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Productivity and nutrient use efficiency of maize, sorghum, and cotton in the West African Dry Savanna

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Abstract

Sustainable agricultural practices are needed to improve food security and support livelihoods in West Africa, where soil nutrient deficiencies and rainfed production systems prevail. The objective of this study was to assess the productivity and nitrogen (N) and phosphorus (P) use efficiencies of three dominant crops (maize, sorghum, and cotton) under different soil management strategies in the dry savanna of northern Benin. Data were collected for each crop in experiments with (1) an un-amended soil as control, (2) a low use of external inputs, (3) an integrated soil–crop management practice, and (4) a high mineral fertilizer use, as treatments. Data were collected through researcher-managed and farmer-managed on-farm trials in 2014 and 2015, and analyzed using linear robust mixed effects model and Pearson's correlation. Above-ground biomass accumulation did not differ significantly among the control, integrated soil–crop management practice, and high mineral fertilizer use up to 30, 50, and 60 d after planting for maize, cotton, and sorghum, respectively. Thereafter, the differences in growth were substantial for each crop with highest biomass monitored with high mineral fertilizer use and lowest with the control. Biomass and economic yields at harvest were highest under high mineral fertilizer use and integrated soil–crop management practice, although the magnitude was crop-specific. With the integrated soil–crop management practice and high mineral fertilizer use, N and P uptake by all crops was higher than for the un-amended soil conditions. Inter-seasonal changes in N uptake were higher for sorghum and cotton, but lower for maize. The highest agronomic efficiency and apparent recovery of N and P as well as positive N and P partial balances were obtained with the integrated soil–crop management practice for all three crops tested. The integrated soil–crop management strategy gave the highest yields and significantly improved N and P use efficiencies. The findings can contribute to formulating site and crop-specific recommendations for sustainable agricultural practices in the Dry Savanna zone of West Africa.

Key words: Benin / dry savanna zone / *Gossypium hirsutum* / *Sorghum bicolor* / sustainable agriculture / *Zea mays*

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1 Introduction

Sustainable production systems are a key for achieving food security in West Africa. However, widespread land degradation and soil fertility depletion in the region, often mirrored in macronutrient deficiencies (*Schlecht* et al., 2007; *Bationo* et al., 2012), are threatening crop growth and productivity. The prevailing agricultural land-use practices in rainfed cropping systems enhance soil fertility depletion in West Africa (*Christianson* and *Vlek*, 1991) with negative effects on yields (*Lal*, 2006), productivity (*Wu* and *Ma*, 2015), and nutrient use efficiency (*Dobermann*, 2007; *Murrell*, 2009). Faced with declining productivity and concurrent growing food demands, West Africa has become a net food importer (*Rakotoarisoa* et al., 2011), exerting a massive strain on the foreign exchange expenditures.

Agricultural land-use practices in the West African Dry Savanna agro-ecological zone are characterized by diverse cropping systems including crop rotations, intercropping, monocropping, mixed cropping, and fallow rotations or combinations thereof (*Callo-Concha* et al., 2013). Current cropping systems are predominantly based on staple crops such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), millet (*Pennisetum glaucum* L.), and yam (*Dioscorea* sp). The cropping systems also include the industrial cash crop cotton (*Gossypium hirsutum* L.) and legumes such as groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna anguiculata* L). Legumes are typically intercropped with the staple crops. However, their direct contribution to soil fertility enhancement is limited owing to low planting densities (*Naab* et al., 2008)

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and low rates of biological N_2 fixation (*Sanginga*, 2003). Furthermore, existing soil fertility management recommendations are insufficiently adjusted to soil, crop or even cropping system (*Bationo* et al., 2012), and are rarely financially viable (*Lamers* et al., 2015a, 2015b).

Given the ongoing increase in pressure on land resources, the predicted climate change and variability, and the diversity of crops and cropping environments, the existing "blanket"-type of fertilizer recommendations (*Saidou* et al., 2012; *Igue* et al., 2015) is unsuitable to sustain food production now and in the future. To counterbalance current nutrient deficiencies, they need to be revised by taking into account site and system-specific requirements, whilst considering and assessing the feasibility of sustainable cropping strategies such as integrated soil fertility management (*Bationo* et al., 2007; *Vanlauwe* et al., 2010) or integrated nutrient management (*Wu* and *Ma*, 2015). However, identifying sustainable soil fertility management practices necessitates knowledge and understanding of crop-specific response patterns, plant nutrient uptake and use efficiency, which have until today rarely been assessed for the Dry Savanna agro-ecological zones in West Africa, including northern Benin. To support a better-informed decision making on site and crop-specific soil fertility management, the objective of this study was to assess the productivity and nitrogen (N) and phosphorus (P) use efficiencies of three dominant crops (maize, sorghum, and cotton) under different soil management strategies in the dry savanna of northern Benin.

2 Material and methods

2.1 Site description

Experiments were conducted during the 2014 and 2015 cropping seasons in the village of Ouri Yori (10°49′16′′N, 1°4′7′′E) in the Dassari catchment (10°44′0.15′′–10°56′0.6′′N, 01°01′37′′–01°11′33′′E) in northern Benin (Atakora department), West Africa. Trials were established on the three dominant soil types in the catchment, which are Plinthosols and Luvisols on the crests and upper slopes of the inland valleys and Alisols on lower slopes and valley bottom lands (*IUSS Working Group WRB*, 2014). The Alisols and Plinthosols have a loamy sand texture, whilst Luvisols have a sandy loam texture (*Steup*, 2016). The initial characteristics of the three soil types are presented in Tab. 1.

The catchment exhibits a dry savanna climate, characterized by a distinct wet (May–October) and dry (November–April) season. Total annual rainfall amounted to 937 mm in 2014 and 1096 mm in 2015 (Fig. 1). During the two growth seasons, daily rainfall (mm) and minimum and maximum air temperatures (°C) were measured at the experimental site with a Campbell Advanced Weather Station (CR1000). Rainfall in 2014 peaked in September (347 mm), but in 2015 already in August (429 mm). The mean annual air temperature was 29.3°C in 2014 and 28.9°C in 2015. The hottest month in 2014 was March (38°C), and April in 2015 (40°C), whilst the coldest month was December in both 2014 (18°C) and 2015 (16°C).

The livelihoods of the population are based on the production of staple and cash crops in combination with livestock rearing, forestry, and off-farm income generating activities (*Callo-Concha* et al., 2013). The population of the Atakora department amounted to 772,262 in 2013, with 50.7% being female. Growth rates were as high as 3.1% between 2002 and 2013 (*INSAE*, 2015).

2.2 Field experiments

Three field experiments were conducted to assess the response of an improved cultivar of maize (cv. EVDT-97 STR)

Table 1: Initial soil physical and chemical properties at the experimental sites in 2014.[a]

Parameters	Unit	Gleyic Alisols			Dystric Plinthosols			Ferric Luvisols		
		Depths (cm)			Depths (cm)			Depths (cm)		
		0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
pH $_{(H20,\ 1.0:2.5)}$		5.9	6.1	5.9	6.5	6.8	7.0	6.6	6.4	6.5
C_{org}	g kg^{-1}	2.8	1.4	1.3	7.0	1.8	1.7	6.8	3.1	2.3
N_{tot}	g kg^{-1}	0.5	0.4	0.6	0.9	0.6	0.5	0.8	0.6	0.6
Bray 1P	mg kg^{-1}	1.0	1.0	1.0	3.0	1.0	2.0	4.0	3.0	1.0
CEC	cmol$_c$ kg^{-1}	6.2	7.8	5.8	6.4	8.6	7.2	8.5	4.6	8.7
Sand	%	82.4	82.1	79.4	75	77.2	63.9	68.7	63.1	27.9
Silt	%	15.2	12.8	10.7	19.9	19.4	26.4	21.1	29.3	32.9
Clay	%	2.5	5	10.9	4	4.5	10.8	4.8	9.3	31.2
Bulk density	g cm^{-3}	1.4	1.4	1.4	1.5	1.5	1.4	1.5	1.5	1.5

[a]Source: Data sets from *Steup* (2016).

