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Nutrient flows and balances in intensively managed vegetable production of two West African cities

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Abstract

This study reports and analyzes nutrient balances in experimental vegetable production systems of the two West African cities of Tamale (Ghana) and Ouagadougou (Burkina Faso) over a two-year period comprising thirteen and eleven crops, respectively. Nutrient-use efficiency was also calculated. In Tamale and Ouagadougou, up to 2% (8 and 80 kg N ha^{-1}) of annually applied fertilizer nitrogen were leached. While biochar application or wastewater irrigation on fertilized plots did not influence N leaching in both cities, P and K leaching, as determined with ion-absorbing resin cartridges, were reduced on biochar-amended plots in Tamale. Annual nutrient balances amounted to +362 kg N ha^{-1}, +217 kg P ha^{-1}, and –125 kg K ha^{-1} in Tamale, while Ouagadougou had balances of up to +692 kg N ha^{-1}, +166 kg P ha^{-1}, and –175 kg K ha^{-1} y^{-1}. Under farmers' practice of fertilization, agronomic nutrient-use efficiencies were generally higher in Tamale than in Ouagadougou, but declined in both cities during the last season. This was the result of the higher nutrient inputs in Ouagadougou compared to Tamale and relatively lower outputs. The high N and P surpluses and K deficits call for adjustments in local fertilization practices to enhance nutrient-use efficiency and prevent risks of eutrophication.

Key words: biochar / horticulture / leaching / nutrient budgeting / volatilization / wastewater irrigation

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1 Introduction

In sub-Saharan Africa, urban and peri-urban agriculture (UPA) has repeatedly demonstrated to reduce urban poverty and food insecurity while also contributing to the development of the local economy (*Lydecker* and *Drechsel*, 2010; *Drechsel* and *Keraita*, 2014). Urban farming can provide part-time or full-time employment, whereby farm output is used to supplement household income (*Drechsel* and *Keraita*, 2014). The fast-growing population of urban areas increases the demand for fresh vegetables while reducing the available land for UPA. Following demand increases, farmers intensify their production, which may lead to large annual nutrient surpluses (*Buerkert* et al., 2005; *Predotova* et al., 2011). These may be caused by lack of knowledge of efficient fertilizer application, market demand for dark green produce poor fertilizer dosing and the unavailability of well-known, appropriate fertilizer combinations (*Kaiser* and *Nelson*, 2014). The latter authors reported that farmers often simply follow what their neighbors are doing due to lack of extension services, with the risk of adopting inefficient practices. Aside mineral fertilizers, untreated wastewater is also used for irrigation and can provide large amounts of plant nutrients (*Thebo* et al., 2014) despite related potential health hazards. Intensive fertilization may ultimately lead to large gaseous and leaching losses of nutrients (*Graefe* et al., 2008). Among other benefits, biochar improves N-use efficiency and reduces leaching and gaseous emissions (*Steiner* et al., 2008; *Zhang* et al., 2016). A number of studies have been conducted to estimate horizontal fluxes and leaching losses in UPA (*Diogo* et al., 2010; *Lehmann* et al., 2001; *Predotova* et al., 2010; *Safi* et al., 2011). However, not much research has been done in the area of intensively managed UPA systems on the use of biochar as a soil amendment in combination with wastewater irrigation.

Nutrient balances may be a quantifiable indicator for the sustainability of an agricultural system (*Eckert* et al., 2000), and there is a long history of employing this approach at different levels of matter flow since *Stoorvogel* and *Smaling* (1990) have started propagating this approach and assessing its implication for food production.

In view of the above, this two-year study aimed at quantifying inputs and outputs such as organic and mineral fertilizers, harvested crops, leaching losses and gaseous emissions in irrigated UPA vegetable gardens at two locations in West Africa. In this context, nutrient balances and use efficiencies were calculated. We hypothesized that (1) high fertilizer rates, particularly in combination with wastewater irrigation, will lead

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to inefficient nutrient use and high losses of major nutrients due to leaching and volatilization especially during the rainy season, and that (2) amending soil with biochar will improve nutrient-use efficiencies.

2 Material and methods

2.1 Study area

The study comprised two field experiments conducted in Tamale, the capital city of the northern region of Ghana (9°28′28.75′′N latitude and 0°50′53.48′′W longitude, 151 m asl) and in Ouagadougou, the capital city of Burkina Faso (12°24′16.3′′N latitude and 1°28′41.0′′W longitude, 305 m asl). These two cities were selected to investigate and compare site-specific, farmer-tailored innovations for improved and sustainable crop production. Both locations have a unimodal rainfall distribution of 1111 mm at Tamale (sub-humid conditions) and 788 mm at Ouagadougou (semi-arid conditions) with average annual temperatures of 27.9 and 28.2°C, respectively (*Akoto-Danso* et al., 2018). Soils in the two cities are considered highly degraded with poor soil fertility, with the majority of households of the two cities depending on agriculture for their livelihoods (*Tully* et al., 2015). The cropping pattern in the two cities was similar. In the dry season, fields are typically cultivated with lettuce (*Lactuca sativa* L.), cabbage (*Brassica oleracea* L.), and green leafy vegetables such as roselle (*Hibiscus sabdariffa* L.) and amaranth (*Amaranthus cruentus* L.). In the wet season (June–September), farmers cultivate staple crops such as maize (*Zea mays* L.), rice (*Oryza sativa* L.), and sorghum (*Sorghum bicolor* Moench.), but also vegetables such as pepper (*Capsicum* sp.) and okra (*Abelmoschus esculentus* L. Moench) of we selected a few representative species for our study. The soils in the study area of we selected a few representative species for our study as a Petroplinthic Cambisol in Tamale and a Haplic (Cutanic) Lixisol in Ouagadougou (*Häring* et al., 2017; Tab. 1).

2.2 Experimental setup

Data collection occurred in a multi-factorial split-plot field experiment comprising four soil fertility management practices combined with two levels and qualities of irrigation water: untreated wastewater (ww) and clean water (cw)—each at full (f) or reduced (r, 2/3 of f) quantities (Tabs. 2 and 3). The fertility management practices included farmers' practice (FP_1) of fertilization in comparison to an unfertilized control (FP_0), biochar (BC) addition, and FP_1+biochar (FP_1+BC) yielding a total of 16 treatments. These were replicated in four blocks comprising plots of 8 m^2.

Table 1: Soil and biochar properties at the two study cities of Tamale (northern Ghana) and Ouagadougou (capital city of Burkina Faso; data indicate means ± SD, *n* = 72 for soil, *n* = 3 for biochar).[a]

	Soil[b]				**Biochar**	
	Ouagadougou		**Tamale**		**Rice husks**	**Corn cobs**
Soil depth (cm)	**0–20**	**20–40**	**0–20**	**20–40**		
Sand (%)	59.6 ± 5.2	54.7 ± 4.1	45.7 ± 8.5	46.1 ± 6.8	–	n.a
Silt (%)	34.8 ± 4.2	37.7 ± 3.1	47.0 ± 8.6	47.1 ± 6.1	–	n.a
Clay (%)	5.3 ± 1.3	7.5 ± 1.2	5.9 ± 0.9	6.5 ± 1.0	–	n.a
Bulk density (g cm^{-3})	1.60 ± 0.14	1.71 ± 0.2	1.4 ± 0.1	1.5 ± 0.0	–	n.a
Textural class	Sandy loam	Sandy loam	Sandy loam	Sandy loam	–	n.a
Total N (%)	0.06 ± 0.0	0.03 ± 0.0	0.04 ± 0.0	0.03 ± 0.0	0.60	0.88
Total OC (%)	0.57 ± 0.1	0.27 ± 0.1	0.41 ± 0.1	0.22 ± 0.1	42.4	68.4
pH (CaCl$_2$)	5.9 ± 0.3	5.5 ± 0.4	5.1 ± 0.3	5.2 ± 0.3	9.1 ± 0.1	10.3 ± 0.0
CEC (mmolc kg^{-1})	56.7 ± 14.3	46.0 ± 14	36.1 ± 12.2	34.2 ± 4.4	81.2 ± 0.5	11.2 ± 0.2
Available P-Bray (mg kg^{-1})	135.8 ± 30.4	n.d	7.7 ± 2.6	nd	nd	n.d
P (mg kg^{-1})	534.6 ± 139.1	n.d	110.9 ± 34.0	nd	861.3 ± 25.3	1406.2 ± 18.6
K (mg kg^{-1})	29.6 ± 5.6	27.1 ± 8.6	38.9 ± 13.6	23.0 ± 3.9	977.1 ± 38.3	3296.1 ± 3.4
Ca (mg kg^{-1})	940.1 ± 246	765.5 ± 259.9	530.4 ± 186.1	523.9 ± 68.4	1571.6 ± 124.0	3512.6 ± 57.6
Mg (mg kg^{-1})	80.5 ± 26.2	44.3 ± 8.5	116.0 ± 38.3	83.3 ± 17.3	948.5 ± 23.5	1150.1 ± 16.3
Total hydrogen (%)	–	–	–	–	2.1	2.6
Total oxygen (%)	–	–	–	–	11.5	11.2
O/C (molar ratio)	–	–	–	–	0.27	0.16

[a] nd: not determined;
[b] *Häring* et al. (2017).

