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Inorganic fertilizer use efficiency of millet crop increased with organic fertilizer application in rainfed agriculture on smallholdings in central Senegal

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ABSTRACT

Much effort has been spent on formulating guidelines for inorganic fertilizer use in millet crops in Sub-sahelian farms. However, these guidelines do not take into account the diversity of manuring practices. In this study we analyzed over two years (2016–2017) the use efficiency of an inorganic NPK fertilizer as affected by the two most contrasted categories of organic manure strategies (OMS) found in millet fields of central Senegal. 19 farmers' fields were selected in a village typical of that region, 11 and 8 of which respectively corresponding to categories OMS1 and OMS2 as follows: OMS1, locally referred to as Homefields, were fields continuously cropped with millet over the last 15 years, having received organic manure regularly in the past, and manured again at the onset of the 2016 rainy season. OMS2 fields locally referred to as Outfields, were not manured in 2016 and were rarely manured in the past. Four of them were continuously cropped with millet and the others had followed a triennial millet-peanut-fallow rotation. In 2017, no manure was applied in any of the OMS1 or OMS2 fields. A pairwise treatments with and without the same inorganic fertilizer dose was applied in each field in both 2016 and 2017 cropping seasons. In 2016, the higher the manure application, the higher the use efficiency of the inorganic fertilizer applied. The use efficiency of the inorganic N was most closely related to soil bulk density and P availability. In 2017, with no new manure amendment, millet yield in OMS1 was about three times higher than in 2016. It was close to the water-limited yield, suggesting that the residual effect of the manure applied in 2016 was high. The use efficiency of the inorganic N was generally low under these conditions. In OMS2, millet yield and use efficiency of inorganic fertilizer remained low in both years. The crop rotation with peanuts did not enrich the soil compared to the millet returning every year, but it reduced *Striga hermontica* infestation and increased the millet 1000-grain weight. The methodological approach developed here may help in formulating guidelines to deal with the diversity of farming practices in Sub-sahelian villages.

1. Introduction

In central Senegal a typical semi-arid area of the Sudano Sahelian West Africa (SSWA), although drought risks are high, nutrient shortages are often the major limiting factor for millet yields (Affholder et al., 2013). The low availability of crop residues and animal manure in smallholdings would justify using inorganic fertilizers to sustain or increase crop yields as a way to help farmers out of the poverty trap in which they find themselves (Tittonell and Giller, 2013). Nevertheless, inorganic fertilizers are rarely used for growing millet (Audouin et al., 2015). This may be due in large part to socioeconomic constraints such as high fertilizer prices, limited availability of these fertilizers and low prices for millet, but another reason may be that inorganic fertilizers are not sufficiently effective or reliable in increasing millet yields in this region.

The role of manure application in improving the use efficiency of nutrients in cereal crop production in SSWA is controversial. In his extensive review on soil fertility in this area, Pieri (1989) had come to the conclusion that a balanced and routine use of organic and inorganic fertilizer may reverse, within a few years, soil degradation where it had

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already occurred, and sustain crop yields well above those obtained under the current soil fertility management. Furthermore, several studies in other regions of Sub-Saharan Africa have suggested that long term continuous cultivation without sufficient organic restitution may degrade soils to such an extent that they may become “non responsive” to inorganic fertilizers with low use efficiency of the applied nutrients (Zingore et al., 2007; Tittonell et al., 2008; Tittonell and Giller, 2013; Vanlauwe et al., 2011; Fofana et al., 2008). However, more recently, a thorough analysis of a 25 years fertility experiment showed that combining organic and inorganic fertilizer did not provide any yield advantage compared to supplying the same amounts of nutrients using exclusively organic or inorganic sources (Ripoche et al., 2015). These apparently contradictory results may be partly explained by the fact that the inorganic fertilizer application may interact with many components of the cropping systems and their environment, and these may vary greatly between fields and years.

The objective of this paper was to quantify, in-situ, the use efficiency of inorganic fertilizer by pearl millet in selected fields typical of rainfed agriculture in central Senegal. We assessed the role of organic manure, crop rotations, *Striga hermontica* infestations, P limitation and water stress on the variability of millet yield response to inorganic fertilizer application. The novelty of this study was the use of a diversity of farmers’ fields, each comprising a single and constant experimental NPK fertilizer dose and its control without fertilizer, to determine the interactions of various farming practices on the inorganic fertilizer use efficiency.

2. Materials and methods

2.1. Study area and currently practiced cropping systems

This study was conducted in the village of Diohine (14º30'4"N, 16º30'10"W) in the region of Fatick, Senegal (Fig. 1). The climate is Soudano Sahelian, with a long dry season between November and June, and a short rainy season between July and October. The annual rainfall record from the Fatick meteorological station shows a succession of very dry years from 1968 to 1974 and then increasing, but highly variable, annual rainfall, between 300 mm in 1986 and 900 mm in 2010. The mean temperature varies between 24 and 30 °C during the year. The average solar radiation is 20–24 MJ m^{-2} day^{-1} during the rainy season. The soils are arenosols (FAO-Unesco, 1976). These soils have long been described as poor in organic matter and nutrient stocks (Pieri, 1989; Diouf, 1990), but no recent data on changes have been reported in the literature. Their sandy texture and a bulk density around 1.5 g cm^{-3} are such that their volumetric soil moisture at field capacity and permanent wilting point are around 13 % and 4 % respectively, resulting in a water reserve of 90 mm per meter depth of soil (Affholder, 1995, citing Hamon, 1980 and Imbernon, 1981).

The cases studied here are particularly typical since the soil fertility management follows a “ring cultivation system” (Pelissier, 1966) that is still common across the whole Sub-Saharan Africa (e.g. Affholder, 1995; Fofana et al., 2008; Tittonell et al., 2007). In this system, the fields near the homestead (homefields) are more fertile as they benefit from continuous application of the household’s organic waste and receive substantial amounts (ranging 4 to 20 t ha^{-1} of dry matter) of cattle and small ruminant manures every year or two, whereas the fields located further away (outfields) are poor in organic matter and nutrients, resulting from far less frequent organic fertilization.

2.2. Experimental design

The experiment was laid out in 2016 and 2017, in 19 farmers’ fields belonging to two main categories of organic manure strategies (OMS1, OMS2) found in the study area. OMS1 contained 11 fields continuously cropped with millet over the last 15 years, having received organic manure regularly in the past, and manured again at the onset of the 2016 rainy season. The other 8 fields, belonging to OMS2, were not manured in 2016 and were very rarely manured in the past. In 2017, no manure was applied in any of the OMS1 or OMS2 fields. A pairwise treatments with and without the application of inorganic fertilizer was set up in each field. The OMS categories were treated as main plots in a split plot design, and the pairwise treatment as two split-plot treatments

