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Original Article

Nutrients Budgets of the Sedentary Yam-Based Cropping Systems with Herbaceous Legumes in the Guinea-Sudan Transition Zone of Benin

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Abstract

In West Africa, yam cultivation is now facing increasing scarcity of fertile soils. With the aim of designing more sustainable yam cropping systems in Central Benin, we compared smallholder farmers' traditional yam-based cropping systems with late maturing *Dioscorea rotundata* -'Kokoro' (1-year fallow of *Andropgon gayanus*-yam rotation, Maize+ 100 kg $N_{14}P_{23}K_{14}$ + 50 kg Urea –yam rotation) with yam-based cropping systems integrating legumes (*Aeschynomene histrix*/maize intercropping + 100 kg $N_{14}P_{23}K_{14}$ + 50 kg Urea –yam rotation and *Mucuna pruriens* var *utilis*/maize intercropping + 100 kg $N_{14}P_{23}K_{14}$ + 50 kg Urea –yam rotation) in a 4-year experiment comprising two year rotations. The objective of the study was to assess the nutrientsbudget of the sedentary yam-based cropping systems with herbaceous legumes and highlight interactions between factors. The experiment was conducted with 32 farmers, eight in each site. For each of them, a randomized complete block design with four treatments and four replicates was carried out using a partial nested model with five factors: Year, Replicate, Farmer, Site, and Treatment.Yam based cropping systems with legumes improved significantly the N, P, and K balances in comparison with the traditional systems. ANOVA partial nested model showed that Nutrients budgets of nitrogen, phosphorus and potassium differed significantly depending on the factors Treatment ($P<0.05$), Farmer ($P<0.001$), and Replication ($P<0.001$). The factor Site was not significant for nutrients budgets. Year × Treatment ($P<0.001$), and Year × Site ($P<0.001$) interactions were significant.

Keywords: Deforestation, Herbaceous legumes, Nutrients balance, Soil conservation, Yam

Introduction

Because of anthropogenic pressure, forest ecosystems in humid and sub-humidlowland regions of West Africa are undergoing increasingly intense degradation (Conservation International, 2007). In these areas, cropping systems are based on tuber crops, mainly yam (*Dioscorea* spp.) (Onwueme and Haverkort, 1991). Current yam-based cropping systems, which involve slash-and-burn practices or short fallow, often result in deforestation and soil nutrient depletion, and yam cultivation is currently facing increasing scarcity of fertile soils (Cornet et al., 2006). West Africa produces more than 40 million tons of yams per year, representing 90% of the world production (FAOSTAT, 2011). Benin is the world's fourth ranking producer, after Nigeria, Côte d'Ivoire, and Ghana. In Benin, yam production increased from 1 285 858 tons on an estimated 117 255 ha harvested area in 1995 to 1 802 944 tons in 2008 on 204 683 ha (FAOSTAT, 2011). This 40% increase in production was obtained thanks to a 74% increase in land under yam, indicating that intensification was limited. In Benin, yam is grown by smallholder farmers. Nowadays, it is impossible for farmers to practice long fallow periods and yam is cultivated in 1 or 2-year herbaceous fallow–yam or maize-yam rotations with manual incorporation of residues into the soil. Depending on the availability of cash and inputs, smallholders fertilize the maize they grow on depleted soils. However, they avoid using fertilizers on yam because it is "presumed to have a negative effect" on the quality of pounded yam (Vernier and Dossou, 2003). On depleted soils in the study area, the production of profitable yam cultivars has either decreased significantly, or changed from early maturing *Dioscorea rotundata* in favor of less profitable species such as late maturing *D. rotundata* or *D. alata*, that arebetter adapted to poor soils (Vernier and Dossou, 2003). Carsky et al. (2001) reported low yields, with an average of 10 t ha^{-1} fresh yam for *D. cayensis-rotundata*, whereas for species like *D. rotundata* grown in fertile soil, the potential yield can reach 25-30 t ha^{-1} (Vernier and Dossou, 2003) and 60-75 t ha^{-1} for *D. alata* (Martin, 1974; Zinsou, 1998**)**. Yam requires more than 1 000 mm water in the first 20 weeks of growth (Ghosh *et al*. 1988), and variable rainfall (delayed rainfall, drought, and flooding) can have negative impacts on crop growth and development. Ghosh et al. (1988) consider delayed rainfall to be one the main reasons for the decrease in yam production. Yam is a demanding crop in terms of organic matter and nutrients. Degras (1986) reported that for a 30 t ha^{-1} yield of fresh yam yield 120 N kg ha^{-1}, 5.1 P kg ha^{-1} and 111 K kg t^{-1} was required. Tropical soils can supply such quantities of nitrogen (N) when it is virgin land which has been newly cleared. Nitrogen is generated by the breakdown of inherent organic matter and needs to be supplemented with other sources of organic materials or mineral fertilizer. It is possible to stop ongoing soil degradation and the decrease in yield thanks to new farming practices, such as rotations including improved short fallows or intercropping with herbaceous legumes. However, up to now, such practices have generally focused on cereals, and very rarely on root and tuber crops, especially yam (Aihou, 1998; Cornet et al., 2006). Over the past 30 years, studies have been conducted to find ways to improve soil fertility management and conservation using herbaceous legumes such as *Mucuna pruriens* or *Aeschynomene histrix* (Becker and Johnson, 1998; Carsky et al., 1999). In West Africa, in the last decade, *M. pruriens* has been tested as green manure or in a short fallow in a maize rotation and was found to considerably increase maize grain yield (Fofana et al., 2005). These crops have only recently been introduced in research projects and are therefore not yet widely reported in the literature (N'Goran et al., 2007). In Benin and Togo, Sodjadan et al. (2005) studied the effect on the yam crop of short fallows based on *Mucuna pruriens* var *utilis,Aeschynomene histrix*, or *Pueraria phaseoloides*, and reported that a 1-year fallow planted with *M. pruriens* led to a significant increase in yam yields. In West Africa, in the last decades, *Mucuna pruriens*has been tested as a green manure or a short fallow in maize rotations and was found to considerably increase maize grain yield (Fofana et al., 2005). Incorporating a legume increases the N stocks in the soil because of its ability to fix N2 from the atmosphere. Osei-Bonsu and Buckles (1993) as well as Sanginga et al. (1996) estimated that Mucuna as an intercrop or as a sole crop provided an equivalent of more than 100 kg N ha^{-1} to the following maize, about 70% being derived from biological N fixation (Peoples & Craswell, 1992; Ladha and Garrity, 1994). Where smallholders' access to N fertilizer is limited, legume-based fallows could provide more N than natural fallow to maize crops (Becker et al., 1995; Peoples et al., 1995). To promote more sustainable yam production in West Africa, we conducted on-farm research on sedentary yam-based cropping systems in the Guinea-Sudan transition zone of Benin. The aim of our study was to assess the nutrient balance of the sedentary yam-based cropping systems with herbaceous legumesin the Guinea-Sudan transition zone of Benin.

