Title

Determinants of sustainability in urban and peri-urban agriculture

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Introduction

Urban and peri-urban agriculture (UPA), which often illegally uses open space in and around cities in developing countries, has been reported to significantly contribute to fulfilling urban demands for fresh vegetables (10-90%), meat (up to 70%), eggs (up to 100%) and to providing income for un(der)employed people (Maxwell, 1995; Madaleno, 2000; Cofie et al., 2003). This is particularly true for West Africa whose urban population grew from 4% in 1930 to 40% in 1990 and is projected to reach 63% by 2020 (Drechsel et al., 2005). As the structure and intensity of UPA widely varies according to market conditions, climate, consumer demand, availability of space and tenure status, the percentage of urban dwellers involved in UPA was found to range from 10-57% (Ellis and Sumberg, 1998; Howorth et al., 2001; Asomani-Boateng, 2002; Cofie et al., 2003). While, quantitative data on the determinants of bio-physical sustainability of these mostly very intensively managed systems are lacking, claims about an indiscriminate use of inputs in the immediate proximity of human settlements, leading to risks for human health and the environment (N-leaching and emanation, heavy metal accumulation, produce contamination with faecal pathogens) are on the rise (Ezedinma and Chukuezi, 1999; Howorth et al., 2001; Asomani-Boateng, 2002; Matagi, 2002; Binns et al., 2003; Bryld, 2003; Cofie et al., 2003; Drechsel et al., 2005). However, solid spatially explicit and management dependent data are lacking to make informed decisions on how to effectively improve the input use efficiency and output (produce) quality of the typically intensive UPA systems (Drechsel et al., 2005; Hedlund et al., 2003) and about how to decrease their negative externalities. To contribute to filling this gap of knowledge quantitative on-farm studies are needed. This study reports on such work being conducted through a multi-national research network since 2006 in seven major cities of sub-Saharan Africa (Nigeria, Niger, Burkina Faso, Mali and Niger) measuring horizontal (inputs and outputs) and vertical (leaching and gaseous emissions of C and N) matter fluxes in UPA vegetable gardens of different intensities, in cereal fields and during the storage of manure, a major input into most UPA systems. As it is also debated how species-diverse the often very small UPA gardens are and how they may contribute to the *in situ* conservation of germplasm (Niñez, 1985, Linares, 2004; Wiersum 2006), the number of species cultivated in vegetable gardens and surrounding fences was also investigated. These data were related to potentially relevant socio-economic characteristica such as garden size, degree of market orientation and ethnic affiliation of garden owners/managers.

Materials and Methods

1. Horizontal and vertical matter fluxes

Horizontal fluxes. The most complete data set on matter fluxes has so far been collected in Niamey, Niger (13.5°N, 2.2°E; 220 m asl), characterised by a hot semi-arid climate with a unimodally distributed 30-year average annual rainfall of 542 mm. Daily average temperatures peak in May, at 34 ºC and drop to 25 ºC in December (World Climate, 2008). Most of the UPA activities, especially gardening, are located along a major wadi draining wastewater and on the eastern side of the Niger River. Niamey's UPA is characterized by intensive vegetable and some cereal farming associated with intensive sheep and goat husbandry in the city centre and extensive cattle keeping at the outskirts of the city (Graefe et al., 2008; Diogo et al., 2010). At the city's outskirts (peri-urban area) millet (*Pennisetum glaucum* L.) and sorghum (*Sorghum bicolor* L.) intercropped mainly with cowpea (*Vigna unguiculata* L.) and occasionally groundnut (*Arachis hypogea* L.) are cultivated. For our study 10 gardens and 9 fields representing the diversity of UPA crop production systems were selected whereby three and five monitoring plots were installed in each garden and field, respectively. Partial (horizontal) matter fluxes were quantified from 1/2006-1/2008 by subtracting harvested produce (outputs) from inputs such as fertilizers (animal manure, mineral fertilizers, ash, compost), irrigation water, wet and dry deposition and estimates of legume derived N_2-fixation. Fluxes of C, N, P and K were estimated by multiplying the mass of material by their concentrations of these elements and subsequent extrapolation of the results to a per hectare basis.