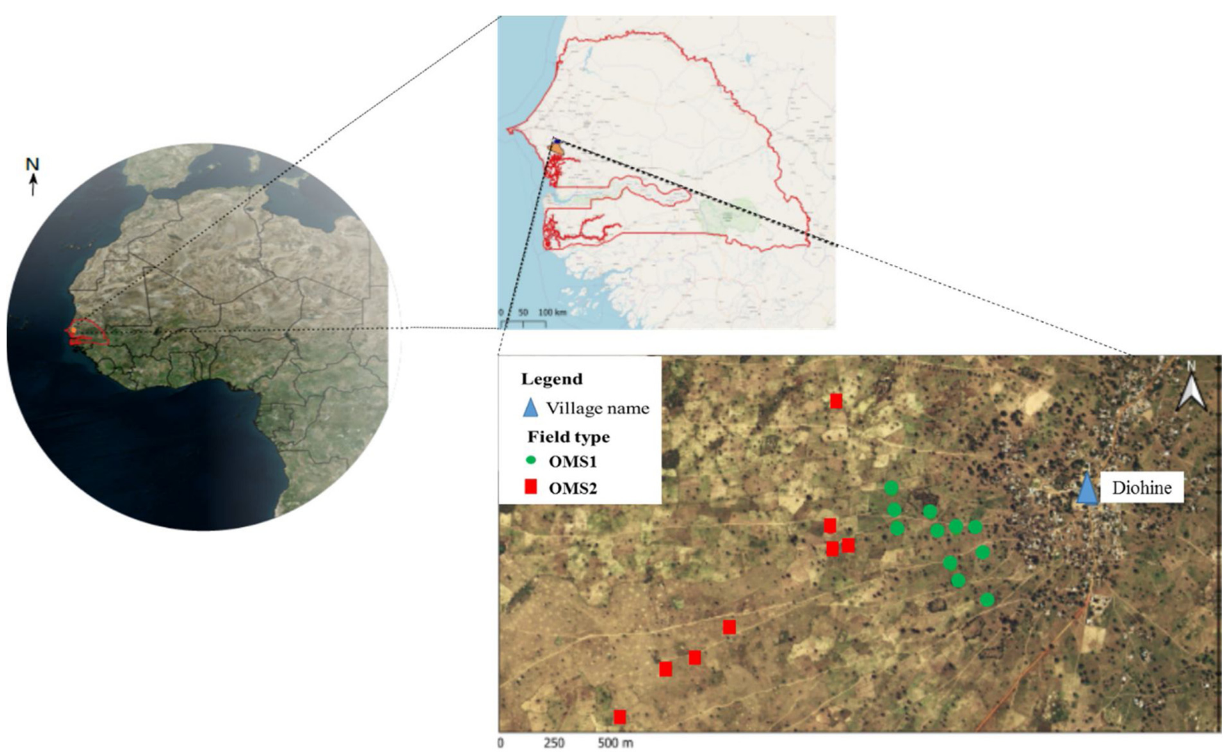

Fig. 1. Study area (Diohine 14°30'4"N, 16°30'10"W) in Senegal with the 19 farmers’ fields used. (■): Outfields (OMS2); (●): Homefields (OMS1).

Table 1
Characteristics of the "Organic Manure Strategies" referred to as the "main plots" of the experimental design.

Organic manure Strategies	OMS1 (Homefields)			OMS2 (Outfields)	
	OMS1low	OMS1medium	OMS1high	OMS2rot	OMS2cont
Manure dose applied in 2016 (t ha^{-1})	5–8	10–15	18–20	0	0
Rotation crop	Continuous millet	Continuous millet	Continuous millet	Peanut/Millet/Fallow	Continuous millet
Number of fields (main plots)	3	5	3	4	4

within each main plot. The 11 and 8 fields of respectively OMS1 and OMS2 were treated in the statistical analysis as replicates.

The main plots had a surface area of 150 m^2. They were selected within each field to be as uniform as possible, this means, with a similar amount and quality of manure applied and similar crop succession history, no visible termite mounds, trees, bumps, erosion strips, or color differences. Based on the manure dose applied in 2016, the two main OMS were classified in subcategories as follows (Table 1).

- OMS1low, OMS1medium and OMS1high which received 4, 10 and 15 t (dry matter) of farmyard manure in 2016. Surveys of the farmers suggested that the same dose ranges were applied in their fields every year or two for the last fifteen years.
- OMS2rot and OMS2cont which were never manured and only different by the cropping history: the fields of the OMS2rot were cultivated with a triennial peanut/millet/fallow rotation, whereas those of the OMS2cont were with a continuous millet.

The split plot treatments were laid out in subplots of 36 m^2 (6 m × 6 m):

- T0: the control, without additional application of an inorganic fertilizer,
- T1: application of 150 kg ha^{-1} of NPK, of formula 10-10-20, supplying 15 kg N ha^{-1}, 7 kg P ha^{-1}, 25 kg K ha^{-1}.

This experimental design was replicated in 2016 and 2017 in the same fields. The farmers were asked to not apply manure in the main plot treatments in 2017. The inorganic fertilizer dose was about half the recommended minimum dose for millet (Fofana et al., 2008; Pandey et al., 2001; Adams et al., 2016). The fertilizer formula was NPK 10-10-20 as this was the main available fertilizer formula in the area, and the most commonly used for cash crops, such as tomatoes, cabbage, carrots and lettuce.

2.3. Farmyard manure characteristics

The farmyard manure samples were collected from the 11 selected fields of OMS1, at the time of its use in the fields. The farmyard manure was made of various organic residues available on the farm: dung from cows, horses and sheep mixed with crop residues such as millet stubble, peanut and cowpea leaves and stems, peanut shells. It had the appearance of a mixture of straw with fine compost or fertile loam. After grinding the vegetable components and mixing them with the fine compost, the average N, P and K contents of the mixture were 0.93 % (± 0.23), 0.28 % (± 0.11) and 1.72 % (± 0.99) respectively. Their C/N ratio averaged 28 (± 5.17). It was assumed that the effects of differences in quality between the smallholders' stocks of manure were much lower than the effects of OMS on the use efficiency of the inorganic fertilizer.

2.4. Millet cultivation

Short-cycle (90 days), low photoperiod millet variety *Souna 3* (CEDEAO, 2016 was sown at a density of 12000 hills ha^{-1} (90 cm × 90 cm spacing) with 20–30 seeds per hill. The same batch of seed was used for all fields. The grain was sown in June, by the end of the dry season and before the first rains. The millet was thinned to three plants per hill 1 week after germination. The fertilizer was applied around the hills during the crop tillering period. The ground was hoed three times: at the same time as thinning, 10–15 days after thinning and 10–15 days after that. No pesticides were applied. The millet crop was harvested 85–90 days after emergence. The same practices were used for all fields. Except for the application of inorganic fertilizer to the T1 plots, the practices were typical for millet in the region.

2.5. Measured variables

2.5.1. Millet water limited yield and water stress

The water limited yield and the water stress for each of the two years of the study were estimated using the simulation model PYE (Potential Yield Estimator, Affholder et al., 2013).Using a daily time step, PYE (https://ur-aida.cirad.fr/expertise-produits-et-services/produits-et-services/potential-yield-estimator) simulates the development, growth and water balance of a crop to estimate its potential (Y0) and water limited (Yw) yields, the latter being defined as the yield that would be achieved without any growth limitation other than temperature, solar radiation, and rainfall (van Ittersum et al., 2013). As recommended by Sinclair and Seligman (1996) for ad hoc modeling, PYE was designed to be as simple as necessary for its purpose, making it easier to parameterize and calibrate and running faster than generic models designed to account for more factors influencing growth and yields. PYE re-uses existing model components that have long proved their robustness: equations for crop development and growth were taken from STICS (Brisson et al., 2003, 1998), and the water balance module, using a standard tipping bucket model, was taken from SARRA (Traore et al., 2011; Affholder, 1997; Forest and Clopes, 1994). After calibration, PYE was found suitable for estimating Yw and Y0 for pearl millet in central Senegal (Affholder et al., 2013). In the present study we simulated Yw, Y0, the current water storage at root depth (mm), Leaf Area Index, the 50 % water storage capacity at root depth (mm) and the water drainage (mm) for each year and for a typical sandy soil of the study area. We considered that water stress potentially occurs when the predicted water storage at root depth is less than 50 % of the predicted water storage capacity at root depth.

