Vertical nutrient fluxes in urban vegetable production of Niamey, Niger




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Dedication

To

Jean Jacques Melapie
Our son Yan Youmbi Melapie

The memory of my grandmother Amálie Rebcová

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Summary

The importance of urban and peri-urban agriculture (UPA) in sub-Saharan Africa is rapidly increasing given its contribution to meeting the food demands of growing urban populations. The very intensive mode of production typically practised in UPA is characterized by high inputs and positive nutrient balances which are expected to lead to substantial nutrient losses. The aim of this study therefore was to quantify the vertical nutrient fluxes in representatively selected vegetable gardens of Niamey, the capital city of Niger, and to design strategies on how to improve resource use efficiency in these gardens.

Gaseous nitrogen (N) and carbon (C) losses were measured using a closed chamber system with a mobile infrared photo-acoustic multi-gas monitor in two gardens using river water (R_1 and R_2) and in one garden using sewage water (W) for irrigation. The horizontal nutrient fluxes measurements showed highly positive yearly N and C balances reaching 369 kg N ha^{-1}, 593 kg N ha^{-1} and 2,987 kg N ha^{-1} and 28,320 kg C ha^{-1}, 10,091 kg C ha^{-1} and 785 kg C ha^{-1} in gardens R_1, R_2 and W, respectively. In each garden were chosen three double plots with six measuring spots per double plot (n=18 per garden). The gas measurements were conducted during the coldest (6-8 am) and hottest (1-3 pm) part of the day in order to capture the lowest and highest gas efflux rates. While morning emissions of NH_3-N and N_2O-N were negligible throughout the year, they increased substantially in the hot afternoons and varied between seasons. In both river gardens the ratio between NH_3 and N_2O was similar throughout the year, while in the garden using sewage water for irrigation N_2O emissions, peaking in April 2006 with 30 g N_2O-N ha^{-1} h^{-1}, dominated with 65% of the total N gaseous losses. Measured CO_2 emissions similarly increased at the end of the hot dry season and at the beginning of the rainy season, reaching afternoon maxima of 4.5 kg CO_2-C ha^{-1} h^{-1}, 3.4 kg CO_2-C ha^{-1} h^{-1} and 5.5 kg CO_2-C ha^{-1} h^{-1} in gardens R_1, R_2 and W, respectively. The highest gaseous losses occurred during the hot dry season from March to May (30-40% of N and about 28% of C) and at the

onset of the rainy season in June and July (10-20% N and 20-25% C). In 2006 estimated annual N and C losses reached 53 kg N ha^{-1}, 25 Mg C ha^{-1}; 48 kg N ha^{-1}, 20 Mg C ha^{-1} and 92 kg N ha^{-1} and 26 Mg C ha^{-1} in R_1, R_2 and W, respectively. The data show that especially during the hot dry and the first half of the rainy season, Niamey's UPA vegetable farmers should pay more attention to nutrient management strategies and thereby decreasing gaseous N and C losses.

During the rainy season 2007 cumulative leaching losses of mineral N and phosphorus (P) were quantified in the same gardens as the gaseous emissions, using cartridges filled with ion-exchange resins mixed with sand. These were installed at 0.6 m depth under the root zone of cultivated vegetables before the onset of the rainy season and removed one month after the last rain. For analysis the ion-exchange resin – sand mixture in the containers was separated into four layers and adsorbed nutrients were extracted by 0.5M NaCl solution. Mean mineral N cumulative leaching losses during the rainy season amounted to 5.9 and 7.3 kg N ha^{-1} in gardens R_1 and W with a sandy soil and to only 2.2 kg N ha^{-1} in the R_2 garden with 40% silt and clay in the soil. Phosphorus leaching in all three gardens did not exceed 0.7 kg P ha^{-1}. The relatively low leaching losses in this study might be explained by the below average precipitation (371 mm in 2007 compared to a long term average of 542 mm), therefore longterm experiments would be needed to better understand the effects of inter-annual fluctuations in precipitation on nutrient leaching in UPA gardens. The used method was not able to quantify the leaching losses of potassium (K) due to the high background K concentration of the ion-exchange resin - sand mixture.

Gaseous and leaching losses of N and C were also measured in an animal manure storage experiment conducted once in the hot dry season and once in the rainy season. For this experiment, 70 kg of fresh mixed small ruminant and cattle manure were heaped on 1 m^2 metal tables. An unprotected control (C) simulating the traditional dung storage in the

vegetable gardens was compared to a dung storage protected by a plastic roof (R) and a roofed treatment with addition of finely ground locally available Tahoua rock phosphate (RP; 333 g RP kg^{-1} DM manure); all treatments were replicated four times. Gaseous emissions were measured similarly as in the gardens during mornings and mid-days with the closed chamber system connected to the mobile infrared photo-acoustic multi-gas monitor. Leaching and run-off losses were assessed by capturing the seeping liquid in a container. The emission of all four measured gases (NH_3, N_2O, CO_2 and CH_4) peaked in both seasons immediately after installation of the dung heaps and during the first week of the experiment. The addition of finely ground RP significantly decreased the NH_3-N emissions in the hot dry season being responsible for > 70% of total gaseous N losses across all treatments. Plastic sheet roofing completely eliminated leaching and run off losses occurring after rainfall events. The data show that simple techniques may help to effectively decrease nutrient losses during dung storage and thus increase nutrient use efficiency in UPA gardens of Niamey.

Zusammenfassung

Die Bedeutung der urbanen und peri-urbanen Landwirtschaft in Afrika südlich der Sahara nimmt derzeit stark zu, weil sie wesentlich zur Deckung des Nahrungsmittelbedarfs der rasch wachsenden Stadtbevölkerung beiträgt. Wahrscheinlich führt die sehr intensive Produktion, die durch hohe Inputs und positive Nährstoffbilanzen gekennzeichnet ist, auch zu hohen Nährstoffverlusten. Die Aufgabe dieser Studie war es deshalb, die vertikalen Nährstoffverluste in ausgewählten Gemüsegärten von Niamey, der Hauptstadt der Republik Niger, zu bestimmen.

Mit einem mobilen photo-akustischen Infrarotgasmessgerät, das durch Schläuche mit einer geschlossenen Kammer gekoppelt war, wurden in zwei mit Wasser aus dem Niger-Fluss bewässerten Gärten (R_1 and R_2) und in einem mit Abwasser bewässerten Garten (W) die gasförmigen Verluste an Stickstoff (N) und Kohlenstoff (C) bestimmt. Die Messungen wurden jeweils während des kältesten (6.00 - 8.00 Uhr) und wärmsten (13.00 - 15.00 Uhr) Tagesabschnitts durchgeführt, um die vermutlich niedrigsten und höchsten Gasemissionen des Tages zu erfassen. Während die morgendlichen Emissionen von NH_3-N und N_2O-N über das ganze Jahr hinweg gering waren, stiegen sie am Nachmittag wesentlich an. Die Höhe der Emissionen unterschied sich zu den verschiedenen Jahreszeiten. Verluste durch gasförmige Emissionen von NH_3-N und N_2O-N waren in den beiden mit Flusswasser bewässerten Gärten im Jahresverlauf gleich groß, während in dem mit Abwasser bewässerten Garten N_2O-N mit 65% den größten Anteil der Stickstoffverluste ausmachte. Im mit Abwasser bewässerten Garten wurde im April der mit 30 g N_2O-N ha^{-1} h^{-1} höchste Wert für N_2O-N Emissionen gemessen. Die höchsten gasförmigen Verluste wurden in der heissen Trockenzeit, von März bis Mai (30-40% N und etwa 28% C), sowie am Anfang der Regenzeit, im Juni und Juli (10-20% N und 20-25% C) beobachtet. Emissionen von CO_2-C stiegen in der heissen Trockenzeit und am Beginn der Regenzeit in ähnlicher Weise und erreichten maximale

mittägliche Werte von 4,5 kg CO_2-C ha^{-1} h^{-1}, 3,4 kg CO_2-C ha^{-1} h^{-1} und 5,5 kg CO_2-C ha^{-1} h^{-1} in den Gärten R_1, R_2 und W. Im Jahre 2006 betrugen die auf der Grundlage der Messwerte geschätzten jährlichen Gesamtverluste an Stickstoff (N) und Kohlenstoff (C) 53 kg N ha^{-1} und 25 Mg C ha^{-1} im Garten R_1, 48 kg N ha^{-1} und 20 Mg C ha^{-1} im Garten R_2 und 92 kg N ha^{-1} und 26 Mg C ha^{-1} im Garten W. Es ist offensichtlich, dass vor allem während der heissen Trockenzeit und in der ersten Hälfte der Regenzeit Strategien zur Senkung gasförmiger Verluste von Stickstoff (N) und Kohlenstoff (C) mehr Aufmerksamkeit geschenkt werden sollte.

In der Regenzeit des Jahres 2007 wurden kumulative Sickerwasserverluste von Stickstoff (N) und Phosphor (P) auf den gleichen Versuchsflächen R_1, R_2 und W mit Hilfe eines Ionenaustauscherharz-Sand Gemischs bestimmt. Die Ionenaustauscher wurden vor Beginn der Regenzeit unter der durchwurzelten Zone der angebauten Gemüsepflanzen in einer Bodentiefe von 60 cm eingegraben und einen Monat nach dem letzten Niederschlagsereignis am Ende der Regenzeit wieder ausgebaut. Das Gemisch von Ionenaustauschern und Sand wurde dann schichtweise aus dem Behälter entnommen und die aus dem Sickerwasser an die Ionenaustauscher adsorbierten Nährstoffe mit einer 0,5 molarer NaCl-Lösung extrahiert. Kumulative Stickstoffverluste in der Regenzeit lagen im Mittel bei 5,9 und 7,3 kg N ha^{-1} in den Gärten R_1 und W mit sandigen Boden und bei nur 2,2 kg N ha^{-1} im Garten R_2, in dessen Boden der Anteil von Ton und Schluff an der Korngrößenverteilung bei 40% lag. Die Sickerwasserverluste von P lagen unter 0,7 kg P ha^{-1}. Die relativ niedrigen Sickerwasserverluste können durch den relativ geringen Jahresniederschlag von 371 mm im Jahr 2007 im Vergleich zum langjährigen Jahresmittel von 542 mm erklärt werden. Mehrjährige Messungen wären nötig, um den Einfluss unterschiedlicher Jahresniederschlagsmengen auf die Auswaschungsverluste beurteilen zu können.

Sickerwasserverluste von Kalium (K) konnten mit der angewendeten Methode nicht bestimmt werden, da die Konzentrationen an Kalium (K) in den benutzten Materialien (Ionenaustauscherharz und Sand) zu hoch waren.

Zusätzlich wurden Gasemissionen und Sickerwasserverluste in einem Dunglagerungsversuch einmal in der heissen Trockenzeit und einmal in der Regenzeit gemessen. Jeweils 70 Kilogramm eines frischen Dunggemischs, das von kleinen Wiederkäuern und Rindern stammte, wurde auf Metalltischen (Fläche = 1m^2) aufgehäuft. Vier der Tische wurden als Kontrolle (C) ungeschützt belassen, um damit die traditionelle Dunglagerung in den Gemüsegärten zu simulieren. Die Kontrolle wurde mit zwei anderen Behandlungen verglichen: Überdachung des Dungs mit einer Plastikfolie (R) und überdachte Lagerung mit Zusatz von fein gemahlenem Tahoua Rohphosphat (RP; 333 g kg^{-1} Trockenmasse Dung). Die Gasemissionen wurden, ähnlich wie im Feld, am Morgen und am Mittag mit dem mobilen foto-akustischen Infrarotmessgerät gemessen. Von der Oberfläche der Tische ablaufendes Wasser wurde in Sammelbehältern aufgefangen und auf seine Gehalte an Kohlenstoff (C), Stickstoff (N), Phosphor (P) und Kalium (K) untersucht. Die Emissionen aller gemessenen Gase (NH_3, N_2O, CO_2 und CH_4) waren unmittelbar nach der Einrichtung der Dunghaufen und innerhalb der ersten Woche des Versuchs am höchsten. Die Zugabe von gemahlenem Rohphosphat hatte die NH_3-N Emissionen, die in der heissen Trockenzeit 70 % der gesamten Sickstoffverluste betrugen, signifikant reduziert. Zusätzlich konnte ein einfaches Überdachen der Dunghaufen Sickerungverluste während der Regenzeit verhindern. Es konnte nachgewiesen werden, dass auch mit einfachen Maßnahmen der Nährstoffverlust während der Lagerung von Dung reduziert und dadurch die Effizienz des Nährstoffmanagements wesentlich erhöht werden kann.

Chapter 1.

General introduction, research objectives and hypotheses

1.1. General introduction

1.1.1. Urban and peri-urban agriculture

At present the global population accounts for 6.7 billion and is expected to reach 9 billion in 2040 (U.S. Census Bureau, 2009). Simultaneously, the urban-rural distribution of the population is changing in favour of the urban. While the global urban population in 1970 accounted for 35%, it increased to 45% in 1995. Nowadays half of the population is living in the cities and this share of the population is projected to reach 70% in 2050 (United Nations, 2009). The total population of sub-Saharan Africa reached 782 millions in 2006 with an annual growth rate of 2.5% (World Bank, 2008) and a particularly fast urbanization. In the entire African continent, 33% of the population lives in urban agglomerations with more than 1 million inhabitants (United Nations, 2009). In West Africa in 1930, only 4% of total population lived in cities, whereas in 1990 already around 40% lived in urban centers which at an annual growth rate of 6.3% (Snrech, 1994) is predicted to reach 63% in 2020 (Drechsel et al., 2005).

The consequences of this rapid growth of urban population are often unplanned and informal settlements and increasing demands for food. The local agricultural production within and in the vicinity of the cities has existed since the first urban populations were established hundreds of years ago but it was not until the 1980s that these often very intensive production activities have gained the attention of researchers and policy makers (Castillo, 2003). Since then, numerous mostly qualitative studies have reported that the agricultural production in and at the periphery of cities, thereafter referred to as urban and peri-urban agriculture (UPA), is contributing considerably to meet rising food demands of the producers themselves (auto-consumption) or to supply city markets with fresh vegetables (10-90%), meat (up to 70% in come cities), eggs (up to 100%) and other products such as fruits, oil, cereals and tubers, (Maxwell, 1995; Madaleno, 2000; Cofie et al., 2003; Gockowski et al., 2003; Drechsel et al., 2005; Drechsel et al., 2007; De Bon et al., 2009). In addition to these functions UPA is creating jobs and income opportunities through the production and subsequent marketing of the produce (van Veenhuizen and Danso, 2007). In African cities 10-70% of urban households are reported to be involved in UPA (Ellis and Sumberg, 1998; Howorth et al., 2001; Asomani-Boateng, 2002; Bryld, 2003; Cofie et al., 2003; De Bon et al., 2009). The intensive production often concentrated in the immediate proximity to human settlements is often accused to pose serious risks to human health and the environment. Overdosing and inappropriate application of fertilizers and pesticides, lack of clean irrigation water, absence of adequate waste management strategies, heavy metal pollution and the use of unplanned and uncontrolled commodity chains are reported from studies on UPA in sub-Saharan Africa (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). The intensive application of external inputs, poor application techniques and insufficient nutrient cycling (Drechsel et al., 2005) often lead to positive nutrient balances (Hedlund et al., 2003; Drechsel et al., 2004) that combined with high nutrient losses (Diogo et al., 2009) may result in poor resource use efficiencies.

1.1.2. Gaseous nutrient losses

In hot dry climates gaseous emissions are expected to be one of the main pathways for nutrient losses. Anthropogenic sources account for 74% (Bouwman et al., 1997), 45% (Kroeze et al., 1999) and 70% (Mosier and Parkin, 2007) of the total emissions of ammonia (NH_3)-N, dinitrous oxide (N_2O)-N and methane (CH_4)-C, respectively. Agricultural practices in both crop production and animal husbandry are playing a major role in the man-made emissions (FAO, 2001). The carbon dioxide (CO_2) efflux from agricultural systems, the result of autotrophic fixation and heterotrophic respiration, obviously depends on the site-specific combination of environmental conditions and management practices (Cole et al., 1997; Mosier and Parkin, 2007). Unfortunately, although Africa is so far a very low emitter of greenhouse gases in comparison to other continents, the climatic changes caused by the global increase of gaseous emissions is particularly on this continent increasing the vulnerability to impacts of climate change such as droughts, floods and famines (IPCC, 2001). According to rough estimates of Kreileman (1998) the African continent contributes 12%, 9% and 3% to the global emissions of N_2O-N, NO-N and NH_3-N, respectively, resulting from organic and chemical fertilizer application to crops and grasslands.

Several methods can be used to measure gaseous emissions in the field. Micrometeorological methods have been employed for the measurement of gas fluxes between land surfaces and the atmosphere in large uniform and plane areas as they do not interfere with the gas exchange process (Denmead et al., 1998; Fowler et al., 2001; Griffith et al., 2002; Harper et al., 2009). To the non-interference techniques belong gradient techniques that are based on the concept of turbulent diffusion of gas along its mean concentration gradient (Fowler et al., 2001), mass-balance methods measuring horizontal gas fluxes (Denmead et al., 1998; Sommer et al., 2004) and the backward Lagrangian stochastic analysis which generates measured plot trajectories backward in time and space (Flesch et al., 1995; Flesch et al., 2004; Flesch and Wilson, 2005; Flesch et al., 2009). Another possibility is the tracer gas method where a tracer gas of known concentration is released and the measured gas concentration is calculated from the gas ratio at a downwind position (Czepiel et al., 1996; Denmead et al., 1998; Czepiel et al., 2003; Flesch et al., 2004). Methods that to certain extent interfere with the gaseous emissions from the surface and that are used for detailed measurements on small areas are closed static or dynamic chamber systems (Conen and Smith, 1998; Kirsch et al., 2000; Velthof et al., 2003; Sommer et al., 2004; Reth et al., 2005; van Groenigen et al., 2005; Ruser et al., 2006).

In this study, a static closed chamber connected to a photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark) was used to determine gaseous emissions of C (CO_2 and CH_4) and N (N_2O and NH_3) from UPA gardens at a high temporal and spatial resolution. The photo-acoustic principle of the multi-gas meter is based on the conversion of light energy into sound, the intensity of which depends on the gas concentration in the sample (Figure 1). The air sample in the measuring chamber is irradiated with infrared light of a frequency corresponding to the resonant vibration frequency of the gases in the sample. As light is absorbed some of the molecules will reach a state of higher vibration energy. These molecules will subsequently fall back to the initial vibration state causing an acoustic wave, which is detected with a microphone. The amplitude of this wave is among other factors dependent on the gas concentration in the air sample (LumaSense Technologies A/S, 2009).

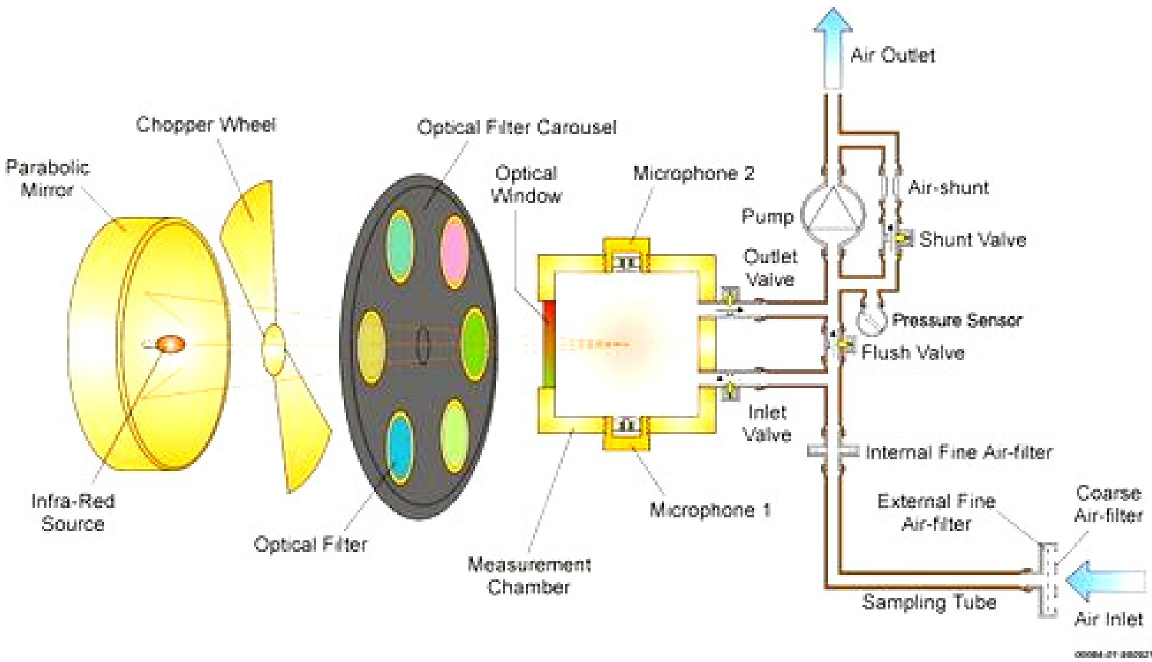

Figure 1. Principle of the photo-acoustic infrared multi-gas meter INNOVA 1412 (LumaSense Technologies A/S, Ballerup, Denmark). Source: www.innova.dk.