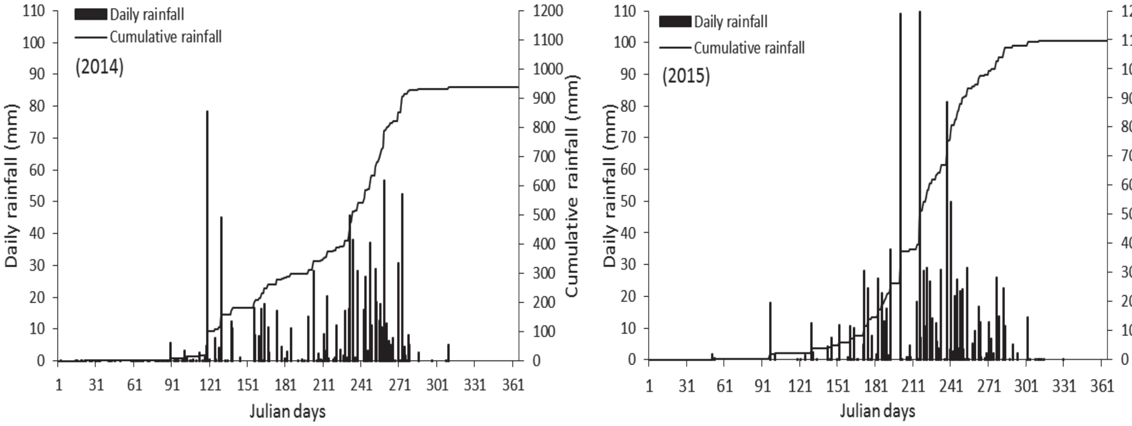

Figure 1: Daily and cumulative rainfall distribution during the 2014 and 2015 cropping seasons at the Ouri Yori village in North Benin. Source: data set from *Steup* (2016).

and cotton (cv. H-279-1), and a local cultivar of sorghum (cv. Local) to four soil fertility management systems (SMS). The experimental design, factors, and number of replications are described in Tab. 2.

In Experiment 1 (on-farm, researcher-managed trial), maize, sorghum, and cotton were grown under high mineral fertilizer use (HMF). Existing fertilizer recommendation rates for the tested crops are 44 kg N ha^{-1}, 15 kg P ha^{-1}, and 17.5 kg K ha^{-1} (*Saidou* et al., 2012; *Igue* et al., 2015). In the high mineral fertilizer treatment, the recommended fertilizer rates were almost doubled to test crop responses under nutrient stress-free and reduced water-stress conditions, and to assess the effectiveness of increased fertilizer use. To minimize water-stress, supplementary irrigation was applied (1.5–8.0 mm per event of watering) during dry spells in Experiment 1. In total, there were seven and nine applications over a period of 30 d after planting (DAP) in 2014 and 38 DAP in 2015. In Experiment 2 (on-farm, researcher-managed trial), treatments comprised an un-amended soil as control (CONT) and an integrated soil–crop management practice (ISC) combining the recommended mineral fertilizer use and return of crop residues. The integration of crop residues and inorganic fertilizer use is reportedly a potential option for sustainable soil fertility restoration in the region (*Lal*, 2006; *Schlecht* et al., 2007). Experiment 3 (farmer-managed trial) comprised the three crops with a low use of external inputs (LEI), *i.e.*, the farmers determined the mineral fertilizer rate. Although the farmers intercropped the maize and sorghum with cowpea, the density of the intercropped cowpea hardly reached 1 plant m^{-2}. Due to this very low density of the intercrop, these systems were considered as sole production systems and analyzed as such.

2.3 Crop and soil management

Table 2 presents details on crop planting dates and scheme, types and rates of fertilizers used, and management practices. In both seasons before planting, all experimental plots were tilled to 15 cm depth using an animal-drawn plow. During land preparation of the ISC treatment plots, all crop residues were incorporated into the soil. In the farmer-managed trial, plots were sprayed with glyphosate (300–600 g a.i. ha^{-1}) following tillage to clear any remaining weeds. During both seasons, crops were planted at the first suitable occasions (Tab. 2). Planting densities of all crops and fertilization timing in Experiments 1 and 2 followed local recommendations by the national agricultural extension services (*Saidou* et al., 2012; *Igue* et al., 2015). In Experiment 3, farmers planted all crops according to their own scheme (Tab. 2). Thinning of seedlings was done during the first weeding (≈ 15 DAP) leaving 2 plants per stand in Experiments 1 and 2. Farmers did not thin seedlings in Experiment 3.

In Experiment 1 for maize and sorghum, N was split-applied as urea, 50% of the total amount at 20 DAP and the remaining 50% at 45 DAP (Tab. 2). During the first N application, P as triple superphosphate and K as potassium chloride were applied at rates of 26 and 30 kg ha^{-1}, respectively. For cotton, a compound fertilizer containing NPK as well as sulfur (S) and boron (B) was applied at the rates of 21, 15, 17.5, 7.5, and 0.25 kg ha^{-1}, respectively. During this application, the quantity of N, P, and K was topped up with 19, 11, and 12.5 kg ha^{-1} using urea, triple superphosphate, and potassium chloride, respectively. Nitrogen was top-dressed at a rate of 40 kg N ha^{-1} using urea bringing the total N applied to cotton to also 80 kg ha^{-1} (Tab. 2). In Experiment 2, maize and sorghum received N, P, and K for the first fertilization at the rates of 21, 15, and 17.5 kg ha^{-1} as urea, triple superphosphate, and potassium chloride, respectively. The same amounts of N, P, and K were applied to cotton but using the compound fertilizer NPKSB, thus, applying 7.5 kg S ha^{-1} and 0.25 kg B ha^{-1}. Each crop received 23 kg N ha^{-1} as urea for the second fertilization bringing the total N applied to all crops to 44 kg ha^{-1} (Tab. 2). In Experiment 3, only maize and cotton were fertilized by the farmers with a combination of compound fertilizer and urea (Tab. 2), as is typically done, leading to different rates of application (Tab. 3).

Cotton was sprayed against pests in all experiments between first flowering (35–40 DAP) and physiological maturity (≈ 120 DAP). In the Experiments 1 and 2, cotton was sprayed six times. The first and second sprays involved Emamectin benzoate (24 g a.i. ha^{-1}) and Acetamiprid (32 g a.i. ha^{-1}), the third and fourth Lambda-Cyhalothrin (7.5 g a.i. ha^{-1}) and Pro-

Table 2: Description of experimental treatments, design and management practices in the three field experiments carried out during the 2014 and 2015 cropping seasons.

