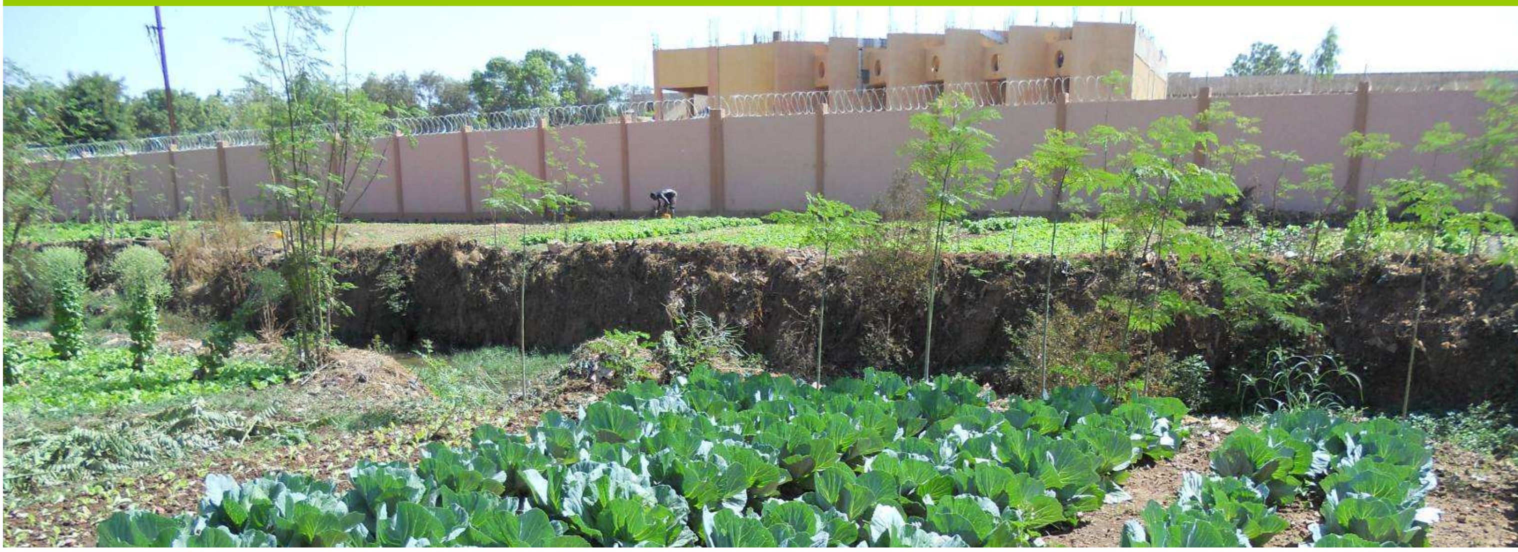
Matter flows and balances in urban vegetable gardens of Bobo Dioulasso, Burkina Faso (West Africa)



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Matter flows and balances in urban vegetable gardens of Bobo Dioulasso, Burkina Faso (West Africa)

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Dedication

To the memory of my father Lamoudi Jean-Pierre Lompo

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Summary

In Sub-Saharan Africa, urban and peri-urban agriculture (UPA) is practiced as a survival strategy of the urban poor. In the past decade, it has gained more attention from local authorities, political authorities and researchers. Numerous studies have been conducted about UPA and have provided solid data thereby improving our knowledge on its characteristics and possible social, economic and environmental impacts. However, still missing are more comprehensive basic data sets especially regarding nutrient flows and balances that allow to develop management practices to improve UPA sustainability. The purposes of this research therefore was (i) to determine horizontal flows of nitrogen (N), phosphorus (P), potassium (K) and carbon (C), and to calculate their balances for diverse urban production systems; (ii) to monitor gaseous emissions of N and C for diverse production systems. The study was conducted in urban vegetable gardens of Bobo Dioulasso, the second largest city of Burkina Faso (West Africa). A nutrient-balance approach was used to determine N, P, K, and C fluxes and balances from March 2008 to March 2009 for two production systems classified as: the "commercial gardening + field crops and livestock system" (cGCL), and the "commercial gardening and semi-commercial field crop system" (cGscC). For monitoring of C and N emissions from soils, two representative gardens of the two production systems were selected and ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) emissions were determined during the coolest and the hottest periods of the day using a closed chamber system.

Nitrogen, P, K, and C inputs in all gardens exceeded the amounts recommended by the extension service for the Sudano-Sahelian countries. Their balances were similarly positive in both production systems and reached annual averages of 688 kg N ha^{-1}, 251 kg P ha^{-1} yr^{-1}, 189 kg K ha^{-1}, and 31 t C ha^{-1}. For both production systems, apparent use efficiency was highest for K (95 and 89% for cGCL and cGscC, respectively) followed by N (55 and 61%) and P (38 and 35%).

The highest emission rates occurred during the hot middays and peaks were observed after fertilizer applications reaching fluxes of up to 1,140 and 154 g ha^{-1} h^{-1} for NH_3-N and N_2O-N, respectively. The estimated total annual losses of N reached 419 and 347 kg ha^{-1} for cGCL and cGscC systems. This accounted for 36% and 49% of the N surpluses in cGCL and cGscC. Emissions of NH_3 accounted for 73% and 77% of the total estimated N losses for cGCL and cGscC systems.

The study indicates that nutrient management practices in UPA vegetable production in Bobo Dioulasso would greatly benefit from better synchronizing nutrient input rates with crop demand and adjusted fertilization techniques to mitigate N losses. Further studies are needed to determine the rates of solid waste and synthetic fertilizer to apply and also to explore ways of improving nutrient management in urban vegetable gardens. Management recommendations should be geared towards increasing nutrient use efficiencies by better tailoring nutrient availability to crop demand and adjust fertilization techniques to mitigate N losses.

Zusammenfassung

Städtische und stadtnahe Landwirtschaft (Englisch: Urban and Peri-urban Agriculture, UPA) wird oft als wichtige Überlebensstrategie der ärmeren Bevölkerungsschichten im Subsaharischen Afrika angesehen. In den vergangenen zehn Jahren wurde dieser Bewirtschaftungsform zunehmend Beachtung durch lokale Behörden, Politiker und Wissenschaftler geschenkt. Es existieren bereits zahlreiche Studien über UPA, die unser Wissen über UPA-Charakteristika und deren Auswirkung auf soziale und ökonomische Gefüge, sowie auf die Umwelt verbessern. Jedoch fehlen umfangreichere Basisdaten zu Stoffflüssen und –bilanzen, die zur Entwicklung von Managementstrategien notwendig sind und die Nachhaltigkeit von UPA steigern.

Das Ziel dieser Forschungsarbeit war es, (i) die horizontalen Flüsse von Stickstoff (N), Phosphor (P), Kalium (K) and Kohlenstoff (C) and deren Bilanzen in verschiedenen städtischen Produktionssystemen zu bestimmen und (ii) die N- und C-Gasemissionen verschiedener Anbausysteme zu messen. Die Studie wurde in städtischen Gemüsegärten von Bobo Dioulasso, der zweitgrößten Stadt Burkina Fasos (West Afrika) von März 2008 bis Dezember 2009 durchgeführt.

Ein Nährstoffbilanzierungsansatz erlaubte es, N-, P-, K- und C-Flüsse und -Bilanzen für zwei Anbausysteme zu bestimmen: “Kommerzieller Gartenbau mit Getreidebau und Viehhaltung“ (cGCL) und “Kommerzieller Gartenbau und halb-kommerzieller Getreidebau“ (cGscC).

Zur Messung der Gasemissionen wurden zwei representative Gärten ausgewählt und die Ammoniak- (NH_3), Lachgas- (N_2O), Kohlenstoffdioxid- (CO_2) and Methan- (CH_4)-Emissionen aus den Böden während der kühlsten und der heißesten Zeit des Tages mit Hilfe eines geschlossenen Kammersystems gemessen.

Die N-, P-, K- und C-Einträge überstiegen in allen Gärten die empfohlene Menge. Die Bilanzen waren in beiden Anbausystemen ähnlich und erreichten jährlich Mittelwerte von 688 kg N ha^{-1}, 251 kg P ha^{-1}, 189 kg K ha^{-1}, and 31 t C ha^{-1}. Für beide Anbausysteme war die Nutzungseffizienz von K (95 und 89% für cGCL bzw. cGscC) am höchsten, gefolgt von N (55 und 61%) und P (38 und 35%).

Die höchsten Emissionsraten traten während der heißen Mittagszeit auf und die Emissionspitzen nach Düngemittelanwendungen, sie erreichten bis zu 1140 ha^{-1} h^{-1} NH_3-N und 154 g ha^{-1} h^{-1} N_2O-N.

Der geschätzte jährliche Gesamtverlust an N betrug 419 und 347 kg ha^{-1} für cGCL- bzw. cGscC-Systeme, was gleichzusetzten war mit 36% und 49% des N-Überschusses in cGCL bzw. cGscC. NH3-N Emissionen betrugen 73% und 77% des geschätzen Gesamt-N-Verlustes für cGCL- bzw. cGscC-Anbausysteme.

Die Daten belegen, dass die Nährstoffmanagementpraktiken in der UPA Gemüseproduktion in Bobo Dioulasso stark von einer besseren Synchronisation der Düngemittelgaben an den Bedarf der Feldfrüchte und von angepassten Düngetechniken profitieren würden, um N-Verluste zu mindern. Weitere Studien sind notwendig, um die hier beschriebenen Ergebnisse zu verifizieren und Wege eines verbesserten Nährstoffmanagements in städtischen Gemüsegärten von Bobo Dioulasso zu erarbeiten. Dabei sollten Bewirtschaftungsempfehlungen auf erhöhte Nährstoffnutzungseffizienzen, auf den Bedarf der jeweiligen Feldfrucht und auf besser angepasste Düngetechniken abzielen.

Chapter 1. General introduction, research objectives and hypotheses

1.1. General introduction

1.1.1. Challenges of agriculture today

In the past decades, the objective of agriculture consisted in the increasing food production through the development of new technologies. The Green Revolution has resulted in higher yields, especially in industrialized countries. However, it has also had negative impacts on the environment and has not been effective in developing countries (IAASTD, 2008). Nowadays, environmental degradation has reached an alarming level, becoming a major concern of humanity (Kulkarni and Ramachandra, 2006). In addition to environmental degradation, the situation is worsened by continuously increasing demands for food and for already limited natural resources, and by persistent poverty, malnutrition, and poor food and diet quality (Kulkarni and Ramachandra, 2006; IAASTD, 2008). Therefore, agriculture today faces the challenge of satisfying human food needs over the long term while also taking into account socio-economic and environmental factors.