Predawn leaf water potential (Ψp) was used as an indicator of millet water stress. It was measured using a pressure chamber (PMS Instruments pump-up chamber) between 05:30 am and 06:30 am on the last fully expanded leaf (with ligule) on millet plants randomly selected in each treatment. Ψp was measured when there had been 5 days without rain. Measurements were, therefore carried out at 27 and 70 days after germination in 2016 (Fig. 2a), and at 38 and 74 days after germination in 2017 (Fig. 2b).

2.5.2. Soil physical and chemical properties

Soil samples were collected from the topsoil layer 0 − 10 cm, on June 28, 2016 and May 18, 2017. In 2016, each sample was analyzed for pH (soil/water ratio of 1:2.5), total organic C and total N (CHN), available P (Olsen), exchangeable K, Ca and Mg (extraction in 1 N ammonium acetate). Soil bulk densities were determined before sowing in 2016 by measuring the dry weight of the soil in a steel cylinder 5 cm high and 100 cm^3 volume with five replicates. In 2017, only Olsen P

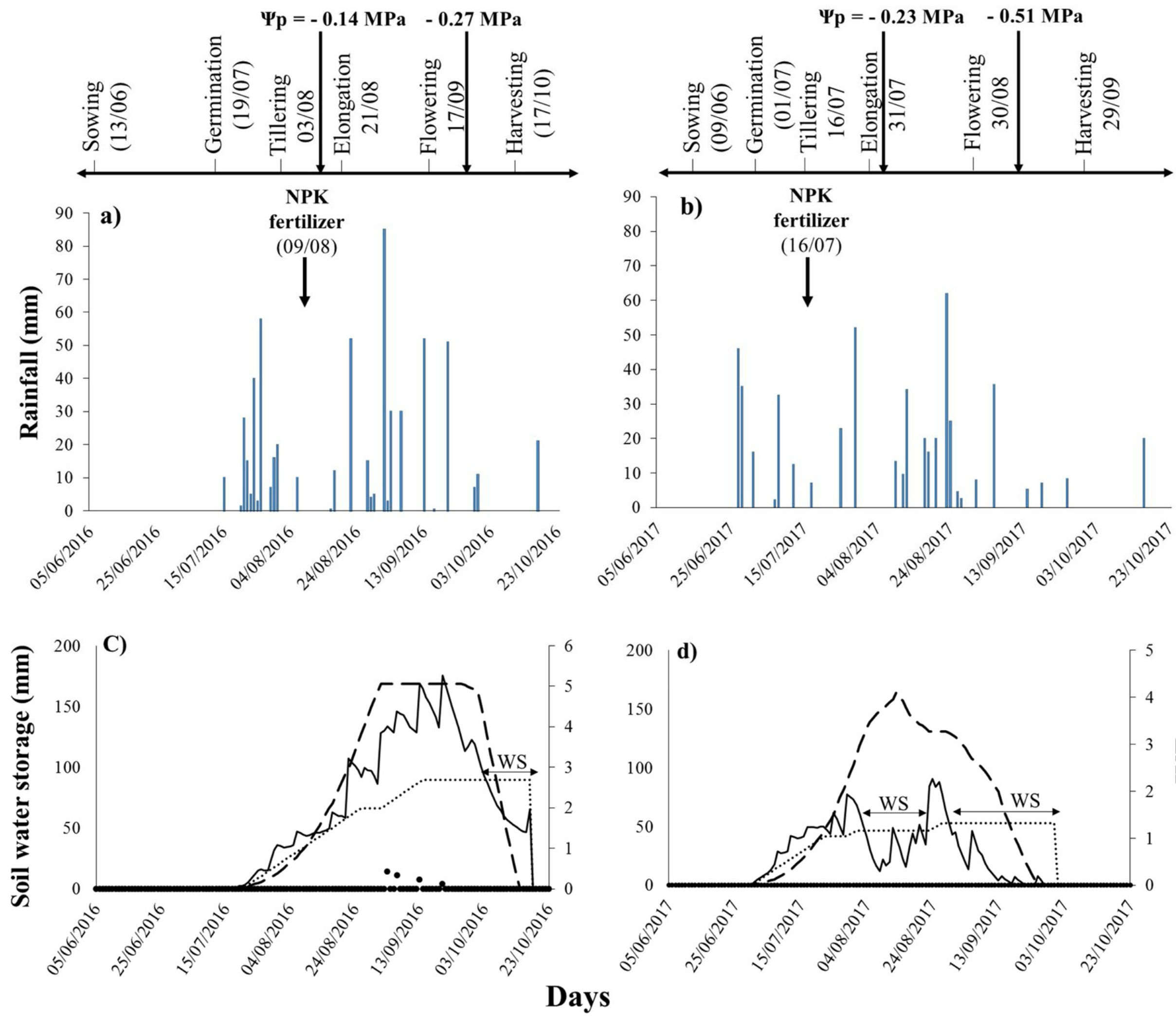

Fig. 2. Rainfall distribution, development stages of millet, predawn leaf water potential (Ψp) in 2016 (a) and 2017 (b), and PYE simulations of soil water storage and LAI in 2016 (c) and 2017 (d). In 2016 Ψp was measured at 27 DAG (Days After Germination) and 70 DAG. In 2017 they were measured at 38 DAG and 74 DAG. (- - - -): Simulated LAI (Leaf Area Index); (—): Simulated current water storage at root depth (mm); (.....): Simulated 50 % water storage capacity at root depth (mm); (•): Simulated drainage (mm); $\overset{\text{WS}}{\longleftrightarrow}$: Water Stress periods. Water stress were when the simulated water storage at root depth was less than 50 % of the simulated water storage capacity at root depth.

and exchangeable cations were measured because we assumed that the bulk densities, pH and total C and N would not significantly change in one year.

2.5.3. Millet grain and straw yield and components of grain yield

The number of hill plants and the number of panicles were determined by counting before harvest from an 8 m^2 sampling area located in the center part of each subplot; then 5 hills subsamples were randomly harvested before grain yield harvest to determine grains per panicle after threshing, grain weight, and straw weight. These subsamples were added back to the rest of the 8 m^2 area for determination of grain and straw yield per hectare. 1000-grain weight, total grain and straw yields were expressed in dry matter by drying at 65 °C for 48 h, one subsample of grain yield and of straw for each subplot. Harvest indexes were calculated for each subplot as the ratio of grain yield to the sum of grain and straw yields.