Designations	Experiment 1[a]	Experiment 2[bd]	Experiment 3[c]
Treatments	HMF with maize (cv. EVDT-97 STR), sorghum (cv. Local), and cotton (cv. H-279-1) as test crops	Un-amended soil as control (CONT), and integrated soil–crop (ISC)	Low external inputs (LEI)
Exp. design	Randomized complete block design (RCBD)	RCBD	RCBD
Replications	3	3	3 farms per cropping system
Plots size	6 m × 5 m	7 m × 4.2 m	0.5–1.5 ha
Test crops	Maize, sorghum, and cotton	Maize, sorghum, and cotton	Maize, sorghum, and cotton
Soil type	Gleyic Alisols	Gleyic Alisols	Alisols, Plinthosols, Luvisols
Planting dates	Season 2014: July 19 Season 2015: June 23	Season 2014: July 4 Season 2015: June 25	Season 2014: July 18–31 Season 2015: June 23–July 25
Planting scheme	For maize and sorghum: · 80 cm × 40 cm For cotton: · 80 cm × 30 cm	For maize and sorghum: · 80 cm × 40 cm For cotton: · 80 cm × 30 cm	For each main crop 70–80 cm × 40–50 cm
Density at seeding	For maize and sorghum: · 6 plants m^{-2} For cotton: · 8 plants m^{-2}	For maize and sorghum: · 6 plants m^{-2} For cotton: · 8 plants m^{-2}	5–7 plants m^{-2}
Fertilizer rates	80 kg N ha^{-1} , 26 kg P ha^{-1} , and 30 kg K ha^{-1}	CONT: no fertilizers; ISC: 44 kg N ha^{-1} , 15 kg P ha^{-1} , and 17.5 kg K ha^{-1} + residues retention	Different rates according to farmers (Tab. 3)
Type of Fertilizers used	For maize and sorghum: Urea (46%), Triple superphosphate (TSP, 46% P_2O_5), and Potassium chloride (60% K_2O) For Cotton:, $N_{14}P_{23}K_{14}S_5B_1$, Urea , TSP, Potassium chloride	For maize and sorghum: Urea, TSP, Potassium chloride For Cotton: $N_{14}P_{23}K_{14}S_5B_1$, Urea , TSP, Potassium chloride	For maize and cotton: $N_{14}P_{23}K_{14}S_5B_1$ and urea
Fertilizer application dates	First application: · Season 2014: 20 d after planting (DAP) · Season 2015: 21 DAP Second application: · Season 2014: 45 DAP · Season 2015: 44 DAP	First application · Season 2014: 21 DAP · Season 2015: 21 DAP Second application: · Season 2014: 40 DAP · Season 2015: 44 DAP	First application: · Both season: about three weeks after planting Second application: · Both season: about three weeks after the first application
Weeding	Regularly weeded manually	Regularly weeded manually	Weeded twice in each season
Net plot	4 m × 2 m	4 m × 2 m	4 m × 2 m, 3 replications per plot

[a] Experiment 1: On-farm researcher-managed trial with high mineral fertilizer use (HMF).
[b] Experiment 2: On-farm researcher-managed trial with an un-amended soil as control (CONT) and integrated soil-crop management (ISC).
[c] Experiment 3: On-farm farmer-managed trial with low use of external inputs (LEI).
[d] In 2015, Experiment 2 was re-designed to include supplementary irrigation as an additional treatment. However, only results from rainfed treatments are considered here.

fenofos (100 g a.i. ha^{-1}), and the fifth and sixth Lambda-Cyhalothrin (20 g a.i. ha^{-1}) and Acetamiprid (15 g a.i. ha^{-1}). The farmers in Experiment 3 conducted 4–6 phytosanitary sprays always with the same pesticides.

2.4 Data collection

2.4.1 Assessment of above-ground biomass and economic yields

From 20 DAP till harvest, above-ground biomass (AGB) was assessed fortnightly in Experiments 1 and 2 during the 2015

Table 3: Rates of N, P, and K applied by farmers ($n = 3$) participating in Experiment 3 to maize and cotton in 2014 and 2015 cropping seasons.

Seasons	Nutrients	Units	Maize/Cowpea intercropping[a]			Sole cotton		
			Farmer 1	Farmer 2	Farmer 3	Farmer 1	Farmer 2	Farmer 3
2014	N	kg ha^{-1}	35	47	28	18	50	27
	P	kg ha^{-1}	25	33	20	13	10	9
	K	kg ha^{-1}	29	39	23	15	12	11
2015	N	kg ha^{-1}	12	23	23	18	47	23
	P	kg ha^{-1}	8	4	6	3	10	6
	K	kg ha^{-1}	10	5	7	3	14	7

[a] Although farmers included cowpea as an intercrop, the density was less than 1 plant m^{-2}. Due to this very low density of the intercrop, this crop arrangement was considered as a sole crop during further analyses.

season, resulting in seven measurements for maize and nine for both sorghum and cotton. At each AGB assessment, whole plants were cut from three randomly selected plant stands in the outer bordered rows. The fresh AGB was chopped, mixed, and weighed with a portable scale and subsampled. The subsamples were weighed and oven-dried at 70°C till constant weight. The oven-dried samples were weighed again and dry matter (DM) content extrapolated to kg DM ha^{-1}.

At final harvest in 2014 and 2015, economic (grain of maize and sorghum and seed + lint of cotton) and stover yields were determined by harvesting the net plots in each experiment (Tab. 2). The fresh weight of all harvested fractions was weighed with a portable scale in the field, subsampled, and oven-dried at 70°C till constant weight to determine the moisture content and dry matter (kg DM ha^{-1}). The fresh total AGB from the net plot was weighed, and subsamples were taken and oven-dried to determine total AGB.

2.4.2 Soil and plant sampling and analysis

In Experiment 2, soils were sampled twice in 2014 (before planting and at final harvest) and three times in 2015 (3 weeks before planting, at planting, and at final harvest) for determination of nitrate-nitrogen (NO_3-N) and available P. At each sampling event, the soil was sampled at 3 random spots in each plot over three soil depths (0–20, 20–40, and 40–60 cm). The samples from each depth were bulked per plot and thoroughly mixed. The composite subsamples were analyzed for NO_3-N according to *IITA* (1982) and available P following the Bray-1 procedure (*Bray* and *Kurtz*, 1945).

The dried subsamples of maize and sorghum grain and seed cotton as well as the stover of all crops from the net plot at final harvest were ground with a Wiley mill to pass a 2-mm sieve and subsampled. The subsamples were analyzed for N and P contents according to *IITA* (1982). A fraction of each ground sample (0.5 g) was digested in a mixture of sulfuric acid, selenium oxychloride, and salicylic acid by heating gradually until complete mineralization. Concentrations of N and P in each digest were determined with an auto-analyzer (SKALAR) using Nessler's reagent as an indicator for N and ammonium molybdate solution as an indicator for P (*Anderson* and *Ingram*, 1993). The N and P uptake by grain or cotton seed was determined by multiplying the yields with the N and P concentrations. The N and P uptake of stover was calculated accordingly, albeit by using the stover yield and corresponding N and P contents. The total N and P uptake was extrapolated to kg ha^{-1} by adding the results of the N and P uptake of all fractions (economic product and stover components).

2.5 Evaluation of nutrient use efficiency

N and P use efficiencies were evaluated using the agronomic efficiency (AE) as an indicator for the improvement of productivity per unit of nutrient applied and the apparent recovery efficiency (RE) as a proxy for assessing nutrient uptake by crops relative to the amount of nutrient applied (*Dobermann*, 2007; *Murrell*, 2009). The indicator ratios were computed as:

$$AE = (Y - Y_0)/F, \tag{1}$$

$$RE = (U - U_0)/F, \tag{2}$$

where Y is the yield of the harvested portion of the respective crops (maize, sorghum, and cotton) with nutrients applied (kg ha^{-1}), Y_0 is the yield without nutrients applied (kg ha^{-1}), F is the amount of nutrients (N and P) applied (kg ha^{-1}), U is the total nutrient (N and P) uptake in above-ground biomass with nutrients applied (kg ha^{-1}), and U_0 is the nutrient uptake in above-ground biomass without nutrients applied (kg ha^{-1}).

