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Yields and soil chemical property changes in an intensive vegetable cropping system in the Sahel

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Irrigated vegetable production is an important agricultural activity and a significant source of income for millions of smallholder farmers in the Sahel. There is little information on the potential effects of intensive vegetable production using African Market Garden (AMG) technology on vegetable yields and soil chemical properties. Three contiguous 500-m^2 plots were established to evaluate three vegetable management practices: (1) AMG, (2) Improved Management (IM), and (3) Farmer Practice (FP). These management practices were arranged in a randomized block design. AMG and IM management practices produced higher yields as compared to farmer practices. Tomato and onion yield for IM were 50 and 300% higher than for AMG, respectively; while yields for FP were consistently lower. The soil chemical properties at the end of the experiment displayed marked changes in all treatments compared to the initial soil status. Except for pH, which decreased by 0.2, 0.4, and 1.1 pH units, respectively, for FP, IM, and AMG, soil chemical properties increased as a direct response to management practices. These findings indicate that regular and high rates of manure application combined with mineral fertilizer enhance sandy soil fertility in the Sahel. These findings are important for developing sustainable vegetable production in the Sahel.

Key words: Vegetable production, Drip irrigation, Farmer's practice, Productivity, Soil fertility.

INTRODUCTION

Vegetable production provides a significant source of income for millions of smallholder farmers in the Sahel (Woltering et al., 2011a). Vegetables are typically cultivated on 0.01-0.50 ha plots of land, using traditional crop husbandry, fertility management, and irrigation techniques. Traditional irrigation methods or small gasoline-powered pumps are used by Sahelian vegetable producers to lift water from wells or surface water. The water is then spread across the field using traditional methods (Bustan and Pasternak, 2008). These traditional practices are time-consuming and losses of water and energy. However, in the Sahel, 80% of gardens are still irrigated by hand using watering cans and buckets (Drechsel et al., 2006; Dittoh et al., 2010). The African Market Garden (AMG) which is a holistic horticultural production system for small producers based on low-

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pressure drip irrigation combined with a crop management package was initiated by ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) in 2004 (Woltering et al., 2011b). ICRISAT and partners have tested various AMG models in West Africa's Sudano-Sahel, including thrifty (80 m^2) and commercial (500 m2 drip kits), clusters (multiple kits of 5000 m^2), and communal systems, which allow producers to benefit from collective use of water, energy resources, land purchasing, and cultivated product marketing (Woltering et al., 2011b). The drip irrigation system is at the heart of the AMG. Drip irrigation has been used as an alternative to other irrigation techniques, particularly for horticultural crops, since the mid-1960s (Bernstein and Francois, 1973; Lamm, 2016). Drip irrigation distributes water uniformly over the field at regular intervals, avoiding the negative effects of under- (plant stress) or over-irrigation (leaching and waterlogging) in specific areas of the irrigated area (Bustan et Pasternak, 2008). Drip irrigation increases crop water use efficiency by reducing evaporation because it does not wet the entire soil surface (Simonne et al., 2007; Luo and Li, 2018). Water can be combined with soluble fertilizer (fertigation) and delivered directly to the crop's root zone. As a result, drip irrigation generally increases yield and water savings by about 50% while requiring significantly less labor than other systems (Woltering et al., 2011a, Kuscu et al., 2014; Badr et al., 2016). Cetin and Uygan (2008) reported a 42% increase in WUE in tomato under drip irrigation. One of the most significant benefits of AMG was the significant increase in profits at a low environmental cost due to improved crop and water management practices.

However, there is little information on the potential effects of intensive vegetable production using AMG technology on vegetable yields and soil chemical properties in the Sahel. The current study is novel in that it addresses this knowledge gap, which has significant implications for developing a guideline for sustainable vegetable production in the Sahel.