2.5.4. *Striga hermontica* infestation

Over the post flowering period, *Striga hermontica* infestations were assessed by counting the number of millet hills in each subplot that were infested by *Striga hermontica* shoots. The infestation rate was calculated as the ratio of the number of infested hills to the total number of hills.

2.5.5. Agronomic use efficiency of the applied NPK fertilizer

The agronomic use efficiency of the inorganic fertilizer for grain (AEg (kg kg^{-1})) was calculated as the difference of grain yield (kg ha^{-1}) between T1 and T0 divided by the amount of N applied (kg ha^{-1}) with the NPK fertilizer in treatment T1 (Eq. (1)).

$$AEg = (\text{grain yield}_{\ T1} - \text{grain yield}_{\ T0}) \ / \ \text{applied N dose} \tag{1}$$

Given the valuable role of the millet straw for livestock and for soil fertility recycling in the Soudano Sahelian cropping systems, the agronomic use efficiency of the NPK fertilizer for the straw yield (AEs (kg kg^{-1})) was also calculated (Eq. (2)).

$$AEs = (\text{straw yield}_{\ T1} - \text{straw yield}_{\ T0}) \ / \ \text{applied N dose} \tag{2}$$

2.6. Statistical analysis

Statistical analysis were performed with STATISTICA 8.0. StatSoft, Inc. 2007. The Shapiro-Wilk W Normality test indicated that the data collected was normally distributed. Two Way ANOVA was used to test the effects of OMS categories (with 5 subcategories) and inorganic fertilizer application (two levels) on the measured variables. When a factor had a significant effect, the means of each level for this factor were compared using the Student Newman Keuls test at 5% probability. Stepwise multiple regression analysis was conducted to determine the variables that best predicted millet yields and use efficiency of inorganic N for grain yield (AEg of N). Of seven variables, only the variables that were found to be significantly associated with AEg of N were used in the regression analysis: soil bulk density ($r = -0.67$), Olsen P ($r = 0.55$), soil pH ($r = 0.52$), and *Striga hermontica* infestation ($r = -0.60$). Therefore soil total C and N, and exchangeable K were not used. Variance Inflation Factor (VIF) was used to measure the impact of collinearity among the variables in the regression model. VIF was always lower than 1.5 indicating that the assumption of no multicollinearity was justified.

3. Results

3.1. Rainfall distribution, predawn leaf water potential (Ψp) and simulations with PYE

The total rainfall was 593 mm in 2016 and 518 mm in 2017. The rainy season started almost one month later in 2016 than in 2017. The low photoperiod sensitivity of the *Souna* accession, allowed full flowering around 60 days after emergence in both years. PYE model simulations indicated that water stress occurred only at the end of growth cycle in 2016, which is 77 days from germination to harvest. Moreover, there was a risk of nutrient leaching and, possibly, waterlogging around the flowering stage. Yw and Y0 simulated with PYE reached 3.4 and 3.5 t ha^{-1} respectively. In 2017, there was a long period of water stress from flowering until harvest and there were also water stress episodes during the stem elongation phase. Yw and Y0 simulated with PYE in 2017 reached 2.6 and 3.5 t ha^{-1} respectively. The OMS subcategories, the inorganic fertilizer application and their interaction had no effect on the measured Ψp values (not shown). The average Ψp after tillering and during grain filling were −0.14 and −0.27 MPa respectively in 2016 (Fig. 2a) and −0.23 and −0.51 MPa respectively in 2017 (Fig. 2b). The very low Ψp value during the grain filling phase in 2017 was consistent with the long period of water stress predicted by PYE.

3.2. Effects of the “Organic Manure Strategies” (OMS) on the soil properties

The OMS had a significant effect on the soil bulk density (Fig. 3a) and pH (Fig. 3b). Soil bulk density was lower in the OMS1 ($d = 1.55$ g cm^{-3}) than in the OMS2 ($d = 1.66$ g cm^{-3}). The soil was close to neutral in the OMS1 and slightly acidic in the OMS2. The OMS2 with a triennial rotation with fallow and peanuts (OMS2rot) were significantly more acidic than the OMS2 with a millet crop returning every year (OMS2cont). The OMS also had significant effects on total C and N contents and stocks, Olsen P and exchangeable K (Fig. 3c, d, e, f, g and h). The lowest C and N contents were in the OMS2. C stocks were 3.5 t ha^{-1} in the 0−10 cm soil layer in the OMS2, and 5.27 t ha^{-1} in the OMS1. Soil C/N ratios were significantly higher in the OMS2 than in the OMS1. The measured soil properties were not significantly different between subcategories in OMS1. Soil Olsen P was low in all the OMSs. It was particularly low in OMS2cont. Olsen P and exchangeable K were often higher in 2017 than in 2016.

3.3. Millet yield and yield components

In 2016, in the non fertilized plots (T0), the OMS1, particularly the OMS1high subcategory, have tended to be more productive in terms of both grain and straw yield than the OMS2 (Fig. 4a and b). Inorganic fertilizer (T1) had a significant effect on grain yield in OMS1, with grain yield two to three times higher in T1 than in T0 (Fig. 4a). The inorganic fertilizer had no significant effect on the straw yield (Fig. 4b). The correlations between the grain yield and the yield components were significant, with $r = 0.47$ for the number of panicles m^{-2}, $r = 0.91$ for the grains $panicle^{-1}$ and $r = 0.43$ for the 1000-grain weight (not shown). The number of panicles m^{-2} averaged 5.36 (± 1.47) in 2016 and was not affected by either the OMS category or by the inorganic fertilizer application (Fig. 4c). The number of grains $panicle^{-1}$ was significantly improved by the inorganic fertilizer in the OMS1 exclusively (Fig. 4d). The 1000-grain weight was significantly lower in OMS2 than in OMS1 and was not significantly improved by the inorganic fertilizer application (Fig. 4e). The harvest index was significantly higher in T1 than in T0 with the highest value of 30 % in OMS1high and the lowest of 10 % in OMS2cont (Fig. 4f).

In 2017, the grain and straw yields in T0 were higher than in 2016 independently from the OMS field category. The highest grain and straw yields were in the OMS1 (Fig. 5a and b). Unlike 2016, inorganic fertilizer had a non-significant effect on grain yields independently of the OMS while it had a significant positive effect on straw yield in OMS1high. The correlations between the grain yield and the yield components were significant with $r = 0.63$ for the number of panicles m^{-2}, $r = 0.72$ for the grains $panicle^{-1}$ and $r = 0.53$ for the 1000-grain weight (not shown). The number of panicles m^{-2} in the T0 plots tended to be higher in the OMS1 than in the OMS2 though the difference was not statistically significant (Fig. 5c). The number of grains $panicle^{-1}$ was higher in the OMS1 than in OMS2rot but it was not improved by the inorganic fertilizer application (Fig. 5d). As in 2016, the 1000-grain weight was lower in OMS2cont than in OMS2rot, and was not affected by the inorganic fertilizer application (Fig. 5e). 1000-grain weight was generally lower in 2017 than in 2016. The harvest index was less than 25 % and was not significantly affected, by either the OMS or by the inorganic fertilizer application (Fig. 5f).