2.3 Field management practices

Agronomic practices particularly nursing of seedlings, planting distance, weeding, tillage, and soil loosening during cropping cycles were in accordance with farmers' practice, whereby a total of 13 crops was cultivated sequentially during the experimental period. Before the commencement of each cropping cycle, individual plots were tilled with hoes to a depth of 0.2 m (*Akoto-Danso* et al., 2018; Tabs. 2 and 3).

2.4 Quantification of nutrient inputs and outputs

2.4.1 Biochar

Biochar was produced from rice husks for the Tamale study site and from corn cobs for Ouagadougou. The feedstock was air-dried before submission to pyrolysis in a kiln at 500°C. Thereafter, corn cob biochar was milled to a particle size < 2 mm. At the onset of the experiment in both cities, 20 t ha^{-1} of biochar were incorporated in the soil at a depth of 0–0.2 m.

2.4.2 Irrigation water

Crops were irrigated with clean and wastewater. In Tamale, wastewater use refers to a mix of grey water and domestic sewage from a military barrack, diluted with rainwater in the rainy season, and in Ouagadougou to canal water which received a mix of urban runoff. Plots were irrigated with watering cans once or twice a day with a predefined water quantity, reflecting farmers' perception of the weather-related crop water demand. In the rainy season, the amount of rainfall was taken into account for irrigation. Irrigation water was sampled weekly for nutrient analysis, while rainwater samples were collected after rains and pooled at the end of the week for analysis. NO_3-N, NH_4-N, and PO_4-P were determined photometrically with an UV/VIS spectrophotometer (Pharo 300 Spectroquant, Merck KGaA, Darmstadt, Germany). Total amount of K was determined using an ICP-OES (Ciros CCD, SPECTRO Analytical Instruments GmbH, Kleve, Germany).

2.4.3 Fertilizer inputs

Crops were fertilized with mineral fertilizers (NPK 15-15-15 and urea 46-0-0) as practiced by farmers. In Ouagadougou,

Table 2: List of cultivated crops, irrigation quantities (mm), and nutrient inputs in (kg ha^{-1}) of a multi-factorial vegetable growth experiment in Ouagadougou (capital city of Burkina Faso).[a]

Cropping season	2014 rainy season (Season 1)		2014/15 dry season (Season 2)			2015 rainy season (Season 3)			2015/16 dry season (Season 4)		
Crop number	1	2	3	4	5	6	7	8	9	10	11
Crop	Lettuce	Cabbage	Amaranth	Lettuce	Amaranth	Jute mallow	Amaranth	Jute mallow	Roselle	Lettuce	Carrots
Planting date	May	Jul	Oct	Dec	Feb	May	Jul	Sept	Oct	Dec	Jan
Harvesting date	Jun	Oct	Nov	Jan	Mar	Jun	Aug	Oct	Nov	Jan	Apr
Crop duration (d)	35	92	29	43	32	28	36	27	31	43	81
Full irrigation	185.3	118.6	222.6	383.5	318.5	224.3	52.0	63.4	243.8	416.0	819.0
Reduced irrigation	143.8	118.6	165.8	279.5	214.5	211.3	35.8	42.3	162.5	279.5	546.0
Rainfall[b]	120.6	513.6	1.4	0.2	0.0	132.8	311.8	70.0	0.4	0.0	20.2
Nutrients inputs from mineral and organic fertilizer and irrigation water											
Mineral fertilizer-N	87.4	87.4	174.8	87.4	174.8	87.4	74.0	74.0	32.6	84.4	85.6
Organic fertilizer-N	199.8	171.2	136.4	281.2	283.4	112.5	149.3	128.6	0.0	108.8	279.2
Organic fertilizer-P	55.2	47.3	36.8	60.0	84.3	62.5	39.7	33.2	0.0	27.9	85.2
Organic fertilizer-K	85.5	73.3	32.3	168.5	119.8	192.5	78.6	54.8	0.0	67.6	109.7
ww-N	4.1	3.4	36.2	3.1	11.7	3.7	1.4	1.1	9.4	16.0	31.5
ww-P	2.7	1.7	3.2	2.0	1.5	1.8	0.3	0.5	1.5	2.6	5.2
ww-K	32.4	14.9	28.0	48.1	40.1	29.1	5.9	8.0	30.7	52.4	103.1
cw-N	3.5	2.3	51.7	1.9	1.5	0.9	0.2	0.3	0.1	0.1	0.2
cw-P	2.6	1.6	3.1	0.9	0.9	0.5	0.0	0.1	0.6	1.0	1.9
cw-K	12.2	3.9	7.4	7.9	10.6	9.2	2.4	2.1	8.1	13.8	27.2

[a] cw = clean water; N = nitrogen; P = phosphorus; and K = potassium; ww = wastewater.

[b] Rainfall quantities are the same for full and reduced irrigated plots.

Table 3: List of cultivated crops, and irrigation quantities (mm), and nutrient inputs in (kg ha^{-1}) of a multi-factorial vegetable growing experiment in Tamale (northern Ghana) between 2014 and 2016.[a]

Cropping season	**2014 wet season (Season 1)**			**2014/15 dry season (Season 2)**			**2015 wet seasons (Season 3)**				**2015/16 dry season (Season 4)**		
Crop number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Crop	Maize	Lettuce	Cabbage	Amaranth	Lettuce	Amaranth	Jute mallow	Jute mallow	Amaranth	Jute mallow	Roselle	Lettuce	Carrots
Planting date	May	Jun	Jul	Oct	Dec	Feb	Apr	Jun	Jul	Sep	Oct	Dec	Jan
Harvesting date	Jun	Jul	Oct	Nov	Jan	Mar	May	Jul	Aug	Oct	Nov	Jan	Apr
Crop duration (days)	31	28	72	30	48	30	31	30	34	35	36	35	91
Full irrigation	198.0	339.6	204.9	242.0	431.8	176.0	200.8	160.9	38.5	8.3	264.0	242.0	540.4
Reduced irrigation	126.5	228.3	145.8	170.5	298.4	118.3	148.5	115.5	27.5	8.3	180.1	166.4	391.8
Rainfall[b]	42.2	69.8	542.3	10.4	0.0	37.3	18.8	72.7	146.4	170.6	13.8	0.0	125.9
Nutrients inputs from mineral fertilizer and irrigation water													
Fertilizer-N	84.4	85.5	58.8	31.9	54.1	31.9	115.1	119.5	30.6	45.4	45.2	46.1	57.2
Fertilizer-P	36.1	36.5	25.1	13.6	23.1	13.6	0.0	0.0	11.6	17.2	17.1	17.5	21.7
Fertilizer-K	52.3	53.0	36.5	19.8	33.6	19.8	0.0	0.0	15.0	22.3	22.2	22.6	28.1
ww-N	30.8	52.9	19.3	32.7	172.0	55.0	86.9	91.2	15.0	2.3	55.0	95.6	258.8
ww-P	4.6	7.9	3.5	12.5	53.8	28.5	14.7	13.8	1.4	0.1	33.4	44.8	87.3
ww-K	7.2	12.7	5.9	7.3	20.1	9.1	8.0	7.8	4.0	1.2	37.3	36.0	80.4
cw-N	0.5	0.9	0.5	1.7	3.0	1.2	1.1	0.5	0.1	0.0	1.3	1.2	2.6
cw-P	0.0	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.5	0.1	0.3
cw-K	2.3	3.9	1.5	2.7	4.8	2.0	2.1	1.4	0.7	0.2	5.8	5.3	11.8

[a] cw = clean water; N = nitrogen; P = phosphorus; K = potassium; ww = wastewater.

[b] Rainfall quantities are the same for full and reduced irrigated plots.

organic fertilizer in the form of cow manure was also applied. All inputs were surface-broadcast. A representative sample of mineral fertilizer and manure was collected at each application event for analysis (Tabs. 2 and 3).