Vertical fluxes. From the above mentioned 10 gardens a sub-set of three was chosen for measurements of gaseous C and N emissions from April 2006 till November 2007 using a closed chamber system described earlier (Buerkert et al., 2005; Predotova et al, 2010a). Two of these gardens belonging to the low input group (R_1 and R_2) were located on the bank of the Niger River providing water to irrigate the crops and the third was a high input garden along the wastewater filled *wadi* (W). In the three gardens leaching losses were assessed through cartridges filled with anion/cation exchange resins (Bischoff et al, 1999, Siemens and Kaupenjohann, 2004).

Manure storage losses

The experiment to determine C and N leaching and volatilization losses consisted of two periods of 3.5-month duration each, beginning in April and in mid-July 2007, respectively (Predotova et al., 2010b). In both periods, 12 dung heaps of 70 kg fresh mass (30 kg DM), consisting of a 1.8 : 1 w:w mixture of fresh dung from cattle and small ruminants, were subjected to the following treatments repeated four times: (i) heaps without roofing (that is farmer's control with full exposure to sun and rain); (ii) heaps shaded and protected from rain by a roof made from a double plastic sheet and mounted on four 0.7m high posts; and (iii) manure homogeneously mixed with finely ground Tahoua RP (10.3% P at 19.3% solubility in citric acid and 34% solubility in formic acid; McClellan and Notholt 1986) at a rate of 333 g rock powder kg^{-1} manure DM and roofed as in (ii). All heaps had a base area of 1 m^2 and were about 0.5 m high. Each heap was placed on an individual 1 m^2 iron sheet which had a slope of about 2% to facilitate after-rain run-off in the rainy season. Gaseous C and N emissions from the manure heaps and dung decomposition were determined seven times during each 3.5 months period with our closed chamber analysis system, while the run-off was assessed whenever it occurred after a rainfall event.

2. Contamination of produce with faecal pathogens and heavy metals

To assess pathogen contamination of produced vegetables, samples of irrigation water and of the main leafy vegetables lettuce (*Lactuca sativa* L.), cabbage (*Brassica* spp) and amaranth (*Amaranthus cruentus* L.) were regularly collected and analysed for total mesophilic aerobic micro-organisms (*Staphylococcus* sp.) and for faecal pathogens of human or animal origin (*Salmonella* spp., *Escherichia coli*, *Streptococcus* and total coliforms following standard procedures. In Kano, Nigeria (12°N, 8.5° E; 477 m asl) and Niamey, Niger vegetable irrigation water was also analysed for the total concentrations of the heavy metals copper (Cu), cadmium (Cd), lead (Pb), zinc (Zn) and Nickel (Ni) using ICP-AES.

3. Determinants of plant species diversity

In Niamey, from January-August 2007 a total 29 urban and 22 peri-urban gardens were surveyed and socio-economic data (origin, ethnic affiliation, profession and income sources of the gardener, household size, number and size of land holdings) and garden-related information (useful plant species - including ornamentals, plant uses, portion of sold products, use of fertilizers, pesticides and wage laborers, among others) collected (Bernholt et al., 2009). A garden was defined as commercial if more than 50% of its produce was sold. Species density was determined as the estimated number of species in a 1000 m² garden and complemented by determination of the Shannon index (H') and the Shannon evenness index (E). Stepwise multiple linear regression analysis was performed to identify factors determining plant species richness and diversity.

Results

Horizontal matter fluxes

Vegetable gardens. Nutrient inputs varied significantly between the high and the low input gardens (Figure 1). Mineral fertilizers were the major sources of N and P in the high input gardens, accounting for 48% and 80% of total N and P inputs, respectively. Total amounts of C, N, P and K exported through harvests in high input vegetable gardens exceeded the exports in low input gardens several-fold ($P < 0.05$; Table 1).