In the 1990s, the sustainable agriculture movement emerged and defined sustainable agriculture as “an integrated system of plant and animal production practices having a site-specific application that will, over the long term: (1) satisfy human food and fiber needs; (2) enhance environmental quality and the natural resource base upon which the agricultural-economy depends; (3) make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; (4) sustain the economic viability of farm operations; and (5) enhance the quality of life for farmers and society as a whole" (Gold, 1999).

Sub-Saharan Africa has the lowest food production compared to other regions of the world (UNECA, 2009; Hazell et al., 2010) and there is a critical gap between food demand and food production. This gap is projected to increase because crop yields are decreasing while the population is continuously increasing. Food production has to be increased. One of the options is to increase rate at which arable land is exploited, presently only 3.8% of the total arable land in Africa (733 million hectares, UNECA, 2009). However, land degradation in Africa is an important concern since up to 65% of arable land is already degraded (Pretty, 1999). Therefore, food production must be increased from the currently exploited arable land (Pretty, 1999; IFPRI, 1995). Past approaches which resulted in agricultural development in industrialized countries have not been particularly successful in Africa (Pretty, 1999; Hazell et al., 2010). Therefore, food production must be enhanced using sustainable methods that have recently been identified (Pretty, 1999). African agriculture, more specifically Sub-Saharan African agriculture is practiced by smallholders and pastoralists for their subsistence (Hazell et al., 2010). It is characterized by low investment and low productivity, lack of infrastructure, insufficient financing for agricultural research, low use of new opportunities generated by science to increase productivity, insufficient linkages between agriculture and other sectors, unfavorable policy and regulatory environments, and increasingly affected and threatened by climate change (UNECA, 2009). In this context, can African countries use the new technologies to meet the challenge to increase agricultural productivity? If so, can this be achieved without damaging the environment?

1.1.2. Overview on urban agriculture in Sub-Saharan West African countries

The growing of plants and the raising of animals for food and other uses called urban and peri-urban agriculture (UPA) is an old activity which has always taken place within and around cities and towns. Neglected for a long time, urban farming today attracts the attention of municipal and governmental authorities as well as researchers (Cissé et al., 2005; van Veenhuizen and Danso, 2007). Indeed, urban agriculture is an important solution for diverse problems resulting from rapid urbanization that local and national governmental authorities are struggling to solve, especially in developing countries. Urban agricultural outputs include staple crops like maize, cassava, plantains; vegetables including local varieties of tomatoes, peppers and leafy vegetables, and more exotic vegetables, such as lettuce, cucumber, cauliflower and carrot; and livestock such as poultry, cattle, goats and other small ruminants (Armar-Klemesu, 2000). UPA has a significant share in the food supply of many cities in the world (van Veenhuizen and Danso, 2007).

In Sub-Saharan Africa, UPA is often practiced as a survival strategy by vulnerable groups to minimize their food insecurity problems (Armar-Klemesu, 2000; RUAF, 2005; van Veenhuizen and Danso, 2007). It enhances urban food security and household diets (Armar-Klemesu, 2000; van Veenhuizen and Danso, 2007). Additionally, UPA contributes to employment and income generation. In several African cities, income earned by urban farmers was found to be a significant contributor to household maintenance (Nugent, 2000). Other side effects of UPA are its contribution to urban environmental management by using urban solid and liquid wastes as resources, by contributing to a better urban climate and by managing the urban landscape (Armar-Klemesu, 2000; RUAF, 2005; van Veenhuizen and Danso, 2007). Finally, UPA contributes to social development through social inclusion, HIV-AIDS mitigation, etc. (Armar-Klemesu, 2000; RUAF, 2005; van Veenhuizen and Danso, 2007). An increasing number of cities and national governments in Sub-Saharan Africa are adapting their policies and programs regarding UPA (van Veenhuizen and Danso, 2007) and new approaches are currently underway to reinforce the formal establishment of allotment garden schemes and other forms of urban agriculture in cities of Sub-Saharan Africa (RUAF, 2005).

UPA farming systems are typically much more intensive than rural ones (UNDP, 1996; Rosendahl et al., 2009). For instance, unlike the negative nutrient balances generally reported for rural farming systems (Stoorvogel et al., 1993; Bationo et al., 1998; Anthofer and Kroschel, 2000; De Jager et al., 2001; Haileslassie et al., 2006), from Niamey (Niger), Diogo et al. (2010) reported annual horizontal balances of 9,936 C ha^{-1}, 1,133 N ha^{-1}; 223 P ha^{-1} and 312 kg K ha^{-1} indicating low fertilizer use efficiencies and leading to substantial losses by leaching and volatilisation (Drechsel et al., 1999; Huang et al., 2007; Wang et al., 2008; Diogo et al., 2010; Predotova et al., 2010, 2011). Consumer health may also be at risk due to: excessive applications of pesticides on vegetables (Amoah et al., 2006); the use of municipal solid wastes and untreated irrigation water contaminated by heavy metals (Anikwe and Nwobodo, 2002; Singh et al., 2004; Abdu et al., 2011, 2012); and the use of poultry manure contaminated by faecal coliforms and helminths (Amoah et al., 2005). In other words, the sustainability of UPA is an important issue. With regard to this, great efforts, reflected in the number of international organizations (FAO through many programs, UNHCR, UNICEF, UNWHO, UNCHS, UNDP, IDRC, World Bank, GTZ, NRI, etc.), research programs and policy-makers interested in the UPA issues, are undertaken to mitigate UPA's negative effects while maintaining and/or improving its positive social, economic and environmental effects. Many studies have already provided good qualitative and case study data, thereby contributing to a good understanding of UPA. However, still missing are more comprehensive basic data set on:

1) numbers, locations and characteristics of farms;
2) volume and type of food produced;

3) costs and prices of food produced and sold;
4) formal and informal markets;
5) income earned from farming;
6) inputs and farming methods used;
7) environmental impacts;
8) veterinary and public health effects;
9) effects of the use of urban wastewater and solid waste;
10) water needs and availability among all competing uses (http://www.fao.org/unfao/bodies/COag/cOAG15/X0076e.htm).

It is within this context that an urban food project has been initiated in three West African countries (Burkina Faso, Mali and Nigeria) to investigate the “Challenges and opportunities for nutrient efficient agriculture in West African cities”.

1.1.3. Overview on gas emissions from agricultural soils

Agriculture is responsible for the emission of many environmentally destructive gases (Harrison and Webb, 2001). The main gases emitted include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ammonia (NH_3) (Jones, 2009). According to the intergovernmental panel on climate change (IPCC, 2001), the first three cited gases are the most important greenhouse gases (GHG) contributing to global warming. NH_3 contributes to acidification and eutrophication when deposited to soils and waters (Harrison and Webb, 2001) and to the secondary formation of N_2O (Rotz, 2004). In addition, nitrogen gas emissions represent fertilizer losses for farmers. Therefore, numerous efforts are being undertaken to identify management practices that are agronomically feasible, economically attractive to farmers and able to mitigate environmental impact (Matson et al., 1998).

Gas emissions from soils occur naturally. The emission rates depend on soil properties such as pH, temperature, water content and mineralizable organic carbon and nitrogen, which all influence microorganism activity (Smith et al., 2003; Sánchez-Martín et al., 2008). Agricultural practices have the potential to modify soil properties, thereby influencing gas emission rates.

NH_3 emission

NH_3 is emitted from croplands through volatilization which is a physicochemical process where manure or solution derived ammonium nitrogen is transformed to ammonia gas following equation 1 (Meisinger and Jokela, 2000):

$NH_4^+ \leftrightarrow NH_3 + H^+$ (1)

Ammonia volatilization is the major process leading to nitrogen loss from surface-applied fertilizers (Rochette et al., 2009). According to Meisinger and Jokela (2000), nitrogen losses through ammonia volatilization range from a few percent to closed to 100%. The emission rates vary between studies depending on many factors. In a controlled experiment, Rochette et al. (2009) reported NH_3 emission rates reaching 1200 g NH_3-N ha^{-1} h^{-1} from intact soil cores of a long-term tillage experiment in Quebec (Canada) after surface urea application. Lower emission rates of about 83 g NH_3-N ha^{-1} h^{-1} from urea and organic manure applied to lettuce grown on a sandy soil were reported by Asing et al. (2008), while 333 g NH_3-N ha^{-1} h^{-1} were recorded by Ma et al. (2010) in an on-farm experiment. The factors influencing ammonia emissions comprise manure characteristics (dry matter content, pH, NH_4^+-N content), application management (surface application, incorporation, zone application, timing), soil conditions (soil moisture, soil properties, plant or residue cover), and environmental conditions (temperature, wind speed, rainfall, Meisinger and Jokela, 2000).

Accurate estimates of ammonia loss are necessary for sustaining crop production. Most of the studies on NH_3 volatilization have been conducted in industrialized countries. Estimates of NH_3 emissions from agricultural soils in African countries are scarce. Therefore, studies on NH_3 volatilization as affected by management practices and environmental conditions are needed to address the issues of sustainable agriculture in Africa.

N_2O emission

N_2O emission is another pathway by which nitrogen is lost from agricultural soils. N_2O can be produced in soils by biotic reactions as well as by abiotic reactions. However, it is mostly produced biologically through the nitrification and denitrification processes (Hickman et al., 2011). The emission rates depend on several factors such as water-filled pore space (WFPS), temperature and NH_4+ and NO_3- concentrations. The application of fertilizers generally leads to an increase in N_2O emissions (Dobbie and Smith, 2001) and increasing application rates of N generally results in an increase in N_2O flux rates (Mosier and Parkin, 2007; Wagner-riddle et al., 2007; Brümmer et al., 2008). For instance, in the south west of Burkina Faso, Brümmer et al. (2008) reported average daily emission rates of 0.19 and 0.8 g N_2O-N ha^{-1} h^{-1} from sorghum fields fertilized with 52.5 and 140 kg N ha^{-1}, respectively. Reported cumulative flux rates of N_2O vary from 0.01 to 2.00% of the applied mineral N. However, greater cumulative flux rates of up to 6.7% and 8.5% for organic and inorganic fertilizers, respectively, were reported by Khalil et al. (2002) in a controlled experiment. Measuring N_2O emissions from agricultural soils is important for both agronomic and environment aspects (Christensen, 1983).

CO_2 emission

Biological processes are the main sources of CO_2 emissions from soils and include microbial respiration, root respiration and fauna respiration. A secondary source is chemical oxidation, important in higher temperature conditions (Rastogi et al., 2002).