1.1.3. Leaching nutrient losses

Apart from volatilization, leaching is another pathway of nutrient losses which may play a major role on the sandy soils of Niger. While in some studies on nutrient flows leaching losses were simply neglected (Bationo et al., 1998), other studies conclude that volatilization is a main contributor to N losses in West Africa (Christianson et al., 1990; Bationo and Mokwunye, 1991). In their review, Buerkert and Hiernaux (1998) cite data of Hafner et al. (1993) who measured total N leaching losses in a millet field of 150 kg

N ha^{-1} in a six year period. Leaching losses of up to 91 kg N ha^{-1} and 19 kg P ha^{-1} after application of 13 t ha^{-1} of cattle manure were also reported by Brouwer and Powell (1995).

A recent study of leaching losses from vegetable production areas, paddy fields and build up area in Japan showed that vegetable gardens were the principal source of nitrate contamination of groundwater (Babiker et al., 2004). Leaching losses were therefore expected to be high given the high input levels of UPA gardens in Niamey.

To measure leaching losses different approaches have been proposed. Bischoff et al. (1999) discussed the advantages and disadvantages of suction plates, suction cups in combination with water flux modelling, wick samplers and of ion exchange resins. The latter have also been referred to as 'Self Integrating Accumulators (SIA)' by Bischoff (2007) who used cation-anion exchange resins in tubes installed in the soil profile to asses cumulative solutes fluxes at the chosen depth over several months at a relatively low cost and workload. With a sufficient number of replications the SIA method allows to avoid erroneous results from preferential phenomena causing serious errors in leaching measurements (Bischoff, 2007). This method was also successfully used to trace element releases from a forest floor (Lang and Kaupenjohann, 2004). However, it must be known that the application of the method is unfeasible under conditions of stagnating water, flooding, poor soil structure and areas experiencing lateral solute flow (Bischoff and Kaupenjohann, 2008) or where an intimate connection of the resins to the soil can not be established (Siemens and Kaupenjohann, 2004).

1.2. Research objectives

Numerous qualitative and semi-quantitative studies about the status and functioning of UPA in Africa exist, but quantitative research of nutrient flows is scarce. The objectives of this research therefore were (i) to quantify gaseous losses of carbon (C) and nitrogen (N) with their seasonal variation in representative urban gardens throughout the year, (ii) to determine leaching and volatilization losses from livestock faeces and manure storage and (iii) to determine leaching losses of mineral N, phosphorus (P) and potassium (K) in UPA vegetable gardens and from dung storage in the gardens before application. In addition to these experimentally based objectives we also wanted to investigate the current farmer practices of storing animal dung through interviews.

1.3. Research hypotheses

The presented studies were based on the following research hypotheses:

1. The urban vegetable production in Niamey with its positive nutrient balances is characterized by high carbon (C) and nitrogen (N) losses through volatilization especially during the hot dry season.
2. During the rainy season nutrient leaching losses are high given the sandy texture of the garden soils.
3. Animal faeces and the unprotected and sometimes prolonged storage of animal manure in the gardens is accompanied by high gaseous losses throughout the whole year and nutrient run off / leaching losses during the rainy season.
4. Addition of ground rock phosphate (RP) to stored animal manure decreases N volatilization losses and increases the plant-available P concentration.

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Chapter 2.

Emissions of ammonia, nitrous oxide and carbon dioxide from urban gardens in Niamey, Niger

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2.1. Abstract

Urban and peri-urban agriculture (UPA) contributes significantly to meet increasing food demands of the rapidly growing urban population in West Africa. The intensive vegetable cultivation in UPA gardens with its high nutrient inputs is often reported to operate at large surpluses of nutrients and presumably high turnover rates of organic matter (OM) and nitrogen (N) losses via emanation and leaching. Many of these claims are lacking solid data which would allow suggesting mitigation strategies. Therefore, this study aimed at quantifying gaseous emissions of ammonia (NH_3), nitrous oxide (N_2O) and carbon dioxide (CO_2). Measurements were conducted in three representative urban gardens of Niamey, Niger using a closed chamber gas monitoring system. Mean annual N emissions (NH_3-N and N_2O-N) in the two gardens using river water for irrigation reached 53 and 48 kg N ha^{-1} yr^{-1}, respectively, while 25 and 20 Mg C ha^{-1} yr^{-1} was lost as CO_2-C. In the garden irrigated with sewage water from the city's main *wadi*, N_2O was the main contributor to N losses (68%) which together with NH_3 reached 92 kg N ha^{-1} yr^{-1}, while CO_2-C emissions amounted to 26 Mg ha^{-1} yr^{-1}. Our data indicate that 28% of the total gaseous C emissions and 30-40% of the N emissions occur during the hot dry season from March to May and another 20-25% and 10-20% during the early rainy season from June to July. Especially during these periods more effective nutrient management strategies in UPA vegetable gardens should be applied to increase nutrient use efficiency.

Keywords: Closed chamber system, carbon losses, INNOVA, nitrogen losses, urban and peri-urban agriculture.

2.2. Introduction

In West Africa the share of urban population grew from only 4% in 1930 to 40% in 1990 and is projected to reach 63% by 2020 (Drechsel et al., 2005). During this time period the role of urban and peri-urban agriculture (UPA) in providing food and employment for the urban population has been rapidly increasing and today it supplies city markets with fresh vegetable (10-90%), meat (up to 70%), eggs (up to 100%) and other products (Maxwell, 1995; Madaleno, 2000; Cofie et al., 2003; Drechsel et al., 2005). The widely ranging share of households involved in UPA (10-57%) (Ellis and Sumberg, 1998; Howorth et al., 2001; Asomani-Boateng, 2002; Cofie et al., 2003) nevertheless shows large differences in the relative role of this land use system. In many places this intensive mode of production is claimed to be associated with an indiscriminant use of inputs in the immediate proximity of human settlements which may lead to risks for human health and the environment. Overdosing and inappropriate application of fertilizers and pesticides, contamination of drinking water with sewage water and also the use of heavy metal polluted irrigation water leading to produce contamination have been reported as problems associated with UPA production systems in sub-Saharan Africa (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).

Intensive recycling of nutrients through compost application, sewage water irrigation and the often high rates of applied mineral fertilizers (Drechsel et al., 2005) result in positive nutrient balances in UPA gardens (Hedlund et al., 2003) which may cause high nutrient losses. Under the largely hot and dry conditions of the West African Sahel gaseous emissions may be expected to be the main pathway for losses of nitrogen (N) and carbon (C) and thereby contribute to the global anthropogenic emission share of 74% for NH_3 (Bouwman et al., 1997), of 45% for N_2O (Kroeze et al., 1999) and of 3% for CO_2 (Anonymous, 2008).

It is evident that the CO_2 efflux from any agricultural system is the net result of autotrophic fixation and heterotrophic respiration and as such depends on the combination of environmental conditions and management practices (Cole et al., 1997; Mosier and Parkin, 2007). Even if organic and chemical fertilizer applications to crops and grasslands on the African continent as a whole may contribute with 12%, 9% and 3% (FAO, 2001) only little to the global emissions of N_2O-N, NO-N and NH_3-N, respectively, the climatic changes caused by the global increase of greenhouse gases are particularly in Africa most likely to enhance the populations' vulnerability to droughts, floods and famines (Desanker and Magadza, 2001).

Within the context of a larger effort to increase the resource use efficiency in UPA while minimizing its negative environmental effects and increasing food safety, this study was conducted to quantify gaseous C and N losses in urban gardens of a typical Sahelian city from where such data are lacking.

2.3. Materials and methods

2.3.1. Study sites

The measurements were conducted in Niamey (13.5ºN, 2.1ºE, 223 m asl), the capital city of the Republic of Niger. The climate in this southern Sahelian zone is semi-arid with an average annual precipitation of 400 - 600 mm (Wezel and Boecker, 2000) occurring during a single rainy season (June to September). In Niamey, the 30-year average annual rainfall is 542 mm and the daily average temperature peaks in May at 34ºC and drops to 25ºC in December (World Climate, 2008).

In the urban gardens of Niamey of which the total area amounts to 54 ha as determined from aerial and satellite images (Kadaouré, personal communication, 2008), a wide variety of vegetables, herbs, spices and fruits are grown (Bernholt et al., 2009). In an effort to represent the different agro-ecological settings described by Graefe et al. (2008) three garden locations were chosen for our study. Two of these gardens were located on the bank of the River Niger providing water for irrigation of the crops; one of these was in the Goudel city quarter (abbreviated R_1), the second in the Yantala Bas quarter (abbreviated R_2). The third garden was located near a permanently water-carrying affluent to the Niger River (wadi) in the quarter Gountou Yena (W). There, excrement-loaded sewage water was used for irrigation. In the R_1 garden mint (*Mentha* sp.) and hibiscus (*Hibiscus sabdariffa* L.) were cultivated on the experimental plots during the hot dry and rainy season (April – October, 2006) and lettuce (*Lactuca sativa* L.) and cabbage (*Brassica oleracea* L.) were grown from November 2006 till February 2007. Mint was grown during the whole year 2007 and hibiscus occupied one of the three measuring sites in June and July 2007. The main crops on the chosen plots in the R_2 garden were mint and leek (*Allium porrum* L.) (April – July 2006), mint and French beans (*Phaseolus vulgaris* L.) (August – November 2006) and lettuce and leek (December 2006 – February 2007). These were intercropped with mixture of other crops as sweet peeper (*Capsicum annuum* L.), cow pea (*Wigna unguiculata* (L.) Walp.), amaranth (*Amaranthus caudatus* L.), maize (*Zea mais* L.), moringa (*Moringa oleifera* Lam.), celery (*Apium graveolens* L.), parsley (*Petroselinum crispum* (Mill.) Nyman ex A. W. Hill.) and various spices species. Amaranth was the only crop cultivated in the third garden (W) through out the whole measuring period (April 2006 – February 2007). Additionally cabbage was grown in the cold dry season (December 2006 – February 2007). The manual irrigation of the experimental plots with water cans averaged at 5.7 l m^{-2} d^{-1}, 13.2 l m^{-2} d^{-1} and 13.6 l m^{-2} d^{-1} in gardens R_1, R_2 and W, respectively. The highest irrigation rates were observed during the hot dry season reaching 8 l m^{-2} d^{-1}, 27 l m^{-2} d^{-1} and 30 l m^{-2} d^{-1} in gardens R_1, R_2 and W, respectively. For each of these gardens with their specific cropping sequences plot-based nutrient balances were determined by Diogo et al. (2009). In the garden R_1, animal manure was applied at an average rate of 30 t ADW (air dry weight) ha^{-1} together with urea at 17 kg N ha^{-1} two weeks after each replanting of lettuce plants. The mint plots received in average 45 kg ADW ha^{-1} of animal manure approximately every six months. In R_2 garden, the fertilizing management was less regular, the plots with lettuce and mint as a main crop received 17 and 8 t ADW manure ha^{-1}, respectively. Additionally, on some plots urea and NPK were applied once a year at application rates between 70 and 200 kg ha^{-1}. In the garden W, no other fertilizers were applied except the nutrient loaded waste water. The irrigation resulted in cumulative application rates of 650 kg N ha^{-1}, 110 kg P ha^{-1} and 300 kg K ha^{-1} for every cropping period.

On the chosen experimental plots, measurements of gaseous emissions were carried from April 2006 to February 2007 at all three locations and repeated from March to November 2007 in garden R_1.

2.3.2. Experimental set-up

To determine emissions of NH_3, N_2O and CO_2 a closed chamber system composed of a photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark) connected by two 0.5 m long Teflon® tubes as inflow and outflow to a cuvette made of a PVC tube with a diameter of 0.3 m and height 0.11 m was used. To minimize adhesion of gas molecules to the surface, the inside of the cuvette was coated by a self-adhesive Teflon® film (Chemfab Germany GmbH, Cologne, Germany). To obtain tight connection with the measured soil, the cuvette was fitted to a 0.3 m wide and 0.06 m high ring which was firmly pressed about 0.05 m deep into the soil. One cuvette was used for all the measurements, tightly clipped to each ring. The multi-gas monitor was manufacturer-calibrated and set to compensate the cross-interference of gases and water vapor with NH_3, N_2O and CO_2. A sample integration time of 5 s for each gas was chosen for which the lower detection limits were 200 µg kg^{-1} for NH_3, 30 µg kg^{-1} for N_2O and 3.4 mg kg^{-1} for CO_2. After the field experiments in Niamey, verification measurements with defined pure gases and gas mixtures were conducted at Staatliche Umweltbetriebsgesellschaft of Saxony (Radebeul, Germany). These showed errors for NH_3, N_2O and CO_2 of -13%, -12% and 5%, respectively, point to a possible underestimation of N losses.

Inside the cuvette, air humidity and temperature were measured by a digital thermo-hygrometer (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany). This was attached to the cuvette from the outside and only the sensor reached inside the cuvette through a tight screw connector made of PVC. For each gas emission measurement, the soil temperature at 0.05 and 0.1 m depth (in triplicate for each ring) was recorded with a Multi-Digital Thermometer (Carl ROTH GmbH+Co, Karlsruhe, Germany). The actual humidity at 0.06 m depth (in triplicate for each ring) was determined with a tension-humidity meter (INFIELD 7, UMS GmbH, Muenchen, Germany) or gravimetrically (one soil sample per ring taken from 0-0.06 m soil depth). Ambient air temperature and relative humidity was recorded with a data logger HOBO Pro (Onset Computer Corp., Bourne, MA, USA) placed in a standard wooden weather house and rainfall was measured with a manual rain gauge fixed on a metal stick at 1.2 m above ground and emptied regularly.

In each garden, three measuring sites (going to be cropped the whole year long according to the farmer) were selected consisting each of two adjacent plots with an identical crop and management (fertilizer and irrigation). Emission measurements were conducted at each of the three sites during two consecutive days (6 days in total) during the coolest (6 - 8 a.m., further named as morning) and hottest (1 - 3 p.m., further named as afternoon) part of the day in order to capture the expected minimum and maximum of daily emissions. To estimate annual emissions, for each day of assumed sinusoidal distribution of flux rates, measurements of morning and mid-day hours were averaged across the 6-day interval and multiplied by the time span to the next measurement period. Before the first measurements the plants inside of the ring were cut off at a height of about 30 mm above-ground to exclude additional CO_2 emissions from plant respiration. Roots were not removed but left in the soil to avoid disturbance of the soil surface.

At the beginning of the experiment in April 2006 both morning and afternoon measurements lasted for 30 minutes (accumulation period) with two rings placed in each of the two adjacent plots (sub-samples). In order to better account for spatial differences in gas fluxes and to minimize negative feedback effect of prolonged accumulation intervals on concentration readings (Conen and Smith, 1998; Fowler et al., 2001; Hans et al., 2005; Reth et al., 2005a; Reth et al., 2005b) this method was modified after 2 months. The number of rings was increased to six, three on each plot, and the measuring interval shortened to 10 minutes, during which the gas concentrations were measured and recorded by the measuring device nine times at an accumulation period of 62 ± 2 s. After examination of flux rates over time, always the first accumulation period was taken to calculate emissions (see discussion section). Each 10 minute interval was followed by 2 - 3 min of cuvette ventilation (rinsing) allowing fresh air to enter before continuing the measurements on the next ring. To allow measurements to be conducted at exactly the same location throughout the year, all measurement points were marked. The rings were placed on the plots at the first day of the 6-day long measuring period. The gaseous losses were determined eight times in each garden in 2006 and nine times in R_1 garden in 2007.

In each garden five samples of 100 cm^3 were taken from the topsoil (0-0.2 m) for the estimation of bulk density. To analyze the effects of management on soil chemical properties, at the beginning of each measurement period additional soil samples were taken from the same depth in all gardens, air dried and subsequently analyzed for Corg, total N and mineral N.

2.3.3. Data analysis

Flux rates of NH_3, N_2O and CO_2 emissions were calculated by subtracting the gas concentration at the beginning of the accumulation period from the concentration at the end of the accumulation period and dividing the result by the time elapsed. Negative emission rates which occasionally occurred for NH_3 and N_2O were set to zero.

F-statistics to compare treatment effects on gas emission rates over time were carried out with SPSS 11.5 (Backhaus et al., 2003). To facilitate data interpretation, none of the datasets was transformed even if slight deviations from normal distribution of residuals occurred in some datasets; the reported P-values are thus only approximate.

2.4. Results

2.4.1. Ambient conditions

During the hot dry season maximum ambient temperature in garden R_1 reached 48°C and the daily average of relative air humidity was 37%. During the rainy season maximum daily air temperatures varied from 35 to 41°C and minima from 23 to 29°C. Relative humidity fluctuated between almost 100% after a rainfall event to 41% during days without rainfall. During the cold dry season, the highest and lowest ambient air temperature was 34°C and 10°C, respectively, and daily average of relative air humidity declined to 26%.

Afternoon soil temperatures in the upper 0.05 m of the studied soils ranged from 31 to 40°C during the hot dry season and from 22 to 29°C during the rainy season (Figure 1a). From November onwards, morning temperatures in the three gardens decreased to 15-20°C while afternoon soil temperatures in garden W dropped to lower values (17.5°C) than in the other two gardens situated near the river (22°C and 20°C for R_1 and R_2, respectively).

In 2006 local rainfall totaled 362 mm in garden R_1 and 404 mm in garden R_2 while in 2007 a total of 425 mm was recorded in garden R_1; thus both years were very dry as compared to the annual mean.

The texture of all three garden's topsoil (0-0.2 m) was very coarse with sand contents of 96%, 72% and 89% for garden R_1, R_2, and W, respectively (Figure 2). The topsoil of the garden W had with 1.4 g cm^{-3} the lowest bulk density in comparison to 1.5 g cm^{-3} in the gardens R_1 and R_2. The soil in garden R_2 had a leached horizon in the lower half of the profile (depth 0.6-1.0 m), and the clay and fine silt particles fraction reached 28% at 0-0.2 m, 33% at 0.2-0.5 m and 36% at both 0.5-0.8 and 0.8-1.0 m depth. According to the FAO soil classification, the three soils were a Cambic Fluvisol (R_1), a Haplic Luvisol (R_2) and an Arenosol (W).

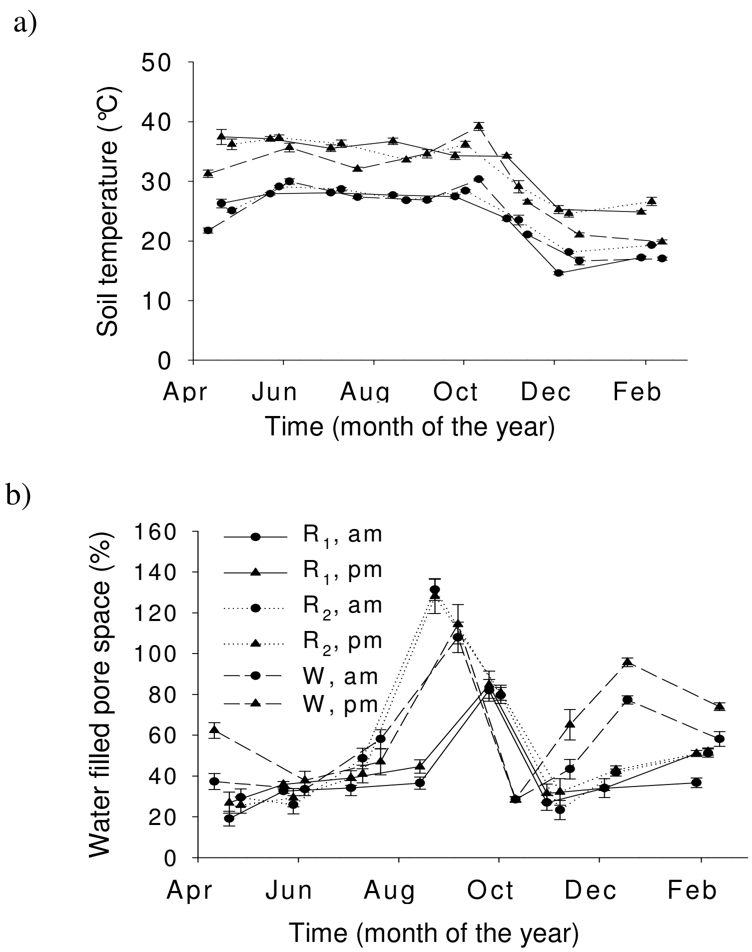

Figure 1. (a) Soil temperature at 0.05 m depth and (b) calculated water-filled pore space (WFPS) of the soil in the two studied river gardens in Goudel (R_1) and Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger (2006/7). Data points are means of 24 replications and vertical bars indicate ± one standard error of the mean.