3.4. Striga hermontica infestation

In 2016, *Striga hermontica* infestation was significantly dependent on the OMS: the lower the organic manure amendment, the higher the *Striga hermontica* infestation (Fig. 6). Moreover, the infestation was significantly higher in OMS2cont where there had been a continuous millet crop in the past, than in OMS2rot where a triennial rotation with peanuts and fallow was followed. In both years, the infestation rate was not significantly affected by the inorganic fertilizer application. In OMS2cont particularly, the infestation was significantly lower in 2017 than in 2016.

3.5. Agronomic use efficiency of the applied inorganic fertilizer

In 2016, the OMS had a significant effect on the AEg of the nitrogen supplied by the inorganic NPK fertilizer (Table 2). The highest AEg of N was in OMS1high subcategory where it averaged 66 kg kg^{-1}, and the lowest value was in OMS2cont where it averaged 7 kg kg^{-1}. The AEs of N was negative in the OMS1high, although we were not able to identify the causes. Of the four variables included in the stepwise regression with the AEg of the applied N, only soil bulk density and Olsen P were significant predictors. These two variables taken together explained 59 % of the variability in AEg of N. *Striga hermontica* infestation and soil pH were not retained in the stepwise regression analysis, as these variables did not provide additional explanatory power (Table 3). In 2017, millet yields were not significantly different between treatments with and without fertilizer. AEg of N did not depend significantly on the OMS category.

4. Discussion

4.1. Manure application improved sustainably the soil properties

The OMS1 category, which comprised the historically most frequently manured fields, had lower soil bulk density, higher pH and

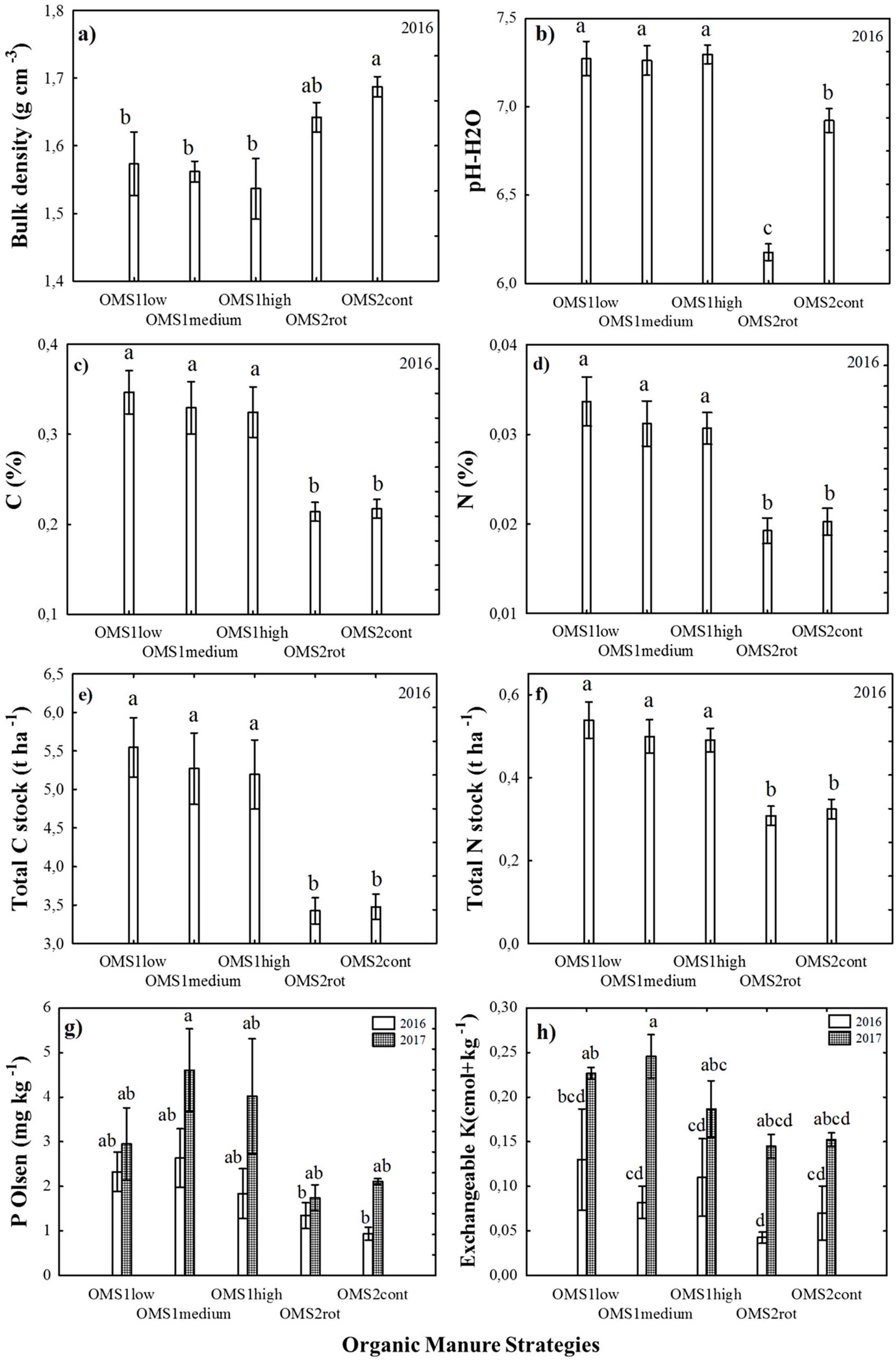

Fig. 3. Soil physical and chemical properties (0–10 cm) in 2016 and 2017 according to "Organic Manure Strategies" (OMS). OMS1low: fields receiving 5–8 t ha^{-1} of farmyard manure in 2016, OMS1medium: fields receiving 10–15 t ha^{-1} of farmyard manure in 2016, OMS1high: fields receiving 18–20 t ha^{-1} of farmyard manure in 2016, OMS2rot: without farmyard manure, and with a triennial peanut/millet/fallow rotation; OMS2cont: without of farmyard manure and with a continuous millet. Means followed by same letter in each figure are not significantly different, N-Keuls test, $p < 0.05$. Bars are standard errors of the means.