The main sources of soil carbon comprise, on the one hand, litter fall, root mortality, application of manures and crop residues decomposed by soil fauna, and on the other hand photosynthetic carbon used by roots. Soil microfauna is responsible for 99% of CO_2 derived from the decomposition of organic matter due to its role in organic matter mineralization. The macro-fauna is mostly responsible of the fragmentation of freshly added organic matter. Root respiration accounts for 50% of soil respiration (Rastogi et al., 2002).

CO_2 emissions from soils are influenced by many factors such as soil texture, temperature, moisture, pH, available C and N content of the soil. Farmers' management practices can modify one or several factors thereby affecting biological processes and consequently CO_2 emissions (Sainju et al., 2008). In a study on crop rotation and nitrogen fertilization effects on soil CO_2 emissions in central Iowa, Wilson and Al-Kaisi (2008) have shown that the monoculture of corn had higher soil CO_2 emissions than the corn-soybean rotation. They explained this difference by the greater crop residue incorporation with the monoculture of corn over a 2-year period compared to the corn-soybean rotation. They also indicated that increasing N fertilization generally decreased soil CO_2 emissions. Finally, they suggested that crop rotation and N fertilizer application have the potential to affect soil CO_2 emissions and the soil C pool. There are however contradictory results in the literature about the effect of N fertilization on CO_2 emissions (Ding et al., 2007). Cao and Woodward (1998) reported an increase in CO_2 fluxes due to N fertilization, indicating a negative effect of N inputs on C sequestration. Jarecki et al. (2008) reported similar cumulative CO_2 emissions for plots fertilized with urea ammonium nitrate and unfertilized plots, while Ding et al. (2007) observed a reduction in CO_2 emission due to N fertilisation. Additionally, application of organic fertilizers have been shown to increase soil CO_2 emission due to the supply of additional C substrate (Jarecki et al., 2008). Irrigation increases soil water content and thereby CO_2 emission from soil (Sainju et al., 2008).

Understanding the factors that control soil respiration is of particular importance to land use and management, since certain measures can be taken to enable lands to sequester atmospheric C (Townsend et al., 1996; Nadelhoffer et al., 1999; Bowden et al., 2004). In West African agricultural systems, numerous studies have been conducted regarding soil organic matter status and mineralization (Bacyé, 1993; Sedogo, 1993; Bado et al., 2004; Pallo, 2008). However, little is known about those aspects in the intensive vegetable production systems especially in cities.

CH_4 emission

CH_4 is produced biologically through the methanogenesis process in anaerobic conditions. The methonogenic bacteria consume carbonate substrates produced from the decomposition of organic matter in soil, leading to CH_4 production. CH_4 emissions normally occur in wetland soils due to anaerobic conditions, while its oxidation occur in upland soils which are not water-saturated, well-aerated and generally oxic (Conrad, 1996). However, upland soils can be sources of CH_4 when aeration and gas diffusivity are altered by agricultural management practices. For instance, organic manure applications to soil inhibit CH_4 oxidation while stimulating its production by supplying additional methanogenic bacteria, by stimulating oxygen consumption and by contributing to creating an anoxic environment (Jarecki et al., 2008). Ussiri et al. (2009) reported that tillage leads to CH_4 emission unlike no-tillage, which induces its oxidation. Tillage has a negative effect on methanotrophic bacteria by disturbing soil structure. It does not allow greater gas diffusivity thereby limiting the rate of atmospheric CH_4 supply to oxidizing bacteria. In the long term, tillage can damage CH_4 oxidizers and subsequently reduce the ability of the soil to oxidize CH_4 (Ussiri et al., 2009). Inorganic N fertilization can reduce the CH_4 oxidation capacity of upland soils, thereby increasing its emissions. It is thought that inorganic N fertilizers inhibit CH_4 consumption activity in arable soils because NH_4^+ is a competitive inhibitor of CH_4 oxidation (Harrison et al., 1995; Chan and Parkin, 2001). Predicting CH_4 emission rates is difficult due to the influence of diverse environmental factors. Since it contributes to global warming, studies need to be conducted for diverse agro-ecological conditions to determine CH_4 emission patterns and to generate and evaluate mitigation strategies.

For agricultural sustainability, several management practices have been identified to reduce gaseous N and C emissions from soils (Desjardins et al, 2002). Zero tillage, cultivating the soil surface before surface application, selection or use of N fertilizers, reducing N application rates during the coolest part of the day or when rain is expected, application of nitrification/urease inhibitors or coated N fertilizers, incorporation and deep placement of fertilizers, and reduction of bare fallow and conversion of croplands to permanent grasslands have all been identified as promising management practices to reduce gas emissions (Desjardins, 2002; Grant et al., 2004). However, reducing the emission of all gases at the same time is a big challenge (Brink et al., 2001). Therefore, investigations on the influence of management practices leading to lower gas emissions at different levels are need (Grant et al., 2004). Accurate estimates of annual GHG emissions at the field, regional and countrywide scale are required in order to compare the impact of management strategies and to identify management practices that will lead to lower GHG emissions.

1.2. Research objectives and hypotheses

This research was conducted to provide quantitative data about nutrient management on smallholder farming systems in the urban and peri-urban area of Bobo Dioulasso. The specific objectives were:

1. To determine horizontal C, N, P and K flows and to calculate their balances for diverse production systems;
2. To monitor gaseous emissions of N and C for diverse production systems;

We therefore hypothesized that in the urban agricultural systems of Bobo Dioulasso:

1. High amounts of C and nutrient are used, exceeding crop requirements and leading to positive C and nutrient balances regardless the production system;
2. Gaseous emissions of N and C occur during the hottest periods of the day and are important pathways of N and C losses for the diverse gardening systems;

1.3. References

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Chapter 2. Horizontal flows and balances of nitrogen, phosphorus, potassium and carbon in urban vegetables gardens of Bobo Dioulasso, Burkina Faso

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Abstract

Little is known about nutrient flows in intensive production systems of urban agriculture in West Africa. This study therefore investigated nutrient management practices in urban vegetable gardens of Bobo Dioulasso, the second largest city of Burkina Faso. Nitrogen (N), phosphorus (P), potassium (K), and carbon (C) fluxes were quantified and nutrient balances calculated for three gardens representing the typical commercial gardening + field crops and livestock system (cGCL) and three gardens representing the commercial gardening + semi-commercial field crop system (cGscC). Nutrient and C balances were similarly positive in both production systems reaching annual averages of 688 kg N ha $^{-1}$, 251 kg P ha^{-1} yr^{-1}, 189 kg K ha^{-1}, and 31 t C ha^{-1}. Inputs in all gardens exceeded the amounts recommended by the extension service by up to 236%, 33% and 187 % for N, P, and K, respectively. In both production systems, apparent nutrient use efficiency was highest for K (95% and 89% for cGCL and cGscC) followed by N (55% and 61%) and P (38% and 35%). Management recommendations should be geared towards increasing N and P efficiencies by better tailoring nutrient supply to crop demand.

Key words: Horizontal fluxes; nutrient balance; nutrient use efficiency; vegetable production.

2.1. Introduction

Worldwide urban and peri-urban agriculture (UPA) can contribute substantially to poor families' income and food security though in some middle or upper-class communities of both developped and developing countries its main impetus may be recreation and relaxation (Drescher et al., 2006). In sub-Saharan Africa, urban farming is increasingly practiced as a survival strategy by families with low purchasing power and restricted access to food (Armar-Klemesu, 2000; RUAF, 2005; van Veenhuizen and Danso, 2007). Its side effects are an improvement of urban environments through recycling of solid and liquid waste, greening of neighborhoods, and in some cases even an improvement of the micro-climate through the existence of irrigated green spaces (RUAF, 2005). UPA is also claimed to play a significant role in achieving Millennium Development Goals (MDGs) such as "Eradication of extreme poverty and hunger", "Promotion of gender equality and empowerment of women", "Combat of HIV-AIDS and other diseases", and "Ensuring environmental sustainability" (van Veenhuizen and Danso, 2007). Therefore, a growing number of international development agencies, research centers, and civil society organizations foster UPA as part of urban policy and development programs (Castillo, 2003).

UPA farming systems are typically much more intensive than rural ones (UNDP, 1996; Rosendahl et al., 2009) with higher nutrient inputs leading to the accumulation of surpluses in the soil and substantial losses by leaching and volatilisation (Drechsel et al., 1999; Huang et al., 2007; Wang et al., 2008; Diogo et al., 2010; Predotova et al., 2010, 2011). From Niamey (Niger), Diogo et al. (2010) reported annual horizontal balances of 9,936 kg C ha^{-1}, 1,133 kg N ha^{-1}, 223 kg P ha^{-1}, and 312 kg K ha^{-1} indicating low fertilizer use efficiencies and an important potential for negative externalities (Gruhn et al., 2000; Smaling et al., 2006; Predotova et al., 2010). Consumer health may also be threatened because of excessive applications of pesticides on vegetables (Amoah et al., 2006) and the use of heavy metal contaminated irrigation water and municipal wastes (Anikwe and Nwobodo, 2002; Singh et al., 2004; Abdu et al., 2011, 2012). Wastewater usage for irrigation without treatment as well as poultry manure can also result in the contamination of vegetables by faecal coliforms and helminths (Amoah et al., 2005).

Recently, many research activities have been undertaken to reduce negative impacts of UPA on the environment and consumers' health. In this context nutrient balance calculations can help to optimize nutrient applications, increase nutrient use efficiencies, and serve as indicators of potential land degradation (Cobo et al., 2010). In Burkina Faso as well as in other sub-Saharan African countries, several studies have been conducted about the effects of nutrient management in rural farming systems (Smaling et al., 1993; Stoorvogel et al., 1993; Bationo et al., 1998), but little is known about nutrient fluxes in intensive UPA production systems. This study therefore aimed at contributing to close this knowledge gap using a series of on-farm experiments and surveys in Burkina Faso.

2.2. Materials and methods

2.2.1. Study site

This study was conducted in Bobo Dioulasso (4°20' W , 11°09' N), the second largest city of Burkina Faso, West Africa, located in the western part of the country at 360 km of Ouagadougou, the capital city. Its surface is approximately 14,000 ha with a total population of 310,000 inhabitants in 1996 and 490,000 in 2006 (INSD, 2008, 2010). The local climate is tropical, Sudano-Guinean with a dry season from November to May and a rainy season from May to October. Annual rainfall varies between 800 and 1,000 mm, distributed in 75-85 rainy days (PANA, 2003).