Given higher inputs of nutrients than removal with harvested produce, partial horizontal balances were strongly positive for both types of gardens. Average partial annual carbon and nutrient balances in high input vegetable gardens amounted to 9,936 kg C ha^{-1}, 1,133 kg N ha^{-1}, 223 kg P ha^{-1} and 312 kg K ha^{-1} as compared to 9,580 kg C ha^{-1} ($P > 0.05$), 290 kg N ha^{-1} ($P < 0.05$), 125 kg P ha^{-1} ($P > 0.05$) and 351 kg K ha^{-1} ($P > 0.05$) in low input gardens (Figure 1).

Millet fields. With 129 kg N ha^{-1}, 25 kg P ha^{-1} and 62 kg K ha^{-1} manure, applied annually at an average rate of 10.3 t DM ha^{-1} (SD = 3.8) in high input fields, accounted for 76%, 91% and 65% of total N, P and K inputs. At an average rate of 1.5 t DM ha^{-1} (SD = 0.2) the annual amount of manure applied to low input fields was significantly lower ($P < 0.05$), supplying only 7 kg N ha^{-1}, 3 kg P ha^{-1} and 7 kg K ha^{-1}. Annual C inputs through manure plus the estimated deposits (root exudates) amounted to 1,723 kg ha^{-1} in high input as opposed to 1,014 kg ha^{-1} in low input millet fields. When accounting for atmospheric inputs and harvest losses partial horizontal balances were positive for C, N, P and K in high input fields with annual carbon and nutrient surpluses of 259 kg C ha^{-1}, 125 kg N ha^{-1}, 20 kg P ha^{-1} and 0.4 kg K ha^{-1}. In contrast, in low input fields, horizontal partial balances were negative for P and K and slightly positive for C and N.

Vertical fluxes of N and C

The weekly average flux rates of NH_3, N_2O and CO_2 were in most cases higher in the early afternoon than in the cooler mornings (Figure 2 and 3). In 2006, NH_3 emissions in garden R_2 peaked with 10 g NH_3-N ha^{-1} h^{-1} in June, whereas in garden R_1 maximum flux rates were reached in August. In April the mean afternoon NH_3 emissions in high input garden W were more than four times higher than at the other two sites ($P < 0.001$), but dropped with the onset of the rains in June, remaining below 3.5 g NH_3-N ha^{-1}h^{-1} during the entire rainy and cool dry season. In 2007, in contrast NH_3 emissions in garden R_1 already reached their maximum before the first rains. In garden W afternoon emissions of N_2O-N during the hot dry season followed the pattern of NH_3-N fluxes. After emission rates of almost 30 g N_2O-N ha^{-1} h^{-1} in April 2006, the values significantly (garden R_1: $P < 0.001$; garden R_2: $P = 0.037$) dropped to less than one third at the onset of the rains (June 2006) and further to almost zero by the end of the rainy season (October 2006). From November 2006 onwards, the average afternoon emissions in garden W rose continually until > 25 g N_2O-N ha^{-1} h^{-1} in February 2007 and were significantly higher than in gardens R_1 and R_2 ($P < 0.001$).