2.4.4 Leaching losses

Nutrient leaching was estimated with resin cartridges filled with an exchange resin-granite sand mixture at a gravimetric ratio of 1 : 1 : 2 for cation, anion exchange resin, and sand, respectively. Installation occurred according to the guidelines of TerrAquat Consultancy (Nürtingen, Germany) as used by *Predotova* et al. (2011). The cartridges were constructed using PVC pipes of 0.12 m height and a diameter of 0.10 m with a nylon net at the bottom to avoid losses of the resin-sand mixture. A trench (2 m × 0.7 m × 0.5 m) was dug on both sides of a plot to install resins cups at a distance of 0.5 m. Resin cartridges were installed at 0.5 m depth in the soil profile under the root zone one month before the onset of the rainy season. After removal of the cartridges from the soil, the resin–sand mixture was separated into five layers for the assessment of the nutrient concentration profile for each cartridge. All layers were weighed and air-dried at room temperature until analysis. A sub-sample of 30 ± 0.5 g was weighed from each layer into a bottle filled with 100 mL of a salty extracting solution and treated six times by shaking horizontally for 1 h. From each layer, a sub-sample was taken to determine dry weight (at 65°C to constant weight). The extract was filtered and poured into a flask and the remaining resin-sand mixture was washed with another 100 mL of the extracting solution.

Nutrient concentrations were determined using continuous-flow analysis (Alliance Instruments GmbH, Salzburg, Austria) for nitrate (NO_3-N), spectrophotometry (Hitachi U–2000, Hitachi Ltd., Tokyo, Japan) at 710 nm using the P-blue method for P, and flame photometry (BWB-XP Technologies Ltd., Braintree, UK) for K. Samples of the washed sand and pure anion and cation-exchange resins were extracted similarly as the samples from the field and used as blanks. The nutrient concentration of each cartridge was examined to determine if the nutrient concentration across layers declined to near zero (*Predotova* et al., 2011).

2.4.5 Gaseous emissions

Data for gaseous emission from the field were collected by *Manka'abusi* (2018) and employed to compute NH_3-N and N_2O-N losses. For this purpose, a closed-chamber system composed of a photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, Lumasense Technologies A/S, Ballerup, Denmark) was used to determine emissions of NH_3-N and N_2O-N. Emission measurements were conducted prior to input (manure and mineral fertilizers) application for four to eight consecutive days during the coolest and hottest part of the day in order to capture the expected minimum and maximum of daily flux rates. Detailed measurement procedure and full results are presented in *Manka'abusi* et al. (2018).

2.4.6 Crop nutrient uptake

The field trial covered two wet and two dry seasons with a total of thirteen crops cultivated in Tamale and eleven in Ouagadougou (Tabs. 2 and 3). All crops were grown and harvested according to nearby farmers practices, whereby in Tamale maize was harvested as fodder at the last vegetative stage. A 3.24 m^2 sample area was harvested to quantify crop biomass and a subsample was used to analyze crop nutrient uptake. Total N was determined with an elemental analyzer (Vario MAX CHN Elementar Analysensysteme GmbH, Hanau, Germany) and total P was measured with a spectrophotometer (Hitachi U-2000, Hitachi Ltd., Tokyo, Japan) at 460 nm using the P-yellow method after extraction with HCl and coloration with an ammonium molybdate/ammonium vanadate reagent. Potassium was measured with a flame photometer (BWB-XP, BWB Technologies Ltd., Braintree, UK). To calculate aboveground nutrient uptake, the dry matter (DM) yield of individual treatments were multiplied by the respective concentrations of total N, P, and K.

2.4.7 Other variables

Other recorded data were: planting date, irrigation date and duration, type of fertilizer applied, and date of fertilization (Tabs. 2 and 3). Air temperature, relative humidity, wind speed, amount of rainfall, and solar radiation were logged continuously at 30 min intervals using a WatchDog 2000 Series Weather Station (Spectrum Technologies Inc., Plainfield, IL, USA) and a HOBO external data logger (Onset Computer Corporation Corp., Bourne, MA, USA).

2.5 Calculation of nutrient balances and use efficiency

The rainy season comprised the period April–November with four to five cropping cycles, while the dry season covered December–March with two cropping cycles per year. Input components (I) were: biochar (I_B), irrigation water (I_{IW}), rainwater (I_{RW}), mineral fertilizer (I_{MF}), and organic fertilizer (I_{OF}). Output included crop harvest (O_H), leaching losses (O_L), and gaseous emissions (O_G). Atmospheric deposition of dust, even though measured, was not included because of its negligible quantity. The balance equation therefore reads as follows:

$$\Delta = (I_B + I_{IW} + I_{RW} + I_{MF} + I_{OF}) - (O_H + O_L + O_G). \qquad (1)$$

Nutrient-use efficiency (NUE) can be estimated using different agronomic factors: unit of crop yield per unit of applied nutrient, unit of crop yield increase per unit applied nutrient, unit of nutrient uptake per unit input, and unit of crop yield increase per unit of nutrient uptake (*Fixen* et al., 2015). In order to assess the efficiency of fertilized and unfertilized crop management systems and to gain an overview of the potential for nutrient loss in crop production, the apparent NUE, according to *Fixen* et al. (2015), was used as indicated by the partial factor productivity (PFP), agronomic efficiency (AE), and recovery efficiency (RE):

$$PFP = \frac{yield}{total\ nutrient\ applied}, \qquad (2)$$

$$AE = \frac{yield_{trt} - yield_{con}}{total\ nutrient\ applied}, \qquad (3)$$

$$RE = \frac{nutrient\ uptake_{trt} - nutrient\ uptake_{con}}{total\ nutrient\ applied} \times 100, \qquad (4)$$

where $yield_{trt}$ denotes the aboveground biomass yield (kg ha^{-1}) of treated crops, $yield_{con}$ is the aboveground biomass yield (kg ha^{-1}) of crops grown on unfertilized plots, $nutrient\ uptake_{trt}$ denotes total nutrient uptake (kg ha^{-1}) of fertilized harvested crop biomass, and $nutrient\ uptake_{con}$ is the nutrient uptake (kg ha^{-1}) of crops grown on unfertilized plots. All nutrient inputs and outputs were calculated as kg nutrient ha^{-1} $season^{-1}$ and the results of the nutrient balances expressed in the same units.

2.6 Statistical analysis

Microsoft Excel (2010) was used for data entry before data were exported to SAS (SAS Institute Inc., Carey, NC, USA) for analysis at each location separately as crops and inputs were different. Data were checked for normality (Shapiro–Wilks test) and visually assessed with qq-plots. Where necessary, data were $\log_{10}$-transformed prior to statistical analysis and submission to Tukey's post-hoc honest significant difference test at $P < 5\%$.

2.7 Study scope

This study assessed leaching losses on four of the 16 treatments. The four treatments, all under full irrigation included: (1) no fertilization + clean water irrigation (C+cw), (2) farmer's practice (fertilization) + clean water irrigation (FP+cw), (3) farmer's practice (fertilization) + wastewater irrigation (FP+ww), and (4) farmer's practice+biochar + wastewater irrigation (FP+BC+ww). In addition to these treatments, gaseous emission measurement covered: (1) no fertilization + wastewater irrigation (C+ww) and (2) farmer's practice + biochar + wastewater irrigation (FP+BC+cw). Based on the nutrient input, leaching losses were extrapolated for the two treatments for which leaching was not assessed, to estimate nutrient balances for all treatments.

3 Results

3.1 Nutrient inputs

In Tamale, mineral fertilizer and wastewater were the major sources of N, P, and K, while in Ouagadougou, organic and mineral fertilizers were the main sources. Nutrient inputs from inorganic fertilizer in Tamale during the two-year trial were 806 kg N ha^{-1}, 233 kg P ha^{-1}, and 325 kg K ha^{-1}, and similar inputs (955 kg N ha^{-1}, 306 kg P ha^{-1}, and 237 kg K ha^{-1}) were estimated for wastewater. 71% of the total nutrient input from mineral fertilizer were applied in the two rainy seasons. In contrast, 64% of the total nutrient input from wastewater were applied in the two dry seasons. The input from clean water was negligible (Tabs. 2 and 3). Rice husk biochar supplied 17 kg P ha^{-1} and 20 kg K ha^{-1} for the Tamale field, while 28 kg P ha^{-1} and 66 kg K ha^{-1} were added with corn cob biochar in Ouagadougou.

In Ouagadougou, the total N input from urea was 1053 kg ha^{-1} during the two years. Organic fertilizer, on the other hand, supplied 1850 kg N ha^{-1} out of which 49% were supplied in the rainy season. Phosphorus and K inputs from the organic fertilizer were 532 kg ha^{-1} and 983 kg ha^{-1}, respectively. Nutrients from wastewater were higher in the dry season (51%) compared to the rainy season. A total input at the end of two years was 122 kg N ha^{-1}, 23 kg P ha^{-1}, and 393 kg K ha^{-1}. Clean water supplied 63 kg N ha^{-1}, 13 kg P ha^{-1}, and 105 kg K ha^{-1} (Tab. 3).