Bobo Dioulasso is partitioned by the river Marigot Houet flowing from the south to the north- east of the town. Despite its high load of liquid and solid wastes, pathogens and hazardous chemicals, the river provides irrigation water for one third of the local urban gardens (Picture 1; Kinané et al., 2008).

Picture 1. One part of the river Marigot Houet with some gardens

2.2.2. Description and selection of gardens

Dossa et al. (2011) had classified the UPA households (HHs) of Bobo Dioulasso based on farm activities, resource endowments and the production orientation. The resulting four groups comprised 'commercial gardening + field crop and livestock' (cGCL), 'commercial gardening +

semi-commercial cropping' (cGscC), 'commercial livestock + subsistence field cropping' (cLsC) and 'commercial field cropping' (cC; Table 1). As the focus of this study was urban gardening, only the two groups categorized as cGCL and cGscC were taken into account. Three HHs were selected from each of the two groups based on the accessibility of the garden and the willingness of the gardener to cooperate during the entire duration of the study.

The cGCL system comprises a combination of commercial vegetable gardening, field cropping and livestock production. Average garden size is about 797 m^2 while the field area averages 4.6 ha, and there are on average 4.4 TLU[1] (Tropical Livestock Unit). The vegetable garden contributes most to HH income, with moderate to large shares also from field crops and livestock activities. Only 10% of the HHs in this group earn a regular salary and 25% generate moderate to low earnings from occasional unskilled off-farm activities.

A typical cGscC HH also comprises market-oriented gardening activities, but these are combined with semi-subsistence field cropping. Average garden size is about 737 m^2 comparable to that of the cGCL system while field size is with an average of 2.4 ha rather small and gardening is the main contributor to total HH income. Field cropping activities contribute moderately to HH income while contributions from occasional and regular off-farm employment are low (Table 2.1; Dossa et al., 2011; Abdulkadir et al., 2012).

Table 2.1. Main socio-economic characteristics of the two studied urban and peri-urban agricultural production systems in Bobo Dioulasso, Burkina Faso (2008).

Production system	cGCL*	cLsC	cGscC*	cC
Garden size (m^2)	797	0	737	0
Field size (ha)	4.6	3.3	2.4	1.8
Livestock number (TLU)	4.4	2.4	0.0	0.0
Farming experience (year)	34.7	20.6	16.3	16.4

cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop; cLsC: commercial livestock + subsistence field cropping; cC: commercial field cropping* production systems concerned by the current study; TLU: Tropical livestock Units

2.2.3. Quantification of horizontal N, P, K and C flows

In each of six selected gardens (three per system, Table 2.2), six representative plots were chosen and the management practices such as sowing and planting, irrigation, type and application rates of fertilizers used were closely monitored from March 2008 to September 2009.

[1] TLU, tropical livestock unit: standardized animal of 250 kg live weight; 1 cattle =0.8 TLU; 1 donkey=0.5 TLU; 1 sheep/goat=0.1 TLU, 1 chicken=0.01 TLU.

Table 2.2. Main characteristics of the selected gardens in the two urban and peri-urban agricultural production systems in Bobo Dioulasso, Burkina Faso (2008).

System	Garden location	Irrigation water source	Type of irrigation	Main vegetables
cGCL	Kodeni 1	Well	Watering using cans	Cabbage, lettuce, carrot
	Dogona 1	River	Watering using cans	Cabbage, lettuce, carrot, tomato
	Dogona 2	River	Watering using cans	Cabbage, lettuce, carrot, tomato
cGscC	Kuinima	Well	Watering using cans	Cabbage, lettuce, carrot, tomato
	Kodeni 2	Well	Watering using cans	Cabbage, lettuce, sorrel
	Kodeni 3	Well	Watering using cans	Cabbage, lettuce, pepper

cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop

Plot-based inputs (IN1) of mineral fertilizers, animal manure, and solid urban waste were quantified for each crop. To this end the amount of fertilizer applied was weighted (Picture 2), a sample was taken, air dried, and analyzed for its concentration of N, P, K, and organic carbon (Corg). The total amounts of N, P, K, and C applied where obtained by multiplying the total amount of the applied fertilizer (dry weight) by the nutrient concentration in the sample. From April 2008 to February 2009 in each garden nutrients added via irrigation water (IN2) were determined by quantifying twice per week the amount of water applied to the selected plots. Two water samples of each 1 l volume were taken once per week and pooled by cropping cycle. Immediately after collection, the water samples were acidified with one drop of 0.1M HCl and stored frozen until analysis for N, P, and K concentrations. Nutrient inputs through irrigation water were estimated by multiplying the nutrient concentration in the water source by the total amount of water applied. Carbon input via photosynthesis (IN3) was estimated from vegetable harvests by assuming that roots and root exudates represent 30 % of the total carbon fixed by photosynthesis (Kuzyakov and Domanski, 2000). As a consequence, the total net C input via photosynthesis was assumed to approximate the harvested parts multiplied by 1.4. Additional C as well as N, P and K inputs via atmospheric deposition (IN4) and biological N_2 fixation (IN5) were estimated from the literature (Table 2.3 and 2.4). Sedimentation and deep capture were not accounted for.

Nutrient removal through crop harvests (OUT1) was quantified by weighing the fresh matter obtained from 1 m^2, oven-drying it at 65°C to constant weight, and mu ltiplied by the total area of the harvested plot. Gaseous losses of N and C were estimated (Chapter 3), while outputs via leaching (OUT2), and water erosion (OUT4) were taken from the literature (Tables 2.3 and 2.4).

Picture 2. Weighing session of manure before application

2.2.4. Sample analyses

At the beginning and the end of the experiment, three composite soil samples per garden were taken at 0-0.2 m depth to examine possible changes in soil fertility parameters during the time of study. Soil samples were analyzed for pH in 1:2.5 soil:water (weight : weight). Organic carbon in soil samples, organic amendments and plants were determined according to Walkley and Black (1934). Total P concentration in irrigation water, inorganic and organic amendments, household waste and plants samples was analyzed calorimetrically as described by Lowry and Lopez (1946) after digestion of samples with H_2SO_4 + salicylic acid + H_2O_2 + selenium. After digestion as for total P, total N in samples was determined colorimetrically with an auto-analyzer (Technicon AAII, Malton, ON, Canada), and total K was obtained by flame emission spectroscopy (Varian ICP-OES, Varian Inc., Palo Alto, CA, USA). Total K in soil samples was analyzed by flame emission spectroscopy after extraction of soil samples with an unbuffered 0.01M solution of silver-thiourea (AgTU) at the prevailing soil pH.

2.2.5. Calculation of nutrient balances and apparent use efficiencies (NUE)

Plot based horizontal balances of N, P, K, and C were calculated by subtracting outputs from inputs (Diogo et al., 2010).

NUE was defined as the amount of nutrients accumulated in the product and calculated as:

$$NUE = \frac{\sum O}{\sum I} \times 100$$

where ‘O’ is the output by the product and ‘I’ the sum of the measured inputs (Hedlund et al., 2003).

Table 2.3. Codification of nutrient flows and sources of data

Code	Flow	Data source
IN1	Input via fertilizers	Measured
IN2	Input via irrigation water	Measured
IN3	Input via atmospheric deposition	Literature
IN4	Input via biological fixation	Literature
OUT1	Output via harvest	Measured
OUT2	Output via leaching	Literature
OUT3	Output via gaseous losses	Literature
OUT4	Output via water erosion	Literature

Table 2.4. Carbon (C), nitrogen (N), phosphorous (P) and potassium (K) flows taken from the literature to calculate the total balance

	Nutrient flow	C (kg ha^{-1} yr^{-1})		N (kg ha^{-1} yr^{-1})		P (kg ha^{-1} yr^{-1})		K (kg ha^{-1} yr^{-1})		Literature
		cGCL	cGscC	cGCL	cGscC	cGCL	cGscC	cGCL	cGscC	
Input	Atmospheric deposition	23	23	4.4	4.4	1	1	3.9	3.9	Maberg et al. (1991); De Jager et al. (2001)
	Biological N-fixation	0	0	6.9	6.9	0	0	0	0	De Jager et al. (2001)
Output	Leaching	0	0	169	169	20	20	107	107	Sangaré et al. (unpublished data)
	Erosion			0	0	0	0	0	0	De Jager et al. (2001)

cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop

2.2.6. Statistical analysis

Data were analyzed using PASW 18.0 (PASW Inc., 2010) whereby the Kolmogorov-Smirnov test was used to test for normal distribution of residuals. Means were compared using one way ANOVA for normally distributed data and else the Kruskal Wallis Test. Confidence intervals were calculated at $P < 0.05$.

2.3. Results

2.3.1. Horizontal flows of N, P, K and C

N, P, K and C input rates

The amounts of nutrient applied during one cropping cycle differed for crops within and across production systems. Cabbage (*Brassica oleracea L.*) was the most intensively fertilized crop in both production systems (Table 2.5). The average N, P, and K amounts added to cabbage in one cropping cycle reached 470 kg N ha^{-1}, 105 kg P ha^{-1}, and 430 kg K ha^{-1} for the cGCL system and 470 kg N ha^{-1}, 95 kg P ha^{-1}, and 380 kg K ha^{-1} for the cGscC system.

Annual N inputs reached on average 1670 and 1440 kg N ha^{-1} for the cGCL and cGscC systems, respectively, and did not differ significantly between systems ($P = 0.557$). Mineral fertilizers and organic fertilizers were the two major N sources, and N inputs from mineral fertilizers represented more than half of total N inputs in both production systems (Figure 2.1).

Averaging 500 and 490 kg ha^{-1}, annual P inputs were similar for cGCL and cGscC systems. Mineral and organic fertilizers contributed 41% and 58% to total P inputs in the cGCL system, and 54% and 46% in the cGscC system. For both production systems organic fertilizers similarly contributed > 70% of total K inputs (Figure 2.1).

The amounts of C applied during a cropping cycle differed between crops within and across production systems. In both systems cabbage received the highest C input reaching 9.7 and 3 t ha^{-1} per cropping cycle for the cGCL and cGscC systems, respectively (Table 2.5).

Table 2.5. Amounts of carbon (C) (t ha^{-1} cropping cycle^{-1}), nitrogen (N), phosphorus (P) and potassium (K) (kg ha^{-1} cropping cycle^{-1}) applied in the form of mineral and organic fertilizers, to different vegetables, from March 2008 to October 2009 in urban vegetable gardens of Bobo Dioulasso, Burkina Faso. Data show means values of 3 gardens plus one standard error.

