Agroforest Syst (2021) 95:717–730
https://doi.org/10.1007/s10457-021-00624-8

Combined effect of trees and soil fertility management practices on millet yields in the Sahel

Mariama B. Diallo · P. B. Irénikatché Akponikpè · Tougiani Abasse · Dougbédji Fatondji · Euloge K. Agbossou

Received: 15 November 2020 / Accepted: 30 March 2021 / Published online: 13 April 2021

Abstract Tree/shrub species are used in farmer fields of sahelian agroforestry parklands to conserve and restore degraded lands, improve soil fertility and increase crop yield. A field study was conducted to investigate the effect of five tree species (*Annona senegalensis*, *Balanites aegyptiaca*, *Faidherbia albida*, *Guiera senegalensis* and *Piliostigma reticulatum*) on soil fertility and crop yield under different fertility management practices in semi-arid Niger. Three factors (tree species, positions to tree trunk and fertilizer management) and four levels of fertilizer microdosing management (DAP, NPK, manure and control) were investigated. We found that tree species improved soil fertility and crop yield differently. *F. albida*, improved the soil quality far better than other four tree species for all soil nutrients analyzed. The highest millet yield was recorded under *P. reticulatum* and *F. albida* for both grain (1011 and 1005 kg ha^{-1}, respectively) and straw yields (3662 and 3786 kg ha^{-1}, respectively). The yield was found to be two- to four-folds higher under direct tree crown compared to close neighborhood or treeless outside. The combined tree species and fertilizer effect were additive and the positive effect can extend to the outside crown. However, the combined effect of mineral fertilizer with tree species on yield was better than that of manure. Integrated tree species and moderate fertilizers was effective and can be used as a sustainable fertility management practice in Sahelian countries where organic amendment is frequently scarce and it is difficult for smallholder farmers to adopt high recommended mineral fertilizer for crop production. Further investigations are needed to assess the economic performance and the long-term sustainability of the integrated trees and soil fertility management in the Sahel.

Keywords Tree species · Tree-crop integration · Fertilizers management · Millet yield · Sahel

M. B. Diallo (✉) · P. B. I. Akponikpè
Laboratory of Hydraulics and Environmental Modeling (HydroModE-Lab), Faculté d'Agronomie, Université de Parakou, 03 BP 351 Parakou, Benin
e-mail: mariama.diallo01@gmail.com

M. B. Diallo · T. Abasse
Institut National de la Recherche Agronomique du Niger (INRAN), BP: 429, Niamey, Niger

M. B. Diallo · E. K. Agbossou
Laboratoire d'Hydraulique et de Maîtrise de L'Eau (LHME), Université d'Abomey-Calavi (UAC), BP: 2819 Cotonou, Benin

P. B. I. Akponikpè
Institute of Science and Technology for Innovation in Africa (ISTIA), Parakou, Benin

D. Fatondji
International Crops Research Institute for Semi-Arid Tropics (ICRISAT), Niger, Niger

Introduction

Pearl millet is the primary staple crop in Niger which is widely grown in semi-arid to arid climate due to its adaptation to erratic and low rainfall, low soil fertility and frequent droughts (Ibrahim et al. 2016). Declining soil fertility was reported to be the primary limiting factor of millet productivity in Sub-Saharan Africa agriculture (Bationo and Mokwunye 1991). A long term low input agriculture on sandy soil texture with a poor structure and low organic matter combined with wind erosion are the major causes of soil fertility decline.

In Niger where soils allocated for crop production are very low in Nitrogen and Phosphorus (Bationo and Mokwunye 1991), application of mineral fertilizers are recommended to improve crop yield (Fatondji and Ibrahim 2018). Ibrahim et al. (2015) reported that plots which received fertilizer microdosing of 6 g NPK /hill and 2 g DAP / hill increased millet grain yield respectively by 39% and 72% compared to control plot. Vanlauwe et al. (2014) reported that the use of mineral fertilizer is a key component for agricultural intensification. But it has been shown from long-term experiments that lone application of this fertilizer could not sustain nutrient reserves and consequently decline soil fertility and crop yields (Schlecht et al. 2006; Camara et al. 2013). The decline in soil fertility and crop yield due to the continuous use of mineral fertilizer might have resulted from many mechanisms such as decreasing soil organic content, base saturation, increasing exchangeable aluminium and aggravation of soil acidification (Adams et al. 2016). In addition, nutrients uptake to straw and grains were higher than were added to the soil (Bationo et al. 2007; Ibrahim et al. 2015). Literature, also showed that combined application of inorganic fertilizer and organic amendment could minimize the negative effect the mineral fertilizer alone (Akponikpè et al. 2008; Ibrahim et al. 2016). The combined use of organic amendment could compensate many environmental functions such as supply of carbon to the soil, improvement of soil micro-organims activity, nutrients mineralization, soil physical quality and rehabilitation of degraded lands, but organic sources are limited in this environment.

Tree-crop integration is a soil management practice used by smallholder farmers in the Sahel and through Sudanian and Guinea Savannah ecozones to improve and maintain soil fertility level, reduce crop water stress, and increase crop yield (Bayala et al. 2012; Abasse et al. 2013). Indigenous trees are also maintained on farm-fields for a wide range of non-timber forest products (NTFPs) (food, fodder, medicines, etc.) and wood-products (poles, wood-fuel, etc.) (Faye et al. 2011). The use of trees in cropland has been shown to increase soil organic matter and improve soil quality (Dossa et al. 2013).

Literature showed that trees presence plays an essential role in soil nutrients improvement and crop yield (e.g. Kater et al. 1992; Bayala et al. 2012). Preliminary studies in Niger under *F. albida* in farmers' fields showed that millet yield was about 36% higher than in the open area (Kho et al. 2001). Other studies showed the potential benefits effect of *P. reticulatum* leaf litter mulching in Burkina Faso to improve soil moisture, restore degraded soil and serve as a windbreak for seedling (Yélémou et al. 2014).

By maintaining soil fertility, trees/shrubs improve nutrients recycling, and soil nutrients use efficiency in low fertility conditions (Wezel et al. 2000; Dossa et al. 2013). In these soil conditions of Saheliens countries, Dossa et al. (2013) reported that the integration of trees/shrubs-crops could be used to minimize nutrient losses through leaching and to recycle part of applied nutrients better. Moreover, the use of crop residues or mulching and manure are among other methods used to avoid soil particle transport by wind, reduce water splash on soil, increase soil moisture and to improve soil fertility (Bationo and Mokwunye 1991; Bielders et al. 2002). To improve crop yield, several practices are often used in spatial combination by Sahelian smallholder farmers in the same field because of the limited nutrients resource. There is, therefore, a need to better understand the differential effect of tree species under different fertilizers management practices on crop yield. The main scientific questions of this study were the following. Do different tree species improve crop yield in the same manner? How is tree effect influenced by fertilizers and manure? Are these effects influenced by distance or position to tree trunk?