3.2 Nutrient outputs

3.2.1 Leaching losses

Nutrient leaching was higher during the rainy than the dry season. Across both locations, wastewater irrigation on fertilized plots (FP) led to similar leaching losses of N, P, and K in the dry season farming. Similarly, biochar addition on fertilized plots (FP+BC+ww) resulted in negligible differences of N, P, and K leaching in the dry season in both cities (data not shown).

In Tamale, estimates of leached N were less than 2 kg ha^{-1} in the first rainy season (2014), while during the second rainy season N ranged from 2–15 kg ha^{-1}. No effect of biochar addition or wastewater irrigation on nutrient leaching was observed. Biochar-amended plots generally showed reduced P and K leaching during the rainy season. Wastewater irrigation on fertilized plots (FP+ww), compared to clean water irrigation (FP+cw) on the other hand, led to higher P and K leaching but these differences were insignificant (data not shown). An exception occurred for P leaching in the first rainy season (2014), when FP+ww was significantly higher.

In Ouagadougou, leached N ranged from 4–30 kg ha^{-1}. Biochar amended plots under wastewater irrigation and fertilized conditions (FP+BC+ww) reduced N leaching by 50% in the first and second rainy season. Wastewater irrigation tended to increase N leaching compared to clean water irrigation on both fertilized and unfertilized plots, but differences were not significant. Biochar amendment and wastewater irrigation did not have a significant effect on P and K leaching (data not shown).

3.2.3 Crop uptake

Crop uptake constituted on average 83% of the total nutrient exports. Nutrient uptake was generally higher in Ouagadougou than in Tamale, apart from wastewater-irrigated plots in the dry seasons (Tab. 4). In Tamale, cumulative nutrient uptake of N, P, and K was higher in wastewater-irrigated plots than in clean water plots irrespective of the season. At the same water quality, biochar amendment on fertilized plots (FP *versus* FP+BC) led to higher nutrient uptake only in the 2014 rainy season. In Ouagadougou, nutrient uptake was significantly higher on fertilized plots than on unfertilized plots, irrespective of the seasons. Wastewater barely had an effect on the seasonal cumulative nutrient uptake compared to clean water. In the first two seasons, wastewater in most cases reduced nutrient uptake. Biochar amendment, on the other hand, improved K uptake by crops in the first two seasons (Tab. 5).

3.2.4 Gaseous emissions

Gaseous NH_3-N and N_2O-N emissions were lower in Tamale than in Ouagadougou, and in both cities, emissions were higher in the rainy season (Tabs. 4 and 5; *Manka'abusi*, 2018). On average, gaseous N emission constituted 15% of the total N exports. Seasonal cumulative NH_3-N emissions in Tamale were 10–12 kg ha^{-1} and 6–12 kg ha^{-1} for the 2014 and 2015 rainy seasons, respectively. N_2O-N emissions for the same period were 19–23 kg ha^{-1} and 8–14 kg ha^{-1}. In Ouagadougou, cumulative NH_3-N emissions for the 2014 and 2015 rainy season were 9–24 kg ha^{-1} and 6–17 kg ha^{-1}, respectively. N_2O-N emissions were 15–88 kg ha^{-1} and 14–24 kg ha^{-1}.

3.3 Nutrient balances

All fertilized treatments showed positive N and P balances in both fields. Considering the high nutrient inputs in Ouagadougou compared to Tamale and the relatively lower output, nutrient surpluses were high in Ouagadougou. Nitrogen surpluses on fertilized plots ranged from 32–579 kg N ha^{-1} in Ouagadougou compared with 2–269 kg N ha^{-1} $season^{-1}$ in Tamale. Phosphorus surpluses were 37–136 kg ha^{-1} in Ouagadougou compared to 24–152 kg ha^{-1} $season^{-1}$ in Tamale. Nutrient export exceeded the inputs on unfertilized plots that were irrigated with clean water (C+cw) in both fields. In Ouagadougou, unfertilized plots irrigated with wastewater (C+ww) had negative balances (–190 to –49 kg N ha^{-1} and –27 to –-15 kg P ha^{-1}; Figs. 1 and 2). In Tamale, positive nutrient balances were observed for wastewater-irrigated plots compared to clean water-irrigated plots. In the first rainy season (2014), biochar-amended, fertilized plots had irrespective of water quality surpluses of up to +107 kg P ha^{-1}, 9% higher than fertilized plots without biochar (Fig. 1). In contrast to Tamale, N and P surpluses in Ouagadougou were similar for wastewater-irrigated plots compared with clean water plots in the first three cropping seasons (Fig. 2).

Table 4: Average cumulative seasonal crop yield, input and output in a multi-factorial cropping experiment conducted from May 2014 to April 2016 in Tamale (northern Ghana).[a]

Year	**Season**		**DM yield (kg ha^{-1})**	**Cumulative nutrient input and output**												
				Nitrogen (kg ha^{-1})					**Phosphorus (kg ha^{-1})**				**Potassium (kg ha^{-1})**			
				Input	Crop uptake	Leaching	Gaseous emissions[b]	**Balance**	Input	Crop uptake	Leaching	**Balance**	Input	Crop uptake	Leaching	**Balance**
2014	rainy	C+cw	2154	4	64	0	32	**–92**	0	7	0	**–7**	10	62	21	**–73**
		C+ww	4252	136	116	1	33	**–14**	28	14	0	**14**	33	115	29	**–111**
		FP+cw	5631	264	169	1	31	**63**	111	25	0	**87**	172	168	29	**–25**
		FP+ww	7430	396	233	0	29	**133**	140	31	0	**109**	195	211	25	**–42**
		FP+BC+cw	7743	264	231	1	31	**2**	128	32	0	**97**	192	246	29	**–83**
		FP+BC+ww	8493	396	265	0	35	**97**	157	39	0	**118**	215	264	26	**–76**
2014/15	dry	C+cw	411	4	8	0	7	**–11**	0	1	0	**–1**	7	14	0	**–7**
		C+ww	3259	227	106	0	8	**113**	82	12	0	**71**	29	135	1	**–107**
		FP+cw	2612	90	78	0	8	**4**	37	13	0	**24**	60	101	1	**–42**
		FP+ww	4369	313	177	0	9	**127**	119	26	0	**93**	83	184	1	**–103**
		FP+BC+cw	2647	90	77	0	7	**6**	37	13	0	**24**	60	101	1	**–42**
		FP+BC+ww	4268	313	175	0	8	**131**	119	27	0	**92**	83	177	3	**–97**
2015	rainy	C+cw	1603	3	32	3	16	**–48**	1	4	0	**–4**	10	26	3	**–19**
		C+ww	5032	250	150	11	16	**74**	63	20	1	**43**	58	113	9	**–64**
		FP+cw	6111	359	207	11	18	**123**	47	22	1	**24**	70	139	9	**–79**
		FP+ww	8870	606	369	15	24	**199**	109	37	1	**71**	118	209	12	**–104**
		FP+BC+cw	5939	359	214	11	22	**112**	47	22	1	**24**	70	127	9	**–67**
		FP+BC+ww	8957	606	365	9	23	**210**	109	38	0	**71**	118	207	7	**–96**
2015/16	dry	C+cw	1213	4	19	0	16	**–32**	0	3	0	**–2**	17	17	0	**0**
		C+ww	3920	342	122	0	20	**200**	132	13	0	**119**	116	71	1	**44**
		FP+cw	2218	107	56	0	20	**31**	40	7	0	**32**	68	36	1	**31**
		FP+ww	4561	445	157	0	22	**266**	171	20	0	**151**	167	98	1	**68**
		FP+BC+cw	2666	107	63	0	18	**27**	40	8	0	**31**	68	47	1	**20**
		FP+BC+ww	4389	445	151	0	25	**269**	171	19	0	**152**	167	105	3	**60**

[a] BC = biochar; C = control (no fertilizer, no biochar); cw = clean water; FP = farmer's practice; FP+BC = farmer's practice + biochar; and ww = wastewater. The rainy season covers April–November with four to five cropping cycles, while the dry season covers December–March with two cropping cycles per year.

[b] Preliminary data for gaseous emissions obtained from *Manka'abusi* (2018).