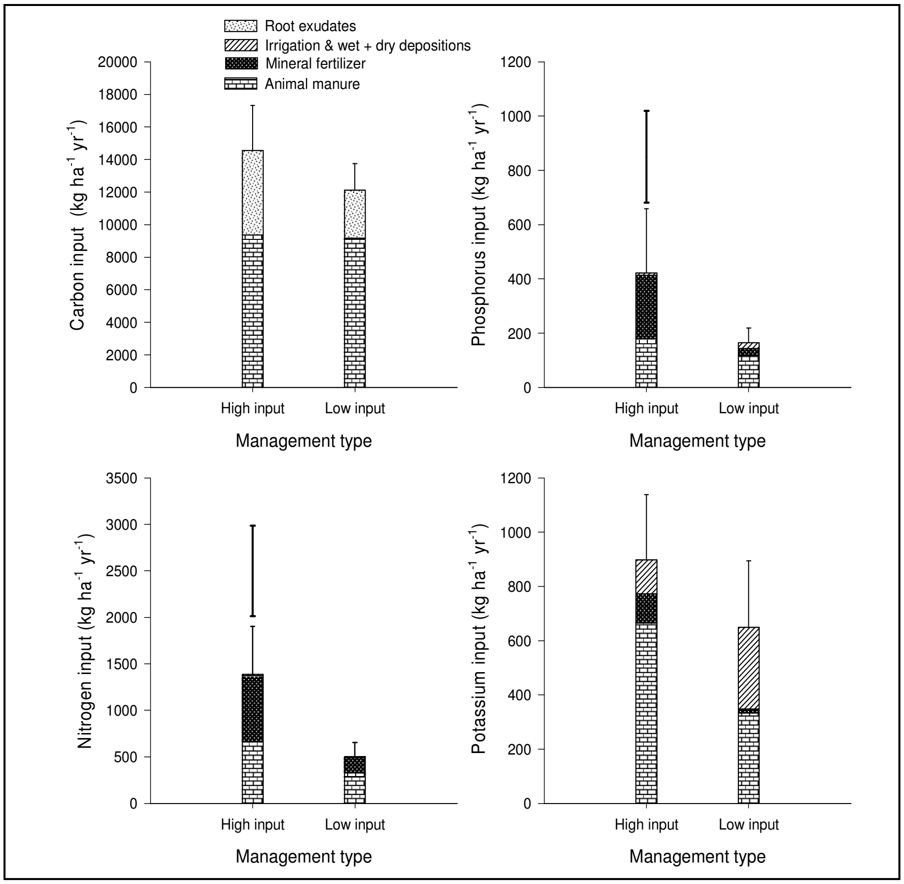

Figure 1. Annual amounts of carbon (C), phosphorus (P), nitrogen (N) and potassium (K) applied in high (n=5) and low (n=5) input vegetable gardens in Niamey, Niger, during January 2006 to January 2008. Data show annual means plus one standard error. Isolated vertical lines in charts indicate the least significant difference ($LSD_{0.05}$) of means for the two management systems. Carbon input resulted from manure and estimated deposits of root exudates.

Table 1. Vegetable crop cycles during the study period (n and (SD)), cumulative yields (t dry matter ha^{-1} 2 yr^{-1}) and average amounts (kg ha^{-1}, one cycle) of nitrogen (N), phosphorus (P) and potassium (K) removed with the edible parts of four vegetables cultivated in low and high input (intensity levels) vegetable gardens of Niamey, Niger, from January 2006 to January 2008. Also shown are cumulative nutrient and carbon exports.

Input intensity	Vegetable	Crop cycles	Yield	N	P	K
High input (n=5)	Lettuce	10.7 (10)	25.6	83	14	173
	Cabbage	5.8 (4)	46.4	260	54	286
	Amaranth	19.0 (11)	45.6	98	15	154
	Tomato	3.0 (1)	1.8	16	3	35
Low input (n=5)	Lettuce	6.4 (4)	16.6	67	14	158
	Cabbage	2.5 (1)	5.3	49	12	93
	Amaranth	1	6.3	202	32	376
	Tomato	1	0.1	3	1	9
			Cumulative export (kg ha^{-1} 2 yr^{-1}).			
			Total C	Total N	Total P	Total K
High input			59,895	4,306	757	6,541
Low input			14,176	756	157	1,629

The annual course of morning and afternoon CO_2 emissions were similar for all gardens. Strong increases of emissions at the end of hot dry season and the beginning of the rainy season in May/June 2006 were followed by declines towards the cooler end of the year (Figure 3). In R_1 and W maximum afternoon flux rates reached 4.5 and 5.5 kg CO_2-C ha^{-1} h^{-1}, respectively, while emission rates of CO_2-C in R_2 were with 1.3 to 3.4 kg CO_2-C ha^{-1} h^{-1} substantially lower. For leaching mean annual N losses ranged from 2.2-7.3 kg N ha^{-1} and annual P leaching was with $\leq$ 0.7 kg P ha^{-1} negligible (Predotova et al., unpublished data).