Gardening type	Vegetable	Number of cropping cycles	N	P	K	C
cGCL (n = 3)	Cabbage	3	470±78	106±24	430±125	9.7±4.1
	Lettuce	3	215±8	96±5	322±75	7.3±0.6
	Tomato	2	382±222	69±35	246±138	2.3±0.1
	Carrot	3	297±104	52±26	177±45	4.3±0.3
cGscC (n = 3)	Cabbage	3	470±49	95±21	378±39	3.0±0.5
	Lettuce	3	187±28	75±22	278±27	2.1±0.3
	Sorrel	2	79±40	19±6	97±44	2.0±0.3
	Pepper*	1	142	49	179	2.4

* Vegetable grown in only one garden among the selected gardens; cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop.

Total annual C inputs were with an average of 84 t C ha^{-1} similar in both systems whereby the main sources of C were organic fertilizers and photosynthesis. For the cGCL system, C inputs from organic fertilizers were slightly higher than estimated inputs from photosynthesis, but in the cGscC system C inputs from organic fertilizers were only about one third of total estimated C inputs (Figure 2.1).

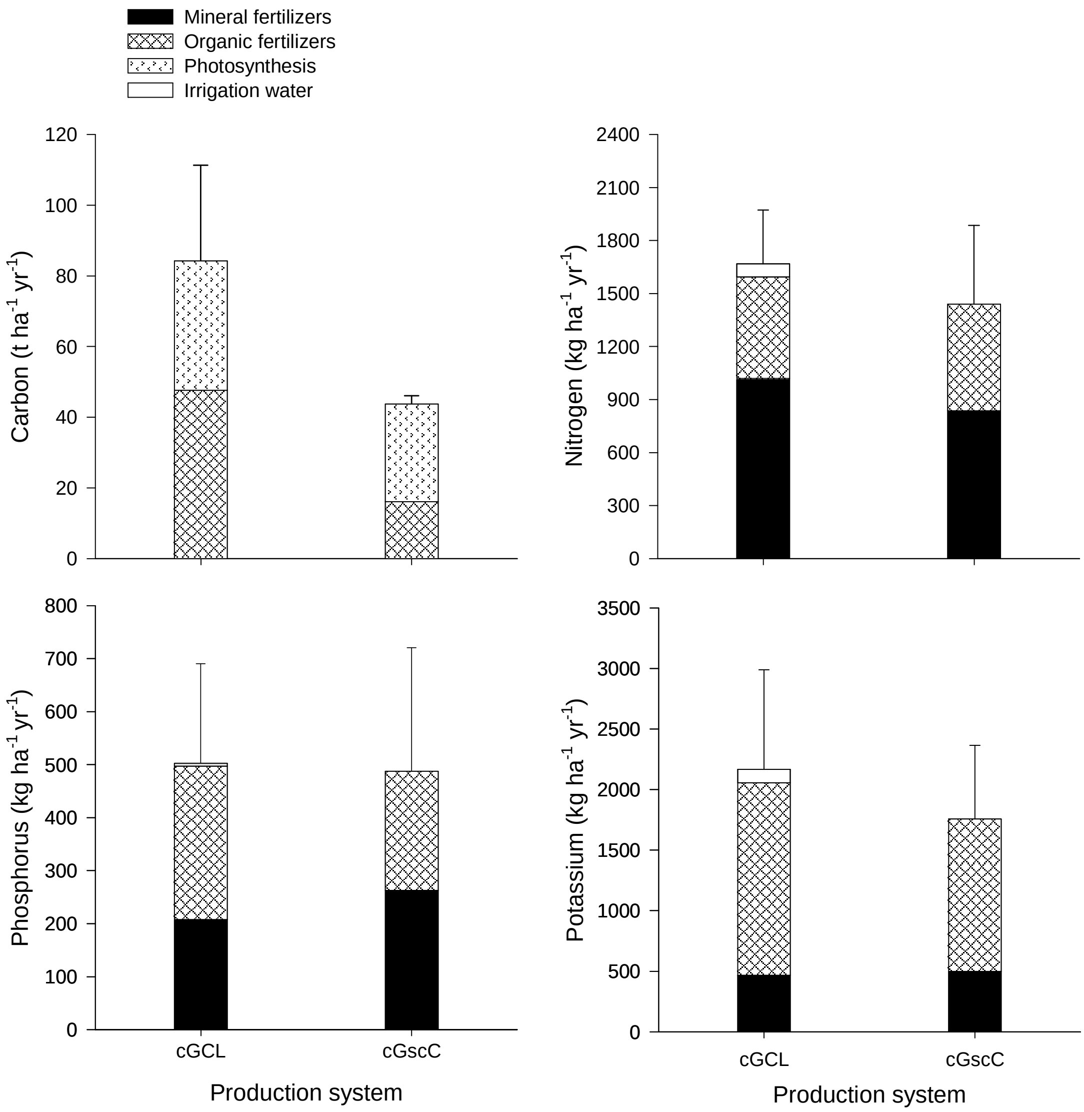

Figure 2.1. Total amount of carbon, nitrogen, phosphorus and potassium originating from different sources, applied in cGCL (n =3) and in cGscC (n = 3) urban vegetable gardens from March 2008 to September 2009 in Bobo Dioulasso, Burkina Faso. Data show annual mean plus one standard error. cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop

Vegetable yields, N, P, K and C exports

Maximum cabbage yield reached 10,370 kg DM ha^{-1} for the cGCL system exceeding that of cGscC gardens which was about 8,240 kg DM ha^{-1}. Amounts of N, P, K, and C exported by cabbage followed the same trend reaching up to 462, 73, 581, and 7,778 kg DM ha^{-1} for cGCL gardens. Lettuce (*Lactuca sativa L.*) yields were with 2,455-3,080 kg DM ha^{-1} substantially higher for the cGCL than with 2,094-2,423 kg DM ha^{-1} for cGscC gardens. Tomato (*Solanum lycopersicum L.*) and carrot (*Daucus carota L.*) were grown only in cGCL gardens with yields varying between 243-517 kg DM ha^{-1} for tomato and 15,152-16,965 kg DM ha^{-1} for carrot. The respective N, P, K, and C exports were about 19, 3, 11, and 300 kg ha^{-1} and 237, 85, 526, and 10,171 kg ha^{-1}. Sorrel (*Rumex acetosa L.*) and pepper (*Capsicum annuum L.)* were exclusively grown in cGscC gardens with maximum yields of about 3,342 kg DM ha^{-1} and 2,847 kg DM ha^{-1} (Table 2.6).

Table 2.6. Average yields (kg DM ha^{-1}) and amounts of carbon C, N, P and K (kg ha^{-1} cropping cycle^{-1}), exported with the edible parts of different vegetables cultivated from March 2008 to October 2009 in the selected urban vegetable gardens of Bobo Dioulasso, Burkina Faso. The yield data show the mean values of 3 plots plus one standard error.

System	Garden	Cropping cycle	Crop	Yield	C	N	P	K
cGCL	Garden 1	1	Cabbage	6238±416.0	5323	237.0	26.3	318.1
		2	Cabbage	4664±266.3	3980	177.2	19.8	237.9
		3	Cabbage	3823±458.1	3262	137.6	31.3	195.0
		4	Cabbage	4727±144.1	4034	179.6	30.4	256.7
	Garden 2	1	Tomato	517±116.0	300	18.5	2.7	11.4
		2	Cabbage	10370±1679.0	7778	461.5	72.6	580.7
		3	Carrot	15152±2673.0	9091	365.2	47.0	560.6
		4	Lettuce	2455±1024.0	1475	100.7	16.7	108.0
	Garden 3	1	Tomato	243±172.0	141	5.1	1.9	4.1
		2	Carrot	16956±1799.0	10174	237.4	84.8	525.6
		3	Lettuce	3080±460.0	1848	110.9	23.1	110.9
		4	Cabbage	5994±485.0	4496	185.8	24.6	305.7
GscC	Garden 4	1	Cabbage	7043±156.8	6001	293.5	37.1	345.1
		2	Cabbage	4966±210.4	4231	203.8	26.2	243.3
		3	Cabbage	8240±392.7	7021	340.3	43.3	403.7
		4	Cabbage	4063±172.1	3461	173.3	21.4	199.1
	Garden 5	1	Lettuce	2094±298.7	1294	81.0	15.3	115.0
		2	Lettuce	2423±316.5	1479	91.7	17.9	181.6
		3	Sorrel	2012±402.6	1345	69.7	17.4	133.5
		4	Lettuce	2184±384.6	1332	82.0	20.4	164.6
		5	Sorrel	2761±151.9	2240	115.2	10.3	148.6
	Garden 6	1	Sorrel	3342±80.3	2727	107.4	14.0	75.8
		2	Cabbage	3582±295.6	3042	85.5	16.4	185.1
		3	Cabbage	6351±330.1	5392	149.7	28.3	310.3
		4	Pepper	2847±93.6	2370	70.4	5.2	155.3

cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop

2.3.2. Horizontal balances of N, P, K, and C

Horizontal balances of N, P, and K were positive for both production systems (Figure 2.2), averaging 810 kg N ha $^{-1}$ yr^{-1}, 255 kg P ha^{-1} yr^{-1} and 140 kg K ha^{-1} yr^{-1} for the cGCL system and 565 kg N ha^{-1} yr^{-1}, 250 kg P ha^{-1} yr^{-1}, and 240 kg K ha^{-1} yr^{-1} for the cGscC system (Table 2.7). Overall calculated surpluses were higher in the cGCL production system except for K, but the differences were not statistically significant (P = 0.557 for N, P = 0.963 for P, and P = 0.700 for K). For both systems, C balances were also positive ranging from 22 – 39 t C ha^{-1} yr^{-1} (P = 0.208; Table 2.7).