Table 5: Average cumulative seasonal crop yield, input and output in a multi-factorial cropping experiment conducted from May 2014 to April 2016 in Ouagadougou (capital city of Burkina Faso).[a]

				Cumulative nutrient input and output												
Year	**Season**		**DM yield (kg ha^{-1})**	**Nitrogen (kg ha^{-1})**					**Phosphorus (kg ha^{-1})**				**Potassium (kg ha^{-1})**			
				Input	Crop uptake	Leaching	Gaseous emissions[b]	Balance	Input	Crop uptake	Leaching	**Balance**	Input	Crop uptake	Leaching	**Balance**
2014	rainy	C+cw	3691	58	143	7	26	**–119**	7	32	0	**–25**	24	93	37	**–107**
		C+ww	4109	44	105	7	24	**–93**	8	24	0	**–17**	75	80	37	**–42**
		FP+cw	6210	914	254	18	85	**557**	147	44	1	**102**	215	174	33	**8**
		FP+ww	4922	901	203	28	91	**579**	147	34	0	**113**	266	139	36	**91**
		FP+BC+cw	6074	914	241	12	113	**549**	175	45	0	**129**	281	203	54	**23**
		FP+BC+ww	5652	901	229	12	113	**547**	175	39	0	**136**	332	181	54	**97**
2014/15	dry	C+cw	2477	3	69	0	6	**–71**	2	15	0	**–13**	19	56	22	**–59**
		C+ww	2595	15	62	0	7	**–55**	3	19	0	**–16**	88	95	22	**–29**
		FP+cw	8100	830	380	0	37	**413**	146	58	0	**88**	307	310	2	**–5**
		FP+ww	8746	842	359	1	38	**444**	148	58	0	**90**	377	296	5	**75**
		FP+BC+cw	8511	830	345	0	34	**451**	146	60	0	**86**	307	359	1	**–54**
		FP+BC+ww	8480	842	374	0	42	**426**	148	57	0	**91**	377	402	1	**–27**
2015	rainy	C+cw	5622	1	125	4	20	**–148**	1	20	1	**–20**	22	84	8	**–70**
		C+ww	3923	16	175	4	26	**–190**	4	30	1	**–27**	74	156	9	**–91**
		FP+cw	12516	660	535	14	34	**77**	137	98	2	**37**	348	557	9	**–218**
		FP+ww	12925	674	574	30	37	**32**	140	96	1	**43**	400	565	9	**–175**
		FP+BC+cw	12823	660	549	15	38	**58**	137	95	1	**41**	348	617	8	**–277**
		FP+BC+ww	12952	674	574	15	39	**46**	140	100	1	**38**	400	636	8	**–245**
2015/16	dry	C+cw	4426	0	47	0	14	**–61**	3	18	0	**–15**	41	50	22	**–31**
		C+ww	2852	48	81	0	15	**–49**	8	22	0	**–15**	155	113	22	**21**
		FP+cw	11346	561	307	0	33	**221**	116	64	0	**52**	218	235	2	**–18**
		FP+ww	10391	609	282	1	33	**292**	121	55	0	**66**	333	277	5	**51**
		FP+BC+cw	11973	561	334	0	29	**198**	116	67	0	**49**	218	260	1	**–43**
		FP+BC+ww	11126	609	270	0	28	**310**	121	53	0	**67**	333	288	1	**44**

[a] BC = biochar; C = control (no fertilizer, no biochar); cw = clean water; FP = farmer's practice; FP+BC = farmer's practice + biochar; and ww = wastewater. The rainy season covers April–November with four to five cropping cycles, while the dry season covers December–March with two cropping cycles per year.

[b] Data for gaseous emissions obtained from *Manka'abusi* (2018).

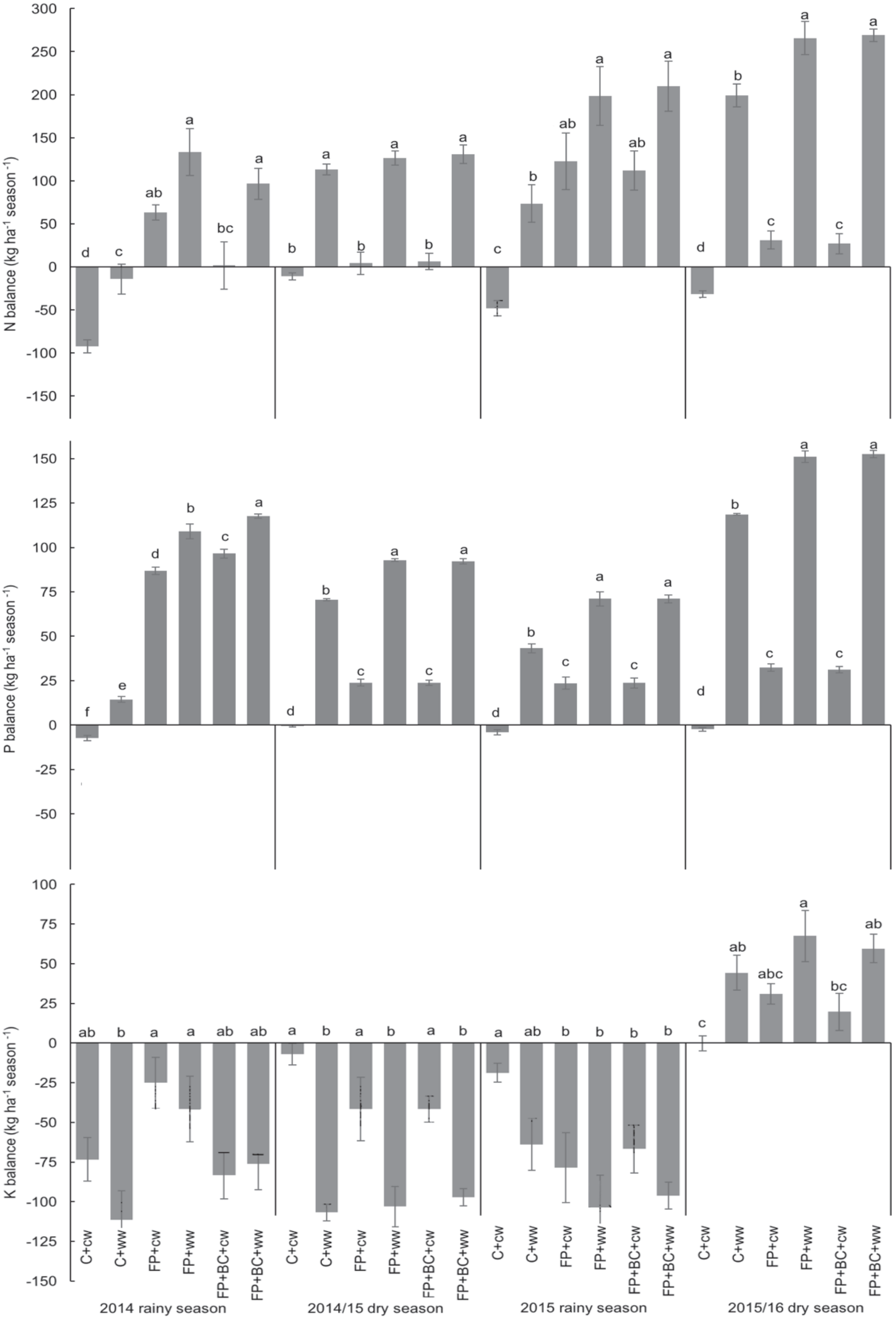

Figure 1: Cumulative seasonal NPK balances (input – output) ± one standard error of the mean in a multi-factorial cropping experiment conducted from May 2014 to April 2016 in Tamale (northern Ghana). Balances with same letters within a season are not different according to Tukey's test at $P < 5\%$. BC = biochar; C = control (no fertilization); cw = clean water; FP = farmer's practice (of fertilization); FP+BC = farmer's practice + biochar; ww = wastewater. The rainy season covers April–November with four to five cropping cycles, while the dry season covers December–March with two cropping cycles per year.