Materials and Methods

Study sites and experiment design:

The study was carried out in Central Benin, in the Guinea-Sudan transition zone (7°45'- 8°40' N, 2°20'- 2°35' E) using four sites (Miniffi, Akpéro, Gbanlin, and Gomè). The climate is tropical transitional Guinea-Sudan with a rainfall distribution gradient from bimodal (Southern Benin) to monomodal (Northern Benin). During the studying period, the average annual rainfall was 1052 mm (2002), 1 386 mm (2003), 983 mm (2004), and 797 mm (2005). The rainfall regime in the study area is variable and unequal distribution (i.e. number of rainy days per month) varies from one site to another. The 2002 and 2003 cropping seasons were wet and had better rainfall distribution with an average annual precipitation of 1200 mm whereas 2004 and 2005 were dry (890 mm) with relatively low rainfall distribution. Most of the soils are tropical ferruginous soils (Dubrouecq, 1977), originally from Precambrian crystalline rocks (granite and gneiss), and classified as plinthosols (Gbanlin and Akpéro), and luvisols (Miniffi and Gomè) (Agossou & Mouïnou, 2002). Miniffi and Akpéro are locatedon a plateau (well drained soils) while Gomè is on lowland (more poorly drained soils).

Experiment design:

The experiment was conducted with 32 farmers, eight in each site. In each site,traditional yam-based cropping systems with late maturing *Dioscorea rotundata* -'Kokoro' (1-year fallow of *Andropgon gayanus*-yam rotation, Maize+ 100 kg $N_{14}P_{23}K_{14}$ + 50 kg Urea –yam rotation) with yam-based cropping systems integrating legumes (*Aeschynomene histrix*/maize intercropping + 100 kg $N_{14}P_{23}K_{14}$ + 50 kg Urea –yam rotation and *Mucuna pruriens* var *utilis*/maize intercropping + 100 kg $N_{14}P_{23}K_{14}$ + 50 kg Urea –yam rotation) in a 4-year experiment comprising two year rotations.For each of them, a randomized complete block design with four treatments and four replicates was carried out using a partial nested model with five factors: Year, Replicate, Farmer, Site, and Treatment. The random factors were "Year" and "Replicate" and "Farmer". Farmer was considered as nested within "Site", and "Replicate" nested within "Farmer". The fixed factors were "Treatment" and "Site". Sites were considered as fixed based on certain criteria such as landscape (lowland, plateau), soil type, and initial soil fertility.