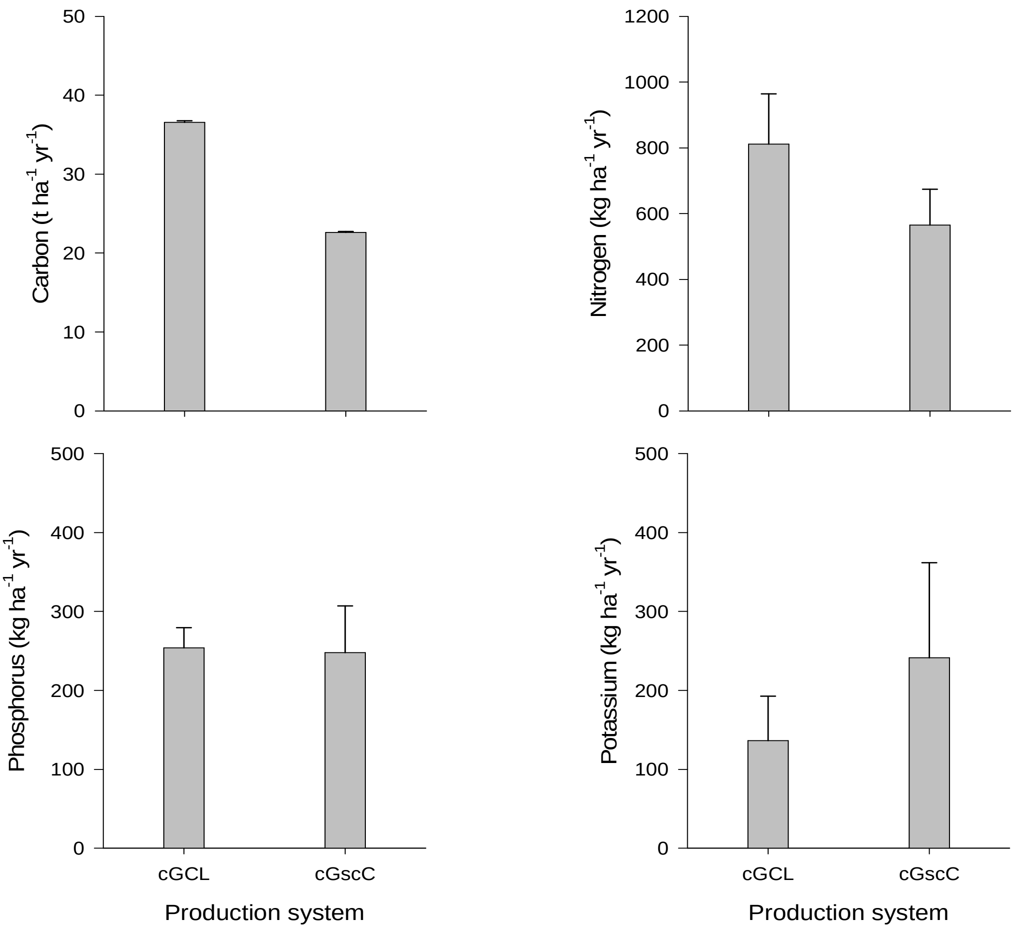

Figure 2.2. Annual horizontal balances of carbon, nitrogen, phosphorus and potassium in cGCL (n = 3) and cGscL (n = 3) urban vegetable gardens in Bobo Dioulasso (Burkina Faso) from March 2008 to September 2009. Data show means plus one standard error. cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop.

For both systems, C balances were also positive ranging from 22 – 39 t C ha^{-1} yr^{-1}. There was no significant difference (P = 0.208) between the two systems with respect to the C balance (Table 2.7).

Table 2.7. Carbon (C), nitrogen (N), phosphorous (P) and potassium (K) inputs, outputs and partial balances (kg ha^{-1} yr^{-1}) for the selected urban gardens in Bobo Dioulasso from March 2008 to September 2009.

System	Garden	Inputs				Outputs				Partial Balances			
		C	N	P	K	C	N	P	K	C	N	P	K
cGCL	Garden 1	63046	2061	471	1324	20586	908	132	1248	42460	1153	339	76
	Garden 2	60108	2073	437	1568	22234	1145	170	1510	37874	929	268	58
	Garden 3	68130	1421	570	1846	31998	915	265	1740	36132	506	305	106
cGscC	Garden 4	45047	1729	463	1281	20855	1019	129	1199	24192	711	334	82
	Garden 5	40049	1378	464	1890	18034	1029	186	1726	22015	349	278	164
	Garden 6	41530	1293	256	1126	19716	653	95	911	21814	640	161	216

2.3.3. Apparent nutrient use efficiency and soil fertility status

For both production systems alike, K apparent use efficiency was highest reaching almost 100% while N apparent use efficiency was 60% and P apparent use efficiency 40% (Figure 2.3).

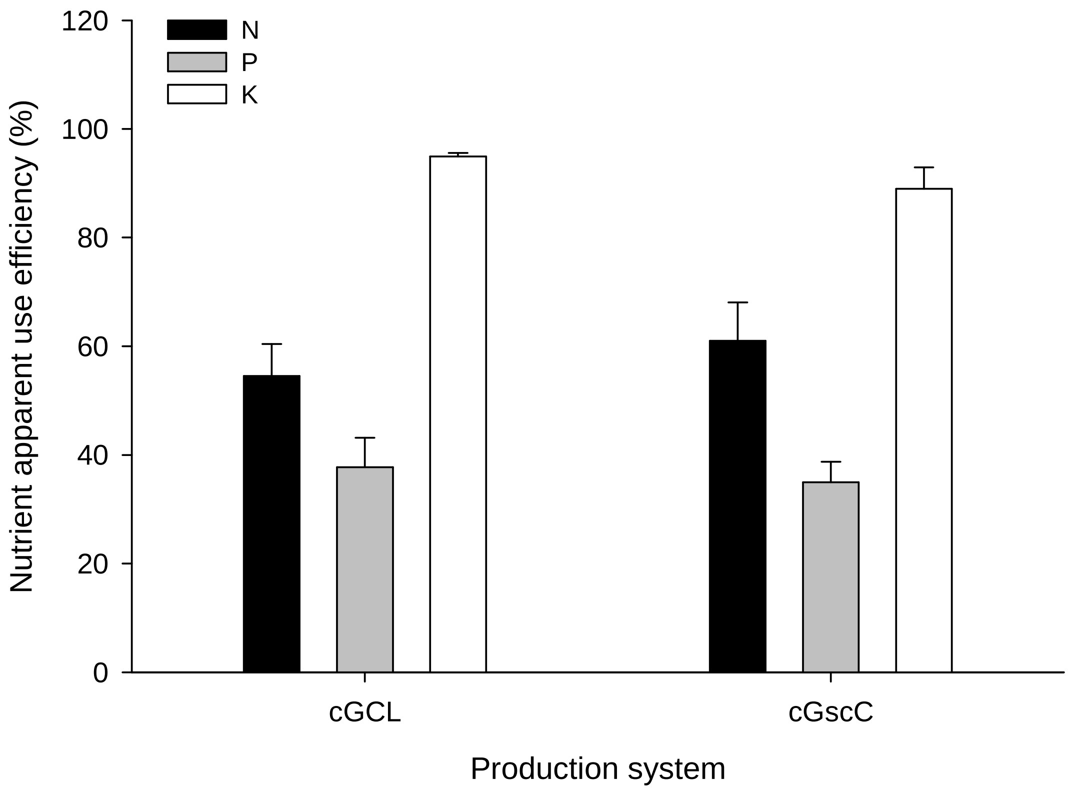

Figure 2.3. Nutrient apparent use efficiency of nitrogen (N), phosphorus (P) and potassium (P) in cGCL (n = 3) and cGscL (n = 3) urban vegetable gardens from March 2008 to September 2009 in Bobo Dioulasso, Burkina Faso. Bars show means plus one standard error. cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop

For the cGCL system, soil Corg, pH (H_2O), total N, and total P did not change significantly from March 2008 to September 2009, but for the same period soil C/N increased significantly ($P = 0.002$) from 12.2 to 15.7, while total K decreased significantly ($P = 0.011$) from 3,878 to 2,475 mg K kg^{-1} (Table 2.8). For the cGscC system soil parameters did not significantly change over time except for total P and the C/N ratio which changed significantly from 484 to 501 mg P kg^{-1} and from 14 to 12 ($P = 0.019$ and 0.016 respectively; Table 2.8).

Table 2.8. Soil fertility parameters in March 2008 and September 2009 as influenced by the two production systems in Bobo Dioulasso, Burkina Faso. Data show means one standard error.

System	Sampling date	Total Corg ($g\ kg^{-1}$)	pH-H_2O	Total N ($mg\ N\ kg^{-1}$)	Total-P ($mg\ kg^{-1}$)	Total K ($mg\ K\ kg^{-1}$)	C/N
cGCL	03.2008	19±2.9	6±0.0	1597±316.5	1631±105.8	3878±156.7	12±0.3
	03.2009	19±3.0	7±0.2	1289±336.5	1449±77.9	2475±651.8	16±1.6
cGscC	03.2008	12±0.7	5±0.3	882±55.6	484±9.9	2122±172.4	14±0.4
	03.2009	12±1.7	6±0.4	941±132.5	501±11.0	2143±174.8	12±0.2
Overall	03.2008	15±1.9	6±0.3	1240±214.9	1057±260.9	3000±406.3	13±0.5
	03.2009	15±2.2	6±0.3	1115±179.4	975±214.9	2309±310.8	14±1.0

cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop;

2.4. Discussion

In both production systems average input rates reached 470 kg N ha^{-1}, 110 kg P ha^{-1}, 430 kg K ha^{-1} and 10 t C ha^{-1} per cropping cycle. This greatly exceeds the recommended rates for vegetables in the Sudano-Sahelian zone which are about 5 t C ha^{-1} for all crops and vary crop-specific from 70 – 140 kg N ha^{-1}, 40 - 80 kg P ha^{-1}, and 100 – 150 kg K ha^{-1} (d'Arondel de Hayes and Traoré, 1990). The input rates recorded in our study are comparable to those reported by Hedlund et al. (2003) and Diogo et al. (2010) for urban farms in Vietnam and Niamey, respectively.

These inputs resulted in positive partial balances reaching annual averages for both systems of 715 kg N ha^{-1}, 281 kg P ha^{-1}, 117 kg K ha^{-1}, and 31 t C ha^{-1}. Similar positive nutrient balances ranging from 31-882 kg N ha^{-1}, 23-644 kg P ha^{-1}, and 9-770 kg K ha^{-1} were reported by Hedlund et al. (2003), Huang et al. (2007) and Khai et al. (2007) for UPA systems elsewhere. This is in sharp contrast to the negative nutrient balances often reported for rural agricultural systems in sub-Saharan Africa (Stoorvogel et al., 1993; Anthofer and Kroschel, 2000; De Jager et al., 2001; Haileslassie et al., 2006) and is probably due to the fact that UPA systems are largely market-oriented, allowing for investments in soil amendments. Another fact is the ready availability of urban waste as effective inputs at no or only nominal cost. Furthermore, urban gardens are typically small sized (< 1 ha) which reduces the absolute quantities of fertilizers required and facilitates their application.

The matter surpluses obtained in this study did not significantly differ between production systems. The main difference between the two systems was livestock keeping. The results of our study indicate, however, that livestock husbandry did not contribute significantly to nutrient management practices in the cGCL system, suggesting little coupling between crop and animal production. A similar observation was made by Hedlund et al. (2003) in their nutrient flow studies of smallholder UPA farms in southern Vietnam.