Biochar amendment increased P surpluses in the first rainy season in both cities ($P > 5\%$). For K, the first three seasons in Tamale recorded mainly negative balances in all treatments ranging from –111 kg ha^{-1} to –7 kg ha^{-1}. On the other hand, in the last dry season, all treatments with the exception of C+cw (–0.3 kg K ha^{-1}) had positive nutrient balances. The respec-

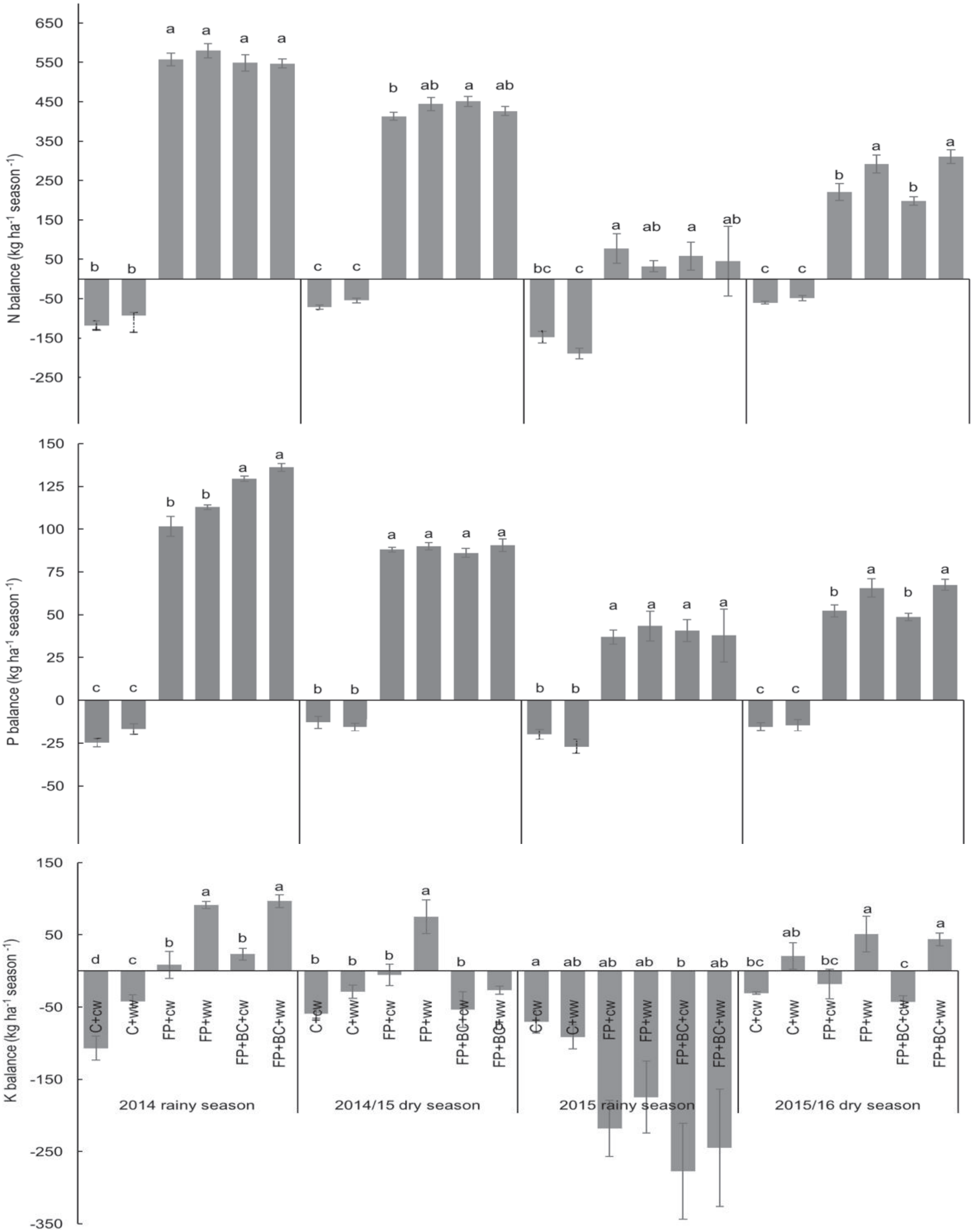

Figure 2: Cumulative seasonal NPK balance (input – output) ± one standard error in a multi-factorial cropping experiment conducted from May 2014 to April 2016 in Ouagadougou (central Burkina Faso). Balances with same letters within a season are not significantly different according to Tukey's test at P < 5%. BC = biochar; C = control (no fertilization); cw = clean water; FP = farmer's practice (of fertilization); FP+BC = farmer's practice + biochar; ww = wastewater. The rainy season covers April–November with four to five cropping cycles, while the dry season covers December–March with two cropping cycles per year.

tive balances were +44, +31, +68, +20, and +60 kg K ha^{-1} for C+ww, FP+cw, FP+ww, FP+BC+cw, and FP+BC+ww, respectively. The influence of wastewater on fertilized plots was only effective in the dry seasons when significant differences were observed (Fig. 1). In Ouagadougou, largest K deficits (kg K ha^{-1}) were observed in the 2015 rainy season with fertilized plots having a balance of over –175 kg ha^{-1} compared to up to –91 kg ha^{-1} on unfertilized plots (Tab. 5).

Mean annual balance estimations indicate that, for Tamale, N surplus was highest in FP+ww (+362 kg ha^{-1}) followed by FP+BC+ww > C+ww > FP+cw > FP+BC+cw > C+cw. Potassium balance followed a similar order: FP+BC+ww > FP+ww > C+ww > FP+BC+cw > FP+cw > C+cw with surpluses of +217, +212, +123, +88, +83, and a deficit –7 kg ha^{-1}, respectively. Finally, K showed deficits in the order C+ww > FP+BC+ww > FP+ww > FP+BC+cw > FP+cw > C+cw with –119, –105, –90, –86, –57, and –50 kg ha^{-1}. In Ouagadougou, mean annual N and P balances followed a similar order with the fertilized and wastewater-irrigated plots recording highest values. Potassium balance on the other hand followed the order FP+ww > FP+BC+ww > C+ww > FP+cw > C+cw and FP+BC+cw with +21, –66, –71, –117, –134, and –175 kg P ha^{-1}, respectively.

3.4 Nutrient use efficiencies

Nutrient-use efficiencies of N, P, and K in the two fields increased over the study period. The last season (2015/16 dry season), however, showed a decline in efficiency especially in Tamale. The partial factor productivity (PFP), agronomic efficiency (AE), and recovery efficiency (RE) generally followed a similar pattern.

3.4.1 Nitrogen

At the end of the first season (rainy season 2014) in Tamale, N-use efficiency (PFP) was highest (31 kg kg^{-1}) in unfertilized plots with wastewater irrigation (C+ww). There were no differences between the treatments in AE and RE. For the second season, FP+BC and FP+cw had the highest PFP and AE with efficiencies of 25–29 kg kg^{-1} and over 70% RE. At the end of the last season, N recovery for all management practices was low compared with that of the previous seasons (Tab. 6). Efficiencies were generally lower in Ouagadougou, where PFP, AE, and RE were inconsistent across treatments. Only AE of unfertilized plots with wastewater irrigation (C+ww) was 3–10 times higher (10 kg kg^{-1}) than of plots with the other treatments. Similarly, the PFP of unfertilized plots with wastewater irrigation (C+ww) was significantly higher than of all other treatments across all seasons (Tab. 7).

3.4.2 Phosphorus

In Tamale, agronomic efficiency (AE) of P followed a similar trend as PFP and RE. Efficiencies were highest in clean water-irrigated plots, compared to wastewater under FP and FP+BC during the last three seasons. Agronomic efficiency, RE, and PFP doubled when clean water (instead of wastewater) was used under FP and FP+BC in the 2014/15 dry season. This effect continued throughout the last two seasons for PFP efficiency (Tab. 6). A significant difference was observed in the four seasons when unfertilized plots with wastewater irrigation (C+ww) had a significantly higher PFP than other treatments (Tab. 7). Unfertilized plots with wastewater irrigation also had a higher AE and RE during the first rainy season (2014) and second rainy season (2015), respectively.

3.4.3 Potassium

Compared to all other soil management practices, wastewater irrigation of unfertilized plots (C+ww), proved to be most efficient for K (PFPK, AEK and REP) in the first rainy and dry seasons of Tamale. Efficiency peaked at the end of the first dry season (2014) with a recovery (RE) of over 400%. In unfertilized wastewater-irrigated plots (C+ww), PFPK and AEK were up to 129 kg kg^{-1} and 63 kg kg^{-1}, respectively. During the last two seasons, efficiencies were similar across all management practices (Tab. 6). Potassium-use efficiency in Ouagadougou improved with time whereby the highest efficiencies were recorded in the third season (2015 rainy season). Across seasons, wastewater irrigation on both FP and FP+BC plots led to a reduction in K use (PFPK, AEK, and REP) which was significant during the two dry seasons.

