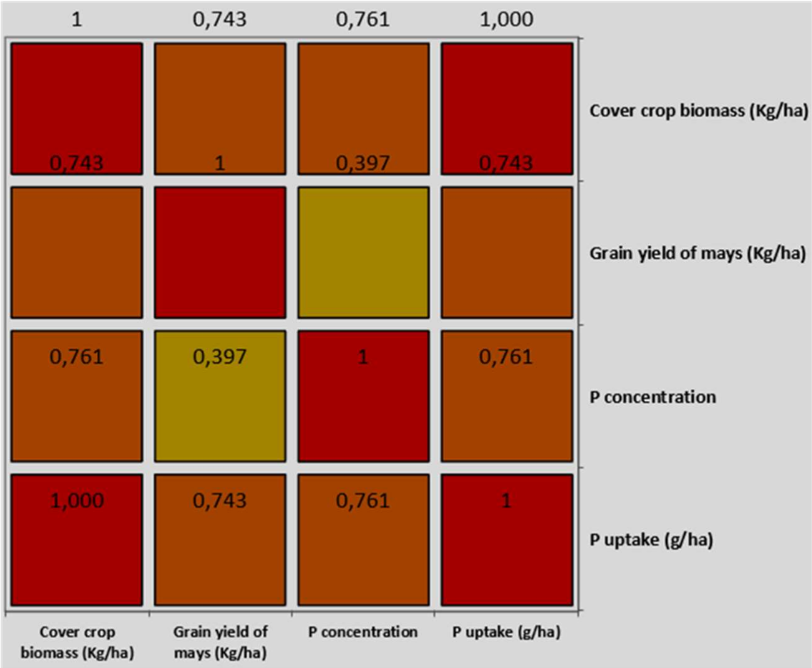

Figure C. Correlation maps of phosphorus dynamics according to incorporated organic matter and crop exports

mobilization of soil nutrients such as P and N and the mineralization of legume biomass, as well as adequate rainfall distribution, could be behind this improvement in productivity. Considering this last crop year, the highest yield (4.9 t/ha maize grain) was obtained under treatment T3 (Muc-PCCS), while the lowest (2.06 t/ha maize grain) was observed under treatment T5 (Desmo-PCCS). It is worth noting that treatment T3 (Muc-PCCS) resulted in a surplus of 673 kg of grain corn compared with pure corn, and 3957 kg of grain corn compared with the yield of the 2023 cropping season for the same treatment. This demonstrates the effectiveness of the Muc-PCCS system in improving soil fertility in the short and medium term.

Main nutrients (N-P-K) exports in corn grain crops

This production is generally accompanied by the export of nutrients stored in the crops (grain and biomass), which in the long term can lead to a drop in the availability of these elements in the soil.

Exports of N, P and K were much higher in the short 2024 cropping season than in the major 2023 cropping season. Indeed, in the 2023 season, the highest exports were 25 Kg of nitrogen, 4.7 Kg of phosphorus and 4.4 Kg of potassium, observed under treatment T5 (Desmo-PCCS). In contrast, during the 2024 season, the highest exports were 123.6 Kg of nitrogen, 19.8 Kg of phosphorus and 24.7 Kg of potassium, observed under treatment T3 (Muc-PCCS). These variations in yield increase were due to the incorporation of biomass from legumes associated with maize over the course of two cropping seasons.

In fact, the matrix shows that soil P mobilization is strongly and positively correlated with the increase in incorporated legume biomass. In addition, these two parameters positively influence maize seed yield as a result of improved phosphate nutrition, as revealed by P export values in harvested maize grain (Figure C).

DISCUSSION

Effects of different cropping systems on the physico-chemical properties of the soil after two cropping seasons

Overall, an improvement in soil properties was observed, especially in plots intercropping maize and *Mucuna pruriens*. The slight drop in pH and OC levels observed was positively correlated with the quantities of legume biomass incorporated into the soil after two cropping seasons. The release of organic acids coupled with the leaching of base cations could explain this downward trend in soil pH (Quantin, 1995; Van Ranst et al., 2008; Nguyen et al., 2024). To this must be added the action of atmospheric nitrogen-fixing microorganisms and the uptake of certain cations by plants (Sanginga and Woomer, 2009).A considerable improvement in available soil phosphorus was recorded under the maize+Mucuna association plots compared with the other cropping systems. This increase of almost 2.3% in available P confirms the ability of the maize+Mucuna association to mobilize several P reservoirs in the soil, thereby improving its availability to crops (Latati et al., 2016; Nguyen et al., 2024). In fact, after exporting the P in the harvested maize grains and cobs, the available P reserves increased by 2.3%, i.e. 28 mg of P per kg of soil. Given the bulk density of the soil (0.913g/Cm3) and a depth of 20 cm, this improvement corresponds to an input of 51 kg of P/ha, which is equivalent to 117 kg of P2O5, or 250 kg of simple Triple Super Phosphate fertilizer containing 46% P2O5. This is an amount that can cover the P requirements for the following season's maize crop (90kg P2O5), with a surplus of 27kg. The release of P previously bound to soil OM, the solubilization of inorganic forms by organic acids (Nguyen et al., 2024) resulting from the rapid mineralization of OM and the increase in the malate exudation rate observed in several legumes are thought to be the cause of the increase in P bioavailability in andosols. In addition, the uptake of insoluble P facilitated by biological interactions such as enzyme activities (acid and alkaline phosphatases), rhizode position and mycorrhization are processes that can explain the high bioavailability of phosphorus under different cropping systems (Kocira et al., 2020, Hallama et al., 2021).