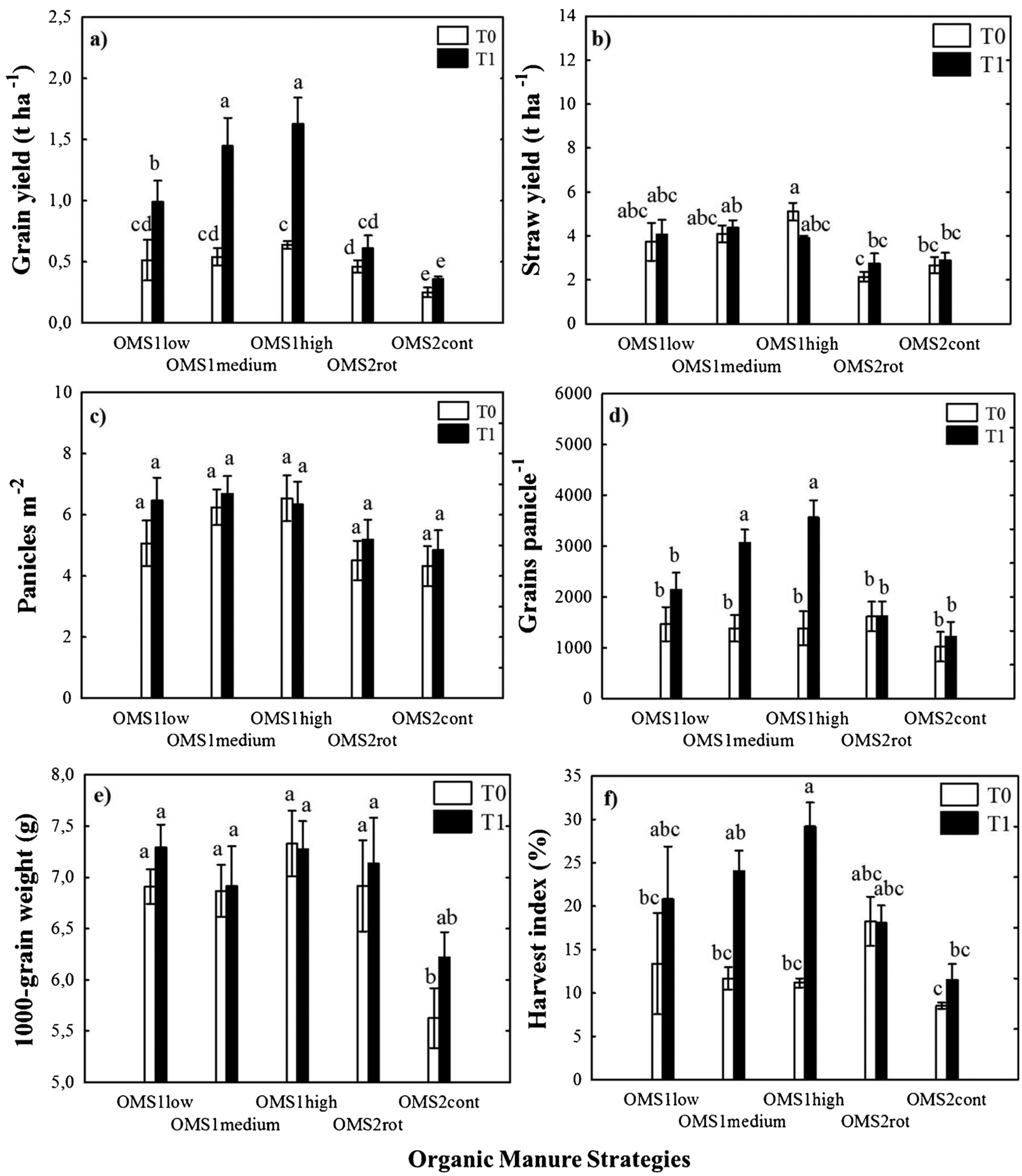

Fig. 4. Grain yield, straw yield, panicles m^{-2}, grains panicle^{-1}, 1000-grain weight and harvest index in 2016 as a function of "Organic Manure Strategies" (OMS) and fertilizer application. OMS1low: fields receiving 5–8 t ha^{-1} of farmyard manure in 2016, OMS1medium: fields receiving 10–15 t ha^{-1} of farmyard manure in 2016, OMS1high: fields receiving 18–20 t ha^{-1} of farmyard manure in 2016, OMS2rot: with a triennial peanut/millet/fallow rotation and no farmyard manure, OMS2cont: with a continuous millet and no farmyard manure. T0: without inorganic fertilizer; T1: with inorganic fertilizer. Means followed by same letter in each figure are not significantly different, N-Keuls test, $p < 0.05$. Bars are standard errors of the means.

higher C and N stocks than the OMS2 which comprised the historically seldom manured fields. This result was consistent with the long-term experiments reported by Adams et al. (2016) and Ripoche et al. (2015) on the effects of manure application in West African soils. The average soil C stock in the OMS1 was close to the potential 0.3 % reported by Feller (1995) for soils with a clay + silt content less than 10 %, suggesting that the average manure dose of 4 t ha^{-1} (the dose applied in OMS1low) was sufficient to achieve the potential soil C stock. We also found little difference between the soil C stocks in the two subcategories of OMS2 in this study. This was consistent with Bationo and Ntare (2000) who reported, from long term experiments carried out in Niger, that millet rotation with peanut and continuous millet had similar soil C stocks. Average Olsen P and exchangeable K were generally higher in 2017 than in 2016, particularly in the OMS1 (Fig. 3g and h). This suggested that the soil P and K replenishment was higher in the year after the manure was applied.

4.2. Comparing the current soil properties with earlier data

Our average soil C contents of 0.3 % in OMS1 and 0.2 % in OMS2 were similar to those reported in the literature for comparable agrosystems. For example, in Niger on sandy soils with 6% clay + silt, Bationo et al. (1993) reported a value of 0.2 % for carbon content in the 0 − 15 cm horizon after 4 years of crop residue restitution and inorganic fertilizer applications. Our Olsen P values averaging 2.63 mg kg^{-1} were close to those reported by Fofana et al. (2008) for sandy soil in Niger,