2.6 Evaluation of N and P partial balances

The N and P partial balances were estimated for the maize, sorghum, and cotton-based production systems during the 2014 and 2015 growth seasons. The N and P input pathways comprised the application of fertilizers and the crop residues retention. The output pathways included the removal of the harvested products and crop residues. All crop residues under the ISC management system were left as surface mulch and incorporated into the soil during land preparation. The residues were removed from the other three fertility management treatments (HMF, CONT, LEI). Additional N-input pathways, such as through biological N_2 fixation, wet and dry deposition, and sedimentation or N losses through, for example, erosion, leaching, denitrification, and ammonia volatilization, were not considered. Similarly, P input through atmospheric deposition or losses through, for example, leaching and erosion were not considered in the analyses. The partial balances for N and P were computed as the difference between the estimated inputs and outputs (*Buerkert* et al., 2005; *Adamtey* et al., 2016).

2.7 Statistical analysis

The effects of the four SMS on the economic yields (grain and seed cotton), AGB, N and P uptake, and N and P-AE and RE of each crop were analyzed within seasons while comparing the inter-seasonal changes. A linear robust mixed effects model (*Milliken* and *Johnson*, 2009; *Mitchell*, 2015) was used under Stata 14.0 to account for repeated measurements, to correct for putative heteroscedasticity, and to analyze the margins with a pairwise comparison between and within factors. Hereby SMS and seasons were considered as fixed effects and replications as a random factor. The least significant difference (LSD), multi-comparisons method was used to separate the mean values at 5% level. The effects of SMS and monitoring time on AGB-DM accumulation of each crop during the 2015 cropping season in the Experiments 1 and 2 were analyzed also with the linear robust mixed effects model. The same method was used to analyze soil NO_3-N and available P in each production system of Experiment 2. Hereby SMS, soil depths, and monitoring time were considered fixed effects and replications as a random factor. The correlation between economic yields, AGB, and N and P uptake was assessed for each production system with Stata 14.0. The N and P partial balances were analyzed graphically using a bar chart.

3 Results

3.1 Above-ground biomass accumulation

In Experiments 1 and 2, there were no significant differences in maize AGB-DM among the treatments (CONT, ISC, and HMF) during the first 30 DAP (Fig. 2a). Thereafter, AGB values were significantly higher with HMF and ISC compared to CONT. Similarly, early-season sorghum AGB accumulation did not differ significantly among the three SMS up to 60 DAP (Fig. 2b). Between 60 DAP and final harvest (128 DAP), differences became substantial: sorghum AGB was the highest with HMF and lowest with CONT. No significant differences were observed in cotton AGB accrual in response to SMS between 20 and 50 DAP (Fig. 2c). Thereafter, cotton AGB increased faster under HMF and ISC relative to CONT.

3.2 Economic and above-ground biomass yields

Maize grain and biomass were significantly affected by SMS and seasons (Tab. 4A). In 2014, maize grain yield with HMF was significantly higher than that of ISC (by 21%), LEI (by 53%), and CONT (by 107%). In 2015, maize grain yields with HMF and ISC were similar, but significantly higher than that of CONT (by 118%) and LEI (by 208%). Grain yield in 2015 was 21% higher with CONT and about 29% higher with both ISC and HMF compared to 2014, but 37% lower with LEI. Maize AGB under HMF was statistically as high as that of ISC in 2014, but was the highest in 2015. The AGB yields were lowest with CONT and LEI in both seasons. Relative to 2014, maize AGB in 2015 increased by 3% with HMF, but decreased by 3% with ISC, 29% with CONT, and 46% with LEI.

In the sorghum-based production systems, SMS and seasons significantly affected grain and AGB yields (Tab. 4B). Sorghum grain yields with HMF and ISC were similar, but significantly higher than with CONT and LEI in both seasons (Tab. 4B). Grain yields under HMF and ISC were consistently higher than with CONT (20% in 2014 and 39% in 2015) and LEI (157% in 2014 and 225% in 2015). The sorghum grain yields in 2015 increased by 14% with LEI, 20% with CONT,

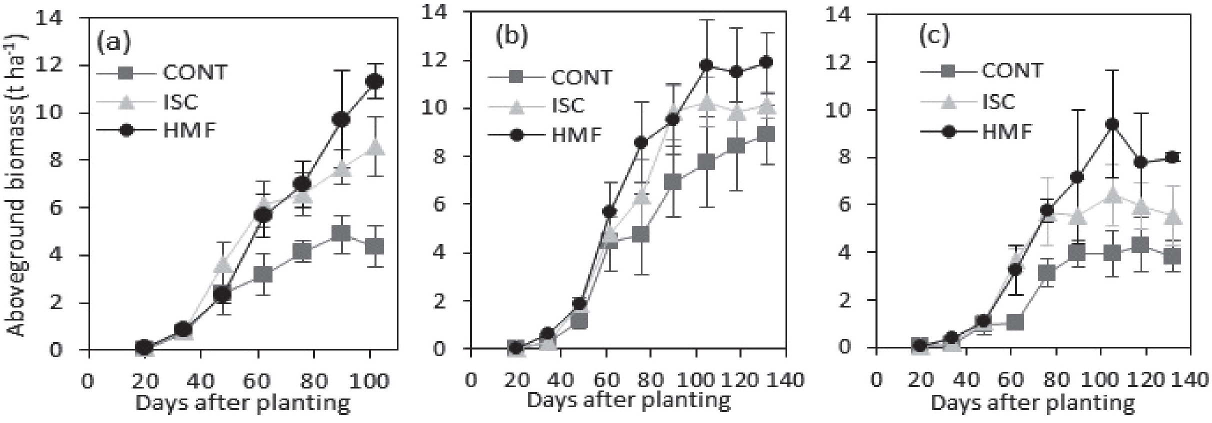

Figure 2: Above-ground biomass response to un-amended soil (CONT), integrated soil–crop management (ISC), and high mineral fertilizer use (HMF) of maize (a), sorghum (b), and cotton (c) during the 2015 cropping season in Experiments 1 and 2. *Source of variation*: SMS (P < 0.1%), time (P < 0.1%), and SMS x time (P < 0.1%), irrespective of the crop.