Materials and methods

Description of study area

The study was conducted in the village of Korto (13° 49′ 29″ N; 2° 69′ 28″ E, 183 m asl), 12 km south of Dantiandou rural district and 90 km West of Niamey the capital, (Niger). In this locality, soils are classified as Arenosol (FAO classification system) or Psammentic Paleustalf (USDA Soil Taxonomy) with 90% of sand in horizon A, high infiltration rate, low organic carbon and low cation exchange capacity CEC (Diallo et al. 2019). The climate is semi-arid characterized by erratic rainfall events and a monomodal rainy season that occurs between June and September, and yearly average rainfall is about 560 mm (Sivakumar et al. 1993). The average temperature is 29 °C.

Subsistence farming is a common practice in Korto. Farmers rely on rain-fed agriculture associated generally with trees and shrubs. The major crop is pearl millet grown alone or in association with cowpea (*Vigna unguiculata*) or roselle (*Hibiscus sabdariffa*) to improve further soil quality, weed control, millet yield and on-farm income.

Tree/shrubs species studied

The present study includes five tree/shrubs species: *Annona senegalensis* (Pers., Annonaceae), *Balanites aegyptica* (L. Del., Zhygophyllaceae), *Faidherbia albida* (Del. A. Chev., Fabaceae), *Guiera senegalensis* (J. F. Gmel, Combretaceae) and *Piliostigma reticulatum* (DC. Hochst., Fabaceae). *B. aegyptiaca*, *F. albida* and *P. reticulatum* are classified as trees of 6–12 m, 20–30 m and 10–15 m optimal natural height respectively, whereas *A. senegalensis* and *G. senegalensis* are considered as shrubs or small trees with 2–6 m and 3–5 m optimal natural height respectively. Characteristics (Height, DBH, crown diameter) of the selected trees are showed in Table 1. *F. albida* and *P. reticulatum* are leguminous species. The five species under study are among the commonly found trees in Sahelian agroforestry parkland and in tropical dry forests. They are adapted to modern yearly pruning known as Farmer Managed Natural Regeneration (FMNR) developed in the region. FMNR consists of leaving a certain number of shoots per stump to regenerate in the field (Cunningham and Abasse 2005). The excess shoots are cut, and side branches trimmed halfway up the stems. These species are recognized not to hinder crop growth (Dossa et al. 2013). They are managed in Sahel regions for their substantial contribution to rural communities' welfare as they provide wood, food, fibre, wood-fuel and medicines and some environmental services like windbreaks, live fences, soil and water conservation and fertility improvement (Faye et al. 2011). When herbaceous forage becomes scarce in dry season, these trees are pruned to feed livestock due to the high nutritive quality of their fodder and their palatability to stall-fed and browsing. Also, trees serve as a habitat for insect pollinator and migratory or native birds that may enhance agroforestry parkland productivity (Sanchez 1995).

Experimental design

The experiment design was a pseudo-split-split-plot design with tree replications. Tree species were considered as main plots, positions to tree trunk (DUC, CNH and OUC) and fertilizer treatments (DAP, NPK, manure and control) as subplots and sub-subplots respectively. The trial was conducted during 2015 and 2016 rainy seasons and three individual mature tree/shrubs of *A. senegalensis, B. aegyptiaca, F. albida, G. senegalensis and P. reticulatum*; were randomly chosen within the individuals of the given species present in one farmer field under parkland used for pearl millet cropping. Each concentric zone around each tree specimen was divided into four equal segments which received a given fertilizer treatment (Fig. 1). Three concentric zones were constituted around each tree according to its crown size (experimental design, Fig. 1.):

1. Direct under crown (DUC) zone: from tree trunk of each tree up to the edge of the crown,
2. Crown Neighbourhood (CNH) zone: from the edge of the tree crown up to 2 m away,
3. Outside Crown (OUC) zone: from 2 m, away from the crown up to 4 m away.

Tree crown was divided in four parts for fertilizer treatment use: Diammonium Phosphate (DAP), Nitrogen- Phosphate-Potassium compound fertilizer (NPK15-15-15), manure and no fertilizer control. Concentric zones were used to reduce directional biases to crop yield variability and to separate the different influence zones of trees. In 2015 cropping

Table 1 Average characteristics of the selected tree species for the study in the village of Korto farmers field (N = 3 for each tree species)

Species (N = 3)	Group	Tree height [optimal height] (m)	Trunk diameter at breast height DBH (cm)	Crown diameter (m)
A. senegalensis	Non-leguminous	1.67 ± 0.29 [2–6]*#	24.34 ± 14.01	3.43 ± 0.16
B. aegyptiaca	non-leguminous	5.84 ± 0.82 [6–12]*#	116.67 ± 28.87	7.02 ± 0.86
G. senegalensis	Non-leguminous	2.14 ± 1.1 [3–5]*#	3.97 ± 0.53	2.2 ± 15.6
F. albida	Leguminous	11.14 ± 3.2 [20–30]#	146.67 ± 61.1	14.8 ± 5.4
P. reticulatum	Leguminous	1.47 ± 0.92 [10–15]*#	22.34 ± 21.46	2.65 ± 0.86

± Standard deviation, *Sotelo Montes et al. (2012), #Orwa et al. (2009)

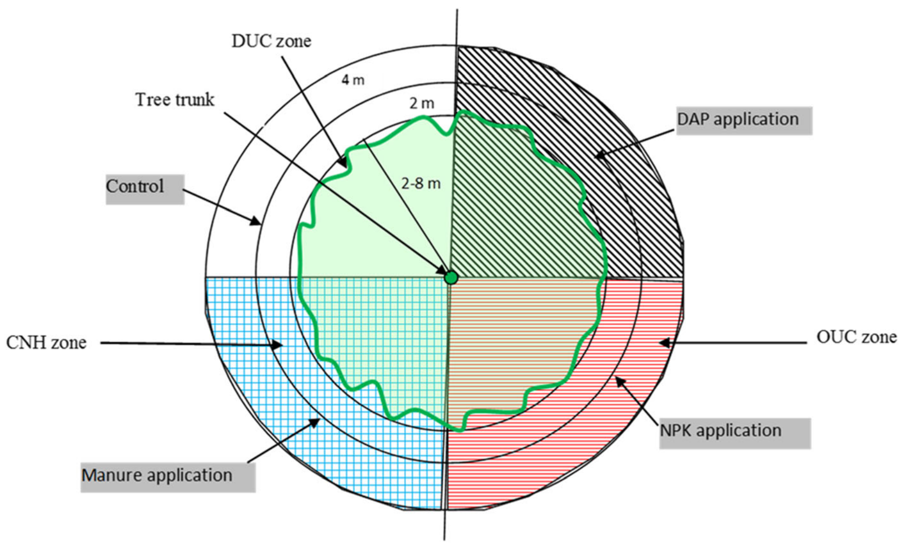

Fig. 1 Experimental design with concentric zones around tree trunk (DUC zone: direct under crown zone, CNH zone: crown neighbourhood or transition zone, OUC zone: outside crown or treeless zone)

year, the only two first modalities of the crown positions factor were considered: direct under the crown (DUC zone) and crown neighbourhood (CNH zone).