Data collection:

Composite soil samples were collected in each field in November 2001 at depths of 0-10 cm and 10-20 cm (32 farm fields × 2 depths = 64 samples).At the end of 2005 after yam harvesting, composite soil samples were collected at the same depths in the mounds along plot transects (32 farm fields × 4 treatments × 2 depths = 256 samples). Consequently, the error that may arise from this soil sampling procedures should be soil physical and chemical characteristics from mounds in 2005 reorganized in comparison with soil sampling in 2001 on a flat field. The aboveground and root biomass of maize, *A. gayanus* and each herbaceous legume were collected separately in October-November 2002 and 2004 in four 1 m² quadrats within each plot. A 100 g subsample of each type of biomass was taken in each 100 m² plot. The four subsamples from four replications of each treatment were mixed to form a 400 g composite sample for each type of biomass and treatment. In total, for each farm we analyzed six aboveground composite plant samples in 2002 and six in 2004: maize stover TM, *A. histrix* biomass TMA, maize stover TMA, *M. pruriens* biomass TMM, maize stover TMM. The biomass samples were dried at 60°C until constant weight and dry weight was determined. At maturity (July), maize grain was harvested in each row in each plot and DM was determined. The fresh weight of the yam tuber was estimated for each plot in December 2003 and 2005 and the DM of yam shoots was determined. The nutrients contents of the soil samples were performed in the Laboratory of Soil Sciences, Water and Environment (LSSEE) of INRAB (Benin National Research Institute).The plant nutrient content was estimated according to the biomass amount (Maliki *et al.*, 2012; Maliki *et al.*, 2016). Soil and plant macronutrients content (N, P, and K) were analyzed. Nitrogen (N) content was analyzed using the Kjeldahl method (Scarf, 1998),available phosphorus with the Bray 1 method (Bray, 1954), potassium with the FAO method (FAO, 1970; FAO, 1977), organic carbon with the Walkley and Black method (Walkley and Black, 1934), soil particles with Robinson method method (Robinson, 1936)and pH (H2O) (using a glass electrode in 1:2.5 v/v soil solution).

Calculation of nutrient balances:

With regard to the estimation and calculation of the nutrient inputs (INs) and outputs (OUTs), the methodology described by Stoorvogel and Smaling (1990) and Smaling and Fresco (1993) was applied to each experimental unit. The following INs and OUTs were assessed:

INPUT1: Application of inorganic fertilizer
INPUT2: Organic fertilizer recycling
INPUT3: Atmospheric deposition
INPUT4: Biological nitrogen fixation
INPUT5: Sedimentation deposition
OUTPUT1: Removal of harvested products
OUTPUT2: Leaching of N and K
OUTPUT3: Gaseous losses of N
OUTPUT4: Erosion

INPUT1 is the application of inorganic fertilizer. The organic fertilizer recycling (INPUT2) is calculated by multiplying the quantities incorporated with the mass fractions of N, P and K. Nutrient supplies by wet and dry deposition (INPUT3) were estimated from the experimental results of Stoorvogel *et al.* (1997a). They found average concentrations ($mmol m^{-3}$) of solutes in rain water of 0.04 P, 3K, 5

$NH4^+$-N and 6 $NO3^-$-N. These concentrations were combined with the total amount of rainfall from January until December in the 2002-2003 and 2004-2005 cropping seasons. Nutrient inputs from Harmattan dust as found by Stoorvogel *et al.* (1997b)were used to estimate the input by dry deposition kg ha^{-1} at 0.11 for P and 2.50 for K. As legume crops were grown, biological N-fixation (INPUT4) consisted of symbiotic and non-symbiotic N_2-fixation. The N_2 fixed by herbaceous legumes in each plot was not analyzed. We used Becker and Johnson (1998) results who reported that legumes could fix 70% of their N. The non-symbiotic N_2-fixation was estimated as a transfer function of mean rainfall (van den Bosch, 1994). The input by sedimentation (INPUT5) was assumed to be negligible. The outputs of N, P and K by the harvest products such as maize and yam tubers (OUTPUT1) were calculated by multiplying the respective quantities of dry matter with the nutrient mass fractions. Leaching (OUTPUT2) of phosphorus was assumed to be negligible. The amount of N leached is assumed to be dependent on clay content, mineral soil N, rooting depth,annual precipitation, organic carbon content and N uptake by the crop. The amount of K leached is assumed to be dependent on exchangeable K, fertilizer K, rainfall and clay content (Smaling *et al.*, 1993). The mineral soil N (in kg ha^{-1}) in the soil top layer was estimated from the $NO3^-$-N and $NH4^+$-N data, the volumic mass (1.4 kg dm^{-3}) and soil depth (20 cm). Gaseous losses of N (OUTPUT3) through ammonia volatilization were assumed to be negligible (Smaling, 1993), although a little NH3 may have escaped because pH (H2O) was around 7. Losses through denitrification were estimated using the transfer function of Smaling,Stoorvogel and Windmeijer (1993) as determinants of rainfall, soil texture (clay content), mineral soil-N, fertilizer-N, N mineralized from organic fertilizer and total N uptake during the cropping season. Soil erosion (OUTPUT4) was estimated with the universal soil loss equation (USLE) (Wischmeier and Smith, 1978):