4 Discussion

4.1 Nutrient inputs

Nutrient inputs differed between the two cities. Wastewater contributed about half of the nutrient inputs (54% of N, 57% of P, and 41% K) in Tamale. The contribution of wastewater to total nutrient inputs in Ouagadougou was < 5% for N and P. However, wastewater irrigation provided 27% of total K inputs. Urea supplied 34% of N, while cow manure was the major source of P (94%). The inputs recorded were similar to those of earlier studies in vegetable gardens elsewhere (*Buerkert* et al., 2005; *Khai* et al., 2007; *Diogo* et al., 2010). From high-input vegetable gardens using municipal sewage water for irrigation in Niamey, Niger for instance, *Diogo* et al. (2010) reported annual nutrient inputs of 1,109–3,816 kg N ha^{-1}, 143–644 kg P ha^{-1}, and 640–2019 kg K ha^{-1}. In the Tamale field, annual inputs were 710–1066 kg N ha^{-1}, 260–280 kg P ha^{-1}, and 287–295 kg K ha^{-1}, while the comparative values in Ouagadougou were 1,281–1,803 kg N ha^{-1}, 265–304 kg P ha^{-1}, and 931–1,465 kg K ha^{-1}. In Tamale, where there is no perennial stream of water, most farmers rely on wastewater from open drains or municipal sewage-water deposits to access reliable water supply during the long dry season (*Drechsel* and *Keraita*, 2014). Some farmers also reported that the combined use of wastewater and inorganic fertilizers enhanced the visual appearance of their vegetables (*Drechsel* and *Keraita*, 2014; *Nyantakyi-Frimpong* et al., 2016).

In Ouagadougou, the contribution of wastewater to total nutrient inputs was minimal. One major difference between the two sites was the combined use of organic and mineral fertilizer in Ouagadougou. Farmers rely largely on the use of manure because of its easy availability (*Roessler* et al., 2016). *Kiba* et al. (2012) estimated that farmers applied on average 35 t ha^{-1} of manure in Wayalguin, Burkina Faso, more than twice of what was applied in the current study.

Table 6: Means ± standard errors ($n = 4$) of NPK use efficiencies for different soil management practices in a multi-factorial cropping experiment conducted from May 2014 to April 2016 in Tamale (northern Ghana).[a]

	Nitrogen (N)				Phosphorus (P)				Potassium (K)			
	2014 rainy	2014 /15 dry	2015 rainy	2015/16 dry	2014 rainy	2014/15 dry	2015 rainy	2015/16 dry	2014 rainy	2014 /15 dry	2015 rainy	2015/16 dry
	Partial Factor Productivity (kg kg^{-1})											
C+ww	31 ± 4a	14 ± 1b	20 ± 2a	11 ± 1a	150 ± 20a	40 ± 2b	79 ± 9b	30 ± 2ab	129 ± 17a	112 ± 7a	87 ± 10a	34 ± 2a
FP+cw	21 ± 2ab	29 ± 2a	17 ± 2ab	21 ± 5a	51 ± 5b	71 ± 6a	131 ± 14a	56 ± 14ab	33 ± 3b	43 ± 4b	88 ± 10a	33 ± 8a
FP+ww	19 ± 1b	14 ± 1b	15 ± 1b	10 ± 1a	53 ± 4b	37 ± 2b	81 ± 7b	27 ± 4ab	38 ± 3b	53 ± 3b	75 ± 6a	27 ± 4a
FP+BC+cw	29 ± 3ab	29 ± 2a	17 ± 1ab	25 ± 5a	60 ± 5b	71 ± 6a	128 ± 10a	67 ± 13a	40 ± 4b	44 ± 4b	85 ± 7a	39 ± 8a
FP+BC+ww	21 ± 1ab	14 ± 1b	15 ± 1b	10 ± 1a	54 ± 3b	36 ± 2b	82 ± 5b	26 ± 1b	40 ± 2b	52 ± 3b	76 ± 5a	26 ± 1a
	Agronomic Efficiency (kg kg^{-1})											
C+ww	15 ± 4a	13 ± 2b	14 ± 2a	8 ± 1a	74 ± 19a	35 ± 5b	54 ± 7a	20 ± 2*a*	63 ± 16a	98 ± 13a	59 ± 7a	23 ± 2a
FP+cw	13 ± 2a	24 ± 1a	13 ± 1a	9 ± 6a	31 ± 4b	59 ± 3a	97 ± 10a	25 ± 17*a*	20 ± 3b	37 ± 2b	65 ± 7a	15 ± 10a
FP+ww	13 ± 1a	13 ± 0b	12 ± 1a	8 ± 1a	38 ± 3ab	33 ± 1b	66 ± 6a	20 ± 3*a*	27 ± 2b	48 ± 1b	62 ± 5a	20 ± 3a
FP+BC+cw	21 ± 4a	25 ± 4a	12 ± 2a	14 ± 6a	44 ± 8ab	60 ± 11a	93 ± 15a	37 ± 15*a*	29 ± 5ab	37 ± 7b	62 ± 10a	21 ± 9a
FP+BC+ww	16 ± 1a	12 ± 1b	12 ± 0a	7 ± 1a	40 ± 3ab	32 ± 2b	67 ± 2a	19 ± 2*a*	30 ± 2ab	47 ± 2b	62 ± 2a	19 ± 2a
	Recovery Efficiency (%)											
C+ww	39 ± 12a	43 ± 4a	47 ± 6a	30 ± 3a	23 ± 8a	13 ± 1b	24 ± 3a	8 ± 1*a*	161 ± 66a	415 ± 21a	150 ± 23a	46 ± 6a
FP+cw	40 ± 3a	78 ± 10a	49 ± 7a	34 ± 11a	15 ± 1a	32 ± 4a	39 ± 5a	11 ± 6*a*	61 ± 10a	144 ± 21b	163 ± 25a	27 ± 11a
FP+ww	43 ± 5a	54 ± 1a	56 ± 5a	31 ± 4a	17 ± 3a	21 ± 1ab	30 ± 3a	10 ± 2*a*	77 ± 11a	207 ± 8b	156 ± 16a	48 ± 9a
FP+BC+cw	63 ± 11a	76 ± 15a	51 ± 7a	41 ± 12a	19 ± 2a	33 ± 5a	39 ± 7a	14 ± 6*a*	96 ± 14a	144 ± 26b	146 ± 22a	44 ± 20a
FP+BC+ww	51 ± 5a	53 ± 3a	55 ± 4a	30 ± 3a	20 ± 1a	22 ± 1ab	31 ± 1a	9 ± 2*a*	94 ± 8a	198 ± 6b	154 ± 6a	52 ± 7a

[a] Values followed by the same letter in a column are not significantly different using a Tukey multiple comparison test at $P < 5\%$. Letters in italics indicate data that were log-transformed before analysis. BC = biochar; C = control (no fertilizer, no biochar); cw = clean water; FP = fertilization according to farmers' practice; FP+BC = farmer's practice + biochar; and ww = wastewater. The rainy season covers April–November with four to five cropping cycles, while the dry season covers December–March with two cropping cycles per year.

Table 7: Means ± standard errors (n = 4) of NPK use efficiencies for different soil management practices in a multi-factorial cropping experiment conducted from May 2014 to April 2016 in Ouagadougou (capital city of Burkina Faso).[a]