Fertilizer application

In this experiment, four fertilizer levels were used. A no fertilizer control, 2 g of DAP per hill corresponding to 20 kg DAP ha^{-1} (equivalent to 4 kg P ha^{-1} and 3.6 kg N ha^{-1}); 6 g of NPK fertilizer per hill corresponding to 60 kg NPK ha^{-1} (equivalent to 4 kg P ha^{-1}, 9 kg N ha^{-1} and 7.47 kg K ha^{-1}). These rates are the standard farmers' recommended microdose ones in the study area (Tabo et al. 2007). Manure was applied by hill placement (Fatondji et al. 2009). Small planting hills were dug and 20 g hill^{-1} of manure was applied which represented 200 kg ha^{-1} (equivalent to 7.5 10^{-3} kg P ha^{-1}, 5.6 kg N ha^{-1} and 0.28 kg K ha^{-1}). For the current study, fertilizer microdosing was applied two weeks after sowing and manure was applied before planting.

Planting and crop management

The local variety of pearl millet “Haini-kirey” (120 maturity days) commonly used in the region was sown at the onset of the rainy season on 24 June in 2015 and 25 June in 2016. The plants were thinned to two plants per hill corresponding to the recommended density of 10.000 hills per hectare.

Data collection

Soil sampling and analysis

Soil samples were taken in 2015 under direct crown (DUC zone) and crown neighborhood (CNH zone) of each tree species. Under DUC zone and CNH zone (1–2 m from crown limit), and prior to fertilizer or manure application one sample was taken under each tree zones for the four cardinal directions (middle). Then, the samples were bulked into one composite sample for each soil depth. Soil samples were taken with soil auger at three depths (0–10 cm, 10–20 cm and 20–30 cm). Soil samples were air dried and sieved (2 mm) before chemical analysis. The soil samples were analyzed in the laboratory of the National Agricultural Research Institute of Niger. Each sample was analyzed for pH (H_2O) using pH meter (with a 1:2.5 soil:water ratio), soil organic carbon (SOC) by Walkley and Black (1934), total nitrogen (N) was determined using Kjeldahl method. Soil available phosphorus was determined using the Bray-1 method described by van Reeuwijk (1993). Exchangeable bases were determined by the ammonium acetate (NH4OAc) solution at pH 7 using the extractable method. In each treatment, the yield parameters were measured at harvest (number of hill, heads, weight of fresh and dry stems and grains).

Statistical analysis

In the present study, data were checked for variance homogeneity and normality. Pairewise *t*-test was used to test the effect of crown positions to the tree trunk because it is not possible to randomize the concentric zones under tree gradient influence (Sanou et al. 2012; Bayala et al. 2015). Therefore, it is not possible to calculate a valid estimation error because residuals of tree influence zones are correlated. The variation between cropping years, tree species and interaction were analyzed using General Linear Model (GLM) analysis of variance in Genstat discovery v9.2. When year by the treatment analysis was significant, the analysis was done for each year. Differences between treatments were considered at an error probability of 0.05 and means were separated using the least significant difference (LSD).

Results

Rainfall distribution during the cropping period

The cumulative rainfall recorded throughout the growing season was higher in 2015 compared to 2016 (774 mm and 668 mm, respectively). Moreover, rainfall was more evenly distributed in 2015 compared to 2016 (Fig. 2). A dry spell of 23 days occurred from 97 to 120 days after sowing (DAS) and coincided with grain filling and maturing stage in 2016. The growing season of 2016 was a harsh year that may severely impact productivity in the region.

Long-term differential effect of trees on soil chemical properties

There was significant difference of tree species for all the parameters analyzed ($P < 0.001$) pH, SOC, N, P CEC K and Mg ($P < 0.01$). The highest values were recorded under *F. albida* (pH, SOC, N, P, CEC, K, Mg, Ca) (Table 2). The lowest means were reported under *B. aegyptiaca* for pH, *A. senegalensis* for SOC, *P. reticulatum* for P, *G. Senegalensis* (for CEC, K, Mg and Ca).

There was a significant difference among positions to tree trunk for only SOC content ($P < 0.01$, Table 2). A slightly higher mean of SOC was recorded under DUC zone ($0.15 \pm 0.01\%$) compared to CNH zone ($0.14 \pm 0.01\%$, Table 2).

Grain and straw yields

Year effect

There was a significant interaction between the cropping years and tree species (Year × Species) for both grain and straw yields. Therefore, the yield of each growing season was analyzed separately (Table 3).

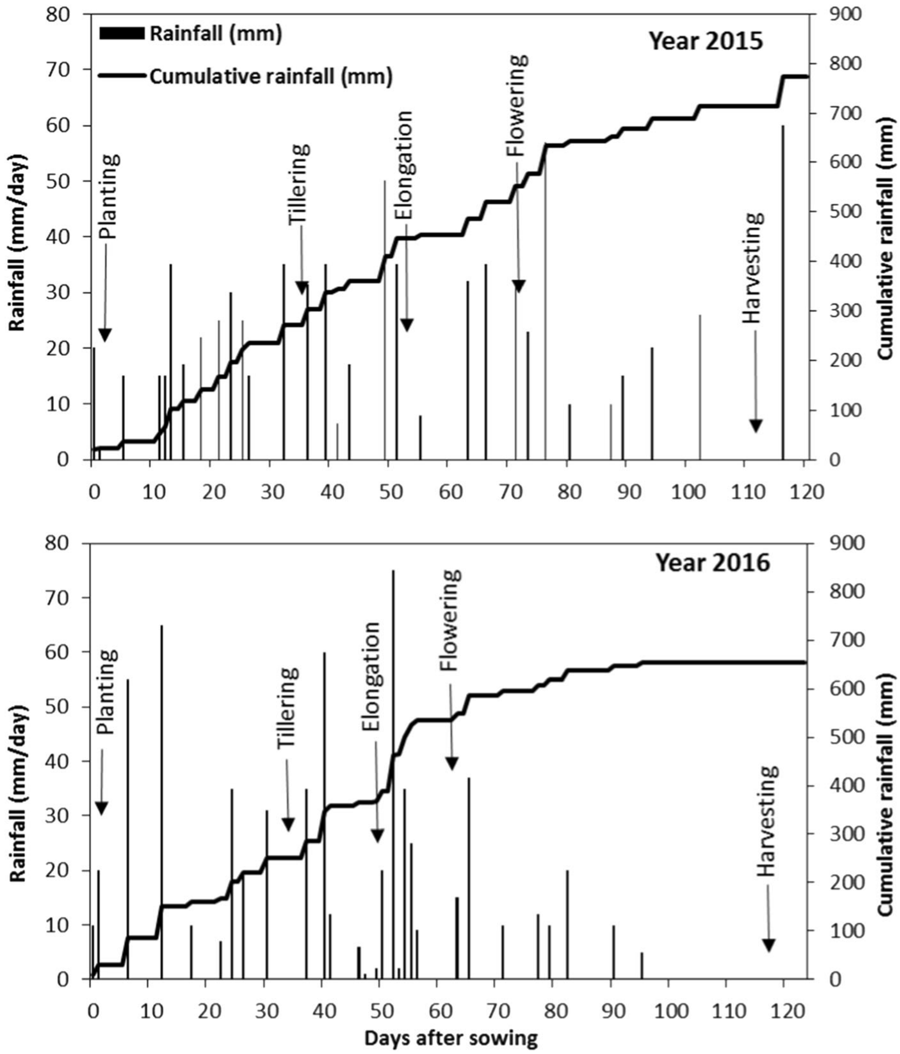

Fig. 2 Rainfall distribution in 2015 (upper panel) and 2016 (lower panel)

The results showed that grain and straw yields were significantly affected by the cropping years ($P < 0.001$) (Table 3). Average millet grain and straw yields were better in 2015 compared to 2016.