The surpluses of N, P, and K combined with the prevailing sandy texture of the UPA soils may lead to leaching losses especially from July to September when rainfall is strongest (Figure 2.1; Predotova et al., 2011). Excessive fertilizer application can also increase disease susceptibility and reduce produce quality of vegetables (Hochmuth et al., 1991; Gruhn et al., 2000; Assogba-Komlan et al., 2007; Wang et al., 2008). Our results on nutrient use efficiency are also in good agreement with those of Sheldrick et al. (2002) and Hedlund et al. (2003).

The positive horizontal balances recorded in our study did not result in the improvement of the measured soil fertility indices of UPA garden soils. However, the levels of chemical soil fertility were much higher than those widely reported from rural production systems throughout the region (Bationo et al., 1998), indicating substantial effects of inputs on soil fertility. While the horizontal balance approach provides information for nutrient management planning (Mikkelsen, 2005), it does not account for possible nutrient losses via leaching, erosion, nitrification, denitrification and volatilization, which can be substantial in the agro-ecological context of Bobo Dioulasso (Predotova et al., 2010, 2011). Therefore the determination of total nutrient balances would give a much better indication of the scope that improved management approaches would have in enhancing nutrient use efficiencies. In our study we used data from the literature to estimate nutrient flows not managed by farmers (Table 2.4) in order to establish full balances of N, P, K and C for the two production systems. The results indicated a positive C total balance for the cGCL system and a negative one for the cGscC system, but the difference was not significant (P=0.280; Table 2.9) suggesting a large variability in organic matter management within the gardens of both clusters. For the same vegetable production systems, annual gaseous CO_2-C and CH_4-C losses of up to 36,400 and 22,800 kg ha^{-1} were recorded for the cGCL and the cGscC, respectively (Chapter 3), representing 94 and 101% of the horizontal C balance, respectively. This underlines the importance of C inputs to sustain intensive urban vegetable gardening activities in Bobo Dioulasso with its year-round high temperatures and apparently biologically very active soils.

Total nutrient balances were similarly positive for both systems (Table 2.9) and averaged 881 kg N ha^{-1} yr^{-1}, 390 kg P ha^{-1} yr^{-1} and 999 kg K ha^{-1} yr^{-1}, suggesting that the practiced management of the two gardening systems should over time lead to improvements in soil chemical fertility. However, our soil data did not reflect such changes which may be due to an underestimation of N losses via ammonia volatilization and nitrification/ denitrification or leaching losses for N, P and K. The total C balance, however, was negative for cGscC gardens indicating a need to improve organic matter management to sequester carbon in the soils.

Table 2.9. Annual total balances of carbon (C), nitrogen (N), phosphorus (P) and potassium (K) in cGCL and cGscL urban vegetable gardens in Bobo Dioulasso (Burkina Faso) from March 2008 to September 2009. Data show means plus one standard error (n = 3).

System	C	N	P	K
cGCL	754 ± 3451.4	881 ± 480.4	390 ± 131.9	999 ± 464.0
cGscC	-8051± 2580.5	254 ± 264.6	346 ± 101.6	683 ± 562.7
P value				

cGCL = commercial gardening + field crops + livestock;
cGscC = commercial gardening + semi-commercial field crop.

2.5. Conclusion

The horizontal matter balances of our study indicate that current nutrient inputs in urban vegetable gardens of Bobo Dioulasso are much higher than nutrient removal by crop uptake. Even if leaching and volatilization losses were not quantified in our study, data from similar studies suggest that such losses would not substantially affect the conclusion with respect to N, P, and K. The total C balance, however, was negative for cGscC gardens indicating a need to improve organic matter management to slow down C turnover. The livestock component in the cGCL system did not seem to have a major effect on nutrient management, suggesting substantial inefficiencies and scope for improvement by coupling plant and animal husbandry.

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Chapter 3. Gaseous emissions of nitrogen and carbon from urban vegetable gardens of Bobo Dioulasso, Burkina Faso

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Abstract

Urban and peri-urban agriculture (UPA) is an important livelihood strategy for the urban poor in sub-Saharan Africa and contributes to meeting increasing food demands in the rapidly growing cities. Although in recent years many research activities have been geared towards enhancing the productivity of this land use system, little is known about turnover processes and nutrient efficiency of UPA. The aim of our study therefore was to determine horizontal fluxes of nitrogen (N), phosphorus (P), potassium (K), and carbon (C) as well as gaseous N and C emissions in urban vegetable gardens of Bobo Dioulasso, Burkina Faso. To this end two gardens referred to as 'Kodéni' and 'Kuinima' were selected as representative for two UPA systems classified as: 'commercial gardening + field crops and livestock system (cGCL)' and 'commercial gardening and semi-commercial field crop system (cGscC)', respectively. A nutrient-balance approach was used to monitor matter fluxes from March 2008 to March 2009 in both gardens. Ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) emissions from the respective soils were measured during the coolest and the hottest period of the day using a closed chamber system. Annual partial (horizontal) balances amounted to 1,153 kg N ha^{-1}, 339 kg P ha^{-1}, 76 kg K ha^{-1}, and 42,460 kg C ha^{-1} at Kodéni and to 711 kg N ha^{-1}, 334 kg P ha^{-1}, 82 kg K ha^{-1}, and 24,192 kg C ha^{-1} at Kuinima. Emission rates were highest during the hot midday hours with peaks after fertilizer applications when fluxes of up to 1,140 g NH_3-N ha^{-1} h^{-1}, 154 g N_2O-N ha^{-1} h^{-1} 12,993 g CO_2-C ha^{-1} h^{-1}, and 408 g CH_4-C ha^{-1} h^{-1} were recorded for Kodéni and Kuinima, respectively. Estimated annual gaseous N (NH_3-N + N_2O-N) and C (CO_2-C + CH_4-C) losses reached 419 kg N ha^{-1} and 36,400 kg C ha^{-1} at Kodéni and 347 kg N ha^{-1} and 22,800 kg C ha^{-1} at Kuinima. This represented 36% and 60% of the N and C surpluses, respectively at Kodéni and 49% and 52% of N and C surpluses at Kuinima. Emissions of NH_3 largely occurred after surface application of manure and mineral fertilizers and accounted for 73% and 77% of total estimated N losses for Kodéni and Kuinima. To mitigate N losses, nutrient management practices in UPA vegetable production of Bobo Dioulasso would greatly benefit from better synchronising nutrient input rates with crop demands.

Key words: Closed chamber system; horizontal and vertical nutrient fluxes; urban agriculture

3.1. Introduction

Given annual mean application rates of only 6 kg N ha^{-1}, compared to world average rates of 100 kg N ha^{-1}, emission of N-derived greenhouse gases from African agriculture is generally considered to be negligible (Smaling et al., 2006). This is certainly true for most rural production systems which generally are subsistence oriented and devoid of external nutrient inputs (Breman et Debrah, 2003). However, the situation may be quite different for urban farming systems that are strongly market oriented (Dossa et al., 2011; Abdulkadir et al., 2012) and characterized by intensive management (UNDP, 1996; Rosendahl et al., 2009). Urban farmers regularly use large amounts of organic and chemical amendments to maximize yields in order to meet the large demands for fresh produce of high visual quality by urban dwellers (Huang et al., 2007; Diogo et al., 2010). Recent surveys indicate N application rates up to 470 kg ha^{-1} per cropping cycle for vegetables in Burkina Faso (Chapter 2) which exceeds by more than four times the recommended rate for vegetable production in the Sahelian zone and causes large N surpluses. These not only represent an economic loss for farmers (Matson et al., 1998), but may also lead to point-pollution via leaching and gaseous emissions (Predotova et al., 2010). In view of the fact that data on soil turnover processes and greenhouse gas emissions are scarce in sub-Saharan Africa and if available, mainly refer to rural farming systems (Brümmer et al., 2008; Dick et al., 2008; Wulf et al., 1999) or tropical forest soils (Castaldi et al., 2006; Alam and Starr, 2009), we aimed at monitoring gaseous emissions of N and C in urban vegetable gardens of Bobo Dioulasso to obtain solid data for subsequent emission modeling of different soil types and management regimes (Mosier, 1994; Saggar, 2010). Such modeling results of the effects of amount, timing, type and application mode of organic and applied mineral fertilizers in UPA vegetable production on nutrient fluxes can then be used to design input management systems that allow to more effectively tailor nutrient supply to crop needs.

3.2. Materials and methods

3.2.1. Study site

The study was conducted in Bobo Dioulasso already described in section 2.2.1.

3.2.2. Selection of gardens

Based on their resource endowments, integration of vegetables, field crops and animal production and of the production orientation, Dossa et al. (2011) and Abdulkadir et al., (2012) identified four different production systems in Bobo Dioulasso. These comprised ‘commercial gardening + field crop and livestock' (cGCL), 'commercial gardening + semi-commercial crop' (cGscC), 'commercial livestock + subsistence field cropping' (cLsC) and 'commercial field cropping' (cC). As the focus of this study was on urban gardening, the groups categorized as 'commercial gardening + field crop and livestock' (cGCL) and as 'commercial gardening + semi-commercial crop' (cGscC) were chosen for further study. The cGCL system comprised a combination of vegetable gardens, field cropping, and livestock production; average garden size was about 797 m^2 while the field area reached 4.6 ha. Livestock ownership averaged 4.4 TLU (Tropical Livestock Unit). The vegetable garden contributed most to household income with moderate to large contributions from field crops and livestock activities. Only 10% of the households earned a regular salary and 25% generated moderate to low earnings from occasional unskilled off-farm activities. The cGscC system also comprised important market-oriented gardening activities, combined with only semi-subsistence field cropping. Average garden size was about 737 m^2 and thus comparable to that of the cGCL system, while field size was smaller, averaging only 2.4 ha. Garden activities were the main contributor to household income with a moderate to high contribution to revenue obtained from field cropping activities and a low to moderate contribution of occasional and regular off-farm employment (Table 3.1; Dossa al., 2011; Abdulkadir et al., 2012).

Table 3.1. Main socio-economic characteristics of the urban agricultural production systems in Bobo Dioulasso, Burkina Faso (2008).

Production system	cGCL*	cLsC	cGscC*	cC
Garden size (m^2)	797	0.0	737	0.0
Field size (ha)	4.6	3.3	2.4	1.8
Livestock number (TLU)	4.4	2.4	0	0.0
Farming experience (year)	34.7	20.6	16.3	16.4

cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop; cLsC: commercial livestock + subsistence field cropping; cC: commercial field cropping; * Production systems concerned by the current study; TLU: Tropical Livestock Unit

In each production system one garden was selected ('Kodéni' for the cGCL system and 'Kuinima' for the cGscC system) based on the accessibility of the garden and the willingness of the gardener to cooperate during the whole period of study. The horizontal flows and balances of N, P, K, and C of the selected gardens are reported in Table 3.2 (Chapter 2).