Soil pH changed little throughout the typical profile (Graef and Stahr, 2000) in gardens R_1 and R_2 while in garden W it increased from 5.7 to 7.3 (Table 1). The high total phosphorus (P) values of 1045 mg P kg^{-1} in the topsoil of garden W were also reflected in the highest concentration of plant available P (255 mg P Bray kg^{-1}) which was 30-40 times higher than in the typical Arenosols of SW Niger. Although total P in garden R_2 was higher throughout the entire soil profile than in garden R_1, P-Bray values in the upper half of the profiles of these two gardens were similar.

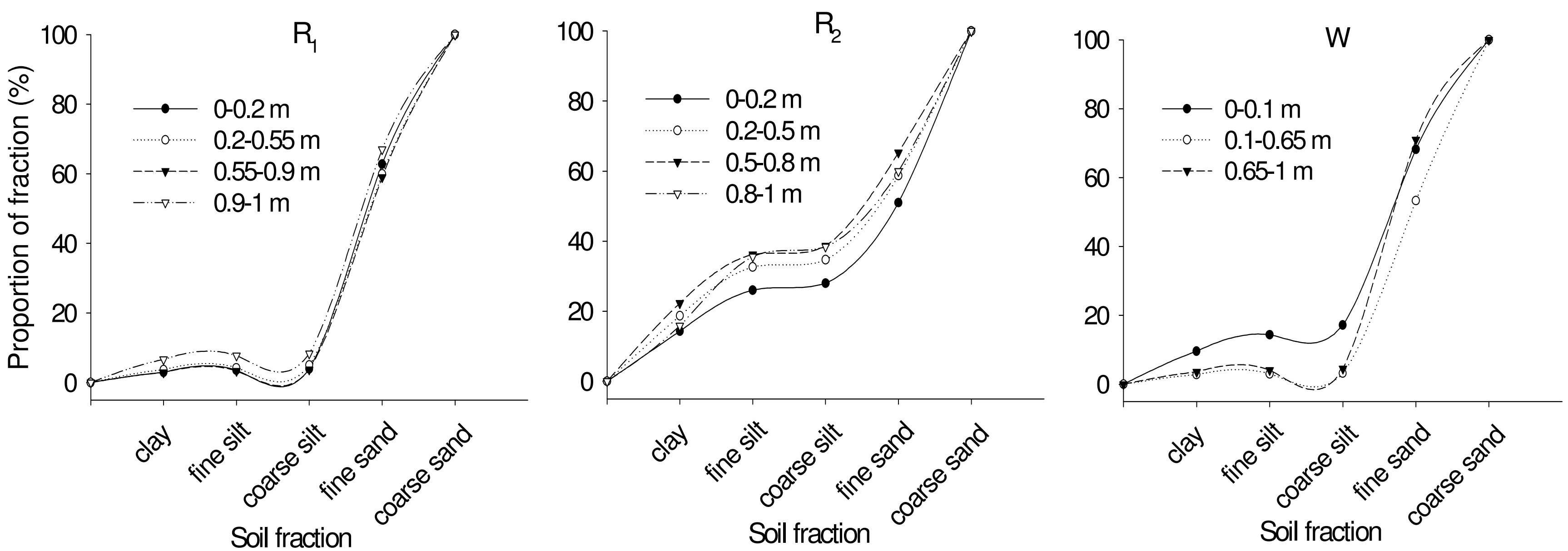

Figure 2. Particle size distribution of the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger. Classes of particle size were: clay < 0.002 mm, fine silt 0.002-0.02 mm, coarse silt 0.02-0.05 mm, fine sand 0.05-0.2 mm and coarse sand 0.2-2 mm.

Table 1. Selected properties of the soil profiles of the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger. Data are from one pooled sample representing three sub-samples per site.

Garden	Depth (m)	pH-KCl	Total-P (mg kg^{-1})	P Bray (mg kg^{-1})	Corg (%)	CEC	Exchangeable cations (cmol kg^{-1}) Al^{3+}	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}
Goudel (R_1)	0.00-0.20	6.1	226	41	0.27	2.92	0.00	0.12	0.15	1.80	0.82
	0.20-0.55	6.2	219	51	0.09	2.92	0.00	0.09	0.15	1.66	1.01
	0.55-0.90	6.3	193	44	0.03	1.94	0.00	0.06	0.16	1.25	0.45
	0.90-1.00	6.3	249	76	0.10	3.75	0.00	0.13	0.34	2.31	0.94
Yantala Bas (R_2)	0.00-0.20	6.7	572	41	0.96	9.57	0.00	0.83	0.30	5.74	2.63
	0.20-0.50	6.7	456	53	0.27	9.57	0.00	1.18	0.21	5.42	2.73
	0.50-0.80	6.5	278	21	0.10	9.73	0.00	1.93	0.21	4.53	3.03
	0.80-1.00	6.6	522	9	0.06	11.34	0.00	3.22	0.08	4.32	3.69
Gountou Yena (W)	0.00-0.10	5.7	1045	255	0.89	6.75	0.00	0.58	0.31	4.49	1.28
	0.10-0.65	6.9	222	67	0.03	2.49	0.00	0.20	0.19	1.86	0.22
	0.65-1.00	7.3	207	44	0.04	3.13	0.00	0.33	0.11	2.41	0.26

The water-filled pore space (WFPS) calculated from volumetric soil water content didn't differ much between morning and afternoon measurements, except for garden W in the cold dry season (Figure 1). Organic carbon content of the top soil (0 – 0.2 m) was stable during the year in the river gardens ranging between 3.6 – 4.9 g Corg kg^{-1} soil and 6.2 – 9.0 g C org kg^{-1} soil for R_1 and R_2, respectively. In the W garden the during hot dry season relatively low Corg content (6.1 and 4.3 g kg^{-1} soil) has increased rapidly during the rainy season up to 10.4 g Corg kg^{-1} soil. For all soils the C/N ratio was lowest in the hot dry season and increased with the onset of the rainy season (Figure 3).

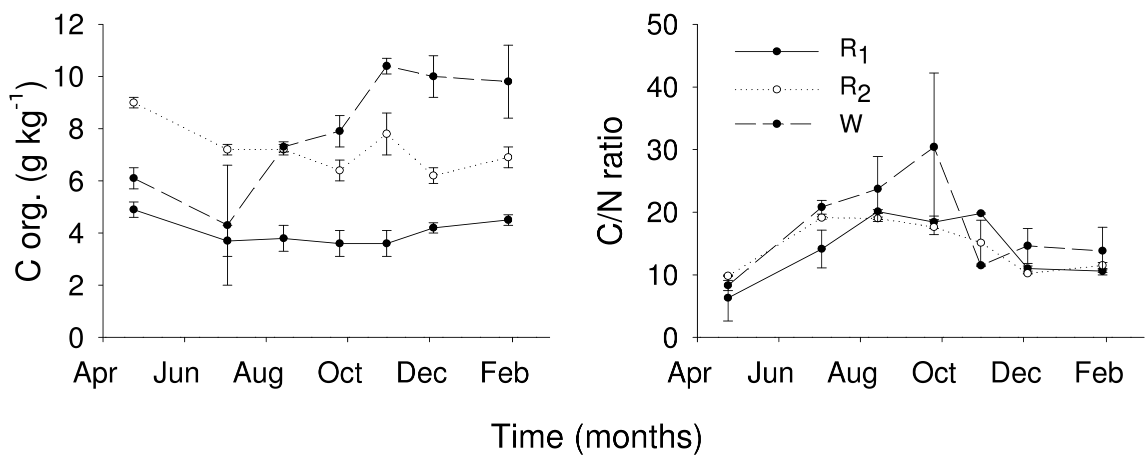

Figure 3. Organic C (Corg) concentration and C/N ratio of the topsoil (0-0.2m) of the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger (2006/2007). Data points are means of 3 replications (for each six sub-samples were pooled) and vertical bars indicate ± one standard error of the mean.

Throughout the year except in July, the Nmin concentration of the surface soil in garden W was significantly higher ($P < 0.001$) than Nmin concentrations in the two gardens on the river banks and it continually increased from the rainy season to the beginning of the hot dry season (Figure 4). While NH_4-N was with an average of 60% dominating the mineral N pool in garden R_1, it accounted for only 38% of Nmin in garden R_2. In garden W, in contrast, NO_3-N dominated the Nmin pool with 73%.

The partial horizontal nutrient balances for 2006 and 2007 indicated very high surpluses of N, P and K at all three sites, particularly in the most intensively managed garden W, where heavily contaminated sewage water was used for irrigation (Table 2).

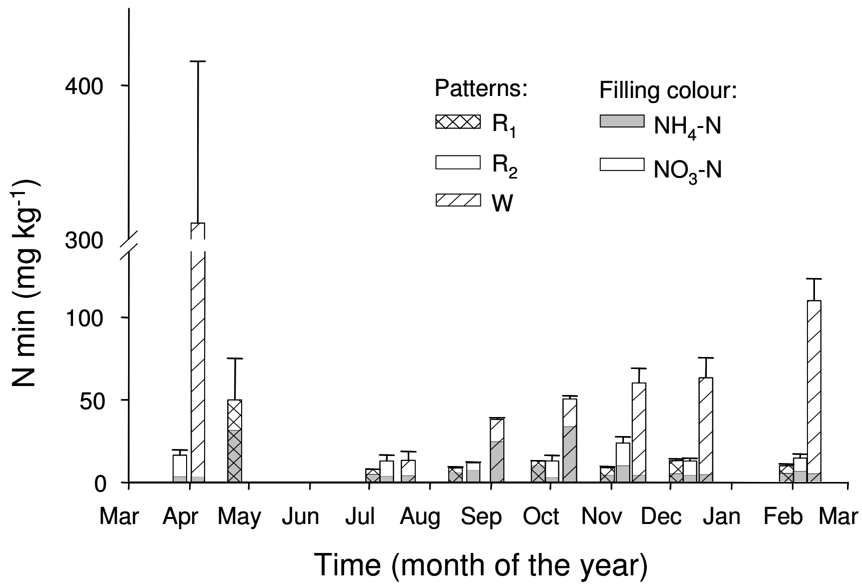

Figure 4. Mineral nitrogen (N min) in the top soil (0 – 0.20 m) of the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger (2006/20077). Data points are means of three replications (six pooled sub-samples per replication) and vertical bars indicate ± one standard error of the mean.

Table 2. Annual input and output of N, P and K of the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger. Averages across two years (2006 and 2007).

Garden	Source/process	Input (kg ha^{-1} yr^{-1})			Output (kg ha^{-1} yr^{-1})		
		N	P	K	N	P	K
Goudel (R_1)	Manure	443	192	433			
	Urea	28	na	na			
	Irrigation water	2	12	81			
	Crop harvest				104	27	242
	Total	473	204	515	104	27	242
	Partial balance	**369**	**177**	**273**			
Yantala Bas (R_2)	Manure	572	141	552			
	Urea	186	na	na			
	NPK	20	20	20			
	Irrigation water	4	8	257			
	Crop harvest				189	34	354
	Total	782	169	829	189	34	354
	Partial balance	**593**	**135**	**475**			
Gountou Yena (W)	Irrigation water	3816	644	2019			
	Crop harvest				829	131	1043
	Total	3816	644	2019	829	131	1043
	Partial balance	**2987**	**513**	**976**			

2.4.2. Gaseous emissions 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. With weekly averages ≤ 5 g N ha^{-1} h^{-1} morning emissions of NH_3-N and N_2O-N did not vary much between gardens and throughout the year, whereas afternoon emissions of both N-forms greatly varied throughout the year and were at all sites highest in the summer months (Figure 5).

NH_3 fluxes

In 2006, NH_3 emissions in garden R_2 peaked with 10 g NH_3-N ha^{-1} h^{-1} in June, while in garden R_1 maximum flux rates were reached in August. In April the mean afternoon NH_3 emissions in garden W were more than four times higher than at the other two locations ($P < 0.001$), 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 cold dry season. In 2007, in contrast NH_3 emissions in garden R_1 already reached their maximum before the first rain.

N_2O fluxes

Throughout the year, N_2O-N emissions from gardens R_1 and R_2 were negligible during the cooler part of the day, but, similarly to NH_3-N, rose in the afternoon, especially at the onset of the rains in June 2006. In 2007, N_2O emissions in garden R_1 reached their maximum before the beginning of the rainy season. In garden W afternoon emissions of N_2O-N during the hot dry season followed the pattern of NH_3-N fluxes. After high 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 ($P < 0.001$).

In the gardens using river water for irrigation, the ratio of N losses in NH_3 and NO_2 was 1:1 (R_1 in the year 2006) or slightly dominated by NH_3 (R_1 in 2007 and R_2 in 2006). In contrast, N_2O was with 68% the main form of N gaseous losses in the garden using sewage water for irrigation (Table 3). The very large estimated N annual losses in the garden using untreated sewage water are reflecting the high N concentration in this untreated liquid (120 mg N l^{-1}).

CO_2 fluxes

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 6). In gardens 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 - 3.4 kg CO_2-C ha^{-1} h^{-1} substantially lower.

Table 3. Annual gaseous nitrogen (N) and carbon (C) losses in the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger. Displayed are means throughout the year with their respective standard errors during 2006 (all gardens) and 2007 (garden R_1 only).

Garden/year	Gas	Morning		Afternoon		Estimated annual losses
		Mean	stand.error	mean	stand.error	
			(kg ha^{-1} yr^{-1})			(ha^{-1} yr^{-1})
R_1 2006	NH_3-N	13	2.4	42	11.8	53 kg N
	N_2O-N	7	1.1	43	10.6	
	CO_2-C	20349	2487	28833	3060	25 Mg C
R_1 2007	NH_3-N	17	1.0	43	3.4	56 kg N
	N_2O-N	8	1.1	44	8.0	
	CO_2-C	24262	1779	36326	1930	30 Mg C
R_2 2006	NH_3-N	17	2.4	40	7.7	48 kg N
	N_2O-N	6	0.8	34	6.7	
	CO_2-C	17358	1562	22056	2055	20 Mg C
W 2006	NH_3-N	15	2.1	42	21	92 kg N
	N_2O-N	14	2.8	112	34	
	CO_2-C	19906	3297	32557	4487	26 Mg C

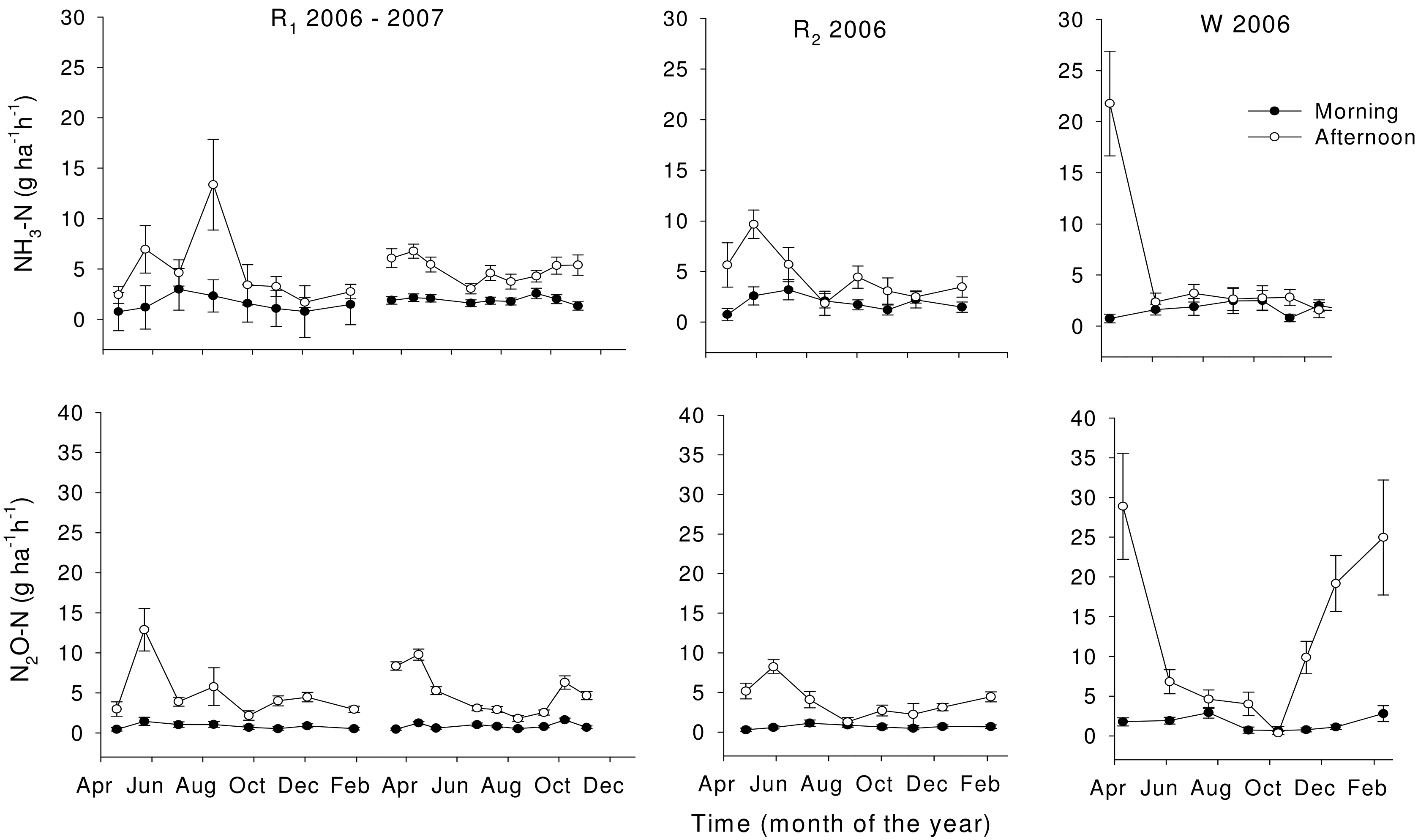

Figure 5. Flux rates of NH_3-N and N_2O-N during morning and afternoon hours in the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger. Displayed are means of 72 weekly measurements with their respective standard errors during 2006 (all gardens) and 2007 (garden R_1 only).

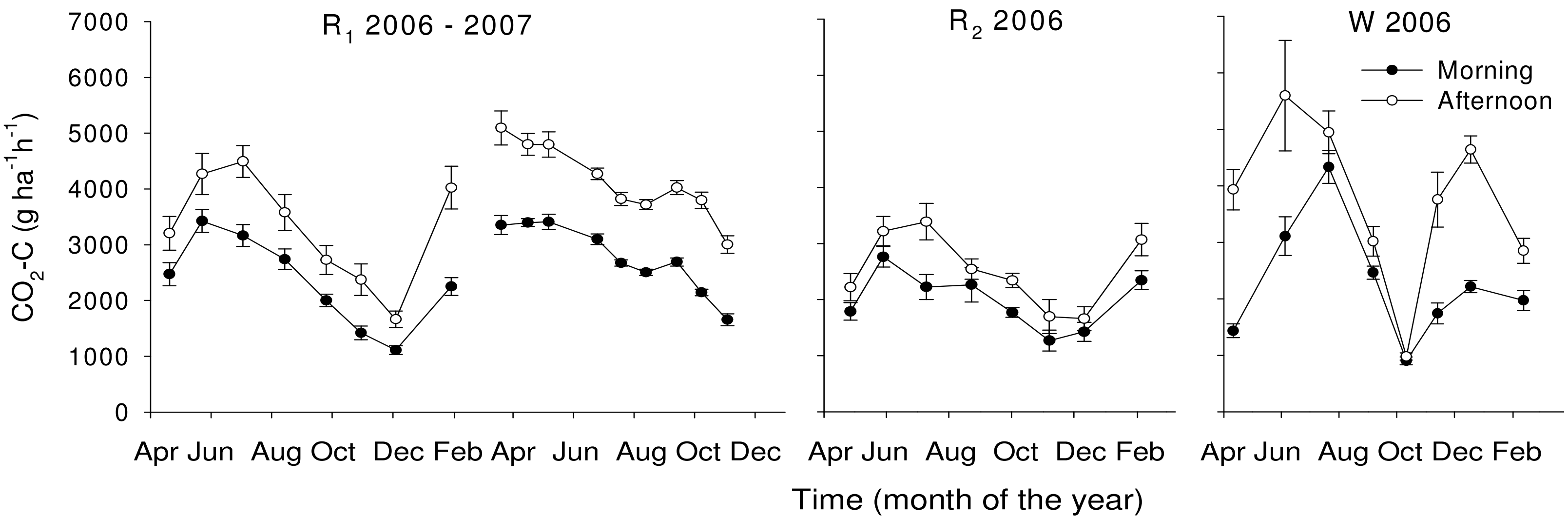

Figure 6. Flux rates of CO_2-C during morning and afternoon hours in the two studied river gardens in Goudel (R_1), Yantala Bas (R_2) and the wadi garden in Gountou Yena (W), Niamey, Niger. Displayed are means of 72 weekly measurements with their respective standard errors during 2006 (all gardens) and 2007 (garden R_1 only).