In fact, this observation is coherentwith the results of Hallama et al. (2019) and Nguyen et al. (2024), who also recorded deliveries of 1 to 30 kgha-1 and 9 kgha-1 of P, respectively, on a vitric andosol by applying green manures from cover legumes. These authors note that whatever the specific climatic and soil conditions, cover legume green manure species have characteristics that improve their ability to mobilize phosphorus from the organic and inorganic reservoirs of soils with low P availability, which corroborates the results of this study (Richardson et al., 2009; Hansen et al., 2022). However, the amount of P mobilized under the maize+Mucuna association is higher than those found by the other authors mentioned above, demonstrating the effectiveness of this cropping system. In addition, the quantities of P mobilized in the soil correspond to a gain of 350 US dollars in terms of the phosphate fertilizer (TSP: 46% P2O5) required for plant nutrition, taking into account the price on the local market (COMIFER, 2019). The gain is even greater if we consider that, by avoiding the use of synthetic fertilizers, the maize+Mucuna cropping system also makes it possible to avoid soil pollution and eutrophication of the groundwater (Nguyen et al., 2024), especially that of Lake Kivu around the experimental site.

Nitrogen content varied little except in the monoculture maize treatment, where a downward trend was observed. This downward trend could be explained by the immobilization of N by the maize crop and the absence of a significant contribution in terms of biological N fixation or mineralization of N from OM, compared with the other cropping systems studied. Considering the low fertilizer input, N losses and quantities exported by crops, this stabilization demonstrates the high mobilization (0.03% N corresponds to an enrichment of 548 KgN/ha) and progressive storage of N in the soil thanks to the maize+Mucuna PCCS system (Brookes et al., 2008; Latati et al., 2016).This enrichment is much higher than that (100 KgN/ha) obtained on maize + leguminous shrub hedges (*Calliandra sp.* and *Leucaena sp.*) in Rwanda (Koenig, 2005). The drop in the C/N ratio of more than 2 units, observed in maize-legume associations, is both the cause and consequence of this significant mobilization of nitrogen.

Maize productivity under different cropping systems

A significant improvement in biomass and grain yields was observed after two consecutive seasons of using leguminous soil covers in association with maize. The best yields were recorded in the 2024 cropping season, reaching almost 5 t/ha of maize grain and 20 t/ha of maize dry biomass under treatment T3 (Muc-PCCS). Maize yields under treatment T3 (Muc-PCCS) are much higher than those obtained under maize+soybean+NPK+Biochar (3.5 t/ha maize grain and 6 t/ha dry biomass) after three cropping seasons in Ghana (Bashagaluke, 2018) and much better than those obtained under maize+Mucuna+NPK+urea (1.4 t/ha maize grain and 1.6 t/ha dry biomass) in Burkina Faso (Coulibaly et al., 2012). This performance is in line with the observations of Husson et al. (2009), who show that in the reality of soils with low or average fertility, the first year of cultivation (year zero) is primarily aimed at producing more cover crop biomass than crop yield. This biomass improves the physical, chemical and biological fertility of the soil, optimizing plant nutrition by improving the availability of nutrients the following season (Dabney et al., 2001).

In this study, there was a high level of soil P mobilization, which was positively correlated with the quantity of legume biomass, leading to an improvement in phosphate nutrition. This phosphate nutrition, reflected in the quantities of P exported in grain maize, increased concomitantly with maize yield. This demonstrates the improvement in soil fertility resulting from the use of the maize+Mucuna PCCS (Husson et al., 2013).

CONCLUSION

Among all the cropping systems used in the experiment, the maize+Mucuna intercropping under a permanent cover system (PCCS) was the one that led to the best improvement in soil fertility, and particularly in the P available for phosphate nutrition in maize. Huge quantities of P were mobilized following the solubilization of phosphorus previously fixed in the soil. Pre-crop soil analyses showed a soil P retention rate of almost 98%. After the two cropping seasons, this P retention rate was reduced by 2 units under the maize+Mucuna intercrop and by one unit under the maize+Desmodium intercrop and under monoculture maize. After exports in harvested grain, available P reserves increased by 2.3%, i.e. 28 mg of P per kg of soil.This quantity covers the P requirements (90Kg P2O5) of the following season's maize crop, with a surplus of 27 Kg, which corresponds to a saving of 350 US dollars relative to the simple phosphate fertilizer (TSP 46% P2O5) required, given the price on the local market. This system also prevents soil pollution and water eutrophication. This improvement has been accompanied by the mobilization of nitrogen and potassium, not overlooking the protection of the soil against soil erosion. As a result, yield increases of 4 t/ha of grain maize and 13 t/ha of dry biomass were obtained in the maize+Mucuna intercropping system during the second cropping season after the incorporation of *Mucuna pruriens* as a cover legume. The maize+Mucuna combination in a permanent cover crop system can be adopted as an effective cropping system in conservation agriculture aimed at high, sustainable and profitable crop production in the context of the volcanic highlands of North Kivu and the African Great Lakes region.

ACKNOWLEDGEMENTS

We are grateful to the Université Catholique la Sapientia de Goma (UCS-Goma) for funding this research, and to the final-year plant production students who helped collect data in the field.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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