Table 4: Economic yield (grain of maize and sorghum, and cotton seed) and above-ground biomass (dried matter), and nitrogen and phosphorus uptake (N-UPT, P-UPT) under four soil-fertility management systems (SMS) in maize (A), sorghum (B), and cotton (C) production systems at the final harvest of 2014 and 2015.[a]

Seasons	**SMS**	**Economic Yield (t ha^{-1})**	**AGB (t ha^{-1})**	**N- UPT (kg N ha^{-1})**	**P- UPT (kg N ha^{-1})**
(A) Maize-based production systems					
2014	CONT	1.4c	4.9b	40.6b	15.2b
	ISC	2.4b	7.8a	79.6a	29.8a
	HMF	2.9a	9.1a	93.5a	35.2a
	LEI	1.9c	5.4b	48.9b	17.3b
2015	CONT	1.7b	3.5c	39.5c	13.7b
	ISC	3.1a	7.6b	80.1b	36.1a
	HMF	3.7a	9.4a	97.9a	43.9a
	LEI	1.2b	2.9c	27.0c	9.0b
P values SMS		< 0.001	< 0.001	< 0.001	< 0.001
P values Seasons		0.024	0.029	0.162	0.326
P values SMS × Seasons		< 0.001	0.059	0.015	< 0.001
(B) Sorghum-based production systems					
2014	CONT	1.5b	6.1b	55.9b	18.9b
	ISC	1.7a	8.5a	82.5a	27.1a
	HMF	1.8a	8.3a	78.9a	26.4a
	LEI	0.7c	2.8c	33.3c	10.1c
2015	CONT	1.8b	7.5b	69.4b	19.7b
	ISC	2.6a	10.8a	109.6a	30.5a
	HMF	2.5a	11.6a	111.3a	32.1a
	LEI	0.8c	3.7c	42.5c	12.5c
P values SMS		< 0.001	< 0.001	< 0.001	< 0.001
P values Seasons		< 0.001	< 0.001	< 0.001	0.049
P values SMS × Seasons		0.002	0.087	0.007	0.502
(C) Cotton-based production systems					
2014	CONT	1.2c	3.2b	35.3bc	11.2c
	ISC	1.8a	4.3a	55.8a	20.8a
	HMF	1.4b	3.4b	45.5b	16.8b
	LEI	0.9d	1.8c	28.2c	9.9c
2015	CONT	1.6b	4.2b	39.8b	13.8c
	ISC	2.2a	5.6ab	70.5a	23.6b
	HMF	2.4a	6.1a	79.2a	29.0a
	LEI	0.8c	2.5c	32.6b	11.2c
P values SMS		< 0.001	< 0.001	< 0.001	< 0.001
P values Seasons		< 0.001	< 0.001	< 0.001	< 0.001
P values SMS × Seasons		< 0.001	< 0.001	< 0.001	< 0.001

[a] **SMS** = Soil fertility management system; **CONT** = un-amended soil as control; **ISC** = integrated soil–crop management; **HMF** = high mineral fertilizer use; **LEI** = low external inputs; **UPT** = Uptake. Means in a column within a season and crop production system with similar letters are not significantly different at the 5% level according to the LSD test.

39% with HMF, and 59% with ISC relative to 2014. Sorghum AGB with HMF and ISC were similar in both seasons. The AGB was significantly higher with ISC compared to CONT (39% in 2014 and 44% in 2015) and LEI (204% in 2014 and 192% in 2015). The sorghum AGB significantly increased in 2015 compared to 2014 with CONT by 23%, ISC by 27%, LEI by 32%, and HMF by 40%.

SMS and seasons, as well as their interaction, significantly affected both seed cotton and cotton AGB yields (Tab. 4C). In 2014, seed cotton yield with ISC was significantly higher than that of HMF (by 29%), CONT (by 50%), and LEI (by 100%). In 2015, seed cotton yield with ISC did not differ from HMF, but was higher than that of CONT (by 50%) and LEI (by 175%). Seed cotton yield increased in 2015 compared to 2014 with ISC (by 22%), CONT (by 33%), and HMF (by 71%), but decreased with LEI (by 11%). In 2014, cotton AGB with ISC was higher than that of CONT and HMF (both by 26%) and LEI (by 139%). In 2015, with HMF cotton AGB was the highest of all SMS, albeit statistically similar to that of ISC. Cotton AGB under HMF in 2015 was 45% higher compared to CONT and 144% higher than that of LEI in the same season. Cotton AGB increased in 2015 compared to 2014 with all SMS, *i.e.*, by 24% with CONT, 30% with ISC, 39% with LEI, and 79% with HMF.

3.3 Nitrogen and phosphorus uptake

Maize N and P uptake (N-UPT, P-UPT) were significantly affected by SMS although this effect differed between seasons (Tab. 4A). The highest N-UPT occurred with HMF in both seasons. In 2014, N-UPT followed the order HMF > ISC (17%) > LEI (91%) > CONT (130%), but in 2015 the trend was HMF > ISC (22%) > CONT (148%) > LEI (263%). Compared to 2014, the N-UPT of maize decreased by 45% with LEI in 2015, but was similar for all other SMS. Maize P-UPT with HMF and ISC was statistically similar in 2014 and 2015, but was significantly higher than that of CONT by 132% in 2014 and 220% in 2015. Compared to LEI, the P-UPT with HMF was 103% higher in 2014 and 388% in 2015. The P-UPT in 2015 decreased by 48% with LEI and 10% with CONT compared to 2014, but increased by 21% for ISC and 25% for HMF over the same period.

Sorghum N-UPT and P-UPT were substantially affected by SMS although this effect differed between seasons (Tab. 4B). The N-UPT as well as P-UPT with HMF in both cropping seasons did not differ from ISC. In 2014, the N-UPT with CONT was 48% and with LEI 148% lower compared to ISC. In 2015, the N-UPT with HMF was 60% higher than with CONT and 162% greater compared to LEI. From 2014 to 2015, the N-UPT increased irrespective of the SMS, *i.e.*, with CONT by 24%, LEI by 28%, ISC by 33%, and HMF by 41%. The P-UPT with ISC in 2014 was 43% higher than that of CONT and even 168% greater than with LEI (Tab. 4B), whilst with HMF in 2015, it exceeded that of CONT by 63% and that of LEI by 157%. From 2014 to 2015, sorghum P-UPT increased by 4% with CONT, 13% with ISC, 22% with HMF, and 24% with LEI.

Significant effects of SMS and season and their interaction were measured for cotton N-UPT and P-UPT (Tab. 4C). In 2014, cotton N-UPT with ISC was significantly higher than that of HMF (by 23%), CONT (by 58%) or LEI (by 98%). In 2015, N-UPT by cotton with HMF and ISC were similar, but both were higher than that of CONT (by 99%) and LEI (by 143%). Cotton N-UPT increased in 2015 compared to 2014 with all SMS, *i.e.*, with CONT by 13%, LEI by 16%, ISC by 26%, and HMF by 74%. Clear differences emerged among the SMS treatments in cotton P-UPT in 2014 and 2015. The P-UPT with ISC in 2014 exceeded that of HMF, CONT, and LEI by 24%, 86%, and 110%, respectively. In 2015, cotton P-UPT with HMF was higher than that of ISC by 23%, CONT by 110%, and LEI by 159%. Cotton P-UPT over time increased by 23% with CONT, 13% with ISC, 73% with HMF, and 13% with LEI. Irrespective of the three crops tested, strong relations existed between economic yield, AGB yield, and N and P uptake (not shown).

3.4 Nitrogen and phosphorus use efficiencies

In the maize-based production systems, N-AE was significantly higher with ISC than with HMF (Tab. 5A). The N-AE in 2015 increased by 37% with ISC and 34% with HMF compared to 2014. No significant differences existed between ISC and HMF in N-RE of maize in both seasons (Tab. 5A). From 2014 to 2015, the N-RE of maize increased by 5% with ISC and 11% with HMF. Similarly, no differences were found between ISC and HMF in P-AE as well as RE of maize within the seasons (Tab. 5A). The inter-seasonal changes in P-AE were greater for HMF (34%) compared to ISC (20%), but the increases for P-RE amounted to 53% with ISC and 51% with HMF.