Effect of tree species and positions to tree trunk on millet performance

There was a significant effect of tree species on both grain and straw yields ($P < 0.001$) in 2015 only (Table 3). Millet yield was higher under *P. reticulatum* and *F. albida* while the lowest yield was recorded under *B. aegyptiaca* (64% less). The highest straw yield was observed under *F. albida* and the lowest under *A. senegalensis*. There was no significant difference in both millet grain and straw among tree species in 2016 (Table 3). Yet, numerically higher millet grain yield was recorded with *P. reticulatum* compared to the lower grain yield observed with *F. albida*. The highest straw yield was observed with *F. albida* and the lowest with *B. aegyptiaca*.

There was a significant difference among positions to tree trunk for both grain ($P < 0.01$) and straw yield ($P < 0.001$) in 2015 and also for both grain ($P < 0.05$) and straw yield ($P < 0.05$) in 2016 (Fig. 3). In 2015, both millet grain and straw yields were higher in DUC zone with an increase of 117% and 122%, respectively, compared to the CNH zone. In 2016, millet

Table 2 Initial soil nutrients under tree species

Treatments	Variables ± STD								
		pH	SOC (%)	N	P (ppm)	CEC (meq/100 g)	K	Mg	Ca
A. senegalensis		4.40 ± 0.28b	0.09 ± 0.01 cd	0.01 ± 0.001b	7.60 ± 6.68b	6.72 ± 2.01b	0.06 ± 0.02c	1.35 ± 0.14b	4.17 ± 1.38b
B. aegyptiaca		4.09 ± 0.24bc	0.18 ± 0.03b	0.03 ± 0.04a	4.42 ± 4.40bc	3.10 ± 0.90c	1.77 ± 0.68b	0.95 ± 0.49c	0.1 ± 0.02c
F. albida		4.70 ± 0.39a	0.22 ± 0.04a	0.04 ± 0.01a	11.72 ± 4.52a	15.56 ± 6.34a	2.38 ± 0.63a	2.81 ± 0.92c	10.04 ± 5.28a
G. senegalensis		4.27 ± 0.34b	0.11 ± 0.01c	0.02 ± 0.01b	6.14 ± 1.95b	0.72 ± 0.29d	0.05 ± 0.01c	0.22 ± 0.24d	0.06 ± 0.04c
P. reticulatum		4.39 ± 0.25b	0.12 ± 0.03c	0.01 ± 0.002b	3.58 ± 1.32c	7.42 ± 1.37b	0.07 ± 0.03c	1.50 ± 0.19b	5.47 ± 1.36b
LSD		0.20	0.02	0.01	2.84	1.91	0.27	0.29	1.58
	df	F pr	F pr	F pr	F pr	F pr	F pr	F pr	F pr
Species	4	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Positions to crown	DUC	4.34 ± 0.24	0.15 ± 0.06	0.022 ± 0.02	6.85 ± 4.05	6.76 ± 5.61	0.90 ± 1.15	1.36 ± 0.83	3.97 ± 4.22
	CNH	4.40 ± 0.22	0.14 ± 0.05	0.020 ± 0.01	6.53 ± 2.96	6.64 ± 5.75	0.83 ± 1.10	1.37 ± 1.07	3.97 ± 4.17

df degree of freedom, *F pr*. Fisher's probability (of significance), *DUC* direct under tree crown, *CNH* tree crown neighborhood, *CEC* cation exchange capacity, *SOC* soil organic carbon, *STD* standard deviation; Different letters show difference between treatments

Table 3 Grain and straw yields in 2015 and 2016

Treatments		Grain yield ± STD (kg ha^{-1})		Straw yield ± STD (kg ha^{-1})	
		2015	2016	2015	2016
A. senegalensis		517 ± 475.68b	ND	1805 ± 1384.01b	ND
B. aegyptiaca		365 ± 266.96b	137 ± 116.58a	1870 ± 1221.50b	499 ± 604.68a
F. albida		1005 ± 453.33a	136.3 ± 119.49a	3786 ± 1767.16a	779 ± 622.69a
G. senegalensis		544 ± 529.34b	ND	2175 ± 1772.51b	ND
P.reticulatum		1011 ± 1025.44a	169.4 ± 125.75a	3662 ± 2774.11a	571 ± 660.14a
LSD		346.4	56.4	1065.7	294.2
	df	F pr	F pr	F pr	F pr
Year	1	< 0.001	< 0.001	< 0.001	< 0.001
Species	4	< 0.001	< 0.001	< 0.001	< 0.001
Year × Species	4	< 0.001	< 0.001	< 0.001	< 0.001
Species (S)	4	< 0.001	< 0.001	ns	ns
Fertilizers (F)	3	ns	< 0.001	ns	< 0.001
Species × Fertilizers	12	ns	0.02	ns	ns

df degree of freedom, *F pr.* Fisher's probability (of significance), Average values ± STD standard deviation, *ND* non-determined, *ns* non-significant; Different letters show difference between treatments