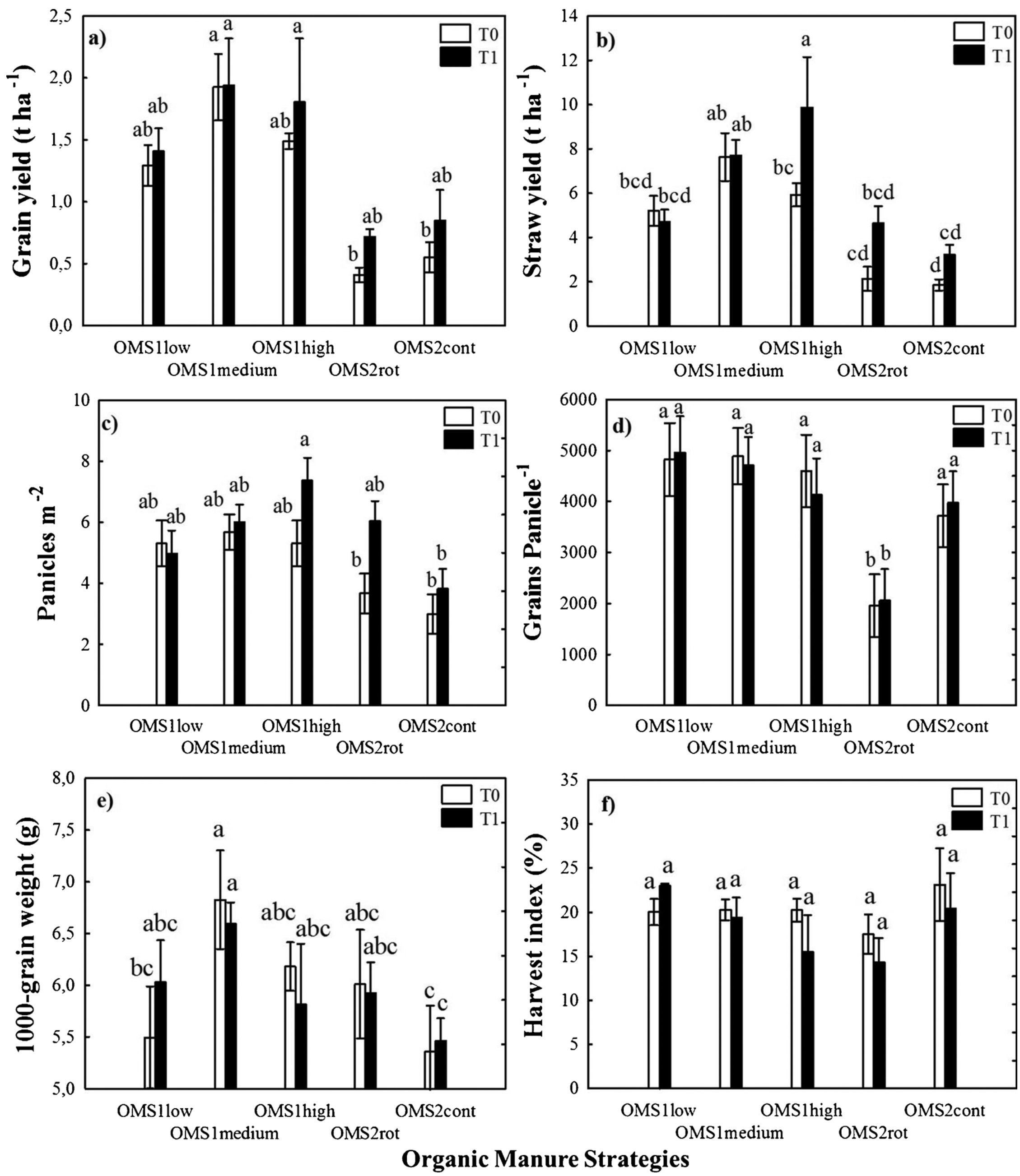

Fig. 5. Grain yield, straw yield, panicles m^{-2}, grains $panicle^{-1}$, 1000-grain weight and harvest index in 2017 as a function of the Organic Manure Strategies (OMS) and inorganic fertilizer application. See Fig. 4 legend for the Organic Manure Strategies and inorganic fertilizer application (T0, T1).

but significantly lower than the range of 7.3–14.9 mg kg^{-1} reported by Affholder (1995) and the average of 29 mg kg^{-1} reported by Badiane et al. (2001) for the 0 − 30 cm soil layer in this area. Based on these comparisons, it is likely that the Olsen P in the soils in the study area have declined very severely over the last 20 years. This would also be the case for K, as the average exchangeable K content of 0.13 cmol kg^{-1} was lower than the average of 0.87 cmol kg^{-1} reported by Affholder (1995) for homefields of the same area, which were managed similarly to those belonging to our category OMS1.

4.3. Is a high manure application dose justified?

The lowest millet grain yields, the poorest soils and the highest infestation of *Striga hermontica* were recorded in the never or scarcely amended fields (OMS2). This indicated that OMS1 was a valuable management to improve the agricultural performance in our context. However, in both years, the differences in grain yields between the T0 treatments of OMS1 subcategories were not significant, suggesting that higher manure doses ranges than 4 − 8 t ha^{-1} would not be very useful for further yield increase. Our results suggested that a manure dose as high as 15 t ha^{-1} enabled to better control the *Striga hermontica* infestation (Fig. 6) and to improve the use efficiency of the inorganic fertilizer (Table 2). Moreover, studies of Affholder (1995), De Rouw (2004) and Fofana et al. (2008) suggested that the concentration of the available organic manure in a few fields, rather than an even distribution across the whole arable land, would be a sound management to reduce the climate risks at household and village levels. In 2017, significant carry-over effects of the manure applied one year before were found as well on the soil fertility, on the millet yield, and on the fertilizer use efficiency. However these carry-over effects did not significantly increase when the manure doses have been increased above the range of 4 − 8 t ha^{-1} in OMS1.

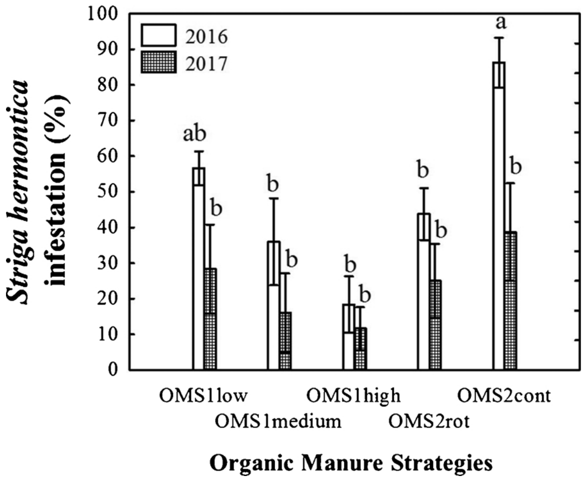

Fig. 6. *Striga hermontica* infestation in 2016 and 2017 as a function of "Organic Manure Strategies" (OMS). See Fig. 4 legend for "Organic Manure Strategies".

Table 2
Effect of the "Organic Manure Strategies" on the Agronomic Use Efficiency for grain (AEg) and for straw (AEs) of the 15 kg ha-1 of N applied with NPK fertilizer in 2016. For each variable, means followed by same letter are not significantly different, N-Keuls test, p < 0.05. See Fig. 4 legend for the Organic Manure Strategies and inorganic fertilizer application (T0, T1).

Organic Manure Strategies		Grain yield increase (kg ha^{-1})	AEg of N fertilizer (kg kg N $applied^{-1}$)	Straw yield increase (kg ha^{-1})	AEs of N fertilizer (kg kg N $applied^{-1}$)
OMS1	low	477.77 ^{ab}	31.85 ^{ab}	331.94 ^{a}	22.13 ^{a}
	medium	906.47 ^{a}	60.43 ^{a}	290.33 ^{a}	19.36 ^{a}
	high	990.02 ^{a}	66.00 ^{a}	−1198.96 ^{b}	−79.93 ^{b}
OMS2	rot	148.3 ^{b}	9.89 ^{b}	612.14 ^{a}	40.81 ^{a}
	cont	108.76 ^{b}	7.25 ^{b}	229.53 ^{a}	15.30 ^{a}
	$P > F$	0.002	0.002	0.02	0.02