Manure storage losses

For manure stored during the hot dry season, cumulative gaseous N losses were with 0.11 g kg^{-1} manure DM highest ($P<0.05$) in the uncovered control treatment accounting for 1.8% of total manure N. Nitrogen losses decreased by 72% under plastic sheet roofing and by 50% under roofing + ground RP application at 333g kg^{-1} manure DM. Carbon losses from manure amounted to 73 g kg^{-1} DM in the control and to 92 g kg^{-1} DM and 68 g kg^{-1} DM under roofing and under roofing + RP, respectively. For manure stored during the rainy season, C losses from the control were 164 g kg^{-1} manure DM and reduced to 77% and 65% of the control by roofing and roofing + RP, respectively. Leaching losses during the rainy season were only observed for the unroofed control and averaged 2.1 g C, 0.05 g N, 0.07g P and 1.8 g K kg^{-1} manure DM.

2. Contamination of produce with faecal pathogens and heavy metals

Irrigation waters from the river, ponds, and wastewater sources were contaminated with *Staphylococcus aureus* and other pathogens mainly in the cool dry but also the hot dry season, whereby the level of contamination was much higher in wastewater than in the other water sources. The outer leaves of vegetables such as amaranth, lettuce and cabbage irrigated with river or wastewater were contaminated with *Salmonell*a spp. as well as with *E. coli*. On cabbage irrigated with wastewater and river water as well as on amaranth irrigated with wastewater, total mesophilic aerobic microorganism counts were with 10^6 CFU g^{-1} fresh matter in the hot dry season above the threshold value recommended by CNERNA-CNRS (1996). However, in the cool dry season, pathogen levels were low on lettuce and cabbage. Although *Salmonella* spp. counts in the wastewater used in garden W amounted to 5 x 10^2 CFU 100 ml^{-1} in the hot dry season, no contamination was determined on cabbage leaves. In the cool dry season *Salmonella* spp. counts in this water source were 12-fold higher (6 x 10^3 CFU 100 ml^{-1}), and the irrigated lettuce harbored the pathogens at a concentration of 9.8 x 10^4 CFU 25 g^{-1} fresh matter of the leaves.

In Niamey heavy metal concentrations in the wastewater running through the wadi varied from 0.03-0.11 for Zn, 0.03-0.04 for Cu and 0.01 for Ni. In pond water of the Niamey study Zn, Cu and Ni concentrations averaged 0.16, 0.12 and 0.04, respectively. Shortly after the rainy season 2006, no Ni was detected in any of the water sources, and Zn was only present in traces in river and pond water, while for wastewater Zn concentrations ranged from 0.02 - 0.04 mg l^{-1}. Post rainy season Cu concentration in upstream and downstream river water was 0.01 mg l^{-1}, while values of 0.01 - 0.02 mg l^{-1} were determined for wastewater and 0.01 mg l^{-1} for pond water.

In Kano extractable Zn in UPA soils was with 35-400 mg kg^{-1}, Ni with 68-250, Pb with 52-250, Cu with 0-21 and Cd with 4-5 mg kg^{-1} above FAO/WHO standards (Nafiu et al, unpublished data). In eatable vegetable tissue Cd was well above the 0.2 mg kg^{-1} threshold, but Ni was below the 68 mg kg^{-1} limit. In lettuce Zn was with concentrations of up to 99 mg kg^{-1} critically high, but Cu and Pb were below detection limits in any of the vegetables.