	Nitrogen (N)				**Phosphorus (P)**				**Potassium (K)**			
	2014 rainy	**2014 /15 dry**	**2015 rainy**	**2015/16 dry**	**2014 rainy**	**2014 /15 dry**	**2015 rainy**	**2015/16 dry**	**2014 rainy**	**2014 /15 dry**	**2015 rainy**	**2015/16 dry**
	Partial Factor Productivity (kg kg^{-1})											
C+ww	94 ± 6a	175 ± 10*a*	252 ± 26a	60 ± 4a	541 ± 32a	750 ± 42*a*	934 ± 95a	367 ± 25a	55 ± 3a	29 ± 2a	53 ± 5a	18 ± 1c
FP+cw	7 ± 1b	10 ± 0*b*	19 ± 1b	20 ± 1b	42 ± 4b	55 ± 1*b*	92 ± 6b	98 ± 7b	29 ± 3b	26 ± 1ab	36 ± 2ab	52 ± 4a
FP+ww	5 ± 0b	10 ± 0*b*	19 ± 1b	17 ± 1b	34 ± 1b	59 ± 1*b*	93 ± 5b	86 ± 7b	18 ± 1c	23 ± 1b	32 ± 2b	31 ± 2b
FP+BC+cw	7 ± 0b	10 ± 0*b*	19 ± 2b	21 ± 1b	35 ± 1b	58 ± 1*b*	94 ± 8b	103 ± 3b	22 ± 1bc	28 ± 1ab	37 ± 3ab	55 ± 2a
FP+BC+ww	6 ± 0b	10 ± 0*b*	19 ± 3b	18 ± 2b	32 ± 1b	57 ± 2*b*	93 ± 14b	92 ± 11b	17 ± 1c	23 ± 1c	32 ± 5b	33 ± 4b
	Agronomic Efficiency (kg kg^{-1})											
C+ww	10 ± 9*a*	8 ± 19a	–109 ± 65a	–33 ± 11*a*	55 ± 51a	34 ± 81a	–405 ± 242a	–202 ± 68*a*	6 ± 5a	1 ± 1b	–23 ± 14b	–10 ± 3c
FP+cw	3 ± 1*b*	7 ± 0a	10 ± 3a	12 ± 1*a*	17 ± 4b	38 ± 2a	50 ± 13a	60 ± 6*a*	12 ± 2a	18 ± 1a	20 ± 5a	32 ± 3ab
FP+ww	1 ± 0*b*	7 ± 0a	11 ± 1a	10 ± 1*a*	8 ± 1b	42 ± 2a	52 ± 6a	49 ± 5*a*	5 ± 0a	17 ± 0a	18 ± 2a	18 ± 2b
FP+BC+cw	3 ± 0*b*	7 ± 0a	11 ± 3a	13 ± 1*a*	14 ± 2b	41 ± 2a	53 ± 14a	65 ± 5*a*	8 ± 1a	20 ± 1a	21 ± 6a	35 ± 2a
FP+BC+ww	2 ± 0*b*	7 ± 0a	11 ± 2a	11 ± 2*a*	11 ± 1b	41 ± 2a	53 ± 10a	55 ± 8*a*	6 ± 0a	16 ± 1a	18 ± 3a	20 ± 3b
	Recovery Efficiency (%)											
C+ww	–89 ± 46*a*	–43 ± 75*a*	320 ± 184*a*	72 ± 17a	–103 ± 60a	129 ± 150*a*	243 ± 162*a*	52 ± 59a	–19 ± 27b	45 ± 14c	99 ± 44a	41 ± 11b
FP+cw	12 ± 2*a*	37 ± 1*a*	62 ± 8*a*	46 ± 4ab	8 ± 3a	30 ± 3*a*	57 ± 5*b*	39 ± 5a	37 ± 6ab	83 ± 4ab	136 ± 13a	85 ± 7a
FP+ww	7 ± 2*a*	34 ± 2*a*	67 ± 5*a*	39 ± 4ab	1 ± 2a	29 ± 3*a*	54 ± 8*b*	31 ± 5a	17 ± 5ab	64 ± 7bc	121 ± 16a	68 ± 6a
FP+BC+cw	11 ± 4*a*	33 ± 2*a*	64 ± 6*a*	51 ± 2ab	7 ± 2a	31 ± 3*a*	55 ± 6*b*	42 ± 3a	38 ± 5a	99 ± 10a	153 ± 22a	96 ± 3a
FP+BC+ww	9 ± 1*a*	36 ± 2*a*	67 ± 14*a*	37 ± 3b	4 ± 2a	29 ± 4*a*	58 ± 11*b*	29 ± 2a	26 ± 4ab	92 ± 1ab	138 ± 21a	72 ± 2a

[a] Values followed by the same letter in a column are not significantly different using a Tukey multiple comparison test at $P < 5\%$. Letters in italics indicate data that were log-transformed before analysis. BC = biochar; C = control (no fertilizer, no biochar); cw = clean water; FP = fertilization according to farmers' practice; FP+BC = farmer's practice + biochar; and ww = wastewater. The rainy season covers April–November with four to five cropping cycles, while the dry season covers December–March with two cropping cycles per year.

4.2 Nutrient outputs

In recent years, several authors have used resin exchange cartridges to measure cumulative leaching in the subtropics (*Predotova* et al., 2011; *Safi* et al., 2011; *Abdalla* et al., 2012; *Goenster* et al., 2014). While this approach entails several constraints, just like any other method of assessing leaching losses, many studies have confirmed the usefulness and reliability of the method (*Lehmann* et al., 2001). Other studies confirm low leaching rates during the dry season (*Predotova* et al., 2011). It was therefore not surprising that the leaching losses from our two fields in the dry seasons were negligible, compared with those of the wet seasons.

Negligible N and P leaching was also recorded in urban intensified and traditional home-gardens in Khartoum, Sudan (*Abdalla* et al., 2012; *Goenster* et al., 2014). On the other hand, a high proportion of K leaching (over 30 kg ha^{-1}) was reported by *Goenster* et al. (2014), which is similar to what was estimated in this study. On a similar sandy loam soil, but with high nutrient and irrigation water inputs, *Safi* et al. (2011) reported from Kabul (Afghanistan) leaching losses of over 100 kg ha^{-1} N and 6.5 P kg ha^{-1}, which caused serious efficiency and environmental concerns.

The high K leaching in the 2014 rainy season observed in this study is similar to values of the study made by *Goenster* et al. (2014) on black cotton soils of Central Sudan. The fact that K leaching was similarly high across treatments could be a result of the exchangeable K in the soil pool, and the soil's low clay content (< 7%) corroborating observations of (*Goenster* et al., 2014). Given the N and P surpluses from the nutrient balances (Fig. 1), the N and P values measured with the resin cartridges are likely underestimated. Ion exchange resins are unable to capture dissolved organic compounds of N (*van Kessel* et al., 2009) and P (*Langlois* et al., 2003). Comparative results from the same field using wick-lysimeters yielded much higher values (Werner et al., 2018, under review).

Nutrient uptake in Tamale from wastewater irrigation was pronounced during the two dry seasons on unfertilized, fertilized, and fertilized+biochar plots. During the dry seasons, more nutrients were supplied through the frequent application of nutrient-rich wastewater (*Akoto-Danso* et al., 2018). In contrast, the use of wastewater did not affect the removal of nutrients by crops in Ouagadougou. In most cases, crop nutrient uptake was higher in clean water-irrigated plots (*Manka'abusi*, 2018). Biochar amendment mainly influenced K uptake in both fields, specifically, at the end of the first season in Tamale and end of the first and second season in Ouagadougou. In Tamale, biochar amendment could have led to sustained soil P availability for crop uptake (*Akoto-Danso* et al., 2018).

4.3 Field balance and nutrient use efficiency

Nutrient surpluses due to intensive agricultural production have been documented in several field studies. An annual positive nutrient balance of up to 882 kg N ha^{-1}, 196 kg P ha^{-1}, and 306 kg K ha^{-1} was reported by *Khai* et al. (2007) from a peri-urban farm in Hanoi, Vietnam. Similarly, an annual positive nutrient balance up to 843 kg N ha^{-1}, 70 kg P ha^{-1}, and 200 kg K ha^{-1} was estimated from an urban vegetable farm in Niamey, Niger (*Diogo* et al., 2010). The magnitude of balances recorded in this study were similar to those in the aforementioned studies. The accumulation of nutrients in Tamale was lower with up to an annual balance of +361 kg N ha^{-1}, +217 kg P ha^{-1}, and –125 kg K ha^{-1}, while Ouagadougou had annual surpluses of up to +692 kg N ha^{-1}, +166 kg P ha^{-1}, and +21 kg K ha^{-1}.

The large N and P surpluses in the two study fields raise environmental concerns. In many countries, agricultural pollution contributes to deteriorating the quality of aquatic systems by eutrophication (*Predotova* et al., 2011; *Wang* et al., 2014). In Tamale, nutrient surpluses in wastewater-irrigated plots compared with clean water irrigated plots during the dry seasons were large, reflecting the effects of excess nutrient supply from wastewater application. The large P surpluses observed in the first rainy season from the two fields could be attributed to the addition of P from biochar. Nitrogen and phosphorus-use efficiencies were generally lower in Ouagadougou than in Tamale.

The K deficit recorded in the first three seasons, particularly in Tamale, was similar to findings of *Siegfried* et al. (2011) on sandy soils of northern Oman, where they measured K losses in two continuing cropping cycles. The additional uptake of K likely came from plant-available K reserves in the soil as found in other studies (*Khan* et al., 2014). Our results from Ouagadougou also corroborate the assertion that K in manure is quite soluble and available for plant uptake or subject to leaching (*Mikkelsen*, 2007).

5 Conclusions

Mineral fertilizer in addition to wastewater were the major nutrient sources for UPA in Tamale, while in Ouagadougou farmers depended on organic and mineral fertilizers as farm nutrient sources. Leaching and gaseous emissions contributed less than 30% to the total nutrient offtake in the field experiment. Generally, nutrient balances were more positive in fertilized and wastewater-irrigated plots. Nutrient use efficiencies of N, P, and K over the study period in the two fields generally increased until the 2015 rainy season. The high N and P surpluses and K deficits call for effective improvement strategies to prevent eutrophication of water sources and enhance fertilizer-use efficiency.

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