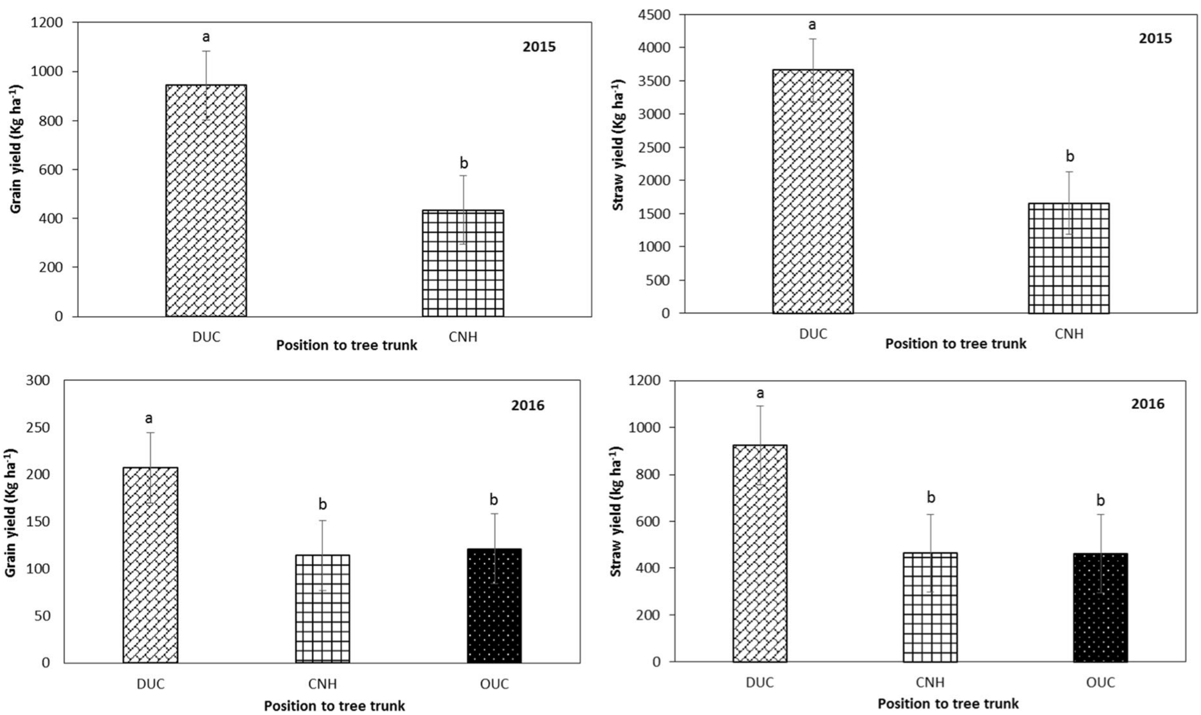

Fig. 3 Average grain and straw yields in 2015 and 2016 under crown positions regardless all tree species and fertilizers treatment. The vertical bars show LSD and different letters indicate difference between treatments

grain yield was higher in DUC zone while the lower grain yield was recorded in CNH zone, although not significantly different from that of the treeless OUC zone. The same trend was observed with straw yield which was significantly higher in DUC zone compared to CNH zone and OUC zone.

Effect of fertilizer on millet performance

There was a significant difference among fertilizer treatments in 2016 for both grain ($P < 0.001$) and straw yields ($P < 0.001$) but not in 2015. In 2016, the highest millet grain yield and straw were recorded with DAP, while the lowest were observed with the control. There was no significant difference between NPK fertilizer and manure amendment. But, the grain yield was numerically higher with NPK fertilizer compared to that of manure while the opposite was observed with straw yield. A similar trend was observed in 2015, although not significant when the higher grain yield was recorded with fertilizer micro-dosing compared to manure and the control. On average, millet yield was increased by 30% for DAP and 13% for NPK. There was no significant difference between manure and the control.

A significant interaction between tree species and fertilizer ($P < 0.05$, Table 3) was observed for grain yield in 2016 (Fig. 4). Under *B. aegyptiaca*, the response of millet grain yield to DAP was the highest while it was the lowest with manure, NKP and the control.

Discussion

Year effect

There was a significant cropping year effect in millet grain yield and straw in the current study, where grain yield and straw were higher in 2015 compared to 2016. This could be attributed to the higher amount and better rainfall distribution observed in 2015 compared to 2016, which favoured better plant growth and productivity (Fatondji and Ibrahim 2018). The interaction between rainfall amount and nutrients use was reported in Sahelian soils conditions and dry spells are detrimental to yield when it occurs at sensitive crop stages like grain filling and maturity (Akponikpè et al. 2008; Ibrahim et al. 2016; Fatondji and Ibrahim 2018). When fertilizer was applied, rainfall is beneficial to dissolve dry fertilizers and move nutrients into the plant rooting zone that can favour crop growth and development. Rainfall by increasing soil moisture increase organic matter mineralization and soil nutrient availability for plants. Dry spells in drought years induce water stress aggravated when fertilizer is applied. In semi-arid zones, where drought is frequent, adequate amount and well distributed rainfall provide the required water, allowing plants to benefit from moisture and nutrient uptake.

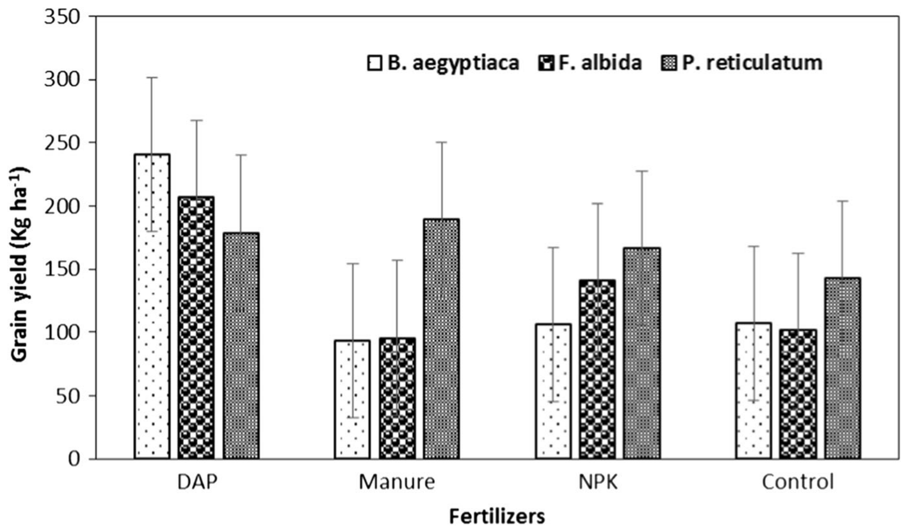

Fig. 4 Interaction effect between tree species and fertilizers in 2016 on millet grain yield. The vertical bars show LSD

Trees species improve differently soil fertility and millet yields

The results showed that millet yield and straw differed among tree species. The grain yield was higher under *P. reticulatum* and *F. albida* compared to other tree species. These results corroborate previous findings on soil fertility improvement by the two species (Dossa et al. 2013; Diallo et al. 2019). In this study, soil nutrients analysis showed that tree species influenced the distribution of soil nutrients differently. The higher mean of pH, SOC, N, P and K analyzed was recorded under *F. albida* and the higher mean of CEC, Mg and Ca was observed both under *F. albida* and *P. reticulatum* compared to other species. The current results reinforce the earlier reported by Diallo et al. (2019) on soil fertility regarding the effectiveness of *F. albida* and *P. reticulatum* to improve soil fertility in millet based systems of Sahelian regions. This difference may be explained by tree leaf nutrients content, released through mineralization and crown morphology (Kater et al. 1992). The importance of *F. albida* and *P. reticulatum* in soil fertility and crop yield improvement have also been shown in the literature (e.g. Kho et al. 2001; Dossa et al. 2013; Yélémou et al. 2014). *F. albida* (N-Fixing) and *P. reticulatum* (not N-fixing) are leguminous tree species which have compound leaves made of leaflets which are prone to a more rapid decomposition and mineralization (Rhoades 1995). In addition, the crown size of tree species may be considered as another factor, which can make a difference in soil fertility improvement and consequently in crop yield. Wezel et al. (2000) reported that *P. reticulatum* trees have denser and compact foliage, which may trap more dust sand than other species. These dust sand ameliorate top soil layers in nutrients (Bielders et al. 2002). In this study, the mean value of CEC was higher under the two species (*F. albida* and *P. reticulatum*, 15.56 and 7.5 respectively) compared to the other species (*A. senegalensis*, *B. aegyptiaca* and *G. senegalensis*, 6.72; 3.1 and 0.72 respectively). High soil CEC indicates high organic matter content and consequently a greater water holding capacity for crop benefit. The decomposition of organic matter increases the availability of essential nutrients such as K, Ca, and Mg for plant uptake, improving crop growth and development. Wezel et al. (2000) reported that the influence of tree species on soil pH explains the CEC behaviour as a function of the species. These authors showed that an increase of one pH unit leads to a decrease of 30% of $Al^{3+} + H^{+}$ saturation and an increase of 30% of Ca^{2+} saturation. Besides, the difference between tree species can be linked to the type of litter produced. Indeed, *G. senegalensis* have acidic litter than *P. reticulatum*, the decomposition of acidic litter leads to leaching of Ca^{2+}, which is replaced by H^{+} and Al^{3+} in the exchange capacity (Wezel et al. 2000). The mean value of pH was higher under *P. reticulatum* than *G. senegalensis*. Higher CEC content in soil increase the availability of nutrients in soil solution that may explain an improved crop yield under their species (*F. albida* and *P. reticulatum*).