MATERIALS AND METHODS

Experimental site

The experiment was carried out at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Sadoré Research Station in Niger (13°15'N, 2°17'E), situated 30 kilometers southeast of Niamey. The climate is Sudano-Sahelian, with a seven-month dry season (November to May) and a five-month rainfall season (June to October), both of which are highly variable in time and space. The average annual rainfall in Sadoré is 560 mm (1983-2018), and the average temperature is 29°C (ICRISAT, climatological database. Figure 1 depicts the rainfall and temperature recorded during the experiment. Evaporation potential is nearly 2,000 mm yr^{-1}. According to the USDA Soil Taxonomy, the soil is a sandy siliceous Psammentic Paleustalf and isohyperthermic, as well as an Arenosol (Deckers and Nachtergaele, 1998). This is characterized by a high sand content, low native fertility, low organic matter, and a low cation exchange capacity, which limits nutrient storage (Table 1). These soils are generally very strongly acidic, with aluminium accounting for a significant portion of the exchangeable cations (Table 1).

Experimental design and crop management

The experiment consisted of three management practices: African Market Garden (AMG) with drip irrigation, Improved Management (IM) with watering can and Farmer Practice (FP). The AMG included an improved crop husbandry package as well as irrigation using low-pressure drip irrigation (Table 2). Drip laterals were 12 mm in diameter, with drip emitters spaced 0.30 m apart. The drip emitter discharge was between 0.4 and 0.5 L h^{-1}. For both okra and eggplant, the distance between the laterals on the planting bed was 1 m. Water was collected in a 4 m^3 reservoir and gravity fed into the plot at pressures ranging from 2.5 to 1 m head (drip emitter discharge 0.4-0.5 L h^{-1}). The reservoir provides 8 mm (4 m^3 per 500 m^2) of irrigation, which corresponds to the maximum crop daily evapotranspiration rates in the area (Pasternak et al., 2006). Before planting, planting beds were prepared with a basic dressing of 4 kg m2 manure and 0.1 kg m^{-2} of 15-15-15, a complete fertilizer containing 15% N, 6.5% P, and 12.4% K. Urea was mixed into the reservoir water (fertigation) daily to achieve a N concentration of 50 ppm in the irrigation water. For the first three days after planting, crops were irrigated by hand at a rate of 4 mm per day. Planting density was determined by extension service recommendations. Improved management (IM) is like AMG in terms of crop management practices, but irrigation is done with watering cans. The amount of water used, the preparation of planting beds, and the planting density were all comparable to the AMG treatment. Water was applied twice per day, with two-thirds applied in the morning (5.3 mm) and one-third applied in the afternoon (2.7 mm). Two 12 L watering cans were emptied over the planting beds at a rate of approximately 300 mm h^{-1}. The total amount of urea applied per crop was equal to the amount applied for the AMG, but it was applied via broadcasting and only twice during crop development; half was applied 21 days after planting and the other half at flowering stage. For lettuce urea was applied 5 and 15 days after planting. Farmer Practice (FP) consisted of current vegetable crop management practices and the use of irrigation watering cans. Farmers and extensionists were interviewed via surveys in and around Niamey to learn about farmers' water application regimes, fertilizer use, planting density, and other crop management practices. The summary of farmers' practices was provided in Table 2. The cropping calendar and variety used for each crop were showed in Table 3. Each management practice was considered a treatment, with each planting beds as replications in a randomized complete block design. Each treatment consisted of 500 m^2 (20 m x 25 m) with ten raised (0.2 m) planting beds each were prepared. The planting beds were 25 m long and 1.8 m wide, with a 0.2 m path between them. There was a 0.5 m path every 8 m across the bed for the treatments irrigated with watering cans, and earthen borders were used to prevent runoff from spilling over into other beds. On five beds, two different vegetables were grown at the same time. The two outer beds were regarded as borders and were excluded from the analysis. Five vegetable crop lettuce (Maya), Okra (var. Konni), onion (violet de Galmi), tomato (Icrixina) and eggplant (var. Black Beauty) were chosen for this experiment because they are popular vegetables in Niamey (Gowda et al., 2010). Tomatoes, onions, and eggplant were grown once each; okra three times and and lettuce four times from 2008 to 2009.