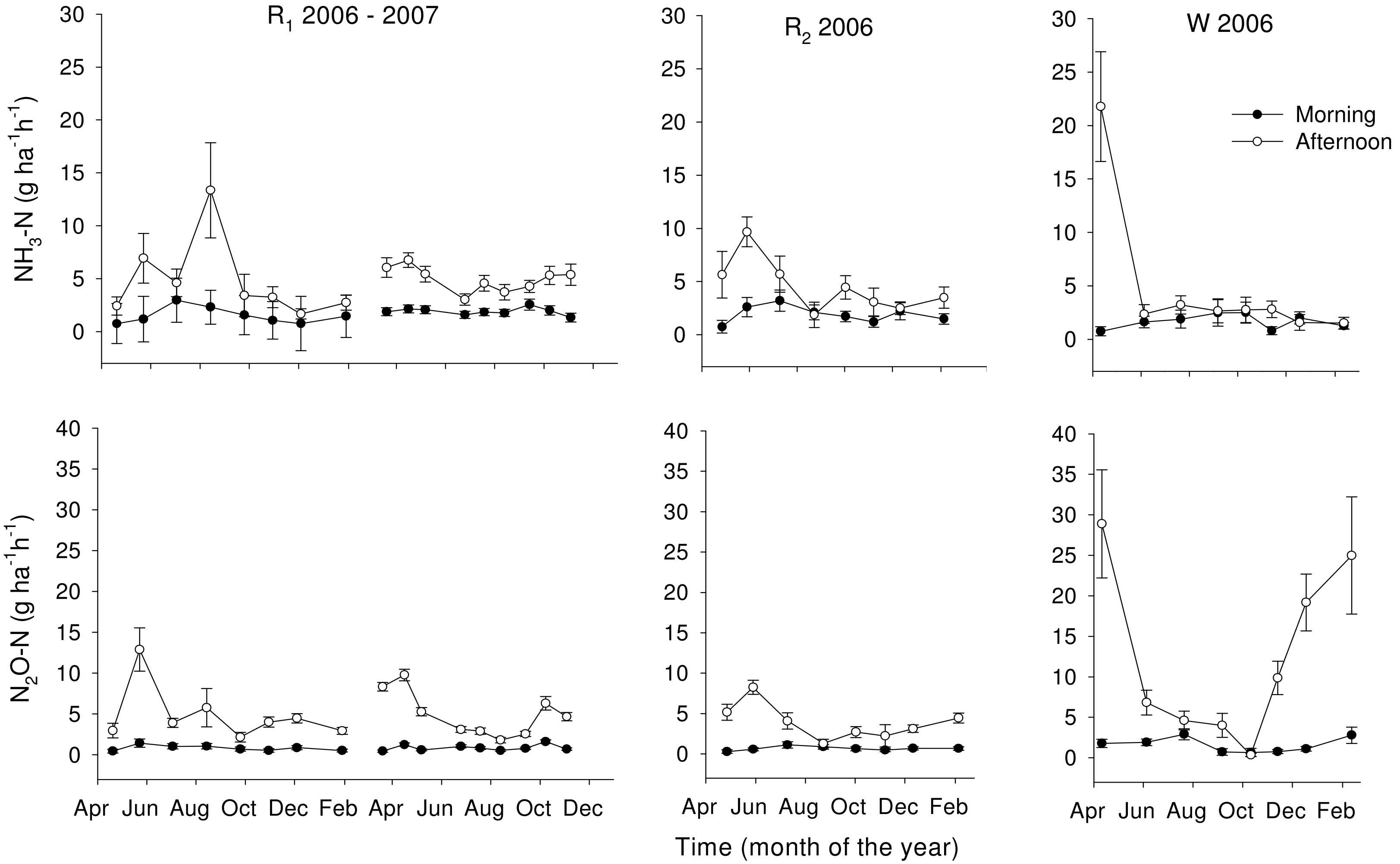

Figure 2. Flux rates of NH_3-N and N_2O-N during morning and afternoon hours in the two studied low input river gardens in Goudel (R_1), Yantala Bas (R_2) and the high input wadi garden in Gountou Yena (W), Niamey, Niger. Displayed are means of 72 weekly measurements with their respective standard errors during 2006 (all gardens) and 2007 (garden R_1 only).