In this study, except for pH, Mg and Ca, all soil nutrients contents were numerically higher under tree crown (DUC) compared to the neighbourhood (CNH) and the outside crown (OUC). Diallo et al. (2019) reported no difference for Mg under DUC and CNH. In the current study, the mean of SOC was higher under DUC compared to CNH. Under direct tree crown, there was an accumulation of organic matter due to the accumulation of leaf litter, which increase micro-organisms activities. The decomposition of organic matter under tree crown increase soil nutrients release (Diallo et al. 2019). Rhoades (1997) reported that the soil near the tree trunk is also rich in nutrients because of the leaching of dust from the leaf surface, scraps of dead insects and nutrients from the tree trunk carried by flowing water or rainfall, which concentrates under tree crown. Also, Wezel et al. (2000) showed that in the presence of shrubs, the soil properties (N, P and K) were significantly high within 0.50 m radius from the tree trunk and became less outside 1.50 m radius. This improvement of soil fertility increase crop yield and straw dry matter under tree crown compared to outside crown.

Another reason for the differential tree species effect on soil quality and crop productivity may be linked to sunlight incidence. Trees and shrubs may reduce the amount of sunlight reaching soils and crops through shading (Bayala et al. 2015) depending on crown dimensions, tree phenology and leaf density. Tree species by reducing sunlight projection under crown, may also moderate soil temperature and evapotranspiration. Light (amount and direction) affect soil organisms repartition that affects organic matter decomposition (Boffa 1999). Under crown, soil moisture is increased and induces organic matter decomposition by soil micro-organisms that better improve soil quality and crop yield under tree crown than outside crown. In Niger, Vandenbelt and Williams (1992) reported an improved millet growth during seedling establishment due to the positive effect of shade on soil water and temperature. In contrast, a yield depression was reported under trees due to the reduction of light intensity for C_4 plants that were adapted to higher sunlight intensities (maize, sorghum) compared to C_3 crops (millet) which were known to tolerate lower light intensities (Sanou et al. 2012; Bayala et al. 2015). Furthermore, *F. albida* has a reverse phenology. In full leaf during dry season it defoliates at the beginning of the rainy season minimizing light competition between trees and crop. Tree crown orientation has also a significant impact on soil nutrients contents due to wind direction or asymmetrical crown distribution on organic matter accumulation. In Mali, Diakité (1995) reported higher soil nutrients concentration in the west side of *V. paradoxa* than in the east due to the north-eastern Hamattan winds. In addition, in Malawi, Rhoades (1995) reported that nitrogen was mineralized more rapidly on the northern and eastern sides of large *F. albida* canopies compared to the southern one, because canopy volume is greater on the north side of trees where the sun trajectory is during the growing season. In the present study, differential sunlight incidence and related effect might have been minimal as tree and shrub species used for experiments were pruned yearly to avoid competition for light, soil nutrients and water between tree species and crops according to the FMNR practice implemented in the region.

Integrated tree species and fertilizers further increase grain and straw yields

The results showed that grain yield and straw differ among fertilizers types. Fertilizer improved millet yield and straw compared to the unfertilized control. The yield improvement was in agreement with the findings of recent studies in West Africa on fertilizer use in farmers' fields (Bielders and Gérard 2015; Tovihoudji et al. 2017). An increase in millet grain yield associated with fertilizer application could be explained by the low inherent soil fertility and low organic matter characteristics of the Sahelian sandy soil, which contribute to the positive response of pearl millet to any application of soil fertility management (Fatondji and Ibrahim 2018). These amendments induce better development and plant growth, which relatively increase yield production. In the present study, the positive response of manure application may have been enhanced because of the hill placement of manure. The positive effect of manure hill placement can be attributed to the supply of additional nutrients such as Ca and Mg and the early root proliferation favoured by this method (Fatondji et al. 2009). Ibrahim et al. (2015) reported that the positive effect of manure hill placement could result from a better scavenging of the limited amount of nutrients by the roots due to the early root proliferation favoured by manure hill placement. The positive effect of manure application in sandy soil can be explained by low organic matter level which may limits nutrients and soil water retention. In addition, manure fertilizer decomposition increases available P and exchangeable K but mineral fertilizer increases strongly available P and to a lesser extent exchangeable K (Tovihoudji et al. 2017). This explains, the present result, which showed that the higher crop yield was recorded with mineral fertilizer microdosing. In general, mineral fertilizers release nutrients faster, making them readily available to be used by plant immediately and its ability to improve the early crop development (Tabo et al. 2007).

Pearl millet response to microdosing depends on the type of fertilizer applied. The study showed that millet yield was better increased with DAP compared to NPK fertilizer. The higher response of pearl millet with DAP in Sahelian sandy was due to the higher supply of ammonium that stimulates plant use of soil water and nutrients (Bagayoko et al. 2000; Bielders and Gérard 2015). The result showed that under tree species the fertilizers microdosing performance is better than that of manure and the control. Moreover, the effect of one fertilizer management alone (like manure or fertilizer micro-dosing and the use of tree species) cannot reach the crop optimal need leaving a gap on yield due to the very low soil fertility in Sahelian soils. The combined effect of tree species and fertilizers management practice can lead to better achieve crop needs and consequently to increase crop yield. Many authors reported that to obtain better crop yield in Sahelian sandy soil, it is necessary for smallholder to combine minerals fertilizer with organic amendment (Akponikpè et al. 2008; Bielders and Gérard 2015).

The presence of trees in Sahelian farmer fields increases soil moisture availability, which enhances micro-organisms activities, including mycorrhizae, leaf litter decomposition, and nutrient mineralization (Dossa et al. 2009).