2.5. Discussion

The intensive vegetable production in UPA gardens of Niamey with 4-5 harvests of lettuce *(Lactuca sativa)* during the cold dry season in R_1 and R_2 and up to 9 annual harvests of amaranth *(Amaranthus caudatus)* in W is characterized by high nutrient inputs (Table 2), year-round irrigation and continuous cropping with only very short or no fallow periods. This is in sharp contrast to the rain-fed millet and cowpea cropping systems in rural areas of Niger, which for the most part hardly receive any chemical fertilizer and also only modest amounts of manure (Bationo and Mokwunye, 1991; Bationo and Buerkert, 2001; Schlecht et al., 2006). This is also reflected in the high pH, Corg, P-Bray, Nmin and CEC values of the UPA soils as compared to millet fields in SW-Niger (Buerkert et al., 2000; Bationo and Buerkert, 2001).

The daily irrigation and the dense vegetation cover of garden soils during most of the year, except for some fallowed plots in a few gardens during the hottest part of the year, locally buffer the effects of extremes in ambient air temperature and relative humidity on soil turnover processes. During the hot dry season, the average maximum ambient air temperature recorded at the AGRHYMET Center in an urbanized part of Niamey was 7°C higher and in the cold dry season 2°C lower than at the garden R_1.

The observed effect of temperature (Maag and Vinther, 1996; Dobbie and Smith, 2001; Mosier and Parkin, 2007) on flux rates of all gases was similar to those reported by Hans et al. (2005) for Oman.

The average total N input in the gardens R_1 and R_2 was 473 and 782 kg N ha^{-1} yr^{-1} of which 95% and 73%, respectively, were applied in the form of manure and urea (Table 2). The continuously moist soil conditions in the gardens together with the high air temperatures are likely to enhance the decomposition of applied OM reported to be heavily termite-dependent in millet fields (Bationo and Buerkert, 2001; Esse et al., 2001). In garden W the only N input came from the irrigation sewage water (3816 kg N ha^{-1} yr^{-1} at an average N concentration of 120 mg l^{-1}), no other fertilizers were applied.

The mean calculated NH_3-N fluxes in the three gardens ranged from 13 to 17 kg NH_3-N ha^{-1} yr^{-1} in the morning and from 40 to 42 kg NH_3-N ha^{-1} yr^{-1} in the afternoon. These emissions largely exceeded the values reported by Hans et al. (2005) who estimated gaseous N losses from a heavily manured, irrigated alfalfa field in Oman at 4 and 37 kg NH_3-N ha^{-1} yr^{-1} in the morning and at mid-day, respectively and average ammonia emissions from arable crops estimated at 1-2 kg NH_3-N ha^{-1} yr^{-1} by Kirchmann (1998). The high N emissions in our study may be partly due to the high N input levels in the studied UPA gardens of Niamey which reached 473-782 kg N ha^{-1} yr^{-1} in the gardens irrigated with river water and 3816 kg N ha^{-1} yr^{-1} in garden W with sewage water irrigation. Studies by Meisinger and Jokela, (2000) showed that surface application of N-fertilizers in hot climates often results in very high immediate losses of ammonia.

On the gardens' irrigated sandy soils with their high organic matter concentrations in the topsoil, aerobic and anaerobic conditions may alternate in time or over short distances which may increase N emissions as nitrification and denitrification both contribute to N_2O-N emissions (Degens and Sparling, 1995; Paustian et al., 2000; Akiyama and Tsuruta, 2003). As it is well known that the spatial distribution of anaerobic microsites and macro-aggregates of soil OM can lead to high variation of N_2O-N fluxes (Paustian et al., 2000; Velthof et al., 2000; Kroeze et al., 2003), the differences in N_2O-N fluxes between the 3 x 2 plots of our study location as reflected in the relatively high standard errors seem reasonable. Measured N_2O-N flux rates ranged from 6 to 14 kg ha^{-1} yr^{-1} in the morning and from 34 to 112 kg ha^{-1} yr^{-1} in the afternoon and peaked at a WFPS of 60-100% in garden W. Similar results were obtained by Ruser et al. (2006) who reported highest N_2O-N emissions at 70% and 90% WFPS. Dobbie and Smith (2001) in contrast observed an increase of N_2O-N emissions at a WFPS from 60 to 80%. In our study, emissions tended to decrease during the rainy season and rapidly increased again after the rain stopped following the nitrate (NO_3^-) concentration in the topsoil (Figure 4). In all three gardens, WFPS peaked in the mid-rainy season and exceeded 100% for gardens R_2 and W indicating an over-saturation of the topsoil caused by an apparently slow percolation in garden R_2 and flooding in garden W bordering the wadi.

Average afternoon emissions of N_2O-N reaching 43, 34 and 112 kg N ha^{-1} yr^{-1} in gardens R_1, R_2 and W, respectively, were several times higher than respective values reported by van Groenigen et al. (2004) for sandy soils in the Netherlands after the application of slurry and fertilizer. With values equivalent to 18 kg N ha^{-1} yr^{-1} Hans et al. (2005) also reported lower N_2O-N fluxes than those measured in the urban gardens of Niamey.

The wide range of the C/N ratio in gardens R_1 and R_2 likely reflected the uneven application of manure and mineral fertilizer to different crops, whereas the organic material deposited by floods in affected areas during heavy rains is probably responsible for the increase of Corg and high variation of the C/N ratio in garden W (Figure 3).

The intensive vegetable cropping with short cultivation periods, high OM inputs, fast turnover of what under the warm and moist conditions in the gardens' microclimate may be responsible for the high CO_2 fluxes observed. Contributing to this could be rewetting effects in the surface soil (after the daily irrigation), which are known to accelerate the mineralization of OM by disturbing the macro-aggregates and consequently releasing aggregate-associated Corg (Paustian et al., 2000; Ruser et al., 2006; Formowitz et al., 2007).

An important determinant of the flux measurements with our set-up was the duration of the gas accumulation interval in the cuvette. Published interval durations vary from 2 to 5 minutes (Hans et al., 2005; Reth et al., 2005a,b) until 1 h (Velthof et al., 2002, 2003; van Groenigen et al., 2004, 2005). Under the conditions of our study, within 3 min the air temperature in the cuvette, even if shaded, increased by up to 3℃, relative humidity reached 100% and water vapor started condensing in the inside of the cuvette. Therefore for the calculation, readings of flux rates were already taken during the first accumulation period (after 1 min of cuvette coverage). Such short accumulation intervals may have led to an underestimation of fluxes on abandoned plots or for morning measurements in cultivated gardens during the cold season when low flux rates would possibly need a longer accumulation time to be better detectable by our set-up.

2.6. Conclusions

Although the combined annual N losses from NH_3 and N_2O estimated at 50 kg N ha^{-1} for gardens with river irrigation water (R_1 and R_2) and at 90 kg N ha^{-1} for the garden irrigated with the heavily N-loaded sewage water (W) exceeded the losses reported from other studies, they may simply reflect the high N input used in urban gardening at Niamey. As such they only account for 11%, 6% (R_1 and R_2, respectively) and 2.5% (W) of applied N, respectively. The high gaseous N losses confirmed our hypothesis that gaseous emissions are an important component of nutrient balances in UPA of sub-Saharan Africa. The real N losses might be even higher if the emissions of NO_x and N_2 were added, which our set-up was unable to detect. The high gaseous N and C flux rates especially during the onset of the rains suggest considerable scope for improvement in management practices and at the same time show the important role of OM recycling in compensating C losses. The incorporation in soil of manure and compost immediately after application and re-scheduling of irrigation during early morning and evening hours rather than around noon may lead to a large increase in resource use efficiency and lower emission rates in the studied high-input-high-output UPA systems.

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Chapter 3.

Nitrogen and carbon losses from dung storage in urban gardens of Niamey, Niger

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3.1. Abstract

Intensive vegetable production in urban and peri-urban agriculture (UPA) of West African cities is characterized by high nutrient inputs, resulting in positive horizontal nutrient balances. However, little is known about carbon (C) and nitrogen (N) losses in these systems, in particular during the storage of manure, the main organic fertilizer in these systems. We therefore aimed at quantifying gaseous emissions of ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) and leaching losses of C, N, phosphorus (P) and potassium (K) from animal manure stored in vegetable gardens of Niamey, Niger. During a first 3.5-month experiment in the hot dry season, cumulative gaseous N losses, measured with a closed-chamber system, 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 to 72% of the control under plastic sheet roofing and to 50% under roofing + ground rock phosphate (RP) application at 333 g 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. In a second 3.5-month experiment conducted in the rainy season, C losses from the control were 164 g kg^{-1} manure DM and declined 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, 0.07 g P and 1.8 g K kg^{-1} manure DM.

Keywords: Africa, gaseous emissions, nutrient leaching, rock phosphate, ruminant manure, urban agriculture

3.2. Introduction

From 1930-1990 the urban population in West Africa has grown at an annual rate of 4% and by 2020 63% of the total population of West Africa is expected to live in towns (Drechsel et al., 2005). Concomitantly the role of agricultural production within and at the periphery of urban areas has been rapidly rising as it provides food and employment for the urban population. Recent studies have shown that UPA supplies 10-90% of fresh vegetables, up to 70% of meat and up to 100% of eggs on the city markets (Maxwell, 1995; Madaleno, 2000; Cofie et al., 2003; Drechsel et al., 2005). The proportion of urban households involved in UPA varies from 10-57% (Ellis and Sumberg, 1998; Howorth et al., 2001; Asomani-Boateng, 2002; Cofie et al., 2003) and so does production intensity and resource use efficiency. Sometimes, high levels of inputs used in the vicinity of human settlements have been reported to cause serious problems to human health and the environment (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).

Unless used otherwise, dung produced in UPA animal husbandry is an important source of nutrients and C for urban farmers (Graefe et al., 2008); however, a recent report from sub-Saharan Africa shows that manure use in UPA gardening is accompanied by substantial gaseous and leaching losses of N (Predotova et al., *revised*). Although according to FAO (2001) the total nutrient application to African crops and grasslands contributes only 12%, 9% and 3% to the global emissions of N_2O-N, NO-N and NH_3-N, respectively, and is thus globally of little environmental relevance, proper dung handling may strongly improve the nutrient use efficiency at the farm level.

Within the context of a larger effort to increase resource use efficiency in UPA, this study was conducted to quantify gaseous emissions of C and N as well as run off and leaching loses of C, N, P and K from dung heaps in market-oriented gardening systems of a typical Sahelian town and to experimentally test approaches that could decrease such losses.

3.3. Materials and Methods

3.3.1. Experimental setup

The present dung storage experiment was conducted in Goudel*,* an inner-city quarter of Niamey (13.5ºN, 2.1ºE, 223 m a.s.l.), capital city of the Republic of Niger. The local southern Sahelian climate is semi-arid, with an average annual precipitation of 400 - 600 mm distributed unimodally from June to September; the 30-year average annual rainfall is 542 mm. Daily average temperatures peak at 34ºC in May and drop to 25ºC in December (World Climate, 2008).

The experiment consisted of two periods of 3.5-months duration each. The first period started with the heaping of dung in the hot dry season (beginning of April 2007), the second dung heaping started at the onset of the rainy season (mid-July 2007). 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: (i) heaps without cover (treatment C, 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 (treatment R); and (iii) manure homogeneously mixed with finely ground Tahoua rock phosphate (RP) (10.3% P at 19.3% solubility in citric acid and 34% solubility in formic acid; Truong et al., 1978; McClellan and Notholt, 1986; van Straaten, 2002) at a rate of 333 g rock powder kg^{-1} manure DM and roofed as in (ii) (treatment RP). 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. The sheet ended in a gutter from where run-off liquid was drained through a 2 mm mesh into a 2 l collecting container which contained 5 ml of 0.1M HCl to minimize N volatilization. The three treatments were arranged in a completely randomized design with four replications per treatment.

3.3.2. Measurements of nutrient losses

Gaseous C and N emissions from the manure heaps and dung decomposition were determined 7 times during each 3.5 months period, namely at the first two days of weeks 1, 2, 4, 6, 9, 12, and 15, while the run-off was assessed whenever it occurred after a rainfall event.

To determine flux rates of ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4), a closed chamber system composed of a photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark; Kauppinen et al., 2004; Zhang et al. 2005) connected by two 0.5 m long Teflon® inflow and outflow tubes to a PVC cuvette with a diameter of 0.3 m and height of 0.11 m was used (Predotova et al., 2009). To minimize adhesion of gas molecules to the surface, the inside of the cuvette was coated by a self-adhesive 0.5 mm Teflon® film (Splengler Fluorkunststoffe GmbH & Co. KG, Wuppertal, Germany). To ensure tight connection with the measured dung surface, the cuvette was fitted to a 0.3 m wide and 0.06 m high ring which was firmly pressed about 0.03 m deep into the dung heap.

The multi-gas monitor was manufacturer-calibrated and set to compensate cross-interferences of gases and water vapor with NH_3, N_2O, CO_2 and CH_4. A sample integration time of 5 s for each gas was chosen for which the lower detection limits were 200 µg kg^{-1} for NH_3, 30 µg kg^{-1} for N_2O, 3.4 mg kg^{-1} for CO_2 and 400 µg kg^{-1} for CH_4. Inside the cuvette the air humidity and temperature was measured with a thermo-hygrometer (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany) and the ambient air temperature and humidity was recorded during measurement periods by a HOBO Pro data logger (Model H08-032-08, Onset Corp., Bourn, MA, USA) at 1 min intervals. Each measurement time lasted for two consecutive days for which flux rates were recorded during the coldest (6-8 a.m.) and hottest (1-3 p.m.) part of the day. Measurements were taken once per heap by reading flux rates during 1 min accumulation periods continuously for five minutes on the top of the heap.

Validation measurements with defined pure gases and gas mixtures conducted at Staatliche Umweltbetriebsgesellschaft of Saxony (Radebeul, Germany) showed errors for NH_3, N_2O, CO_2 and CH_4 of -13%, -12%, 5% and -2% respectively, resulting in a possible underestimation of N losses and a slight overestimation of C losses with our setup.

To determine dung decomposition rates, litter bags made from nylon with a mesh size of 0.2 mm were filled with 50 g (fresh weight, corresponding on average to 21.4 g DM) of dung, numbered, attached to a string and inserted into the dung heap. On day 1 of each gas measurement period, one bag from each heap was pulled out, homogenized and frozen (-18°C) until analysis of dry matter (DM), organic matter (OM) and N. Dry matter was analyzed by drying the samples at 105°C for at least 6.5 hours, OM by burning at 550°C for 8 hours and N was measured colorimetrically by salicylate / nitroprusside method (Houba et al., 1995).

The amount of leached liquids was measured immediately after each rainfall by emptying the collection container into a graded volumetric flask. A sample of 100 ml of the drained liquid was collected into 150 ml flasks and stored frozen (-18°C) until analysis of N, P and K as described by Houba et al. (1995) and Corg by the Walkley-Black method (van Reeuwijk, 1993).

3.3.3. Data analysis

Flux rates of NH_3, N_2O, CO_2 and CH_4 emissions were calculated by subtracting the gas concentration at the beginning of the accumulation period from the concentration at the end of the accumulation period and dividing the result by the time elapsed during the interval. Small negative emission rates which occasionally occurred during the morning measurements in the second half of each 3.5-months experiment were set to zero (Predotova et al., 2009). To estimate cumulative losses, a sinusoidal distribution of the gaseous emissions was assumed with the highest and lowest fluxes during the hottest and coldest part of the day. The results of the morning and afternoon measurements were averaged for each replicate separately across the 2 day measurement interval and multiplied by the time span to the next measurement period.

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F-statistics to compare treatment effects on gas emission rates over time were carried out with SPSS 11.5 (Backhaus et al., 2003). To facilitate data interpretation, none of the datasets was transformed even if slight deviations from normal distribution of residuals occurred in some datasets; F-values are thus only approximate.

To collect information about UPA farmers' practices of dung management, the experiment was accompanied by structured interviews conducted with 215 farmers located in different quarters of Niamey.

3.4. Results

3.4.1. Seasonal and treatment effects on gaseous emissions

During the hot dry season, the average ambient air temperature at the experimental site was 34°C with a maximum of 45°C and a minimum of 21°C. During the rainy season, the temperature averaged 30°C (range: 20 - 39°C). The rainfall in 2007 amounted to 425 mm (Figure 1) of which 25% unexpectedly occurred during the first period of the dung storage experiment, with one intensive rain event at the end of May yielding 23 mm.

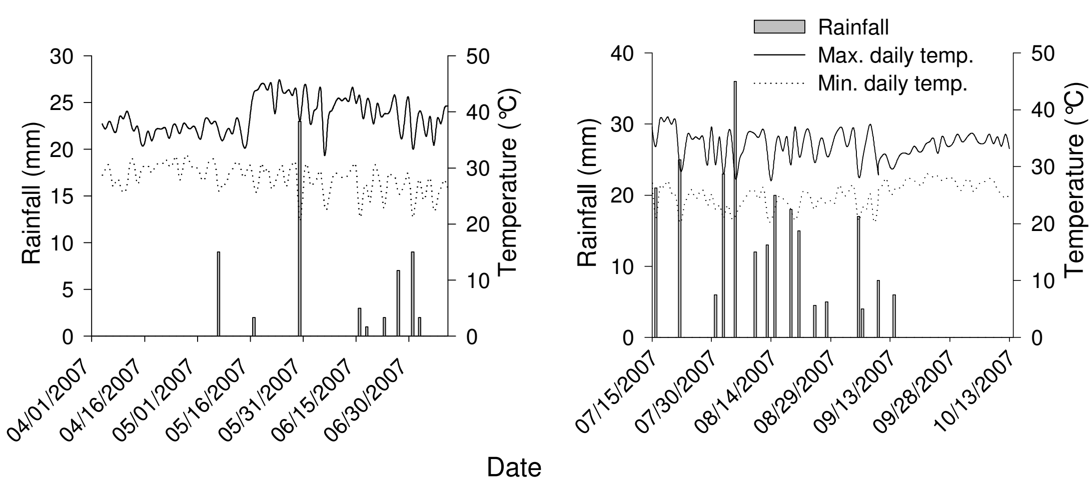

Figure 1. Daily maximal and minimal temperatures (°C) and rainfall (mm) during the hot dry (left) and rainy (right) season in 2007 in the Goudel quarter in Niamey, Niger

During the hot dry season the major form of gaseous N emissions was NH_3–N of which 49 - 82% occurred during the evening the experiment was installed and during the first week of dung storage. Volatilization losses were highest in the R and C treatments and occurred especially during afternoons with their high temperatures (Figure 2). Similarly to NH_3-N, the major portion of the N_2O-N losses occurred during the same evening when the experiment was installed and the following morning. Fluxes of CO_2-C and CH_4-C, in contrast, did not differ much between morning and afternoon hours, but the decrease of emission rates over the duration of the experiment was as fast as for N. During the hot dry season between 31 - 43% of CO_2-C and 16 - 21% of CH_4-C were lost during the first week of the experiment.

During the rainy season, N losses in form of NH_3 and N_2O peaked immediately after the installation of the experiment. From the second week onwards flux rates were below 0.7 and 0.3 mg m^{-2} h^{-1}, respectively (Figure 3). During the first experimental week CO_2-C losses amounted to 13 - 28% of total C losses; they were substantially higher during the hot dry than during the rainy season. After an initial peak CH_4-C emissions decreased slowly over the course of the experiment. Methane losses from control heaps (C) were much higher ($P < 0.05$) than for the two other treatments during weeks 1, 4 and 6.