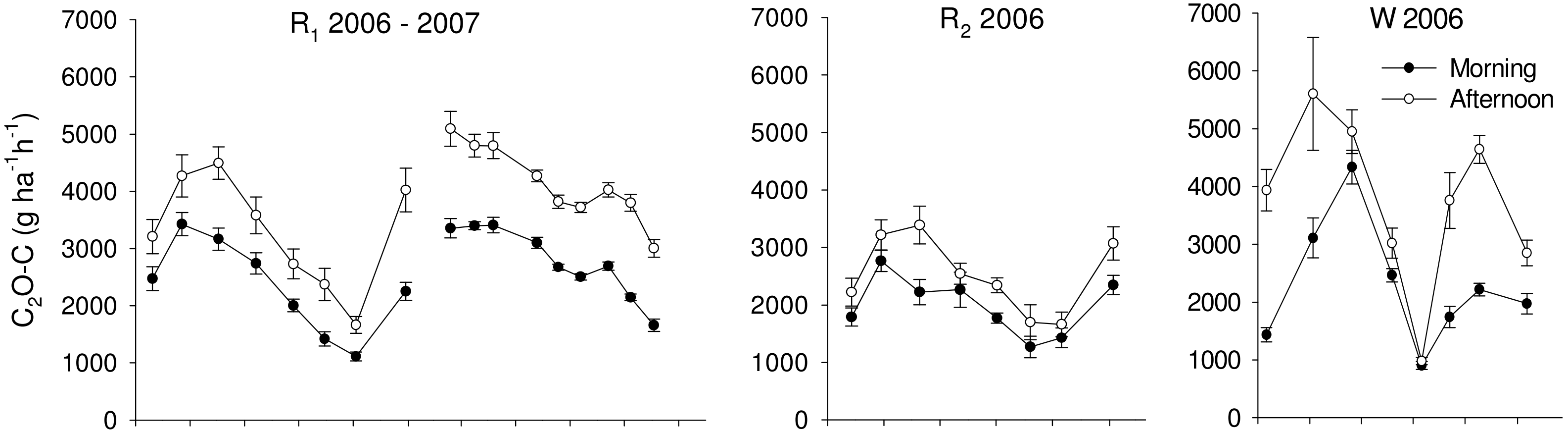

Figure 3. Flux rates of CO_2-C during morning and afternoon hours in the two studied low input river gardens (R_1 and R_2) and the high input wadi garden (W), Niamey, Niger. Displayed are means of 72 weekly measurements with their respective standard errors during 2006 (all gardens) and 2007 (garden R_1 only).

3. Determinants of plant species diversity

A total of 116 different plant species from 50 families were cultivated in the 51 surveyed gardens, 71% of which were exotic and 47% were woody perennials. In the cool season, mean species richness per garden was 14.06 and mean Shannon index was 0.96. The highest Shannon index was found in a very large commercial garden, where many rare species were cultivated. Total species richness continuously decreased from 115 species in the cool to 100 in the hot and 77 in the rainy season. This is mainly due to the decrease in the number of annual species such as vegetables, spices and staples. While total species richness was only slightly correlated with garden size ($r=0.646$; $p<0.001$; Figure 4), larger gardens had a higher number of perennial ($r=0.788$; $p<0.001$) and local plant species ($r=0.797$; $p<0.001$). Compared to commercial gardens non-commercial ones had only a slightly higher Shannon index (1.23 *versus* 0.90; $p=0.082$) and a significantly higher evenness (0.56 *versus* 0.36; $p=0.005$), while species richness was not different (12 *versus* 15, $p=0.495$). Species diversity was also affected by the ethnic affiliation of the gardener. The gardens operated by Gourmanché and Mossi migrants from Burkina Faso, who mostly rented the land, showed significantly lower Shannon index and evenness than gardens managed by the native Djerma and the Peul, respectively. Species richness was lower in gardens managed by women compared to those managed by men (10 *versus* 15; $p=0.024$), but Shannon index and evenness were higher (H': 1.24 *versus* 0.89; $p=0.043$; E: 0.56 *versus* 0.35; $p=0.001$).