Kessler and Breman (1991) reported that long taproot permit species to exploit water and nutrients leached to deep soil layers. These nutrients were then recycled upward to the topsoil through leaf litter (Kessler and Breman 1991). This can explain the case of *F. albida* which has deeper roots that can reach 40 m (Vandenbelt 1992) compared to *B. aegyptiaca* (7 m), *G. senegalensis* (4 m) and *P. reticulatum* (between 2.5 and 3 m) and *A. senegalensis* (between 1.5 and 1.8 m), (Diack et al. 2000; Rabelo et al. 2016).

Moreover *F. albida* is a leguminous tree and leguminous tree are well known for nitrogen fixation, which, also may be limited by soil phosphorus content (Divito and Sadras 2014; Martins et al. 2017). In this study, higher mean content of phosphorus was recorded beneath *F. albida*, which can increase nitrogen fixation (Kessler and Breman 1991). The symbiosis between roots and rhizobia-mycorrhiza association, and leaf litter decomposition by micro-organisms, both influenced by soil moisture, increase nutrients release and uptake by millet crop under F. albida compared to other species (Vandenbelt 1992; Kho et al. 2001; Diallo et al. 2019). Although *P. reticulatum* is not an N- fixing species, several studies suggest that its leaf litter increases micro-organisms activities and nematodes diversity, which improve soil organic matter decomposition and nutrient mineralization, improving soil quality (Kizito et al. 2006; Dossa et al. 2009).

Under *B. aegyptiaca*, the response of millet grain and straw yield to DAP was higher while it was the lowest for other tree species under manure, NKP and the control. The chemical analysis showed that soil under *B. aegyptiaca* was acidic with low CEC indicating low organic matter. Indeed, low soil P content was also recorded beneath this species. The acidity increases Ca^{2+} leaching, which is replaced by H^{+} and Al^{3+} in the exchange capacity (Wezel et al. 2000). Ibrahim et al. (2015) reported that small dose of DAP fertilizer can increase the pH surroundings crop roots zone and increase soil nutrients availability (P, Ca and Mg) at early crop growth and development and might explain the better crop yield with DAP under *B. aegyptiaca* compared to the other species (*F. albida* and *P. reticulatum*).

Conclusion

Tree/shrubs species are essential for soil fertility restoration mainly in semi-arid zone like in Niger where the low soil fertility is the primary constraint of crop production. A field study was conducted to investigate the combined effect of tree species and soil fertility management practice on millet yield. We found that tree species improve soil fertility and crop yield differently and better under direct tree crown compared to the neighbourhood and treeless outside zones. *F. albida* and *P. reticulatum* improved more the crop yield than the other tree species. Integrated tree species and fertilizers performed far better than that of the control. Higher millet grain and straw yields were recorded with mineral fertilizer microdosing (DAP) under tree species. The combined trees and fertility management, mainly mineral ones were effective and can be used as an integrated fertility management practice in Sahelian countries where organic amendment is generally scarce and smallholder cannot affort purchasing the recommended quantity of mineral fertilizer for crop production. We recommend, Tree species selection in farmer field based on soil nutrients improvement and integration with moderate fertilizers to sustain food production for Sahelian smallholder farmers where low soil fertility is yet the primary constraint for crop production. This experiment covers only two years and included few replicates of tree species while tree effect occurs on the long run involving several factors. Further investigations would be needed to assess the the economic performance, for instance using a system productivity perspective, and the long-term sustainability of the integrated trees and soil fertility management in the Sahel.

Acknowledgements We would like to thank the West Africa Agricultural Productivity Program (WAAPP/PPAAO) under the Word bank and the West and Central African Council for Agricultural Research and Development (CORAF/WECARD) for funding this work.

References

Abasse T, Aissatou Y, Zakari AB, Adamou AI, Adam T (2013) Effet de *Piliostigma reticulatum* sur l'infestation des parcelles de mil par les insectes floricoles et *Coniesta ignefusalis* (foreur du mil) dans la zone d'Aguie au Niger. J Appl Biosci 66:5140–5146

Adams AM, Gillespie AW, Kar G, Koala S, Ouattara B, Kimaro AA, Bationo A, Akponikpe PBI, Schoenau JJ, Peak D (2016) Long-term effects of reduced fertilizer rates on millet yields and soil properties in the West-African Sahel. Nutr Cycl Agroecosyst 106:17–29

Akponikpè PBI, Michels K, Bielders CL (2008) Integrated nutrient management of pearl millet in the Sahel combining cattle manure, crop residues and mineral fertilizer. Exp Agric 44:453–472

Bagayoko M, Alvey S, Neumann G, Buerkert A (2000) Root-induced increases in soil pH and nutrient availability to field-grown cereals and legumes on acid sandy soils of Sudano-Sahelian West Africa. Plant Soil 225:117–127

Bationo A, Kihara J, Vanlauwe B, Waswa B, Kimetu J (2007) Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric Syst 94:13–25

Bationo A, Mokwunye AU (1991) Alleviating soil fertility constraints to increase crop production in West Africa: the experience in the Sahel. Fertil Res 29:95–115

Bayala J, Sanou J, Teklehaimanot Z, Ouedraogo SJ, Kalinganire A, Coe R, van Noordwijk M (2015) Advances in knowledge of processes in soil-tree-crop interaction in parkland systems in the West African Sahel: a review. Agric Ecosyst Environ 205:25–35

Bayala J, Sileshi GW, Coe R, Kalinganire A, Tchoundjeu Z, Sinclair F, Garrity D (2012) Cereal yield response to conservation agriculture practices in drylands of West Africa: a quantitative synthesis. J Arid Environ 78:13–25

Bielders CL, Gérard B (2015) Millet response to microdose fertilization in South-Western Niger: effect of antecedent fertility management and environmental factors. Field Crops Res 171:165–175

Bielders CL, Rajot JL, Amadou M (2002) Transport of soil and nutrients by wind in bush fallow land and traditionally managed cultivated fields in the Sahel. Geoderma 109(1):19–39

Boffa JM (1999) Agroforestry parklands in sub-Saharan Africa. FAO Conservation Guide No. 34. Food and Agriculture Organization of the United Nations, Rome, Italy

Camara B, Camara F, Berthe A, Oswald A (2013) Micro-dosing of fertilizer—a technology for farmers' needs and resources. Int J AgriSci 3:387–399

Cunningham PJ, Abasse T (2005) Reforesting the Sahel: farmer managed natural regeneration. In: Kalinganire A, Niang A, Kone A (eds) Domestication des espèces agroforestières au Sahel: situation actuelle et perspectives. Working Paper. World Agroforestry Centre, Nairobi, Kenya, pp 75–80

Diack M, Sene M, Badiane AN, Diatta M, Dick RP (2000) Decomposition of a native shrub, Piliostigma reticulatum, litter in soils of semiarid Senegal. Arid Soil Res Rehabil 14:205–218

Diakité T (1995) Concurrence pour l'eau et les éléments nutritifs entre ligneux et cultures. Le karité et le sorgho en zone semi-aride au Mali. Mémoire M.Sc. Université Laval, Québec, Canada, 69 pp