For treatments R and C, total NH_3-N losses during the hot dry season were significantly higher ($P < 0.05$) than during the rainy season (Figure 4). In the hot dry season, roofing in combination with the addition of RP led to large decreases in NH_3-N losses as compared to the two other treatments. Total N_2O-N emissions were similar in both seasons and amounted to 19%, 18% and 28% of the total gaseous N losses in treatments C, R and RP, respectively. Across all treatments CO_2-C emissions were significantly higher ($P < 0.05$) in the rainy season than in the hot dry season, reaching a cumulative value of 3.8 kg CO_2-C m^{-2} 106 d^{-1}, 3.2 kg CO_2-C m^{-2} 106 d^{-1} and 4.9 kg CO_2-C m^{-2} 106 d^{-1} for treatments R, RP and C, respectively. The cumulative CH_4-C losses were with 27.2 g CH_4-C m^{-2} 106 d^{-1} twice as high for the untreated control as for R and RP in the rainy season (Figure 4).

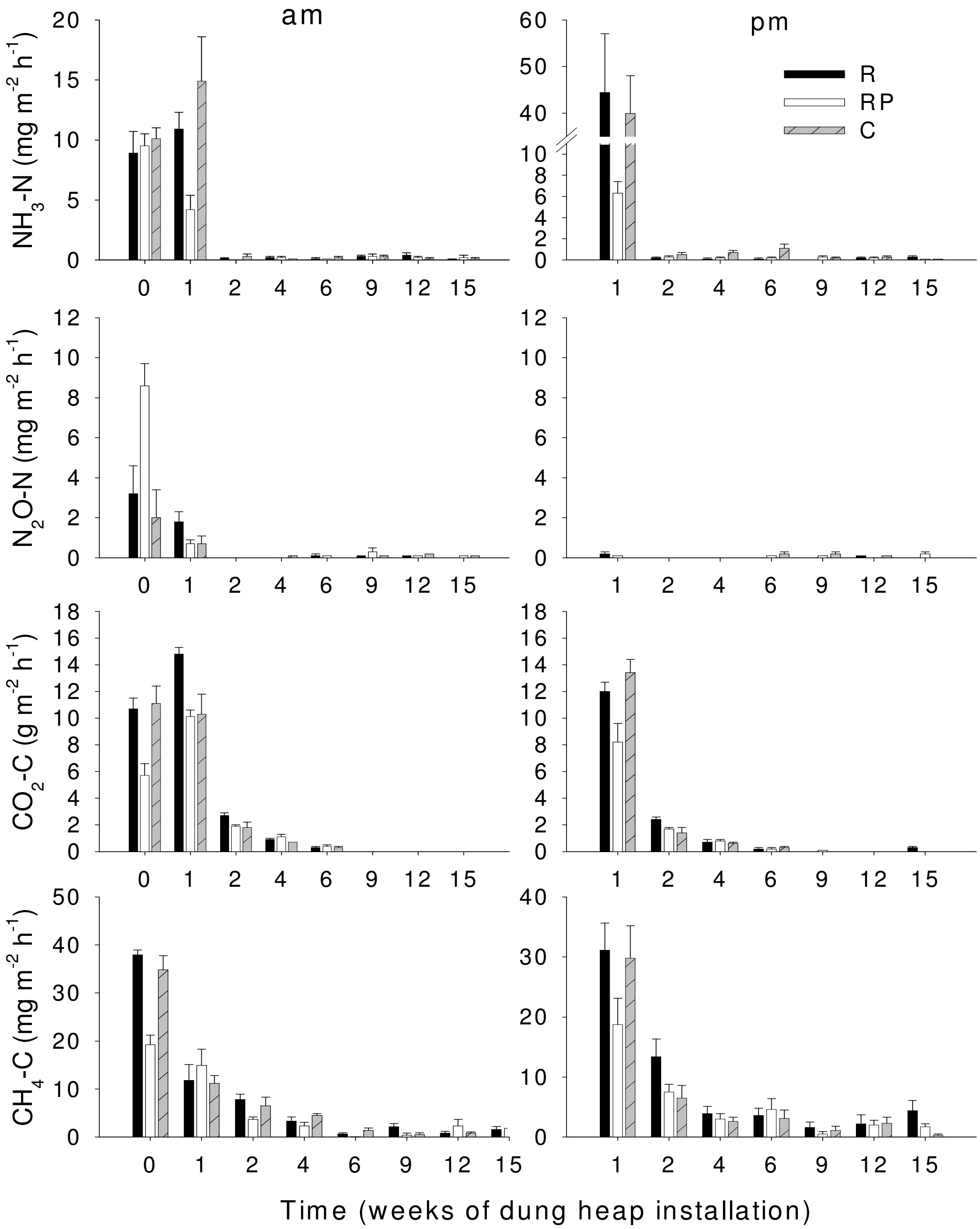

Figure 2. Gaseous emissions of three dung storage treatments in the hot dry season 2007, Niamey, Niger. Data show means (n=8) and standard errors from 1st to 1^{5th} week (n=4 for time zero) of the untreated control treatment (C), dung protection by a plastic roof (R) and roof-protection combined with the addition of 333 g finely ground rock phosphate (RP) kg^{-1} manure DM. The bars at time zero illustrate the emissions immediately after installation of the dung heaps in the late evening when ambient air temperatures were more similar to the morning than during midday conditions.

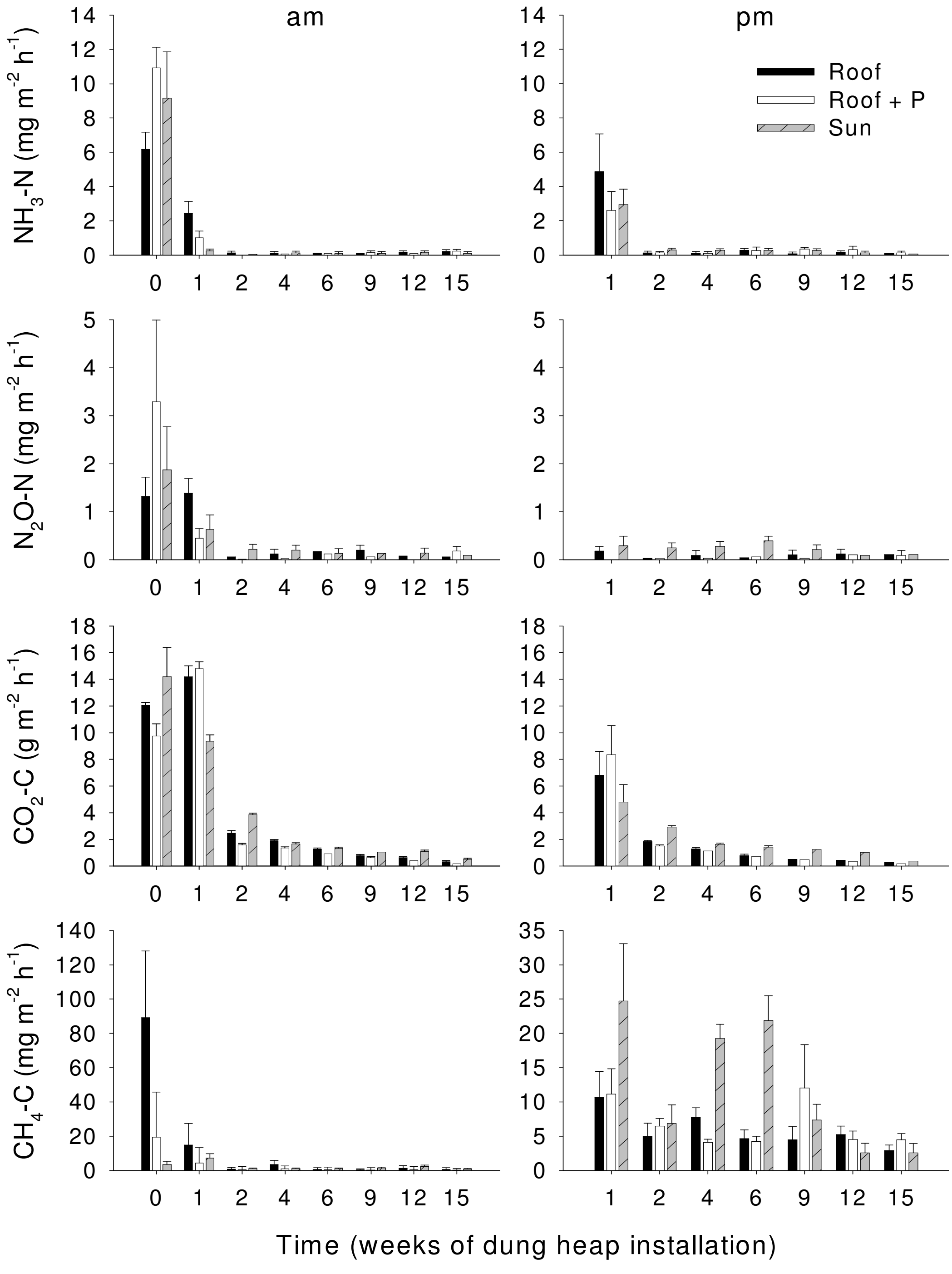

Figure 3. Gaseous emissions of three dung storage treatments in the rainy season 2007, Niamey, Niger. Data show means (n=8) and standard errors from 1st to 1^{5th} week (n=4 for time zero) of the untreated control treatment (C), dung protection by a plastic roof (R) and roof-protection combined with the addition of 333 g finely ground rock phosphate (RP) kg^{-1} manure DM. The bars at time zero illustrate the emissions immediately after installation of the dung heaps in the late evening when ambient air temperatures were more similar to the morning than during midday conditions.

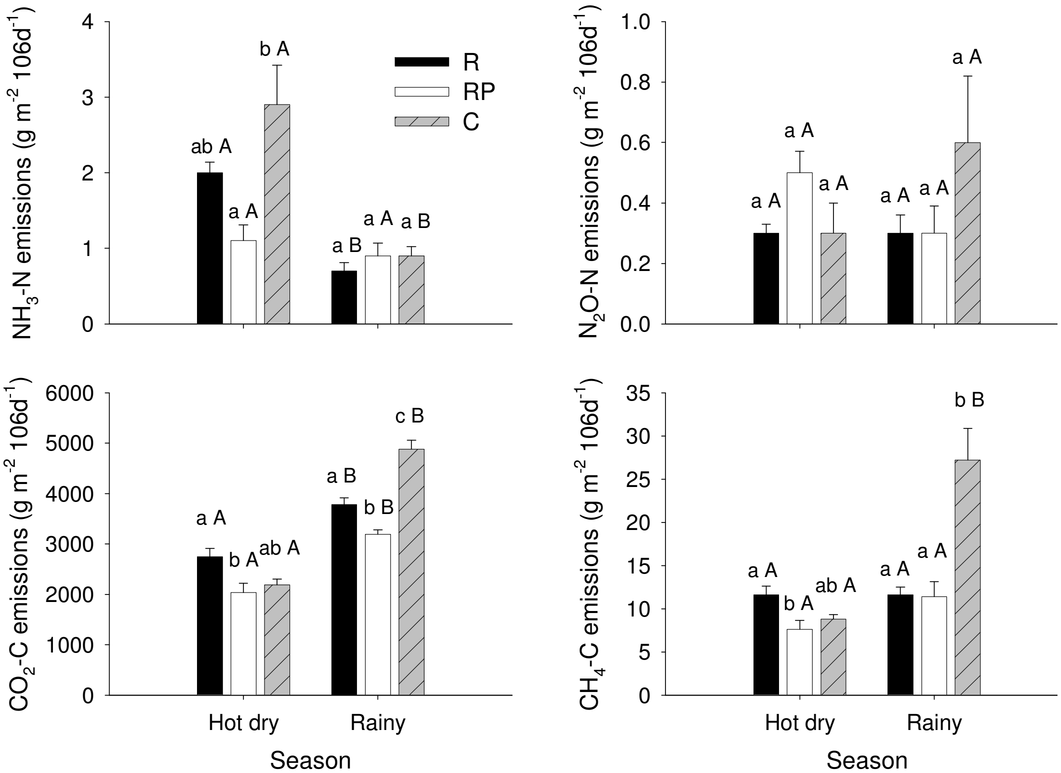

Figure 4. Total N and C losses in form of NH_3, N_2O and CO_2, CH_4, respectively, from a dung storage experiment lasting 106 days. Data show means (n=4) and one standard error of the untreated control treatment (C), dung protection by a plastic roof (R) and roof-protection combined with the addition of 333 g finely ground rock phosphate (RP) kg^{-1} manure DM. Different small letters indicate differences ($P < 0.05$) between treatments within one season; different capital letters indicate differences ($P < 0.05$) between seasons for each treatment.

3.4.2. *Treatment effects on leaching losses and manure decomposition*

Leaching losses occurred only after rainfall events in the unroofed control heaps, which were exposed to the rain. As some unexpected rainfall occurred at the end of the hot dry season, some leaching losses were also recorded in the first period of the experiment; however, cumulative leaching losses were much higher in the rainy than in the hot dry season (Figure 5).

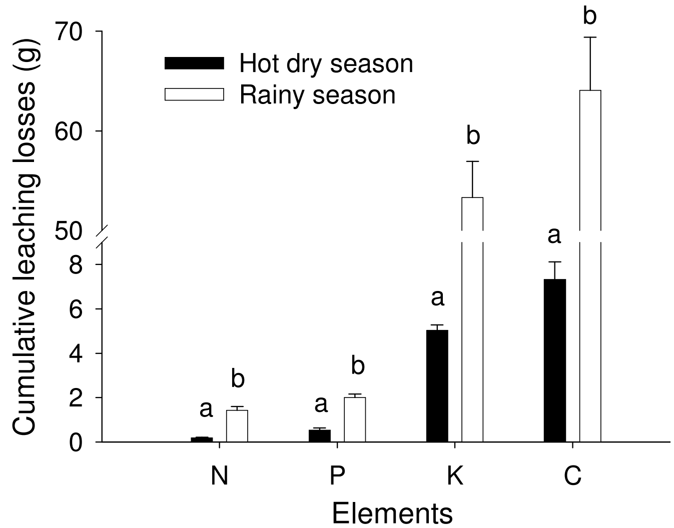

Figure 5. Cumulative leaching losses from the control treatment; means (n=4) and standard errors. Different letters indicate differences (P < 0.05) between seasons.

The DM content of the manure fresh matter inside the nylon bags increased during the hot dry season (Figure 6) from initially 378 g kg^{-1} (R), 470 g kg^{-1} (RP) and 375 g kg^{-1} (C) to 825 g kg^{-1}, 752 g kg^{-1}, and 838 g kg^{-1}, respectively. For treatments R and RP, the drying of the dung heaps was much slower during the rainy season than during the hot dry season. Overall OM decomposition was slow and slightly reduced by RP application (Figure 6). For all treatments, the C/N ratio (Figure 7) of the dung ranged between 23 and 26 during the hot dry season; the only exception being the initial C/N ratio determined for dung mixed with RP. During the 3.5 months of rainy season experimentation, the C/N ratio decreased from 30 to 21 in treatment R, from 34 to 25 in treatment RP and from 28 to 24 in treatment C.

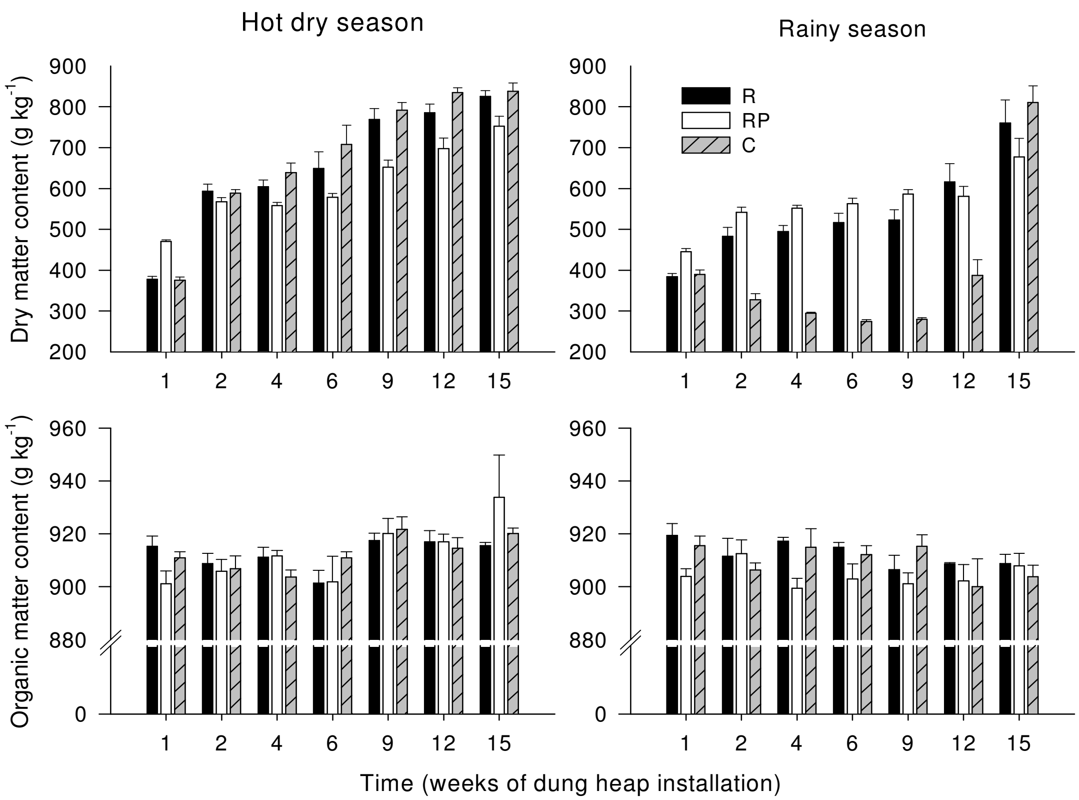

Figure 6. Dry matter and organic matter content of animal manure (dung) incubated in nylon litter bags during the hot dry and rainy season 2007 in Niamey, Niger. Data show means (n=4) and one standard error of the untreated control treatment (C), dung protection by a plastic roof (R) and roof-protection combined with the addition of 333 g finely ground rock phosphate (RP) kg^{-1} manure DM.

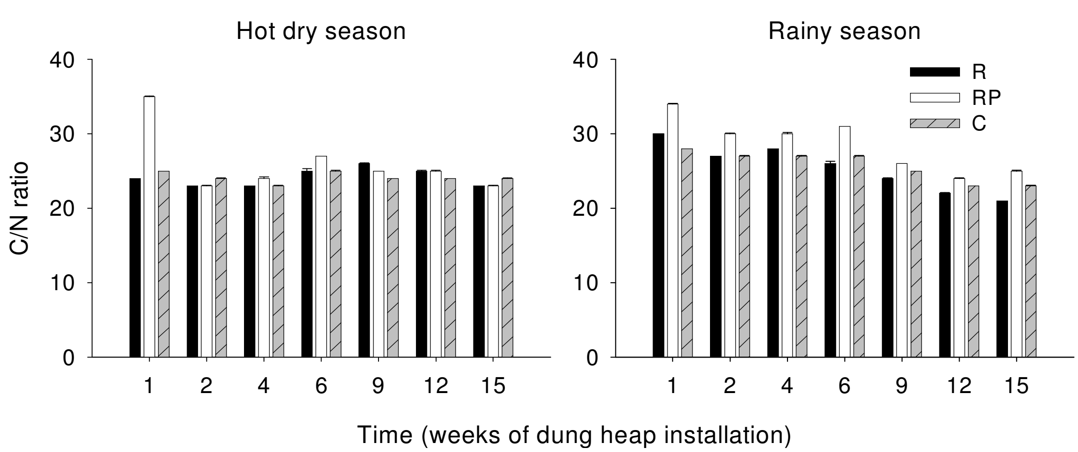

Figure 7. C/N ratio of animal manure (dung) incubated in nylon litter bags during the hot dry and rainy season 2007 in Niamey, Niger. Data show means (n=4) and one standard error of the untreated control treatment (C), dung protection by a plastic roof (R) and roof-protection combined with the addition of 333 g finely ground rock phosphate (RP) kg^{-1} manure DM.