$$A = RKSLCP \quad (7)$$

where A is the annual soil loss in kg ha^{-1}, R the rainfall erosivity, K the erodibility, S the slope gradient, L the slope length, C the land cover and P is the land management. Slope gradients ranged from 3.5 to 4.3%. A detailed explanation is given by Ssegane (2007). We used 0.76 kg, 0.26 kg, and 0.46 kg t^{-1} eroded sediment for N, P_2O_5 and K_2O respectively (Smaling and Fresco, 1993). Next, the balances of available nutrients were calculated.

$$\text{Balance} = \left(\sum input - \sum ouput\right) \quad (8)$$

Statistical analysis:

Analysis of variance (ANOVA) was applied to yam yield using a randomized block design and a partial nested model with five factors as described above. Analysis of variance (ANOVA) using the general linear model (GLM) procedure (SAS, 1996) was applied to the DM production (tubers, shoots), nutrient contribution to the systems and soil properties at depths (0-10 and 10-20 cm). The GLM was computed to assess the interactions between the factors involved. Least square means and standard error were also computed for factor levels, and the Newman and Keuls test was applied for differences between treatments.. Significance was regarded at $p \leq 0.05$.

Results

The ANOVA partial nested model showed that Nutrients balances of nitrogen, phosphorus and potassium differed significantly depending on the factors Treatment ($P<0.05$), Farmer ($P<0.001$), and Replication ($P<0.001$). The factor Site was not significant for nutrient balance. Year × Treatment ($P<0.001$), and Year × Site ($P<0.001$) interactions were significant (Table 1).

Table 1: Main factors effects of nutrients balance for yam-based cropping systems with legumes during the 2002-2003 and 2004-2005 cropping seasons in four villages in Benin

		N		P		K	
Source	DF	F	P	F	P	F	P
Farmer(Site)	28	3.5	0.000	5.3	0.000	5.3	0.000
Year	1	6.0	0.078	0.32	0.596	0.1	0.811
Replicate	3	604.5	0.000	95.1	0.000	90.7	0.000
Site	3	0.1	0.963	5.0	0.019	0.9	0.518
Treatment	3	105.4	0.000	17.4	0.000	7.5	0.042
Site×Treatment	9	8.8	0.000	13.2	0.000	3.1	0.042
Treatment×Farmer(Site)	84	5.6	0.000	1.3	0.047	1.3	0.058
Year×Treatment	3	2.1	0.173	5.7	0.014	16.4	0.001
Year×Site	3	8.8	0.005	5.3	0.022	24.6	0.000
Year×Site×Treatment	9	6.9	0.000	12.3	0.000	2.0	0.038
Error		877		877		877	
Adjusted R-square (%)		97.4		94.5		63.2	

Average amount of nutrient balances was significant and varied from -71.9 to -38 kg N ha^{-1}, -2.1 to 3.4 kg P ha^{-1} and -12.1 to -2.7 kg K ha^{-1} in controls (T0, TM) versus from 33.0 to 44.4 kg N ha^{-1}, 10.1 to 11.5 kg P ha^{-1} and 4.1 to 9 kg K ha^{-1} in yam-based cropping systems with legumes (TMA, TMM) (Table 2).

Table 2: Nutrient balance of nitrogen, phosphorus and potassium (kg ha^{-1}) in legumes/maize and control rotations in four villages in Benin.