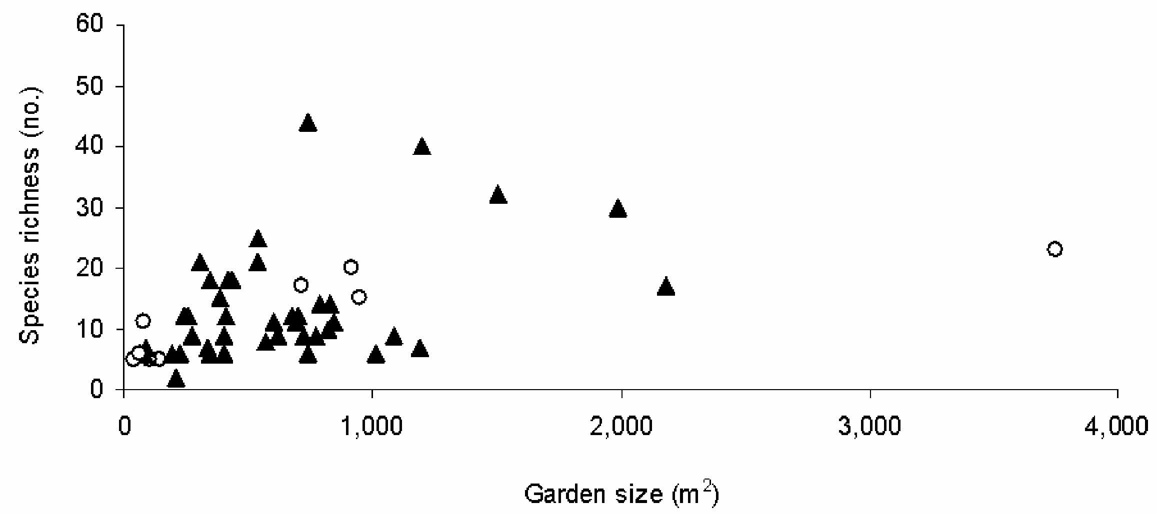

Figure 4. Relation between species richness in the cool season and garden size of nine subsistence gardens (dots) and 41 commercial gardens (triangles) in Niamey (Niger), 2007. Data of one very large commercial garden with a size of 10,355 m² and a species richness of 52 are not shown.

Discussion and conclusions

The first results of UPA data from Niamey indicate vegetable production is across the intensity levels investigated characterized by large surpluses of N, P and K application leading to inefficiencies in nutrient use and management. This is in contrast to peri-urban millet fields which are suffering from the effects of heavy nutrient mining. Our data support earlier reports from UPA systems in Kumasi, Ghana and Cotonou, Benin (Drechsel et al., 2004; Assogba-Komlan et al. 2007) and the agro-pastoral systems in the West African Sahel (Bationo et al., 1998; Buerkert and Hiernaux, 1998). The high C and N volatilisation losses confirmed the initial hypothesis that gaseous emissions are an important pathway of nutrient losses in UPA of sub-Saharan Africa. True N losses might be even higher if the emissions of NO_x and N_2 were added which our set-up was unable to catch. Nevertheless, the results of the study also indicates substantial scope for improvement of nutrient use efficiency in intensively managed UPA vegetable gardens by better matching nutrient applications with plant nutrient demands (split application of amendments, manure incorporation and manure storage under protective roofs plus addition of RP). At present the contamination of UPA produce with heavy metals and pathogens seems to be limited to areas where soils or wastewater used for irrigation are heavily contaminated by industrial waste and pathogenic micro-organisms. This may be critical in leafy crops which are likely to be eaten fresh without further cleaning. Vegetable UPA gardens may also be able to contribute to the *in situ* conservation of plant diversity whereby the determinants of this role merits site-specific research. A closer coupling of animal husbandry and plant production systems leading to a more effective recycling of manure and certification of resource efficient and environmentally safe management systems is desirable to strengthen the sustainability of UPA. The site-specificity of UPA structures underlines the importance of solid experimental data to make valid recommendations for increased resource use efficiencies and decreased negative externalities of UPA, thus enhancing the bio-physical and economic sustainability as well as strengthening policy support for these production systems.

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