Diallo MB, Akponikpè PBI, Fatondji D, Abasse T, Agbossou EK (2019) Long-term differential effects of tree species on soil nutrients and fertility improvement in millet based systems of the Sahelian Niger. For Trees Livelihoods 28(4):240–252

Divito GA, Sadras VO (2014) How do phosphorus, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture legumes? A meta-analysis. Field Crops Res 156:161–171

Dossa EL, Diedhiou I, Khouma M, Sene M, Badiane AN, Samba SAN, Assigbetse KB, Sall S, Lufafa A, Kizito F, Dick RP, Saxena J (2013) Crop productivity and nutrient dynamics in a shrub based farming systems of the Sahel. Agron J 105(4):1237–1246

Dossa EL, Khouma M, Diedhiou I, Sene M, Kizito F, Badiane AN, Samba SAN, Dick RP (2009) Carbon, nitrogen and phosphorus mineralization potential of semiarid sahelian soils amended with native shrubs residues. Geoderma 148(3–4):251–260

Fatondji D, Ibrahim A (2018) Improving nutrient use efficiency from decomposing manure and millet yield under Plinthosols in Niger. Nutr Cycl Agroecosyst 110(3):485–499

Fatondji D, Martius C, Zougmore R, Vlek PL, Bielders CL, Koala S (2009) Decomposition of organic amendment and nutrient release under the zai technique in the Sahel. Nutr Cycl Agroecosyst 85:225–239

Faye MD, Weber JC, Abasse TA, Boureima M, Larwanou M, Bationo AB, Diallo BO, Sigué H, Dakouo JM, Samaké O, Sonogo DD (2011) Farmers' preferences for tree functions and species in the West African Sahel. For Trees Livelihoods 20:113–136

Ibrahim A, Abaidoo RC, Fatondji D, Opoku A (2016) Fertilizer micro-dosing increases crop yield in the Sahelian low-input cropping system: A success with a shadow. Soil Sci Plant Nutr 62(3):277–288

Ibrahim A, Abaidooa RC, Fatondji D, Opoku A (2015) Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system. Field Crops Res 180:29–36

Kater LJM, Kante S, Budelman A (1992) *Vitellaria paradoxa* and *Parkia biglobosa* associated with crops in south Mali. Agroforest Syst 18:89–105

Kessler JJ, Breman H (1991) The potential of agroforestry to increase primary production in the Sahelian and Sudanian zones of West Africa. Agroforest Syst 13(1):41–62

Kho RM, Yacouba B, Yayé M, Katkoré MA, Iktam A, Mayaki A (2001) Separating the effect of trees on crop: the case of *Faidherbia albida* and millet in Niger. Agroforest Syst 52:219–238

Kizito F, Dragila M, Sène M, Lufafa A, Diedhiou I, Dick RP, Selker JS, Dossa E, Khouma M, Badiane A, Ndiaye S (2006) Seasonal soil water variation and root patterns between two semi-arid shrubs co-existing with Pearl millet in Senegal. West Africa J Arid Environ 67:436–455

Martins D, Macovei A, Leonetti P, Balestrazzi A, Araújo S (2017) The influence of phosphate deficiency on legume symbiotic N2 fixation. In: Sulieman S, Tran LS (eds) Legume nitrogen fixation in soils with low phosphorus availability. Springer, Cham, pp 41–75

Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A (2009) Agroforestree database: a tree reference and selection guide. Version 4.0. [Internet] World Agroforestry Centre (ICRAF) Nairobi, Kenya. http://www.worldagroforestry.org/resources/databases/agroforestree. Accessed 10 April 2018

Rabelo SV, Quintans JSS, Costa EV, Almeida, JRGS, Quintans JLJ (2016) Annona species (Annonaceae) oils. In: Preedy VR (ed) Essential oils in food preservation, flavor and safety. Academic Press 221–229

Rhoades CC (1995) Seasonal pattern of nitrogen mineralization and soil moisture beneath *Faidherbia albida* (syn *Acacia albida*) in central Malawi. Agroforest Syst 29:133–145

Rhoades CC (1997) Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. Agrofor Syst 35:71–94

Sanchez PA (1995) Science in agroforestry. Agrofor Syst 30:5–55

Sanou J, Bayala J, Teklehaimanot Z, Bazié P (2012) Effect of shading by baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) on yields of millet (*Pennisetum glaucum*) and taro (*Colocasia esculenta*) in parkland systems in Burkina Faso. West Africa Agrofor Syst 85(3):431–441

Schlecht E, Buerkert A, Tielkes E, Bationo A (2006) A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. Nutr Cycl Agroecosyst 76:109–136

Sivakumar MVK, Maidoukia A, Stern RD (1993) Agroclimatology of West Africa: Niger. Information Bulletin Paper 5. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics, and Niamey: Direction de la météorologie nationale du Niger, 116 pp

Sotelo Montes C, Weber JC, Silva DA, Andrade C, Muñiz GIB, Garcia RA, Kalinganire A (2012) Effects of region, soil, land use, and terrain type on fuelwood properties of five tree/shrub species in the Sahelian and Sudanian ecozones of Mali. Ann For Sci 69(6):747–756

Tabo R, Bationo A, Gérard B, Ndjeunga J, Marchal D, Amadou B, Annou MG, Sogodogo D, Taonda JBS, Hassane O (2007) Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa. In: Bationo A, Waswa B, Kihara J, Kimetu J (eds) Advances in integrated soil fertility management in sub-Saharan Africa: challenges and opportunities. Springer, Dordrecht, pp 201–208

Tovihoudji GP, Akponikpè PBI, Adjogboto A, Djenontin JA, Agbossou EK, Bielders C (2017) Combining hill-placed manure and mineral fertilizer enhances maize productivity and profitability in northern Benin. Nutr Cycl Agroecosyst 110(3):375–393

Van Reeuwijk LP (1993) Procedures for soil analysis. Technical Paper No. 9. International Soils Reference and Information Center (ISRIC), Wageningen, 100 pp

Vandenbelt RJ (ed) (1992) Faidherbia albida in the West African semi-arid tropics: proceedings of a workshop; 22–26 April 1991, Niamey, Niger, Nairobi, Kenya: ICRISAT, Patancheru, India and ICRAF, p 206

Vandenbelt RJ, Williams JH (1992) The effect of *Faidherbia albida* shade on soil temperature in relation to the effect of soil surface temperature on the growth of millet (*Pennisetum glaucum*). Agric For Meteorol 60:93–100

Vanlauwe B, Wendt J, Giller KE, Corbeels M, Gerard B, Nolte C (2014) A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. Field Crops Res 155:10–13

Walkley A, Black IA (1934) An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37:29–37

Wezel A, Rajot JL, Herbrig C (2000) Influence of shrubs on soil characteristics and their function in Sahelian agro-ecosystems in semi-arid Niger. J Arid Environ 44:383–398

Yélémou B, Yaméogo G, Koala J, Bationo BA, Hien V (2014) Influence of the leaf biomass of *Piliostigma reticulatum* on Sorghum production in North Sudanian Region of Burkina Faso. J Plant Stud 3(1):80–90