In the sorghum-based production systems, N-AE with ISC was significantly higher than with HMF in all seasons (Tab. 5B). From 2014 to 2015, the N-AE of sorghum increased by 128% with ISC and 20% with HMF. In contrast to maize, there were differences in sorghum N-RE between ISC and HMF, with the latter being significantly lower (Tab. 5B). Relative to 2014, in 2015 N-RE increased by 98% with ISC and by 134% with HMF. Sorghum P-AE did not differ between ISC and HMF in the 2014 season, but was higher with ISC than with HMF in the 2015 (Tab. 5B). The inter-seasonal increases of P-AE amounted to 128% with ISC and 21% with HMF. No significant effect of SMS was found for P-RE (Tab. 5B) within both seasons. However, inter-seasonal increases in P-RE were observed for ISC (21%) and HMF (71%).

In the cotton-based production systems, N-AE, N-RE, P-AE, and P-RE were higher with ISC than with HMF in the 2014 season. However, in 2015, no differences emerged between ISC and HMF in all indicators (Tab. 5C). From 2014 to 2015, N-AE increased by 21% with ISC and 226% with HMF. The inter-seasonal increases in N-RE amounted to 4% with ISC and 181% with HMF. In 2015, the P-AE was 21% higher for ISC compared to 2014, but 312% higher with HMF over the same period. From 2014 to 2015, a great increase occurred in P-RE of cotton with HMF (181%) compared to ISC (10%).

Table 5: Nitrogen and phosphorus agronomic efficiency (AE) and apparent recovery (RE) of maize, sorghum, and cotton production systems under high mineral fertilizer use (HMF) and integrated soil–crop management (ISC) in 2014 and 2015.

Seasons	**SMS**	**Nitrogen use efficiencies ratios**		**Phosphorus use efficiencies ratios**	
(A) Maize-based production systems		**AE**	**RE**	**AE**	**RE**
2014	ISC	24.7a	0.88a	62.1a	0.83a
	HMF	19.3b	0.66a	59.2a	0.77a
2015	ISC	33.8a	0.92a	74.6a	1.27a
	HMF	25.8b	0.73a	79.4a	1.16a
P-values SMS		< 0.001	0.130	0.935	0.699
P-values Seasons		0.003	0.482	0.182	< 0.001
P-values SMS × Seasons		0.636	0.811	0.751	0.702
(B) Sorghum-based production systems					
2014	ISC	7.5a	0.60a	18.8a	0.47a
	HMF	6.4b	0.29b	19.7a	0.28a
2015	ISC	17.1a	1.19a	42.9a	0.62a
	HMF	7.7b	0.68b	23.8b	0.48a
P-values SMS		0.002	0.010	0.010	0.273
P-values Seasons		0.004	< 0.001	0.004	0.221
P-values SMS × Seasons		0.073	0.238	0.013	0.882
(C) Cotton-based production systems					
2014	ISC	11.9a	0.47a	29.8a	0.49a
	HMF	3.1b	0.16b	7.5b	0.21b
2015	ISC	14.4a	0.49a	36.1a	0.54a
	HMF	10.1a	0.45a	30.9a	0.59a
P-values SMS		0.042	0.006	0.017	0.049
P-values Seasons		< 0.001	0.007	0.002	< 0.001
P-values SMS × Seasons		0.032	0.024	0.073	< 0.001

[a] Means in a column within a season and crop production system with similar letters are not significantly different at the 5% level according to the LSD test.

3.5 Nitrogen and phosphorus partial balances

In the maize-based production systems, N and P partial balances were consistently negative for CONT and HMF, but positive with ISC in both seasons. Whilst the N partial balance for LEI was negative with maize in both seasons, the P partial balance was positive in 2014 and closer to the equilibrium in 2015 (Fig. 3a, b). With sorghum in 2014, the use of HMF resulted in almost balanced N and P input and output flows, but negative balances in 2015. The N and P partial balances for sorghum were largely negative with LEI and positive with ISC in both seasons (Fig. 3a, b). The N and P partial balances for cotton were positive with HMF in 2014, but in 2015 nearly zero for N and even negative for P. With LEI, the N partial balance was nearly zero in both seasons, while the P partial balance was near to zero in 2014 and negative in 2015. Under ISC, the N and P balances were positive in both 2014 and 2015 (Fig. 3a, b).

3.6 Dynamics of soil nitrate-nitrogen and available phosphorus

The soil management systems (SMS) and time of sampling significantly affected NO_3-N, irrespective of the crops. Soil layers affected significantly NO_3-N in both sorghum and cotton-based production systems, but not with maize (Fig. 4A1, B1, C1). Prior to planting in 2014 (166 days of year, DOY), differences existed neither among soil layers and nor between the CONT and ISC treatments in NO_3-N for all crops (Fig. 4A1, B1, C1). At final harvest of each crop, NO_3-N with ISC was higher than with the CONT. Nitrate-N tended to be higher in the 0–20 cm layer than in deeper layers under sorghum and cotton cultivation. In the 2015 cropping season, no differences were monitored in NO_3-N between CONT and ISC or among soil layers at the first sampling (153 DOY). However, around the planting period (176 DOY), NO_3-N tended to be higher under maize and sorghum than under cotton. Under

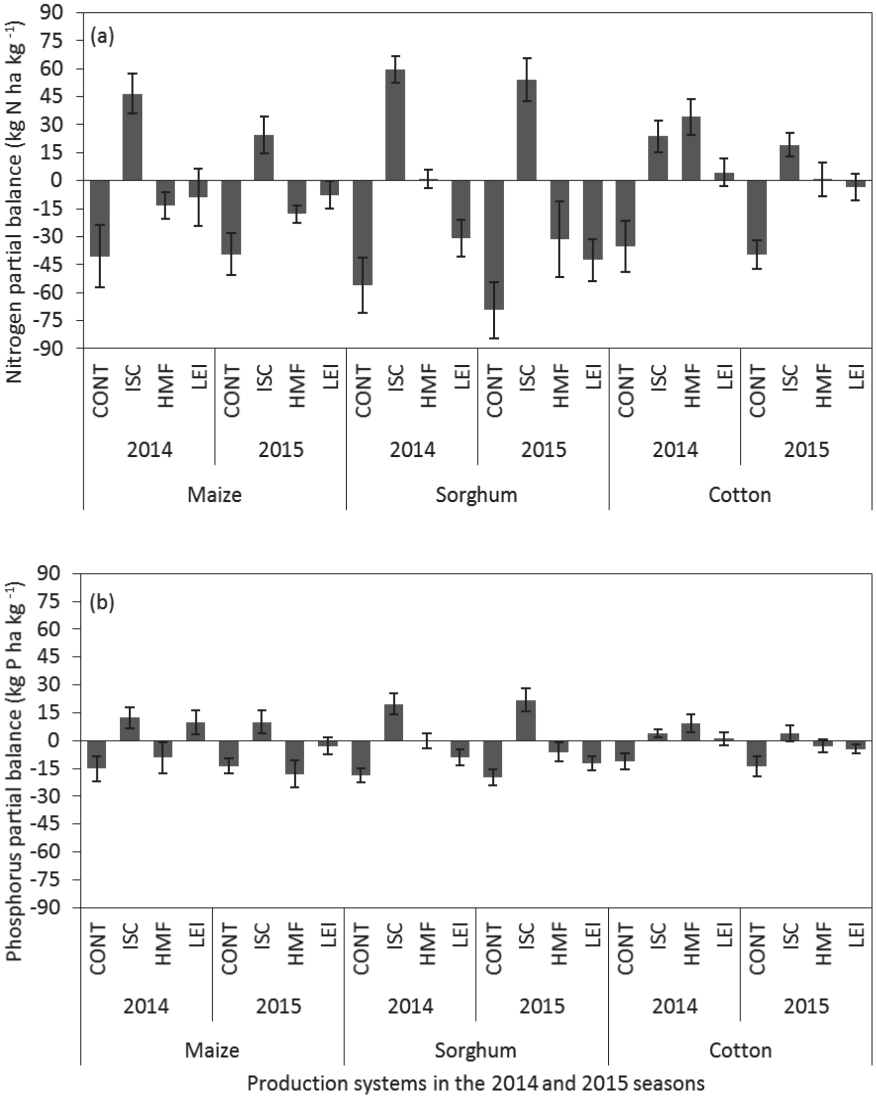

Figure 3: Nitrogen (a) and phosphorus (b) partial balances for the un-amended soil (CONT), integrated soil–crop management (ISC), high mineral fertilizer use (HMF), and low use of external inputs (LEI) under maize, sorghum, and cotton during the 2014 and 2015 cropping seasons.

maize, NO_3-N was significantly higher with ISC than with CONT. Nitrate-N was more variable under sorghum. At final harvest of each crop, differences in NO_3-N between CONT and ISC had diminished.