Data collection and analysis

Agronomic data

For each of the four replications (planting beds) per management

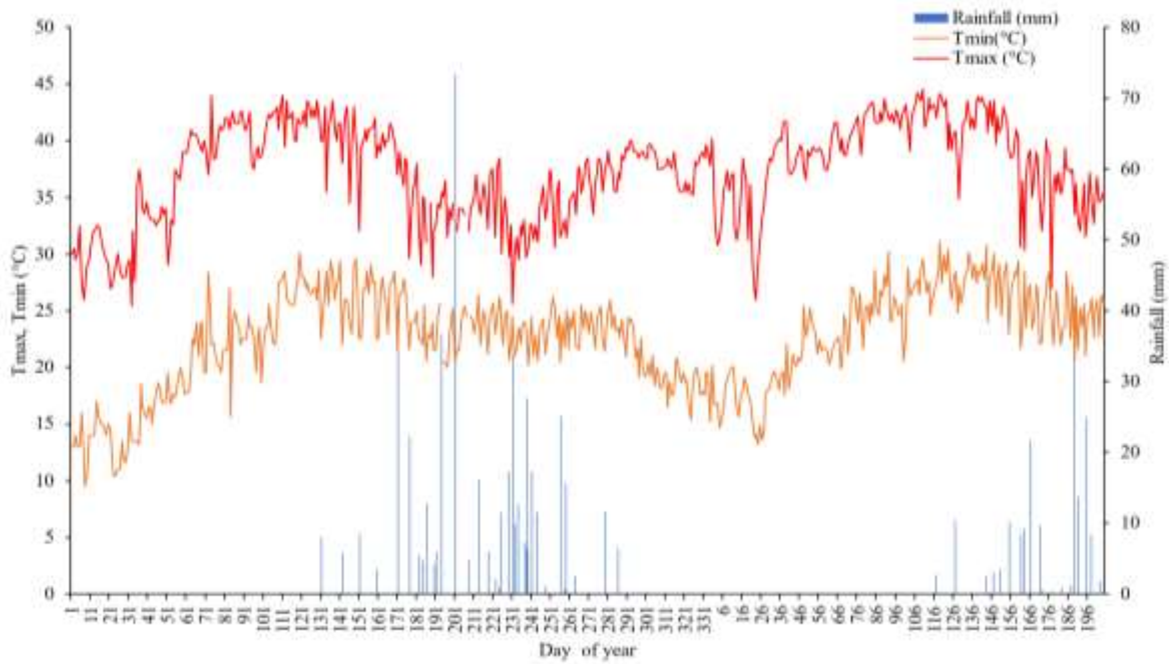

Figure 1. Rainfall and temperature recorded during the experiment period.
Source: ICRISAT-Sadore Weather data

Table 1. Initial soil physical and chemical characteristics.

Soil parameters	FP (n = 8)	IM (n =8)	AMG (n = 8)
Soil texture			
Sand (%)	92.4 ± 0.8	92.3 ± 0.9	92.9 ± 1.2
Silt (%)	2.3 ± 0.6	2.8 ± 0.6	2.5 ± 0.6
Clay (%)	5.3 ± 1.2	4.9 ± 0.7	4.6 ± 0.2
Soil chemical properties			
pH-H_2O (1:2.5)	5.3 ± 0.9	5.2 ± 0.1	5.3[a] ± 0.1
Organic C (g kg^{1})	3.3 ± 0.1	3.2 ± 0.1	3.0[a] ± 0.3
P-Bray 1 (mg kg^{-1})	4.0 ± 0.9	3.7 ± 0.5	3.2[a] ± 0.7
NH_4^+-N (mg kg^{-1})	3.3± 0.6	3.5 ± 0.7	2.7 ± 0.8
NO_3^--N (mg kg^{-1})	0.8 ± 0.03	1.1 ± 0.4	0.69 ± 0.2
Exchangeable bases ($cmol_c$ kg^{1})	1.04 ± 0.04	1.04 ± 0.09	0.95 ± 0.04

AMG, African Market Garden with drip irrigation; IM improved management with watering can and FP, Farmer Practice; n, number of soil samples analysed; ± Standard error.
Source: Author Experimental Data 2008

practice (treatment), fresh fruit yield was collected and weighed. Tomatoes, okra, and eggplant were harvested when there were many ripe fruits in the field, whereas lettuce and onions were harvested when they reached maturity.