3.4.3. Farmers' manure storage practices

The results of the interviews (Table 1) showed that most of the UPA farmers (99.5%) applied purchased or their own animal manure to their fields and gardens; 67% of the respondents applied mineral fertilizers in addition to manure. The dung was transported to the garden by animal drawn carts (13%), manually (27%), by car (25%) or by a combination of the former (35%), often every two (57%) or four (31%) weeks. Almost half of the farmers (49%) transported the dung from a distance < 1 km to the garden, while about one third (28%) fetched the dung from distances > 3 km. All dung was stored in unprotected (un-roofed) heaps before application, which usually occurred within 2 - 3 days (69%) after the dung had been brought to the garden. In most gardens, the dung was applied to the surface of plots after hoeing (93%). The majority of farmers (97%) applied the dung during the cooler parts of the day, that is during mornings or/and evenings.

Table 1. Categorized results of an interview of 215 gardeners in 6 city quarters of Niamey, Niger (2007).

Question	Category (% of total 215 gardeners)			
Nationality	Niger 31	Burkina Faso 69		
Ownership	Owner 29	Rented 71		
Cultivated area	< 250 m^2 51	251-750 m^2 45	> 751 m^2 4	
Area abandoned during hot dry season	< 25 % 8	26-50 % 57	51-75 % 24	> 75 % 11
Chemical fertilizer use	No use 33	Urea only 8	NPK only 31	Urea + NPK 27
Animal dung use (several answers possible)	Cattle 98	Small ruminants 87		
Dung origin	Purchased 69	From own animals 3	Both 28	
Frequency of dung import to the garden	Every 1 week 9	Every 2 weeks 57	Every 4 weeks 31	Not regularly 3
Dung transport distance	< 1km 49	1-3 km 23	> 3km 28	
Dung transport means	Animals 13	People 27	Car 25	Combined 35
Person responsible for the dung transport	Gardener 25	Children 2	Hired labour 43	Gardner + hired labour 30
Duration of dung storage in garden before application	Immediate application 4	1 day 26	2-3 days 69	1 week 1
Type of dung storage	In heaps, unprotected 100	Covered 0		
Dung application time	Mornings 26	Evenings 14	Mornings or evenings 57	Any time 3
Type of dung application	On the surface 6	On the surface after hoeing 93	Incorporated into the topsoil 1	
Reason for using animal manure (several answers possible)	Cheap 32	Accessible 3	Good growth/harvest of crops 98	Own animals' supply 2

3.5. Discussion

The decrease in gaseous emissions over the duration of the experiment was slower for C than for N, with the exception of the CH_4-C efflux in the control treatment during the rainy season (Figure 3). The surprisingly high afternoon flux rates in weeks 1, 4 and 6 in the rainy season might have been caused by concomitant rainfall events leading to temporarily anaerobic conditions in the unroofed dung heaps and favorable conditions for methane producing bacteria (Gupta et al., 2007).

Our results of high gaseous N losses immediately after dung storage on heaps confirm similar data of Sommer (2001) and Sommer and Dahl (1999). These authors reported that during the composting of litter significant NH_3-N emissions only occurred during the first 10 days of the experiments and accounted in total for 1.5% of the total initial N content in the substrate. This figure is similar to the total N losses from treatments C and R in our experiments, which during the hot dry season ranged from 1.3 to 1.8% of total N content in dung heap. Ammonia emissions were the predominant form of N losses (Rufino et al., 2006) and were responsible for 87%, 69% and 91% of the total volatilized N for treatments R, RP and C, respectively. Lower storage losses of N_2O-N than of NH_3-N were also reported by Oenema et al. (2007), Külling et al. (2003) and Sommer (2001). Similarly to our observations, Hellman et al. (1997) reported N_2O production during the first few days of their composting experiment to depend on the availability of NH_3 as a substrate for nitrification. According to Sommer (2001) and Hellman et al. (1997), the subsequent increase of substrate temperature inhibited the nitrification and de-nitrification through thermophobic microorganisms. In contrast to their results, the N_2O-N emissions in our experiment did not increase later on and from the second experimental week onwards the temperatures in the top 0.1 m of the substrate remained between 33 to 40°C and 29 to 32°C during the hot dry and the rainy season, respectively. This might be due to the warm climatic conditions in which our experiment was conducted.

In both seasons the addition of ground RP decreased cumulative N losses to 0.1% of the total initial N stock, which may be due to N absorption by the large surfaces of the fine RP particles. Such effects of finely ground minerals on NH_3-N emissions during composting were also previously reported by Zaied and Van den Weghe (2000). In contrast, RP application did only have minor effects on gaseous C fluxes which reached a total of 15 - 20% of the initial C content in the hot dry season and 24 - 36% in the rainy season. The latter losses are several-fold higher than the 10% C loss reported from composting of dairy cows deep litter during cold part of the year in Denmark (Sommer and Dahl, 1999). This may have been due to the prolonged storage of the manure (Table 1) under more favorable conditions for ruminant dung decomposition under the hot and wet weather conditions during the rainy season in the Sahel (Esse et al., 2001).

For our experiments, the mixture of manure from small ruminants and cattle as typically used by local farmers (Table 1) was brought fresh (1-2 days old) from the stables of urban livestock keepers. Large gaseous N and C losses are likely to occur immediately after manure spreading: Sommer and Hutchings (2001) reported that 50% of the total NH_3-N was volatilized during the first 24 h after application. The results of our interviews show that more than half of the farmers (51%) transported the animal manure from a distance bigger than 1 km every 2 or 4 weeks (Table 1) which resulted in prolonged storage under unroofed conditions. Carbon and N losses that occurred immediately after manure deposition at the farms, during dung mixing, loading at the farm gate, transport to and storage in UPA garden areas (Hao et al., 2001; Sommer, 2001) were not measured, therefore the real N and C losses along the entire manure management chain may be much higher that estimated in our study.

Our study showed that a simple plastic roof effectively eliminated leaching losses of K and C during the rainy season. Sommer (2001) reported cumulative K leaching losses from cattle manure storage during 132 days to range from 8 – 16% of the initial K content, which is similar to the 16% K lost in our rainy season experiment (Table 2). The high C and K leaching losses measured in our study are likely to be representative for UPA gardens in Niamey as none of the interviewed farmer used any cover to protect manure storage heaps. In most years leaching losses may even be higher than during 2007 when total rainfall was with 425 mm much lower than the annual average of 542 mm.

Table 2. Cumulative gaseous and leaching losses (in absolute terms and as a proportion of the total initial C, N, P and K content) from three different dung storage treatments (n=4 / treatment) during the hot dry and rainy season 2007 in Niamey, Niger.

Season	Treatment	Cumulative gaseous losses				Cumulative leaching losses							
		N	C	N	C	C	N	P	K	C	N	P	K
		(g 106 days^{-1})		(% of initial content)		(g 106 days^{-1})				(% of initial content)			
Hot dry	Roof	2.3	2759	**1.3**	**20.1**								
	Roof + P	1.6	2039	**0.1**	**15.1**								
	Control	3.2	2193	**1.8**	**16.1**	7.3	0.2	0.5	5.0	**0.1**	**0.0**	**0.3**	**1.2**
Rainy	Roof	1.0	3793	**0.7**	**27.5**								
	Roof + P	1.2	3201	**0.1**	**23.6**								
	Control	1.5	4904	**0.9**	**35.7**	64.1	1.4	2.0	53.3	**0.5**	**0.3**	**1.2**	**16.0**

In SW Niger many studies have been conducted on how to alleviate the notoriously low P status of the dominant acid sandy soils (Bationo and Mokwunye, 1991; Kretzschmar et al., 1991; Buerkert et al., 1998; Buerkert et al., 2001; Somado et al., 2003). While Sqalli and Nadir (1983) suggested the use of soluble super phosphate for arid Moroccan market gardens, in Niamey the locally available inexpensive Tahoua RP (costs were 0.5 € per 10 kg in 2007) of which high agronomic efficiencies for on-farm millet fields were previously reported by Bationo et al. (1990) might present an effective way of increasing garden soil P stocks while decreasing N losses during dung storage.

Successful use of the closed chamber system with the photo-acoustic infrared INNOVA monitor has been reported in earlier studies measuring gaseous emission from a range of soils. The most critical factor determining the reliability of the method in hot environments seems to be the length of the gas accumulation period. Reported accumulation periods range from 2-3 min (Hans et al., 2005; Reth et al., 2005a) up to 1 hour (Velthof et al., 2003; van Groenigen et al., 2005). Because the rapid increase in gas concentration, the raise in temperature and the built-up of humidity in the cuvette, especially during mid-day measurements, influences the emission flux (feed back mechanisms), we shortened the accumulation period to a 1 minute interval.

3.6. Conclusions

During the hot dry season a simple plastic sheet roofing and addition of ground RP to stored ruminant manure decreased total N gaseous losses by 50% in comparison to dung directly exposed to the sun. In absolute terms these N losses were rather small which was most likely due to the fact that during the transfer of the manure from the stable to the dung heap much of the easily mineralizable and mineral N has already been lost. Plastic roofing also protected dung heaps from leaching losses during the rainy season. In order to decrease N volatilization from dung heaps and simultaneously increase P stocks in garden soils, the addition of finely ground RP to dung heaps seems particularly effective.

A closer linkage between animal keepers and gardeners and increased awareness of simple and locally accessible techniques to reduce volatilization and leaching losses of C and N from manure heaps may help to increase the nutrient use efficiency in UPA gardens across the Sahel.

3.7. References

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Chapter 4.

Leaching nutrient losses from urban gardens in Niamey, Niger

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4.1. Abstract

Urban and peri-urban agriculture (UPA) contributes significantly to meeting the increasing food demand of rapidly growing urban populations in West African cities. The often intensive high input vegetable production results in large positive nutrient balances, being presumably linked to strong nutrient leaching which needs quantification. This study aimed at estimating leaching losses of mineral nitrogen (N) and phosphorus (P) in three representative urban gardens of Niamey, Niger, using ion-exchange resin cartridges installed below the crop rooting zone at 0.6 m soil depth. In 2007, a year with below-average annual rainfall (425 mm as compared to 542 mm), mean leaching of mineral N amounted to 5.9 and 7.3 kg N ha^{-1} for two gardens with > 80% sand fraction and only 2.2 kg N ha^{-1} for a garden with 40% silt and clay. Apparent annual P leaching was ≤ 0.7 kg P ha^{-1} in all three gardens. Additional studies are necessary to assess the effect of inter- and intra-annual variation in precipitation on nutrient leaching in intensive UPA vegetable production of semi-arid West Africa.

Keywords: Leaching, Self integrating ion-exchange resin cartridges, Urban and peri-urban agriculture, UPA

4.2. Introduction

In West Africa the share of urban population grew from only 4% in 1930 to 40% in 1990 and is projected to reach 63% by 2020 (Drechsel et al., 2005). During this time period the role of urban and peri-urban agriculture (UPA) in providing food and employment for the urban population has been rapidly increasing (De Bon et al., 2009). Today, it satisfies large proportions of urban demands for fresh vegetables (10 - 90%), meat (up to 70%), eggs (up to 100%) and other products such as fruits, spices, cereals, tubers and medicinal plants (Maxwell, 1995; Madaleno, 2000; Cofie et al., 2003; Drechsel et al., 2005). The reported wide range of the share of households involved in UPA (10 - 57%) (Ellis and Sumberg, 1998; Howorth et al., 2001; Asomani-Boateng, 2002; Cofie et al., 2003) reflects large differences in the relative role of this land use system to satisfy producer and consumer needs. The intensive production mode in UPA is partly reflected by overdosing and inappropriate application of fertilizers and pesticides close to human settlements which may pose risks to human health and the environment (Binns et al., 2003; Bryld, 2003; Drechsel et al., 2005).

Intensive recycling of nutrients through compost application and sewage irrigation water and the often high rates of applied mineral fertilizers (Drechsel et al., 2005) result in positive nutrient balances in UPA gardens (Hedlund et al., 2003; Diogo et al., 2009). On the predominantly sandy soils of the region this may result in high leaching losses especially during the short rainy season with often intensive rainfall events (Hafner, 1992; Brouwer and Powell, 1995). In most studies on nutrient balances calculated as sum of nutrient input minus nutrient outputs in harvested crops of West African cropping systems, leaching losses were not accounted for (Bationo et al., 1998) or were stated to be negligible (Christianson et al., 1990). For urban vegetable production in West Africa information about leaching losses is lacking altogether.

Various methods have been suggested to determine leaching losses in the field. Wick samplers (Gee et al., 2004; Siemens and Kaupenjohann, 2004; Peters et al., 2005), suction cups (Hatch et al., 1997; Potschin, 1999) or suction plates (Siemens and Kaupenjohann, 2004; Peters et al., 2005) installed at different soil profile depths, under continuous or temporary suction and connected to collection containers allow dynamic (time-specific) soil water solution sampling. The results of these methods are strongly dependent on the stability of the suction and allow the calculation of leaching as affected by rainfall, irrigation, evapo-transpiration and infiltration conditions. Alternatively, freely draining lysimeters (Webster et al., 1993) and gravity pan samplers (Zhu et al., 2002; Peters et al., 2005) have been used.

Another method to collect leachates cumulatively is the use of cation and anion exchange resins placed in cartridges and buried in the soil (Lehmann et al., 2001; Lang and Kaupenjohann, 2004; Siemens and Kaupenjohann, 2004). In the past such resins have been widely used to study N mineralization (Friedel et al., 2000) and transformation (Kjonaas, 1999; Johnson et al., 2005), ion adsorption kinetics (Agbenin et al., 1999; Agbenin and van Raij, 2001) and nutrient diffusion kinetics (Yang and Skogley, 1992; Lang and Kaupenjohann, 1998). Synthetic cation and anion exchange resins installed in longer-term experiments (Langlois et al., 2003) function as sinks for nutrients passing through the cartridges that hold them (Skogley and Dobermann, 1996; Bischoff, 2007). After removing the resin cartridges from the soil, the adsorbed nutrients can be extracted and measured in the laboratory (Schnabel, 1983; Skogley et al., 1996). Several studies confirmed the reliability of ion-exchange resin use in cumulative nutrient leaching measurements (Lehmann et al., 2001; Lang and Kaupenjohann, 2004; Bischoff, 2007) and stress the relatively low labour requirements of this method during the critical field measurement phase. An additional advantage of the exchange resin approach is that its low cost allows increased number of repetitions in order to account for the often observed large spatial variability of leaching due to preferential flow phenomena (Bischoff, 2007) and wetting front instability in unsaturated soils (Selker et al., 1992a; Selker et al., 1992b). We used this method to assess cumulative rainy season losses of mineral nitrogen (N) and phosphorus (P) in typical urban vegetable gardens of West Africa.

4.3. Materials and Methods

4.3.1. Study sites

The study was conducted in Niamey (13.5ºN, 2.1ºE, 223 m asl), the capital city of the Republic of Niger. The climate in this southern Sahelian zone is semi-arid with a 30-year average annual rainfall of 542 mm (Wezel and Boecker, 2000) occurring during a single rainy season (June to September). Daily average temperatures peak in May, reaching 34ºC and drop to 25ºC in December (World Climate, 2008).

The urban gardens of Niamey cover 54 ha as estimated from aerial and satellite images (Kadaouré, unpublished data) and in plots of 5 – 100 m^2, a wide variety of vegetables, herbs, spices and fruits are grown (Bernholt et al., 2009). A sample of three gardens (Figure 1) was chosen to represent the different management conditions described by Graefe et al. (2008), and largely defined by different levels of nutrient inputs and typical sources of irrigation water (Diogo et al., 2009, Predotova et al., 2009). Two of the gardens were located on the bank of the River Niger providing river water for irrigation of the crops; one of these was in the Goudel city quarter (abbreviated R_1), the second in the Yantala Bas quarter (R_2). During the experiment, hibiscus (*Hibiscus sabdariffa* L.) and mint (*Mentha* sp.) were cultivated in the R_1 garden and amaranth (*Amaranthus caudatus* L.) and a mixed cropping of leek (*Allium porrum* L.), sweet pepper (*Capsicum annuum* L.), maiz (*Zea mays* L.) and moringa (*Moringa oleifera* Lam.) in garden R_2.

The third garden was located near a permanently water-carrying tributary to the Niger River (wadi) in the quarter Gountou Yena (W). There, sewage water loaded with human excrements was used for irrigation of hibiscus, lettuce (*Lactuca sativa* L.) and cabbage (*Brassica oleracea* L.). According to the FAO soil classification, the three soils were a Cambic

Fluvisol (R_1), a Haplic Luvisol (R_2) and an Arenosol (W). Before the onset of the experiment in all gardens soil samples were taken from the profile (0 - 1 m) and analyzed for pH, total P, P Bray, organic C (Corg), cation exchange capacity (CEC) and particle size distribution using standard methods. In the two gardens using irrigation water from the river (R_1 and R_2), additionally lacquer profiles were taken for profile description.

Results of plot-based nutrient balance calculations for each of these gardens with their specific cropping sequences were taken from Diogo et al. (2009) and Predotova et al. (2009).

4.3.2. Resin cartridges and the installation in the soil profile

Following the description of Bischoff (2007) and Lang and Kaupenjohann (2004), leaching losses were estimated using of PVC cartridges of 0.1 m height and a diameter of 0.103 m with nylon net in the bottom. The PVC cartridges were filled with an exchange resin-sand (Table 1) mixture at a gravimetric ratio of 1:1:2 for cation, anion exchange resin and sand, respectively and installed according to the guidelines of TerrAquat Consultancy (Stuttgart, Germany), the patent holder of this method. In each garden, three measuring sites composed of two adjacent plots each, were chosen for the installation of the resin cartridges. In the middle of the two plots a 1 m^3 pit was dug for the installation of the cartridges.To place the cartridges below an undisturbed part of the plot, horizontal access tunnels of about 0.11 m height and 0.25 m depth m were dug at 0.6 m profile depth in May 2007, about one month before the onset of the rains. At each measuring site, eight resin cartridges were installed, resulting in a total of 24 cartridges per garden. After installation, the horizontal tunnels were tightly refilled and subsequently the pits were closed to allow farmers cultivating their plots as usual. Removal of the resin-sand cartridges occurred by mid November 2007, 1.5 months after the last rainfall.

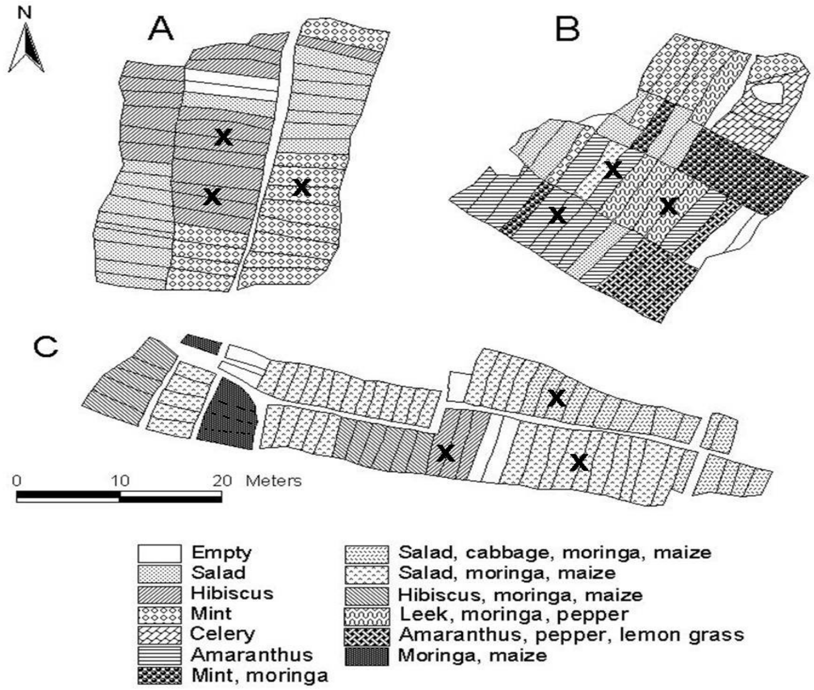

Figure 1. Plot occupation by crops in the two river gardens R_1 (*Goudel* quarter, A), R_2 (*Yantala Bas* quarter, B) and the wadi garden W (*Gountou Yena* quarter, C) during the rainy season 2007 in Niamey, Niger. "X" marks the measuring sites within the gardens.

Table 1. Chemical properties of the used anion- and cation-exchange resins (Rohm & Haas, 2007).