Available P varied substantially with soil layers and time of sampling, but was not significantly affected by SMS for all crops (Fig. 4A2, B2, C2). In the 2014 season, available P prior to planting (166 DOY) was significantly higher in the top 0–20 cm soil layer than that in deeper layers, irrespective of the SMS. The pattern was similar at final harvest, being generally higher in the top than in the bottom layers. In the 2015 cropping season, available P was also higher in the 0–20 cm soil layer compared to the bottom layers at 153 DOY and 176. However at final harvest, clear patterns for differences among soil layers did not exist and neither between the CONT and ISC treatments.

4 Discussion

To support a better-informed decision making on site and crop-specific soil fertility management practices in the Dry Savanna, productivity and N and P use efficiencies of maize, sorghum, and cotton under different SMS were assessed in northern Benin. The findings gained with the four SMS practices reinforced the urgency for updating the current soil fertility recommendations in the region for the three crops while considering crop-specific responses and improvement of soil organic matter.

The monitored magnitude of the initial AGB growth is likely due to a favorable soil moisture induced by sufficient rainfall and its distribution at the onset of the 2015 season (Fig. 1), resulting in a pulse of nitrate around the planting period (Fig. 4). The release of soil nutrients, mainly N, immediately after early-season rainfall (*Lançon* et al., 2007) counterbalanced the initial soil fertility differences caused by the different SMS. Significant effects of N and P application on AGB accumulation was previously reported also (*e.g.*, for maize, *Dzotsi* et al., 2010).

The positive response of the economic and AGB yields of all three crops to fertilizer amendments, confirmed previous findings for maize in the savanna region of Benin (*Igue* et al., 2015), sorghum in the semi-arid regions of Ghana (*McCarthy* et al., 2010), and cotton in the savanna zone in Mali (*Ripoche* et al., 2015). The impact of the SMS tested on economic and AGB yields was, however, crop-specific and caused by a crop-specific use of resources. For instance, the lower level of seed yield of cotton and AGB with HMF relative to ISC resulted probably from the delayed planting in 2014 (Tab. 2). *Lançon* et al. (1989) already reported a depressive effect of delayed planting on cotton seed yield and recommended therefore planting dates before June 30 in the West African Dry Savanna, including northern Benin. In addition, the significantly lower cotton seed and AGB yields under LEI compared to those of CONT were not only caused by the SMS and the resulting differences in soils properties (Tab. 1, Fig. 3), but were also due to other management practices (*e.g.*, delayed planting, lower planting density, inappropriate fertilizer management, and weed competition). Similarly, the low sorghum production under LEI in the farmer-managed trials was due to the lack of fertilizer application during cultivation, because sorghum grain yields increased with ISC and HMF, which confirmed previous findings (*McCarthy* et al., 2010). Furthermore, the effect of ISC on economic and AGB

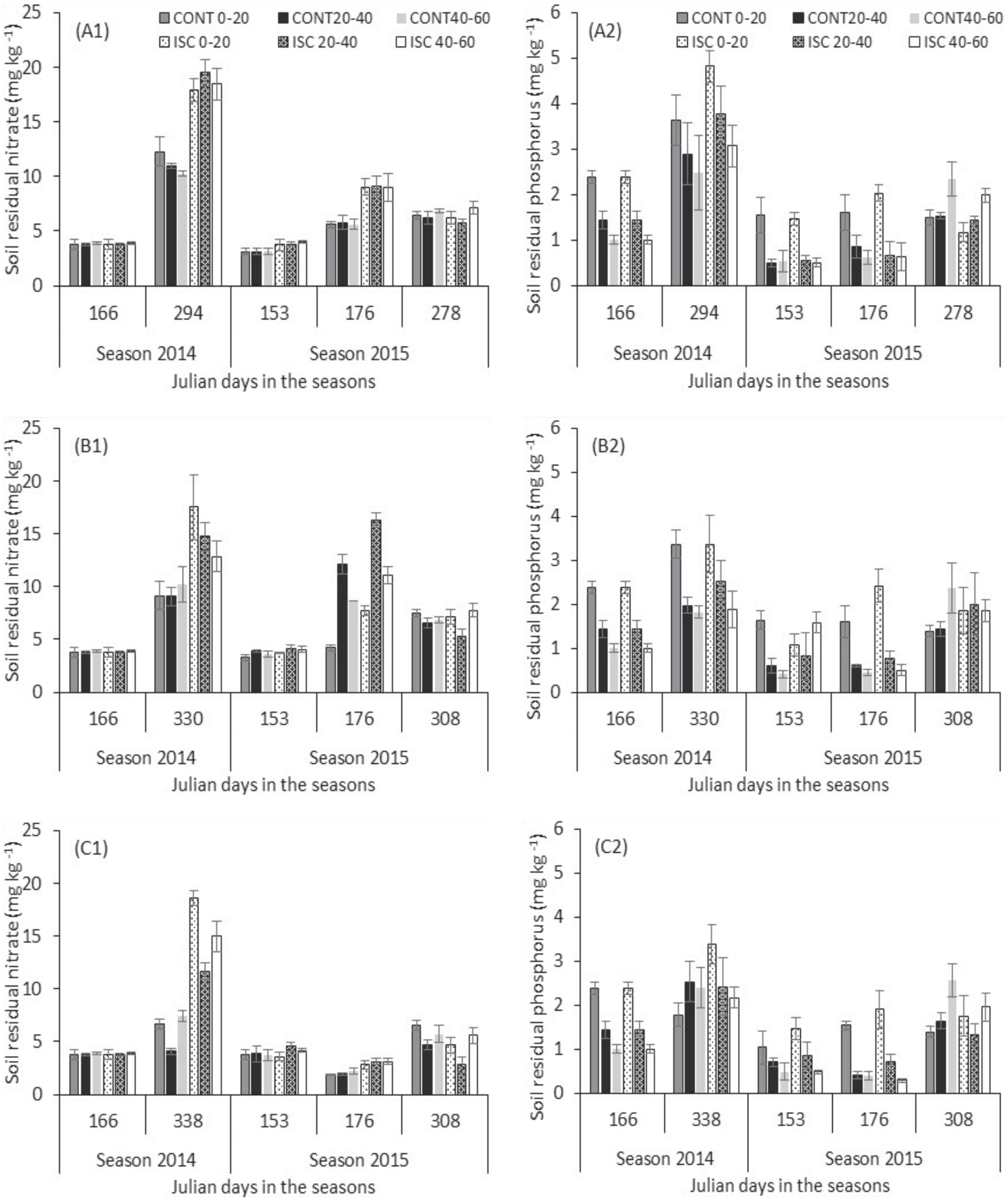

Figure 4: Soil residual nitrate and available phosphorus dynamics in soil without any amendment (CONT) and with integrated soil–crop management (ISC) under maize (A1, A2), sorghum (B1, B2), and cotton (C1, C2) production systems in 2014 and 2015.

yields of all three crops suggests an improved plant nutrition with ISC compared to HMF and probably even a luxury consumption when applying HMF. The current findings together with an archive of worldwide information (*Kumar* and *Goh*, 1999), but more specifically for various regions in West Africa (*Lal*, 2006; *Bationo* et al., 2007), demonstrate a significant contribution of crop residues to soil fertility enhancement and crop productivity (*Buerkert* and *Hiernaux*, 1998; *Schlecht* et al., 2007). This underlines the benefit of an approach that integrates inorganic and organic fertilizers (*Vanlauwe* et al., 2014; *Wu* and *Ma*, 2015).