Soil sampling and analysis

Before and after the experiment, soil samples were collected from each replication (planting bed) at 0-20 cm using a stainless-steel trowel. Five samples were taken from each replication's diagonals. The soil samples from each replication were combined to form a composite. All soil samples were kept refrigerated at 5°C and analyzed within 24 h of collection in the laboratory. Each composite sample was analyzed pH (H_2O) (soil/water ratio of 1:2.5). Organic carbon was determined using Walkley and Black method van Reeuwijk's (1993), total N using the Kjeldahl method (Houba et al., 1995), and Ammonium and nitrate were determined by potassium chloride extraction (Keeney and Nelson 1982). Available phosphorus was gotten using the Bray-1 method (van Reeuwijk, 1993). The ammonium acetate (NH4OAc) solution at pH 7 was used to determine exchangeable bases (Na^+, K+, Ca^{2+}, and Mg^{2+}) using the extraction method described by van Reeuwijk (1993). Ions H^+ and Al^{3+} released on an exchange by an unbuffered KCl

Table 2. Water application, soil fertilization and crop management.

	AMG	IM	FP			
			Lettuce	Tomato, Okra	Eggplant	Onion
Irrigation method	**drip**	**watering can**	**watering can**	**watering can**	**watering can**	**watering can**
Water applied (L m^{-2} day^{-1})	8	8	12	12	10	10
Manure (kg m^{-2})	4	4	1.5	3.2	1	1.3
NPK (g m^{-2})	100	100	0	0	10	18
Urea (g m^{-2})	0.8 day^{-1}	0.8 day^{-1}	12	30	10	0
Plant density (cm)			15 x 15	50 x 50	50 x 50	15 x 15
Lettuce	30 x 30	30 x 30				
Onion	15 x 15	15 x 15				
Other crops	100 x 60	100 x 60				

Source: Data collected from the experiment

Table 3. Cropping calendar and crop varieties of different vegetables.

Crop	Variety	2008												2009						
		Rainy season							Dry season					Rainy season						
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lettuce	Maya	20*	20#							12*	13					18*	19#	22*	20#	
Okra	Konni	26*		8#		13#					27*			13#	10#	23*	15#		9#	
Tomato	ICRIXina		31*			3#	10#													
Onion	Violet de Galmi							12*			16#									
Eggplant	Black Beauty										20*		22#		17#					

*Planting time; #harvesting time
Source: Data collected from the experiment

solution were determined using the method described by van Reeuwijk (1993). Robinson method, as described by, was used to determine particle size distribution.

Statistical analysis

Statistical analyses were carried out using the mixed model procedures in R software, Version 4.0.2. (R Development Core Team, 2020). Treatments were treated as fixed effects, whereas replication was treated as a random effect. When a statistically significant difference was found, the means were compared using the least significant differences (LSD) test with a p-value of 5%.

RESULTS AND DISCUSSION

Vegetable yields

The AMG treatments gave higher crop yields than the farmers practice, except for lettuce production (Table 4). Lettuce yield was found highest for the AMG treatments at the start of the experiment in June 2008, but the converse was true for the subsequent three cropping in 2009, especially in the dry season at the end of 2009 when crop yield in the AMG drip was a factor 10 smaller than in the farmer practice. From the analysis of the chemical status of the soil it became clear that within a 35-month period the pH in the top 40 cm soil went down dramatically for the AMG treatment, from 5.3 to 4.1. The pH for the IM

Table 4. Vegetable yields as affected by different management.