	Anion exchange resin	Cation exchange resin
Producer	Rohm & Haas, Frankfurt am Main, Germany	
Description of producer	Industrial Grade Strong Basic Anion Exchanger Amberjet 4200 ® Cl	Industrial Grade Strong Acid Cation Exchanger Amberjet 1200 ® Na
Matrix	Styrene divinybenzene copolymer	
Physical form	Insoluble, yellow transparent beads	Insoluble, amber beads
Exchange-ion form	Cl^-	Na^+
Specific gravity	1.06 - 1.08	1.26 – 1.3
Total exchange capacity	1.3 eq l^{-1}	2.0 eq l^{-1}

4.3.3. Ion extraction and analysis

After removal of the cartridges from the soil, the resin-sand mixture was separated into four layers (L1 - L4) of about 15 mm each to allow assessment of a nutrient concentration profile for each cartridge (Bischoff et al., 1999). All layers were weighted, labelled and stored in a refrigerator at 8℃ until analysis. Subsequently, from each layer of resin-sand mixture, 5 ± 0.5 g were taken for the estimation of dry weight (65℃). For ion extraction, 30 ± 0.5 g of the mixture were placed into a 250 ml plastic bottle to which 100 ml of 0.5 M NaCl was added as an extractant. The bottles were closed and shaken horizontally for one hour. Then the extract was filtered and poured into a glass jar and the residual resin-sand mixture was washed with another 100 ml 0.5 M NaCl. Four subsequent extractions of each sample were mixed and 50 ml sub-samples frozen until analysis with an Inductively Coupled Plasma Spectrometer (ICP; Model Spectro-Flame, Spectro Analytical Instruments GmbH & Co. KG, Kleve, Germany) for NO_3^--N, NH_4^+-N and PO_4^{3-}-P. Six samples of the washed sand and three samples each of the pure anion and cation exchange resins were extracted similarly as the samples from the gardens and used as blanks.

Pre-tests conducted under laboratory conditions had shown that with four extractions > 97% of all ions attached to the resins were removed from the resins and total recovery rates were 98-100% for NO_3^-, 92-108% for NH_4^+ and 104-114% for PO_4^{3-} (Siegfried et al., unpublished data)

4.3.4. Data analysis

After analysis the nutrient concentration gradient of each cartridge was examined to determine if the data from this cartridge were acceptable, whereby a consistent decrease in nutrient concentration with depth and / or existence of a “zero layer” was required. Based on this screening, it was decided how many layers were to be used for the leaching losses calculation to avoid possible contamination of upper cartridge layers from the bottom layer which may have been affected by lateral intrusion of leacheates such as caused by temporary water logging (Figure 2). Given the defined surface area of the cartridges and their time of residence in the soil, all data were interpreted as kg nutrient ha^{-1} rainy season^{-1}. Datasets were examined for normal distribution of residuals and wherever necessary ln transformed. F-statistics to compare differences between gardens were carried out with SPSS 11.5 (Backhaus et al., 2003).

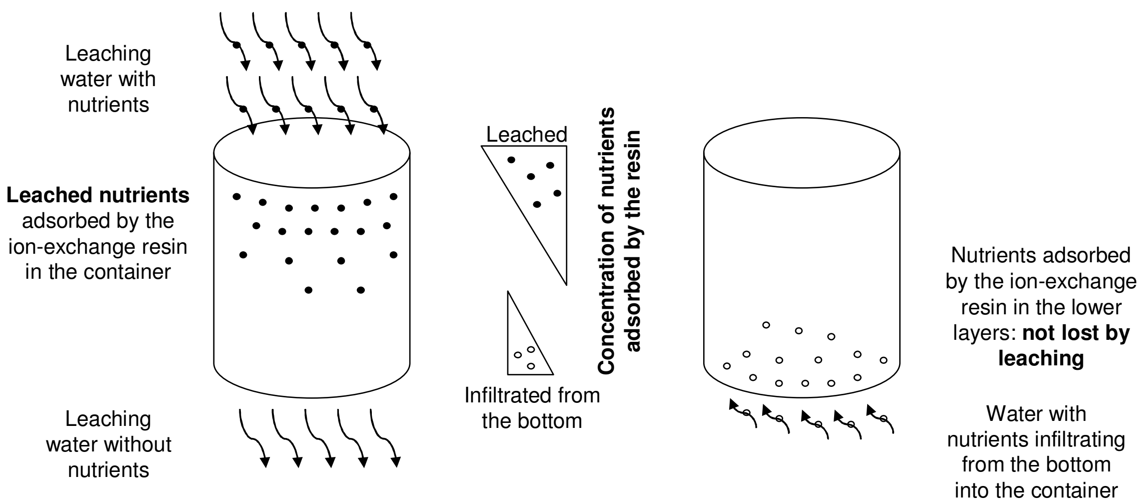

Figure 2. Functional diagram of the nutrient adsorption by the cartridges filled with a mixture of ion exchange resin and sand and installed in the soil profile.

4.4. Results

4.4.1. Field conditions

During the rainy season in 2007, ambient daily temperatures ranged from 20 - 39°C with an average of 30°C. Cumulative precipitation over the rainy season was with 425 mm significantly below the 30-year annual average of 542 mm but well within the typical long-term range of annual rainfall at this Sahelian location.

The particle size analysis of the surface soil (0-0.2 m for gardens R_1 and R_2, 0-0.1 m for garden W) yielded sand contents of 96%, 72% and 83% for garden R_1, R_2, and W, respectively. In garden W, the topsoil (0-0.1 m) contained a slightly higher proportion (17%) of clay and silt than the rest of the profile (Figure 3). The soil in garden R_2 had a leached horizon in the lower half of the profile (0.6-1.0 m), and the clay and fine silt particles fraction reached 26% at 0 - 0.2 m, 33% at 0.2 - 0.5 m and 36% at both 0.5 - 0.8 and 0.8 - 1.0 m depth (Figure 3).

Soil pH changed little throughout the profile in garden R_1 and R_2, while in garden W it increased with depth from 5.7 to 7.3 (Table 2). The high total phosphorus (P) values of 1045 mg P kg^{-1} in the topsoil of garden W were also reflected in the high concentration of plant available Bray-P (255 mg kg^{-1}) and were thus 30-40 times higher than in typical Arenosols of SW Niger (Graef and Stahr, 2000). Although total P in garden R_2 was higher throughout the entire soil profile than in garden R_1, P-Bray values in the upper half of the profiles of these two gardens were similar (Table 2).

4.4.2. Leaching losses of NO_3-N, NH_3-N and PO_4-P

The maximum concentration of NO_3-N in the extracts from the ion exchange resins were 7.9 mg l^{-1}, 17.1 mg l^{-1} and 27.2 mg l^{-1} for gardens R_1, R_2, and W, respectively. The NH_3-N concentration for all cartridges didn't exceed 0.07 mg l^{-1} for any of the three gardens and PO_4-P concentration ranged between 0 - 1.2 mg l^{-1}, 0 - 0.7 and 0 – 1.3 mg l^{-1} for gardens R_1, R_2, and W, respectively. For gardens R_1 and W the anion concentration gradient across layers of all cartridges showed that NO_3-N and PO_4-P were highest at both ends of the cartridges (L1 and L4), but in > 90% of the cartridges L3 had only minimal anion concentration; layers L1 and L2 could thus be used for the calculation of leached anions (Figure 5). In the first two layers of the cartridges from gardens R_1, R_2, and W we found 39%, 22% and 24% of the total NO_3-N and 50%, 47% and 49% of total PO_4-P, respectively (Figure 5). These layers were thus used for the calculation of the leaching losses while the nutrients in the L3 an L4 were considered as having entered from the cartridge bottom and were excluded from the calculations.

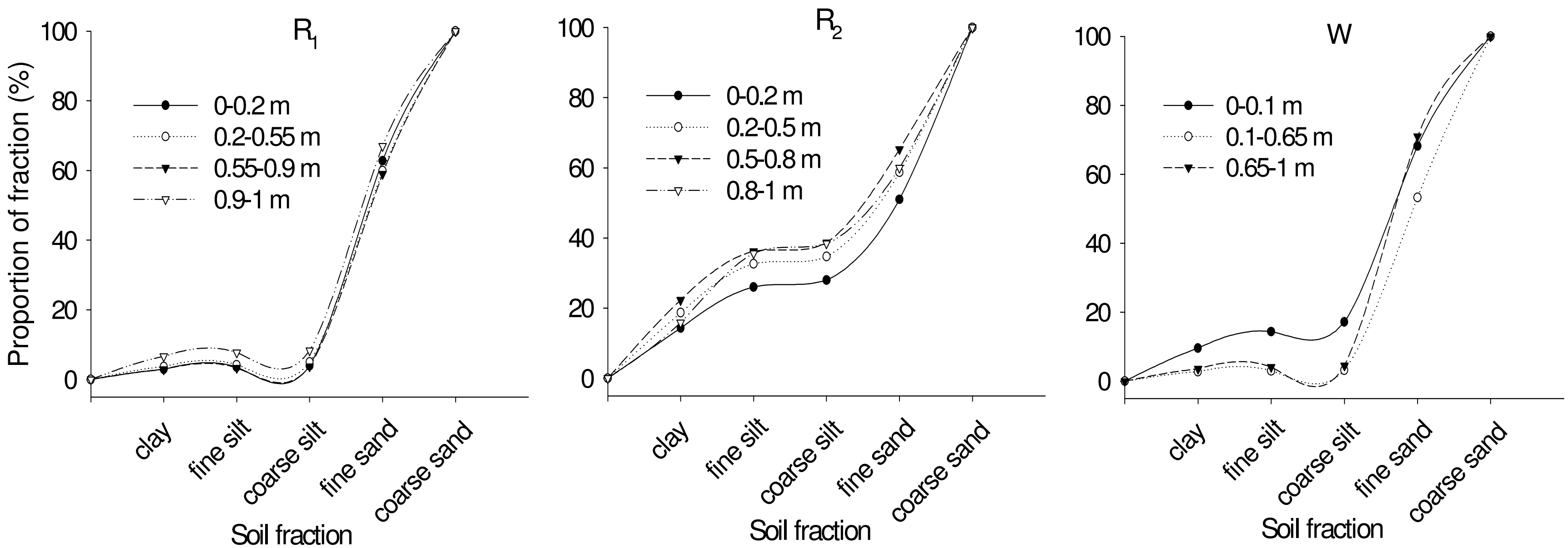

Figure 3. Particle size distribution in the topsoil (0- 0.2 m) of the two studied river gardens in *Goudel* (R_1), *Yantala Bas* (R_2) and the wadi garden in *Gountou Yena* (W), Niamey, Niger. Classes of particle size were: clay < 0.002 mm, fine silt 0.002-0.02 mm, coarse silt 0.02-0.05 mm, fine sand 0.05-0.2 mm and coarse sand 0.2-2 mm. Data are from one pooled sample representing three sub-samples per site and were taken from Predotova et al. (2009).

Table 2. Selected properties of the soil profiles of the two studied river gardens in *Goudel* (R_1), *Yantala Bas* (R_2) and the wadi garden in *Gountou Yena* (W), Niamey, Niger. Data are from one pooled sample representing three sub-samples per site and were taken from Predotova et al. (2009).

Garden	Depth	pH-KCl	Total-P	P Bray	Corg	CEC	Exchangeable cations				
							Al^{3+}	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}
	(m)		(mg kg^{-1})		(%)		(cmol kg^{-1})				
Goudel R_1	0.00-0.20	6.1	226	41	0.27	2.92	0.00	0.12	0.15	1.80	0.82
	0.20-0.55	6.2	219	51	0.09	2.92	0.00	0.09	0.15	1.66	1.01
	0.55-0.90	6.3	193	44	0.03	1.94	0.00	0.06	0.16	1.25	0.45
	0.90-1.00	6.3	249	76	0.10	3.75	0.00	0.13	0.34	2.31	0.94
Yantala Bas R_2	0.00-0.20	6.7	572	41	0.96	9.57	0.00	0.83	0.30	5.74	2.63
	0.20-0.50	6.7	456	53	0.27	9.57	0.00	1.18	0.21	5.42	2.73
	0.50-0.80	6.5	278	21	0.10	9.73	0.00	1.93	0.21	4.53	3.03
	0.80-1.00	6.6	522	9	0.06	11.34	0.00	3.22	0.08	4.32	3.69
Gountou Yena W	0.00-0.10	5.7	1045	255	0.89	6.75	0.00	0.58	0.31	4.49	1.28
	0.10-0.65	6.9	222	67	0.03	2.49	0.00	0.20	0.19	1.86	0.22
	0.65-1.00	7.3	207	44	0.04	3.13	0.00	0.33	0.11	2.41	0.26

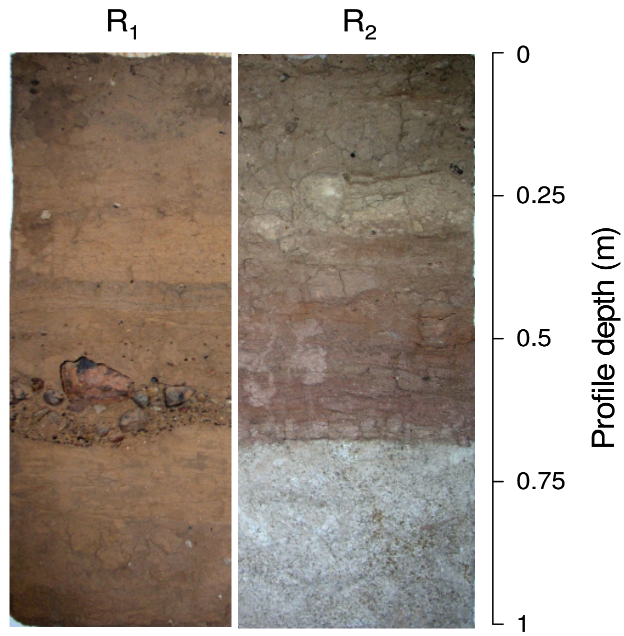

Figure 4. Lacquer soil profiles of gardens irrigated with river water (R_1 and R_2), Niamey, Niger.

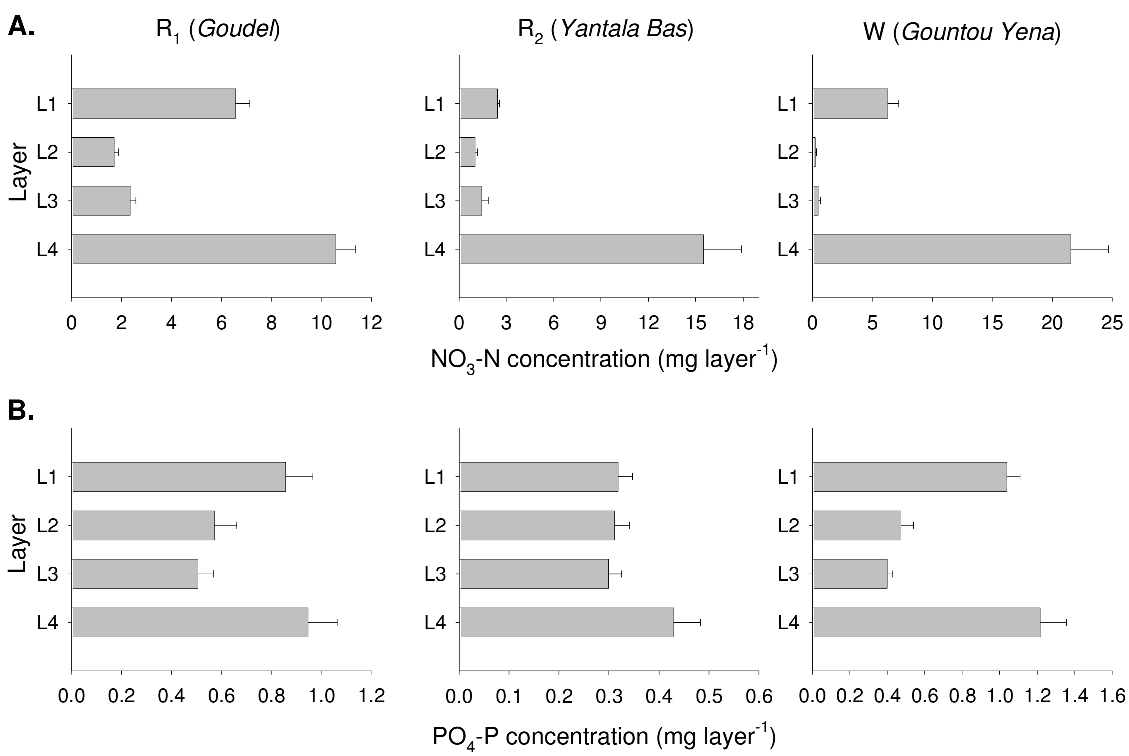

Figure 5. Concentration of NO_3-N (A) and PO_4-P (B) in the four layers of the cartridges filled with an anion-cation exchange resin-sand mixture from the top (L1) to the bottom (L4) as used in three urban gardens in Niamey, Niger (2007). Horizontal bars represent one standard error of the mean (n=21, 22, 18 for R_1, R_2 and W, respectively).

Prior to calculation all data were corrected for the contamination of resins with the respective ions (subtraction of blank values; Table 3). In all cartridges, the concentration of NH_4^+ was below the detection limit, therefore NO_3-N accounted for 100% of the total measured mineral N leaching losses. During the rainy season 2007, total mineral N losses in R_1 and W gardens were with 5.9 and 7.3 kg ha^{-1} significantly higher than in garden R_2 (2.2 kg ha^{-1}; Figure 6). Similar trends were also observed for mineral P leaching, which was significantly higher in garden W (0.7 kg ha^{-1}) than in R_2 (0.1 kg ha^{-1}).

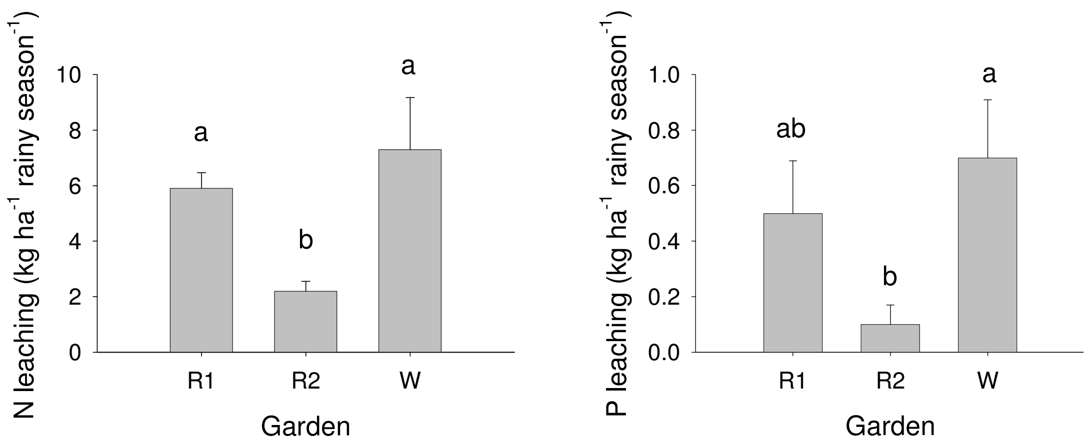

Figure 6. Cumulative leaching losses of N and P in two urban gardens using river water for irrigation R_1 (city quarter *Goudel*) and R_2 (city quarter *Yantala Bas*) and in one garden using municipal sewage water for irrigation W (city quarter *Gountou Yena*) in Niamey, Niger during rainy season 2007. Bars represent one standard error of the mean (n=21, 22, 18 for R_1, R_2 and W, respectively). Different letters above the bars show significant differences (P< 0.05).

Table 3. Nutrient concentrations in the extract of blank samples of cation and anion exchange resins and sand used for the resin-sand mixture. Data show means and standard errors (n=3).

Extracted material	K	NH_4-N	PO_4-P	NO_3-N
		(mg l^{-1} extract)		
Pure cation exchange resin	17.8 ± 1.0	0.0 ± 0.0	0.19 ± 0.02	0.00 ± 0.0
Pure anion exchange resin	4.4 ± 0.4	0.0 ± 0.0	0.60 ± 0.04	2.88 ± 0.2
Sand	9.1 ± 0.7	0.0 ± 0.0	0.26 ± 0.04	0.0 ± 0.0

4.5. Discussion

The choice of the most appropriate method to measure nutrient leaching depends on many factors such as soil type, land use systems, field conditions, the aim of the experiment, and data requirements such as resolution in time and space and the desired precision (Silva et al., 2005; Bischoff, 2007). In a previous experiment, our own measurements of leaching losses by suction plates failed in the sandy Sahelian soils with their typically high concentrations of Al- / Fe-oxides and a short rainy season with irregular rainfall events and prolonged drought spells. Under these conditions we were unable to establish a stable suction pressure, possibly reflecting lack of tight contact between the suction plate and the soil. As the aim of our study was to estimate total leaching losses of mineral N and P during the rainy season and not to collect detailed data on leaching dynamics, the cumulative measurement method by ion-exchange resin cartridges seemed to be an acceptable alternative (Bischoff, 2007). Given its relatively low cost and work load compared to other methods, the use of resin-filled cartridges allows large number of repetitions to account for the potentially high spatial variability of leaching losses often caused by preferential flow phenomena (Selker et al., 1992c; Bischoff et al., 1999).