4.4. Lesson learned from the millet yield components and the harvest indexes

Grain yield is a too global variable to allow identify all the phenomena that took place during the crop cycle. The yield components collected here allowed this chronological analysis, by using them as indicators of the availability of water and nutrients resources during their respective period of establishment (Doré et al., 2008). The yield component panicles m^{-2} was the product of a plant density, a tiller number per plant and a panicle number per tiller. It was determined from the first days of the millet cycle until mid-elongation stage of the stem. The yield component grains $panicle^{-1}$ was fixed from the mid-elongation stage to shortly after flowering, and the components 1000-grain weight, from the end of flowering stage to the grain physiological maturity (Maiti and Bidinger, 1981) (Fig. 2). In 2016, our results showed that the yield component panicles m^{-2} remained low and was neither sensitive to the manure dose nor to the inorganic fertilizer, but the yield component grains per panicle was significantly improved by these factors. This suggested that the nutrients applied at the first days of the crop cycle in 2016 were not immediately available for the crop. This could have been due to the N and P immobilization by the intense soil microbial activity at the beginning of the rainy season. The N mineralization would have occurred by the flowering period, and allowed the yield component grains $panicle^{-1}$ to be highly responsive to the fertilizer. Such interpretation is consistent with the carry-over effect of manure suggested by the soil fertility and yield evolution from 2016 to 2017. It is also consistent with the fact that the soil water availability was not limiting for the crop yield increase in response to fertilizer in 2016 (Fig. 2). In 2017, the correlations between the grain yield at harvest and the yield components were quite stable suggesting that the main causes of yield difference between the fields were present from the beginning of the cycle, as could be the soil nutrient ressources related to the OMS categories. In 2016, The1000-grain weight averaged around 7.6 g in OMS1 and decreased to 6.0 in 2017. The value reached in 2016 was close to the highest range reported for the variety by CEDEAO (2016), and the decrease observed in 2017 was consistent with the increase water deficit simulated with the PYE model during the grain filling period of the crop in 2017 (Fig. 2). In both years, the 1000-grain weight of millet was significantly lower in the never manured fields (OMS2) than in the recently and frequently manured fields (OMS1), probably as an effect of the increased infestation of *Striga hermontica* in the OMS2 fields at the end of the crop cycle (Fig. 6). In the OMS2 fields the rotation with fallow and peanut was efficient to reduce *Striga hermontica* infestation compared to the continuous millet crop (Fig. 6), and this was also associated with a significant increase of the 1000-grain weight in these fields (Fig. 4). Such beneficial effect of the rotation with legumes crops on the *Striga hermontica* infestation was already showed by Samaké et al. (2006).

Millet harvest index remained in the same range values as in Sy et al. (2015). This range was low, consistently with the dual purpose of straw and grain production of the millet varieties used in these agropastoral systems. In assessing technical innovation, attention must be paid to both changes in terms of grain and straw yields respectively.

4.5. AEg was the highest in the most manured fields: the role of soil bulk density and P availability

The highest agronomic efficiencies of the inorganic fertilizer for grain yield were in the most manured fields, the OMS1 category (Table 2). This result was consistent with Zingore et al. (2007), Tittonell et al. (2008), Fofana et al. (2008), Tittonell and Giller (2013) and Vanlauwe et al. (2011). AEg of N in the OMS1 averaged 50 kg kg^{-1}. This was 4–5 times higher than in Pandey et al. (2001), Bationo and Ntare (2000) and Fofana et al. (2008). In the outfields where there was no organic amendment, AEg of N was only 10 kg kg^{-1} in OMS2rot and 7 kg kg^{-1} in OMS2cont (Table 2). Similar ranges were reported for outfields by Wopereis et al. (2006), Tittonell et al. (2007) and Zingore et al. (2007). The relatively high AEg of N in OMS1 might mean that the P and K associated with the N fertilizer have favored the biological release of more N from the soil, and/or that the soil organic amendments prevented factors other than the applied inorganic nutrients from being limiting. These hypotheses were supported by the stepwise

Table 3
Regression analysis between the Agronomic Use Efficiency of inorganic N fertilizer for grain yield (AEg of N) and the independent variables, soil bulk density, Olsen P, *Striga hermontica* infestation and soil pH-H_2O.

Variables	F to enter or remove	Significance	Multiple R	R^2	R^2 Change
Bulk density (g cm^{-3})	13.97	0.00	0.67	0.45	0.45
Olsen P (mg kg^{-1})	5.51	0.03	0.77	0.59	0.14
Striga hermontica infestation (%)	2.14	0.16	0.80	0.64	0.05
Soil pH-H_2O	1.73	0.21	0.83	0.68	0.04

regression which showed that the best predictors of AEg of the applied inorganic N were soil bulk density and available soil P (Table 3). It should be noticed that the soil biological functioning, the water and nutrient dynamics, the micronutrients availability and the root density and architecture, could all be closely linked to these predictors, and therefore be involved in the increased AEg in the most manured fields. Based on these results, it is likely that without significant investments in calibration and modeling studies to take into account these key characteristics of the millet production environment, the current modelling tools such as DSSAT, STICS will fail to predict the millet performances and best way of management of this Sub-sahelian agriculture.

4.6. Soil/plant nutrients fluxes

In 2016, inorganic fertilizer application was only effective in the OMS1 when the soil nutrient availability was very low. The increased availability of soil P and K from 2016 to 2017 and the increased millet yield in the control treatments from 2016 to 2017, suggested that the carry-over effect of the manure applied in 2016 was important. In fact, the average yield of 2 t ha^{-1} achieved in the most amended fields of OMS1 in 2017 was close to the water-limited yield of 2.6 t ha^{-1} predicted by the PYE model and it was within the maximal yield range of 2.4–3.2 t ha^{-1} reported in the official catalogue of millet varieties (CEDEAO, 2016). The hypothesis of an important carry- over effect of manure was consistent with Feller and Ganry (1981) who attributed delayed N mineralization from farmyard manure to the high proportion of shell nut residues insufficiently composted before application to the fields. Siband and Ganry (1976) also showed that compost made of a mixture of millet straw and cattle manure had little effect on the millet nutrition in the year of application. More research is needed on the quality and the mineralization rate of the farmyard manures currently used by the farmers of this area. The decreasing number of cattle as a result of the demographic pressure may have affected the composition of the farmyard manure with consequences in terms of quality and rate of decomposition. In 2017, inorganic fertilizer application was not effective, as the millet vegetative growth and grain yield recorded in the OMS1 were close to the potential. The high vegetative biomass accumulated in 2017 by the crop, suggested consistently with Affholder (1995) that the crop could have been more demanding after flowering when rainfall started declining. This could have contributed to the high 1000-grain weight decrease in 2017. In summary, in average years with high levels of manuring, crops may be prone to nutrient-limitation during the year immediately after manuring, and prone to water limitation in the following year when the soil has been replenished in nutrients. Rather than relying on the usual annual input/output balance approach, the inorganic fertilizer applications should take into account both short term (intra-annual) and long term (year to year carry-over) variations of the nutrient cycles, which arise from rainfall distributions and from the mineralization rates of the various constituents of the manure.

5. Conclusions

The use efficiency of inorganic fertilizer were strongly variable across a sample of fields which covered the diverse past organic manure strategies developed by the farmers in the study area. In the fields which were never or scarcely amended, the fertilizer use efficiency was very low. Low soil bulk density, low P availability and crop infestation by *Striga hermontic*a would be the major causes of this low fertilizer use efficiency. The fields regularly receiving substantial amounts of farmyard manure had a high fertilizer use efficiency. The higher the manure application, the higher the use efficiency of the inorganic fertilizer. However, manure dose ranges higher than 5 – 8 t ha^{-1} did not result in significant higher millet yields. In the never amended fields, crop rotation with a one-year fallow and a legume was efficient to reduce *Striga hermontica* infestation compared to the continuous millet crop.

Currently, public policies are emerging to support the use of fertilizers by Sahelian farmers, for increasing crop yields to ensure food security and a decent income for a rapidly growing population of farmers. Policy makers and stakeholders in the food production chain should be made aware that, although generally positive, the response of millet to moderate doses of fertilizer varies between years and fields. Therefore, the benefits of such policies may not be immediately obvious, and farmers should be protected against the risk that their financial and labor costs for applying organic amendments and inorganic fertilizers may not generate a sufficient return in a given year.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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