Crop	Season	AMG drip (kg/m^2)	IM (kg/m^2)	FP (kg/m^2)	F. prob
Lettuce	RS08	2.0^a	1.3^{ab}	1.1^b	0.057
Lettuce	DS09	3.1^a	3.3^a	3.7^a	ns
Lettuce	RS09	1.0^a	0.9^a	1.0^a	ns
Lettuce	DS09	0.2^b	1.1^a	1.7^a	< 0.001
Tomato	RS08	4.1^b	6.3^a	2.0^c	< 0.001
Okra	RS08	1.5^a	1.4^b	1.0^c	< 0.001
Okra	DS09	1.2^a	0.7^b	0.9^{ab}	0.013
Okra	RS09	1.9^a	1.4^a	0.5^b	< 0.001
Onion	DS08	0.7^b	2.0^a	0.7^b	0.012
Eggplant	DS09	6.2^a	4.1^b	2.5^c	< 0.001

Season: RS08 signifies Rainy Season 2008, DS09 signifies Dry Season 2009.
Source: Data collected from the experiment from 2008 to 2009

dropped from 5.1 to 4.7, and the pH for the FP remained quite similar from 5.2 to 5.0. Drip irrigation with a slightly acidic sandy soil (pH6) in combination with daily application of urea (fertigation) apparently acidified the soil of the AMG resulting in a detrimental effect on the yield of lettuce that seems to be more sensitive to low soil pH than okra and eggplants as this soil pH value is below the optimum pH value for leafy vegetable production is 6.6 (Penas and Lindgren, 1990). Considering the total productivity for all crops over the experimental period, both AMG treatments (with and without drip irrigation) gave higher yield as compared to farmer practice produced (Table 4). The fresh fruit yields of okra and eggplant grown in the AMG with drip irrigation were significantly higher than in the other treatments (Table 4). The findings were also consistent with previous research, which found that vegetable production with fertigation technology can result in a significant increase in crop yield because fertilizer is applied frequently and in small amounts during each irrigation event to ensure an adequate supply of water and nutrients in the rootzone (Vasu and Reddy, 2013; AlKhader et al., 2019). Tomato and onion yields were significantly higher for the AMG watering can treatment. Tomato and onion yield for AMG watering can were found respectively 50 and 300% higher than for AMG drip. This is in contrast with findings from literature where normally onion yields improve around 30% with drip irrigation (Yohannes and Tadesse, 1998; Kumar et al., 2006). It seems possible that the lowest yield recorded in onion could be related to presence of nematodes which significantly affect onion plant development.

Changes in soil chemical properties

The soil chemical properties at the end of the experiment displayed marked changes in all treatments compared to the initial soil status (Figure 2). Except for pH, which decreased by 0.2, 0.4, and 1.1 pH units, respectively, for FP, IM, and AMG (Figure 2a), soil chemical properties increased as a direct response to management practices. The soil organic carbon has increased by 0.9, 1.9, and 2.0g/kg in FP, IM, and AMG, respectively (Figure 2b). The increase in soil carbon in all treatments could be attributed to the amount of manure applied over the 35-month experimental period. During this time, 400 t ha^{-1} and 211 t ha^{-1} of manure were applied in improved practices (AMG and IM) and farmer practices, respectively, significantly contributing to the accumulation of organic matter in the soil. Organic amendments have been shown to increase soil organic carbon levels (Diacono and Montemurro, 2010). These findings suggest that regular and high rates of manure application in the intensive vegetable production system could improve soil organic stock, which has important implications for sustainable soil fertility management in the Sahelian sandy soil with low soil organic carbon (Ibrahim et al., 2015). Similarly, the application of manure in addition to mineral fertilizer (NPK) resulted in increased soil P build-up, particularly in AMG and IM, due to higher amounts of manure and P-based fertilizer applied (Table 2). The cumulative effects of manure and fertilizer application on soil P levels are shown here. This finding supports the findings of Pincus et al. (2016), who found that combining organic amendment and fertilizer increased soil P levels. Soil NO_3-N and NH_4-N content increased on average from 3.2 to 5.7 and from 0.86 to 7.82, respectively as compared to the initial values regardless of management practice (Figures 2d, f). This result indicates that regular addition of mineral fertilizer and organic material to soil enhanced crop N availability and resulted in build-up of N. Similarly, Continuous cropping increased the cation exchange capacity (CEC) in all treatments of the vegetable production system (Figure 2e). It is well known that the application of organic amendment increased CEC due to the colloidal nature of organic matter. The results of the study revealed that