The ion-exchange resin method was used previously for the measurement of nutrients losses in temperate soils (Lehmann et al., 2001; Lang and Kaupenjohann, 2004), but to our knowledge these are the first data from a subtropical environment. The successful installation and adsorption of solutes by the resin cartridge in the soil profile can be verified by the examination of the NO_3-N concentration gradient in every cartridge (Webster et al., 1993; Bischoff et al., 1999). The concentration in the top layers of the cartridge (L1 and L2) typically reflects the leaching losses while L4 often adsorbs nutrients moving on the outside of the cartridge and subsequently infiltrating it from the bottom. The NO_3-N concentration gradients from L1 to L4 of the majority (92%) of the resins cartridges reflected the predicted concentration gradients and they could therefore be used for the estimation of leaching losses of mineral N and P.

The very low NO_3-N concentration in L1 in garden R_2 (Figure 5A), the distribution of PO_4-P concentrations in the four layers (Figure 5B) and the low total amount of apparently leached PO_4-P (Figure 6) provide evidence that leaching rates in this garden were lower than in R_1 and W. This might be caused by the higher proportion of soil particles < 0.05 mm that increased the water holding capacity of the soil leading to lower water percolation through the soil profile (Figure 3).

During the weak rainy season in 2007, the estimated total amounts of mineral N leached below 0.6 m soil depth reached on average 5.9 kg ha^{-1}, 2.2 kg ha^{-1} and 7.3 kg N ha^{-1} in gardens R_1, R_2 and W, respectively (Figure 6). The mineral N losses were significantly higher ($P < 0.05$) on the more sandy soils of gardens R_1 and W than in the R_2 garden. Overall, these N leaching values are much lower than expected given that average annual N surpluses from horizontal nutrient balances for R_1 and R_2 gardens amounted to 369 kg N ha^{-1} and 593 kg N ha^{-1}, respectively and reached up to 2987 kg N ha^{-1} in garden W (Predotova et al., 2009). Also the estimated or measured leaching losses from nutrient budget studies on sandy millet fields with far lower amounts of applied nutrients are with 10 kg N ha^{-1} yr^{-1} (Buerkert and Hiernaux, 1998), 15 kg N ha^{-1} yr^{-1} (Hafner, 1992), 12 kg N ha^{-1} yr^{-1} (Bley, 1990), 15 to more than 25 kg N ha^{-1} yr^{-1} (Hafner et al., 1993) higher than those of our three intensively managed urban gardens. Compared to measured N emanation losses of 53, 48 and 92 kg N yr^{-1} for gardens R_1, R_2 and W reported by Predotova et al. (2009), the measured leaching values likely reflect the below-average precipitation in 2007.

In addition, leached organic forms of N were not accounted for by the ion exchange method. Van Kessel et al. (2009) and Siemens and Kaupenjohann (2002) reported dissolved organic N on sandy cropped sites reaching 6 – 15 % and 6 - 21 % of total leached N, respectively. According to Barton et al. (2005), organic N was with 69 – 87 % the major form of the total N leached in agricultural systems irrigated annually with 2300 mm of domestic effluent. Therefore severe underestimation of the total N losses is likely to occur, particularly in garden W receiving yearly almost 4000 mm of waste water heavily loaded with organic matter.

In some studies on nutrient balances in the Sahel P was considered as immobile in the soil (Krogh, 1997) while in others P movement through a very sandy soil profile played an important role (Brouwer and Powell, 1995). In our study, the cumulative estimated inorganic P losses during the 2007 rainy season reached on average only 0.5 kg P ha^{-1}, 0.1 kg P ha^{-1} and 0.7 kg P ha^{-1} in gardens R_1, R_2 and W. Similarly to mineral N losses, higher amounts of leached P were found in the gardens with a more sandy soil texture, namely R_1 and W, although this difference was significant only between gardens R_2 and W (Figure 5). These values for P leaching are low given the high annual P inputs of organic and chemical fertilizer (Diogo et al., 2009) and resulting P surpluses from horizontal nutrient fluxes reaching 177 kg P ha^{-1}, 135 kg P ha^{-1} and 513 kg P ha^{-1} in gardens R_1, R_2 and W, respectively (Predotova et al., 2009). Brouwer and Powell (1995) reported up to 19 kg P ha^{-1} translocated annually below a depth of 1.5 m after heavy manure application and attributed this to P having been bound to leached organic matter and clay particles. Because organically bound P is not nearly as easily adsorbed by the ion-exchange resins as inorganic P (Langlois et al., 2003), our results may thus underestimate total leaching losses of P in the gardens soils with their comparatively high rates of applied manure.

Combined with profile observations the failed suction plate experiment indicates that in our garden soils leaching is limited to the rainy season when jerry can-irrigation is combined with occasional heavy rainfall events. This is in contrast to Brouwer and Powell (1995) who assumed that nutrient leaching on well draining deep profiles planted with pearl millet continues during the dry season although also in their study highest leaching rates were expected during the later part of the rainy season. Hafner et al. (1993) observed in a 6-yr experiment on sandy millet fields near Niamey that leaching occurred only when single rainfall events exceeded 50 mm. This was supported by Bley (1990) who reported leaching to occur only with single rainfall > 40 mm. During the 2007 rainy season, however, the highest rainfall event recorded amounted to 32 mm (on 4th August), all other rainfall events were < 25 mm. Therefore multi-year measurements of leaching losses are necessary to conclusively assess the inter-annual fluctuations of nutrient leaching losses from UPA gardens in the West African Sahel.

4.6. Conclusions

The small apparent leaching losses of inorganic N and P from gardens with highly positive N and P balances were most likely due to the low rainfall and scarcity of intensive single rainfall events in the year of our study. Long-term experiments are therefore necessary to assess the effects of the large inter-annual variation in intensity and amount of total rainfall typical for Sahelian West Africa on leaching losses of mineral N and P from UPA gardens. The ion-exchange resin method allowed accounting for spatial differences in leaching rates of inorganic N and P on the sandy soils with their high permeability of solutes. However, comparative lysimeter studies of leaching rates would be useful to verify our results and to assess the likely important contribution of organic N and P to total leaching losses.

4.7. References

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Chapter 5.

General discussion and conclusions

5.1. Evaluation of the closed chamber system with the photo-acoustic infrared multi-gas meter for measuring gaseous nitrogen (N) and carbon (C) losses

The used mobile measuring system based on the photo-acoustic infrared multi-gas monitor INNOVA 1312-5 (LumaSense Technologies A/S, Ballerup, Denmark) attached to a closed chamber ('cuvette') appeared to be a very practical device to measure the gaseous emissions from the soil. The easily transportable setup allowed multiple samplings of emitted gases on the relatively small vegetable garden plots within a very short time. We were therefore able to obtain a large number of replications which helped to account for the high spatial variability in gaseous emission rates observed under field conditions (Paustian et al., 2000; Velthof et al., 2000; Kroeze et al., 2003; Konda et al., 2008). The device can be calibrated for measuring five different gases using appropriate filters and compensates directly for the cross-interference between the gases and water vapour interference (LumaSense Technologies A/S, 2009). The later is very useful especially when measuring with the closed chamber system in hot climate conditions such as in Niger, where the relative humidity in the chamber can rise very quickly. The fast flushing rate of the measurement chamber within the multi-gas meter (5 ml s^{-1}) allows a quick gas exchange resulting in a fast response time of the device (LumaSense Technologies A/S, 2009). The measured concentrations can be read directly in the field from a screen which allows for an immediate control of the measurements.

Nevertheless some problems are inherent to this set-up. Firstly, the time period during which the concentration of the gases is measured in the closed chamber, the socalled accumulation interval, may vary from 2 minutes to 24 hours (Velthof et al., 2000; Hans et al., 2005; Reth et al., 2005; van Groenigen et al., 2005). For the reasons discussed in the Chapter 2, we used an accumulation interval of only one minute in order to minimize changes in the gas efflux from the soil caused by changes in the microclimate under the cuvette. Such a short accumulation interval might have led to an underestimation of the gaseous emissions especially during the cooler morning measurements. Secondly, despite the Teflon® coating of the inside of the cuvette, some gas molecules may have adhered to the walls of the measurement cahmber. This may have been particularly the case for the very reactive ammonia (Asman et al., 1998; FAO, 2001). A recent test with different materials coating the inside of the cuvette showed that the Teflon® coating was quite inert for NH_3, N_2O, CO_2 and CH_4 compared to stainless steel (data not shown). The unavoidable disturbance of the soil cover by the use of the closed chamber has in our study been reduced (Chapter 2) by using PVC rings pressed into the soil at the onset of the experiment. It was onto these rings that the cuvette was fitted every time when emissions were measured. These rings were also used in our measurements of gaseous emissions from storage heaps of animal dung (Chapter 3).

The strongly temperature-dependent gaseous emissions were extrapolated assuming a sinusoidal distribution of flux rates throughout the 24h day with the highest and lowest emission rates during the hottest (1-3 pm) and coldest (6-8 am) part of the day (Chapters 2 and 3; Meisinger and Jokela, 2000; Dobbie and Smith, 2001; FAO, 2001; Mosier and Parkin, 2007). However, this simple mode of extrapolation can only be a first approximation and a modelling approach should be used to improve such estimates at the level of days or weeks.

5.2. Measurements of nutrient leaching losses, advantages and disadvantages of the ion-exchange resins method and failure of the suction plate experiment

First reports about the use of ion-exchange resins installed in the soil appeared in the middle 1980s (Crabtree and Kirkby, 1985). Since then, this method was used in numerous studies to determine plant availability and movement of nutrients in soil profiles (Skogley and Dobermann, 1996; Skogley et al., 1996; Bischoff et al., 1999; Lehmann et al., 2001; Lang and Kaupenjohann, 2004; Siemens and Kaupenjohann, 2004; Bischoff, 2007). In comparison to other methods this low cost, little time and labour demanding method allows a high number of replications to account for the typically high spatial variation of the solute flows in agricultural soils (Selker et al., 1992; Silva et al., 2005; Bischoff, 2007) but for N only NO_3^- and NH_4^+ can be recorded as organic N forms are not retained by the resins. This may lead to a sever underestimation of N losses on the UPA garden soils with their high C org concentrations. For our field study information on cumulative leaching losses of nutrients over a longer time period was of primary interest (Chapter 4). High replication numbers (n=24 per garden) which allowed to account for preferential flow phenomena that often occur on sandy soils were advantages of the method (Selker et al., 1992; Bischoff et al., 1999; Bischoff, 2007).

However, the installation of the cartridges with the ion-exchange resins is accompanied by the same difficulties as the *in situ* installation of lysimeters or suction plates. Care has to be taken to avoid disturbance of the soil column above the cartridge to avoid disturbance of the downward water movement. It also is of crucial importance to ensure tight connection of the cartridge with the over-laying soil layer (Schnabel, 1983), but at the same time the creation of a hydraulical barrier must be avoided to allow a free flow of the leachates into the resin container (Siemens and Kaupenjohann, 2004).

To examine whether resin cartridges were exposed to water logging, which would make their use futile, the resin-sand mixture in each cartridge was divided into four layers, which were extracted separately and examined if they showed the concentration gradient described by Bischoff (1999). Given its high mobility in soil solutes, the concentration of NO_3^-N was taken as the criterion of whether to use or not to use any given cartridge for the calculation of leaching losses. About 90% of the cartridges had a third or fourth layer (counted from the top) with very low NO_3^- concentrations, which indicated a consistent downward flux pattern throughout the season (Chapter 4). Cartridges were not used to estimate leaching losses of K as the resin-sand mixtures had very high background values of this nutrient. An ongoing recovery experiment with different resin pre-treatments and an analysis of recovery rates through different pathways will clarify the suitability of the resin method to measure K losses. Skogley (1996) suggested cooling down or freezing the resins between their removal from the soil and nutrient extraction while Lehman et al. (2001) has reported no effect of resin drying on the recovery rate. Further studies are under way to clarify the role of storage conditions on resin performance and ion recovery. The outcome of these studies is particularly important for studies on leaching losses conducted under hot environmental conditions such as in West Africa where cold-storage of resin samples is difficult.

In addition to the ion-exchange resin cartridges, in 2006 six Si-carbid suction plates per location were installed at 0.6 m depth in three urban gardens and two peri-urban fields. In 2007 the experiment was repeated with twelve suction plates in the river garden in the *Goudel* city quarter. The intention of the suction plate measurements was to compare these results with those of the resin cartridges. Unfortunately, in both years the suction plate measurements failed as it was difficult to establish a stable vacuum in the system. At the set suction pressure of -160 h Pa (100 h Pa to obtain the drainage water from the soil and 60 h Pa to transport the drainage water above the soil into the collecting bottles) most suction plates didn't yield any drainage water at all while at the same time and experimental site high quantities of water could be collected from neighbouring plates. Possible reasons for the differences could have been installation errors or an insufficient contact of the soil column above the suction plate with the plate surface. Silva et al. (2005) recommended a 3 week waiting period after installation before the first sampling, while Webster et al. (1993) concluded that the soil disturbance caused by the installation process lasted as long as one year. In our case, the suction plates were installed together with the resin cartridges about one month before the onset of the rainy season (Chapter 4). The irregular and small rainfall events typical for the onset of the wet season likely caused only small drainage which may at least partially explain the difficulties in obtaining a stable suction vacuum in the system despite our efforts to ensure a tight soil-cartridge contact through the addition of mud above the plates during installation (Eijkelkamp, 2007). Morari (2006) reported similar difficulties in his experiments with tension-controlled suction plates during periods with low drainage flux.

Despite the mentioned difficulties the ion-exchange resin method has delivered consistent and overall reasonable results in estimating leaching losses of N and P in contrast to the failed experiment with the suction plates.

5.3. Vertical nutrient losses in urban gardens

In recent years the monitoring and modelling of nutrient dynamics in African agricultural systems has become of increasing interest (van den Bosch et al., 1998; Gachimbi et al., 2005; Abegaz and van Keulen, 2009). The multi-disciplinary and multi-scale approach of the nutrient monitoring toolbox NUTMON used widely in sub-Saharan Africa requires a qualitative and quantitative analysis of the agricultural systems under study to determine their structure, nutrient flows, nutrient balances and economic performance (De Jager et al., 1998). The NUTMON approach allows to identify the nutrient deficits or surpluses and to define the scope for changes under the specific environmental and fertility management conditions of a farm (Schlecht et al., 2006). The model includes economic and social aspects that reach far beyond nutrient balance studies (Stangel, 1995; Bationo et al., 1998; Brouwer and Powell, 1998; Rufino et al., 2006).

To the best of our knowledge, so far no modelling of nutrient flows and analysis of different management strategies on such flows has been done for the urban and peri-urban farming systems in sub-Saharan Africa. Therefore the quantification of horizontal (Diogo et al., 2009) and vertical (this study) nutrient fluxes in the urban gardens of Niamey may help to fill this gap of knowledge and serve as a reference data set for future studies in other UPA systems of West Africa.

The initial claim of high nutrient surpluses in Niamey’s urban gardens with their intensive vegetable production (Graefe et al., 2008) has been confirmed by Diogo (2009). His horizontal nutrient flux measurements showed positive balances with nutrient surpluses reaching annually 1,128 kg N ha^{-1}, 221 kg P ha^{-1} and 275 kg K ha^{-1} in high input gardens (n=5) and 285 kg N ha^{-1}, 123 kg P ha^{-1} and 314 kg K ha^{-1} in low input gardens (n=5).

In this study, the gardens R_1 and R_2 using irrigation water from the river (Chapters 2 and 4) belonged to the group of low input gardens and the garden using waste water (W) was a high input garden. After subtracting the amounts of nutrients lost via volatilization and leaching beyond the rooting zone, the total nutrient balances of N, P and K remained in all three gardens highly positive (Table 1). However, the measurements performed here may raise doubts about whether all the possible gaseous losses were correctly assessed or if other pathways may account for further nutrient leaking from the system. In case of the gaseous N losses, only N_2O and NH_4 were measured, but NO and N_2, which could have been easily emitted (Mosier and Parkin, 2007), were not recorded. In this context it is important to note that Butterbach-Bahl et al. (2004) reported modelled annual NO-N emissions ranging from 0.4-26.3 kg N ha^{-1} from agricultural soils in Germany.

On the other hand, only in garden R_1 the high application rates of animal manure reflecting high C inputs were sufficient to balance the outputs by harvest and gaseous losses (Table 1). In contrast, insufficient manuring in garden R_2 and irrigation water as the only C source in garden W led to highly negative C balances in these two gardens. While CO_2-C losses might be slightly overestimated by additional CO_2 emissions from dark respiration of small plants or cut stems under the cuvette, the high nutrient inputs in form of chemical fertilizers and irrigation water lacking sufficient amounts of organic C in the gardens R_2 and W show the need for recycling of C in year-round irrigated vegetable production of the studied UPA systems.

Table 1. Total carbon and nutrient balances determined from January 2006 – December 2007 in three urban vegetable gardens of Niamey, Niger

Garden		Carbon and nutrients (kg ha^{-1} yr^{-1})			
		C	N	P	K
Goudel	Total input	30518	473	204	515
(R_1)	Output crop harvest	2198	104	27	242
	Gaseous losses	25000	53		
	Leaching losses		6	1	NA
	Total balance	**3320**	**310**	**176**	**273**
Yantala Bas	Total input	12278	782	169	829
(R_2)	Output crop harvest	2187	189	34	354
	Gaseous losses	20000	48		
	Leaching losses		2	0	NA
	Total balance	**-9909**	**543**	**135**	**475**
Gountou Yena	Total input	7816	3816	644	2019
(W)	Output crop harvest	7031	829	131	1043
	Gaseous losses	27000	92		
	Leaching losses		7	1	NA
	Total balance	**-26215**	**2888**	**512**	**976**

In years with higher rainfall than in 2007, higher nutrient leaching losses in UPA gardens can be expected (Chapter 4) and some additional leaching may occur after the rainy season when we stopped our measurements (Brouwer and Powell, 1995). The ion-exchange resin method should be improved to also allow the measurement of K leaching losses. This will require a more intensive rinsing of the resin and sand material used.

To obtain additional information on gaseous C and N losses in urban vegetable production, controlled experiments should be conducted in which measurements of gaseous emissions are synchronized with simulated planting, harvesting, fertilizing and irrigation operations. The controlled dung storage experiment has delivered solid data on the magnitude and temporal distribution of the gaseous C and N emissions as affected by different storage modes (with and without dung coverage) in combination with the addition of rock phosphate dust (Chapter 3). Nevertheless, important information on gaseous losses during dung storage is missing as the highest C and N losses are expected to occur in the animal stables right after defecation (Hao et al., 2001; Sommer, 2001) and immediately after application to the field (Sommer and Hutchings, 2001). Such data would greatly improve our estimates of overall gaseous C and N fluxes and overall assessments of nutrient use efficiency in UPA garden systems.

5.4. Conclusions

This study has confirmed that gaseous C and N losses are an important component of the nutrient balances in the high input – high output urban vegetable gardens of Niamey. As expected, the highest volatilization rates were observed during the hot dry and at the beginning of the rainy season. Especially during these parts of the year, more efficient strategies of nutrient cycling should be used. During the hot dry season C and N losses from unprotected manure heaps are also high, especially during the first days of manure storage in the gardens. The addition of finely ground rock phosphate proved to be effective to decrease N volatilization from the dung heaps. Simple plastic sheet coverage reduced the run-off and leaching losses during the rainy season. In contrast to our initial hypothesis, leaching losses of mineral N and P did apparently not contribute much to the total vertical losses in the urban garden systems in 2007 with its below average amount of rainfall. The only minor role of nutrient leaching in the nutrient-loaded urban gardens should be further examined by multi-year studies.

5.5. References

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Affidavit

I assure that this dissertation was written independently and without non-permissible help and that I used no sources other than those specified in the dissertation. All quotations that have been extracted from published or unpublished sources have been marked as such. No part of this work has been used in other PhD processes.

Hiermit versichere ich, dass ich die vorliegende Dissertation selbständig und ohne unerlaubte Hilfe angefertigt und keine anderen als die in der Dissertation angegebenen Hilfsmittel benutzt habe. Alle Stellen, die aus veröffentlichten oder unveröffentlichten Schriften entnommen sind, habe ich als solche kenntlich gemacht. Kein Teil dieser Arbeit ist in einem anderen Promotionsverfahren verwendet worden.

Witzenhausen, 18h of September 2009 Martina Předotová