It was notable that the inter-seasonal differences, which resulted in increased economic yields for all three crops in 2015, occurred also with the un-amended soil. Given that all factors in 2014 and 2015 had been kept equal, the seasonal-related differences are thus likely a result of rainfall, which in 2015 was, in terms of quantity and distribution, more advantageous compared to 2014 (Fig. 1). In contrast, the marked inter-seasonal decreases in final maize grain and seed cotton yields with LEI under the farmer-managed experiment was a result of the inaccessibility of fertilizers combined with inadequate soil management practices. The lack of consistency in fertilizer rates on the farmer-managed fields (Tab. 3) implies also tradeoffs made by farmers as previously reported (*Theriault* and *Tschirley*, 2014). For instance, since fertilizers are hardly affordable by farmers, fertilizers provided through the input-credit system established for cotton production are (partly) diverted to boost in particular maize production for reaching food security. It therefore has recurrently been underlined that improving access of smallholder farmers to affordable input markets is greatly needed and could boost the sustainable production of all crops (*Theriault* and *Tschirley*, 2014; *Ripoche* et al., 2015).

The known extent of seasonal N (35–69 kg N ha^{-1}) and P (11–19 kg P ha^{-1}) uptake in an un-amended soil under maize, sorghum, and cotton cultivation (Tab. 4) implies an alarming ongoing nutrient mining, which cannot be countered unless amendments are ensured (*Schlecht* et al., 2007). Hence, the N and P uptake, which was highest with ISC and HMF, confirms previous postulations that fertilizer application can enhance and sustain plant nutrition not only in the region (*Vanlauwe* et al., 2014) but also worldwide (*Godwin* and *Singh*, 1998). Despite the differences in applied amounts of chemical fertilizers (Tab. 2), the similar levels of N and P uptake under ISC and HMF are supported by the impact of crop residue recycling and its consequent nutrient release as substantiated by the N and P AE and RE. Units of N and P fertilizers applied as part of the ISC practice resulted in higher economic yields and lower nutrient losses compared to the use of chemical fertilizers alone (HMF). Moreover, the current estimates of N-RE under ISC were even within the range recognized in general as "best management options" (*Snyder* and *Bruulsema*, 2007; *Fixen* et al., 2015).

The lack of a targeted application of external input resulted in unbalanced N and P input and output flows. This was true not only when assuming the CONT for all three crops, but also with regards to sorghum under the LEI in the farmer-managed trial. Hence, under such conditions crop production depends largely on the N and P supplied by the soils alone (*Bowen* and *Baethgen*, 1998). However, the soils have been mined for decades at an alarming rate under the maize, sorghum, and cotton production practices common in Sub-Saharan Africa countries and this process is still going on (*Stoorvogel* and *Smaling*, 1990). These general trends contrast thus with the positive N and P balances estimated for all three crops with the ISC practice, *i.e.*, integrating inorganic fertilizers with crop residues recycling. The other trends of the N and P balances (*i.e.*, negative or near to zero) were estimated under HMF and LEI (Fig. 3) that did not experience a targeted input of organic matter, but of chemical fertilizers only (Tabs. 2 and 3). A comprehensive review on partial and full nutrient balances for several countries in Africa (*e.g.*, Mali, Ethiopia, Kenya, Uganda) pointed at evident N losses, but less remarkable losses for P (*Cobo* et al., 2010). Recently in Kenya, *Adamtey* et al. (2016) estimated positive P partial balances under both low and high inputs compared to conventional and organic production systems. They underlined also the negative trends for N in conventional systems and positive trends for organic high input systems. Overall, it should be noted that the current N and P partial balances, however, did not account for all potential inputs and outputs of N and P and should therefore be treated with caution because, for instance, nutrient depletion by leaching, wind erosion (*Schlecht* et al., 2007), and gaseous losses (*Godwin* and *Singh*, 1998) could be non-negligible.

The levels of NO_3-N and available P at harvest differed with ISC relative to CONT. These differences were driven mainly by the N and P applications, return of residues, and seasonal nutrient uptake. The increased accessibility of NO_3-N at the onset of the rainy season 2015 (Fig. 4) is caused by a mineralization of soil organic matter under CONT or by the mineralization of both organic matter and N-based fertilizers applied under ISC. This phenomenon, known as the N "Birch effect" (*Unger* et al., 2010) for N release mainly, eased in part the recurrently mentioned key biophysical constraints for crop growth and productivity in the dry savanna region (*Lançon* et al., 2007). However, crop residues with relatively high lignin concentrations (*e.g.*, here cotton stems) could reduce the extent of soil-N peaks as observed between the cotton harvest in 2014 and the planting time of 2015 (Fig. 4) due to N immobilization by soil microorganisms (*Kumar* and *Goh*, 1999; *Muhammad* et al., 2011). The similarities noted for NO_3-N and available P between SMS and soil layers at 166 DOY in 2014 and 153 DOY in 2015 could be explained by the more drier conditions (*Unger* et al., 2010).

Irrespective of the SMS tested, all three crops benefited from the sudden flows of nutrients that occurred at the onset of the rainy season. However, to exploit these flows, a careful synchronization of peaks in N release and crop demands is compulsory, which in turn demands good management, *e.g.*, timely planting. Whilst such a synchronization was previously handled and managed by the farmers, the growing increase in erratic rainfall at the onset of the season (Fig. 1), as reported for the region (*Cooper* et al., 2008; *Ouorou Barre*, 2014), renders an effective management by the farming population more and more challenging. Options to counterbalance the growing insecurity and risks at the onset of the growth season include the application of supplementary water to cope, for instance, with in-season dry spells (*Fox* and *Rockström*, 2003; *Reddy*, 2016). The synergetic effect of crop residue retention and fertilizer application on crop production and nutrient use efficiency must be of interest not only to the farmers, but also to decision makers since the affordability of inorganic fertilizers and financial viability of fertilization strategies are still of major concern in the region (*Lamers* et al., 2015a, 2015b).

5 Conclusions

The findings overall indicate that the current soil fertility recommendations for the three crops tested need to be updated while considering crop-specific responses and accounting for the different sources of external inputs. This is true in particular when considering the use and retention of crop residues, since such a practice could concurrently increase competition between the use of crop residues as soil amendment, livestock feed, and/or domestic fuel, which must be avoided when possible. It furthermore becomes clear that the improved soil fertility management practices should be flanked with soil and water conservation options to cope successfully with the weather vagaries at the onset of the season such as dry spells, since crops will otherwise no longer be able to rely on the contribution of early-season organic matter mineralization. The integrated soil–crop management practice improved yields and nutrient use and balances most efficiently, and can thus sustain better the responses of the crop under the ongoing climate variability.

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