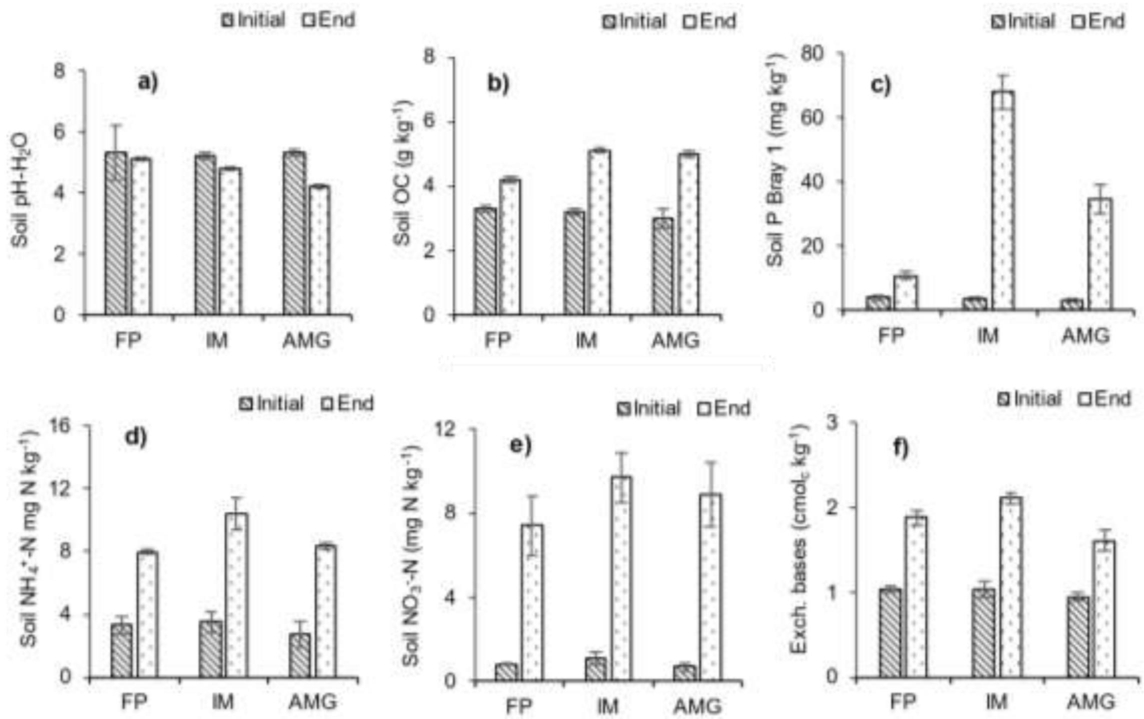

Figure 2. Soil chemical properties as affected by management practices.
Source: Experimental data collected in 2008 and 2009

using organic manures in conjunction with chemical fertilizer increased the soil's cation exchange capacity (CEC) significantly more than the control (Bhatt et al., 2019).

CONCLUSION

The effects of intensive vegetable production on vegetable yields and soil chemical properties were assessed. The results show that regardless of the vegetable irrigation system, regular and high rates of manure application combined with mineral fertilizer improve soil fertility status in the Sahelian sandy soil. These findings are important for developing sustainable vegetable production in the Sahel.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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