Treatment	**2002-2003 cropping season**			**2004-2005 cropping season**		
	N	P	K	N	P	K
T0	-71.9 d	-0.9 d	-12.1 b	-61.4 d	-2.1 c	-9.8 d
TM	-53 c	3.4 c	-12.7 b	-38 c	6.0 b	-2.7 c
TMA	26.9 b	10.1 b	9.0 a	33.0 b	11.2 a	4.1 b
TMM	35.8 a	11.5 a	8.8 a	44.4 a	11.4 a	6.5 a
LSD 5%	4.38	0.88	2.61	4.41	0.73	1.92
SD	13.44	2.72	8.02	13.53	2.24	5.91

a, b, c, d: Means with different superscripts in the same column differ significantly ($P < 0.05$); F-test for differences among means was always significant at $p < 0.001$

Legend: LSD: Least square difference at 5%; SD: Standard deviation; TMA: *Aeschynomene histrix* intercropped with maize-yam rotation; TMM: *Mucuna pruriens* intercropped with maize-yam rotation; T0 control 1: 1-year fallow with *Andropogon*-yam rotation; TM control 2: maize-yam rotation

Discussion

Yam based cropping systems with legumes (TMA,TMM) improved significantly the N, P, and K balances. There were differences among treatment in nutrient INPUTs, and they were caused by differences in the amounts of organic matter that had been incorporated in the soil. The amount of nutrients accumulated varied from 23.3 to 270.3 kg N ha^{-1}, 6 to 34.4 kg P ha^{-1} and 45.7 to 116.6 kg K ha^{-1} in yam based cropping systems with legumes (TMA, TMM) versus from 23.3 to 101.9 kg N ha^{-1}, 2.7 to 18.6 kg P ha^{-1} and 15.6.7 to 55.3 kg K ha^{-1} in controls (T0, TM). The input by atmospheric deposition was estimated at 5.2 kg N ha^{-1}, 0.14 kg P ha^{-1}, and 4.2 kg K ha^{-1}. Differences in nutrient OUTPUTs among treatments were caused mainly by differences in measured yields and nutrient contents. Nutrient balances were negative for the control rotations (T0, TM), except the phosphorus balance on TM that could be related to the inorganic fertilizer P applied on maize.Treatments TMA and TMM had the largest additions of available nutrients. In our study, soil chemical analysis showed that the soil was deficient in N, P and K. Many studies focusing on these elements conclude that there is an indisputable need to correct the lack of N and P in the soil in Africa (Azontondé, 1993; Gaiser, 1999). Rotations with *M. pruriens* and *A. histrix* represented a source of easily available N, P, and K for the yam crop which could be related to their faster decomposition and nutrient release, compared with the slower release of nutrients by poorer quality materials such as maize stover and *A. gayanus* grass. In Ghana, studying the effect of cropping sequences with cassava and legume crops,Adjei-Nsiah *et al.* (2007) indicated that only 30% of *M. pruriens* litter remained six weeks after incorporation of the biomass. Van Noordwijk *et al.* (1995) and Triomphe (1996), who studied the traditional *M. pruriens*-maize rotation in Honduras, estimated that 83% of nitrogen produced by a mulch of *M. pruriens* was available for the following maize crop. They also observed that available P remained practically constant, with 15 to 20 ppm in the surface horizon in spite of P exports by maize. Triomphe (1996) concluded that the practice of continued rotation with *M. pruriens* and maize prevented soil N depletion for at least 15 years. Our results showed that legumesimproved soil P (Table 1). Legumes fallows with *M. pruriens*, are known especially for improving the quantity of available P fractions in the soil for subsequent crops (Salako and Tian, 2003). Nevertheless, it depends on the inherent P levels in the soils. *M. pruriens* root exudates could solubilize P increasing its availability. In the study of Nziguheba *et al.* (1998), organic materials have also been found to reduce P sorption capacity of soils and increase crop yields in P limiting soils. The soil K concentrations were improved in our study (Table 1). Igué (2000) showed the soil K concentration of 0.82 cmol kg^{-1} in the 0-20 cm soil layer and decreased significantly with cultivation. The rate of decline was about 0.023-0.054 cmol kg^{-1} $year^{-1}$ in the 0-20 cm soil layer Igué (2000).

Conclusion

Yam based cropping systems with legumes improved significantly the N, P, and K balances in comparison with the traditional systems. ANOVA partial nested model showed that Nutrients balances of nitrogen, phosphorus and potassium differed significantly depending on the factors Treatment, Farmer and Replication. The factor Site was not significant for nutrient balance. Year × Treatment and Year × Site interactions were significant. We then propose to promote durable and replicable yam-based systems with legumes, through a favorable legislative, economic and political environment to support local initiatives. Collaborations between farmers, research, development and extension structures should also be favored to support the development and dissemination of innovations.

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