Table 3.2. Inputs, outputs and horizontal balances (kg ha^{-1} yr $^{-1}$) of nitrogen (N), phosphorus (P), potassium (K) and carbon (C) at Kodéni and Kuinima vegetable gardens from March 2008 to March 2009 in Bobo Dioulasso, Burkina Faso. The data show average values of four cropping cycles with their respective standard errors.

	Garden	C	N	P	K
Input	Kodéni	63046 ± 9761	2061 ± 407	471 ± 312	1324 ± 706
	Kuinima	45047 ± 18805	1729 ± 1385	463 ± 409	1281 ± 896
Output	Kodéni	20586 ± 4801	908 ± 227	132 ± 20	1248 ± 279
	Kuinima	20855 ± 6482	1019 ± 313	129 ± 40	1199 ± 373
Partial Balance	Kodéni	42460 a ± 3568	1153 ± 185	339 ± 165	76 ± 606
	Kuinima	24192 b ± 6395	711 ± 764	334 ± 221	82 ± 601

Numbers within a column followed by the same letter are not significantly different at P = 0.05; Source: Chapter 1

In both selected gardens, irrigation drew on well water and water cans were used for watering plants (Table 3.3).

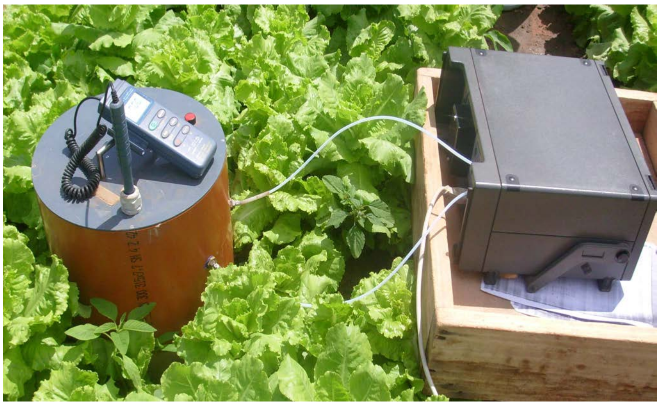
Table 3.3. Selected characteristics of the studied urban vegetable gardens in Bobo Dioulasso, Burkina Faso, as identified in 2008.

Production system	Garden location	Irrigation water source	Type of irrigation	Main vegetables
cGCL	Kodéni	well	Watering using cans	Cabbage, lettuce, carrot
cGscC	Kuinima	well	Watering using cans	Cabbage, lettuce, carrot, tomato

cGCL = commercial gardening + field crops + livestock; cGscC = commercial gardening + semi-commercial field crop.

3.2.3. Measurements of gaseous N and C emissions

In each garden, emissions of ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) from the selected plots were measured during four cropping cycles of cabbage, using a closed chamber system consisting of a cuvette connected to a photo-acoustic infrared gas analyzer INNOVA 1312-5 (Picture 3; LumaSense Technologies, Ballerup, Denmark) as described by Predotova et al. (2010). In order to account for diurnal temperature effects on gaseous emissions, measurements were taken twice a day, during the cool morning hours (5:00-7:00 am) and in the hot afternoons (1:00-3:00 pm). A total of thirty two measurements were done at each period of measurement. Simultaneously to the flux measurements, air humidity and temperature inside the cuvette were determined with a digital thermo-hygrometer (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany). A multi-digital thermometer (Carl ROTH GmbH + Co, Karlsruhe, Germany) was used to record the soil temperature at 0.10 m depth and soil moisture was determined gravimetrically by taking three soil samples from each selected plot. Because of expected large temporal variation of N and C emissions during a cropping cycle, caused by fertilizer applications, measurements were conducted several times during each cropping period: after planting but before fertilization, two or three days after fertilization, and more than ten days after nutrient application. During the whole experiment ambient air temperature and relative humidity were recorded each 30 minutes with a Hobo Pro data logger (Onset Computer Corp., Bourne, MA, USA).



Picture 3. A closed chamber system consisting of a cuvette connected to a photo-acoustic infrared gas analyzer INNOVA 1312-5

3.2.4. Soil sampling and calculation of water filled pore space (WFPS)

At the beginning of the experiment, three soil samples per garden were taken at 0.2 m depth and air dried in order to determine the physical and chemical characteristics.

WFPS was calculated as follows:

$$\mathit{WFPS}\ (\%) = \frac{\mathit{Volumetric\ water\ content} \times 100}{\mathit{Soil\ porosity}}$$

where:

Volumetric water content (g/cm^3) = gravimetric water content (g/g) x bulk density (g/cm^3);

Soil porosity (%) = 1 – (soil bulk density / 2.65)

3.2.5. Sample analyses

Organic carbon of soil samples was determined according to Walkley and Black (1934). Total P content was analyzed colorimetrically (Lowry and Lopez, 1946), after sample digestion with H_2SO_4 + salicylic acid + H_2O_2 + selenium. After this digestion total N was determined colorimetrically with an autoanalyzer (TECHNICON AAII, Malton, ON, Canada) and total K by flame emission spectroscopy (Varian ICP-OES, Varian Inc., Palo Alto, CA, USA) after extraction of soil samples with an unbuffered 0.01M solution of silver-thiourea (AgTU) at the prevailing soil pH. Particle size was determined by sieving for particle size > 50 µm and by pipetting for particles size < 50 µm.

3.2.6. Data analysis

Before and after the field experiments, calibration and verification measurements of the INNOVA gas analyzer with standard pure gases and gas mixtures were conducted at Staatliche Umweltbetriebsgesellschaft of Saxony (Radebeul, Germany). Gas emission rates were calculated by subtracting the gas concentration measured 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 that occasionally occurred for NH_3, N_2O and CH_4 were set to zero. For the calculation of the emission rates an accumulation interval of one minute was used (Predotova et al., 2010). Daily flux rates were calculated by averaging morning and afternoon measured values. To estimate the cumulative losses during a cropping cycle, the measured emission peaks directly after the fertilization were assumed to drop to a basis emission level within five days after the application. For this period of time an average emission between the highest values (immediately after the application) and the lowest values (measured either before the fertilization or more than a week later) were used.
Wherever applicable data were analyzed using SPSS 18.0 (SPSS Inc., 2009) and the Kolmogorov-Smirnov test was performed to test for normality of data residuals. Subsequently, means were compared using the Kruskal Wallis Test at P = 0.05.

3.3. Results

3.3.1. Ambient air temperature and rainfall

In 2008 maximum monthly air temperature exceeded 37℃ in March and April, the hot dry season and dropped to 17℃ in January, the cool dry season. In 2009 minimum monthly air temperature was about 18℃ in January and the maxim um 38℃ in March. Average ambient air temperature was 27.6℃ in 2008 and 27.9℃ in 2009, and total rainfall 998 mm and 945 mm. Heavy rainfall events with up to 53 mm occurred during the peak of the rainy season in July and August (Figure 3.1).

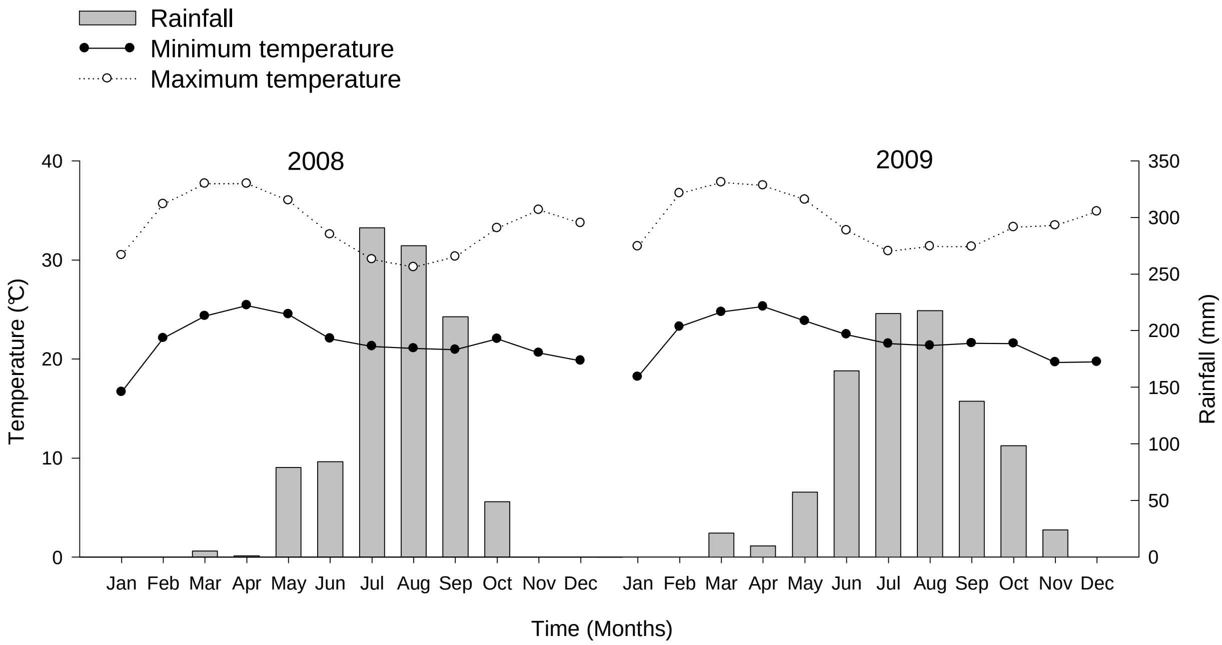


Figure 3.1. Ambient air temperature and rainfall distribution in the experimental years of 2008 and 2009 for Bobo Dioulasso, Burkina Faso.

3.3.2. Soil characteristics

At pH values of 6.7 and 5.8 the soils were clayey (38% sand, 19% silt, and 43% clay) at Kodéni and sandy-clay-loamy (67% sand, 10% silt, and 23% clay) at Kuinima. Soil C_{org} and total N were higher at Kodéni than at Kuinima, but the C/N ratio was higher at Kuinima. In both gardens soil temperatures at 0.01 m depth were with 27℃ substantially higher during the afternoon hours than in the mornings (24℃), but average WFPS did not differ significantly between morning and afternoon hours (P > 0.05; Table 3.4).

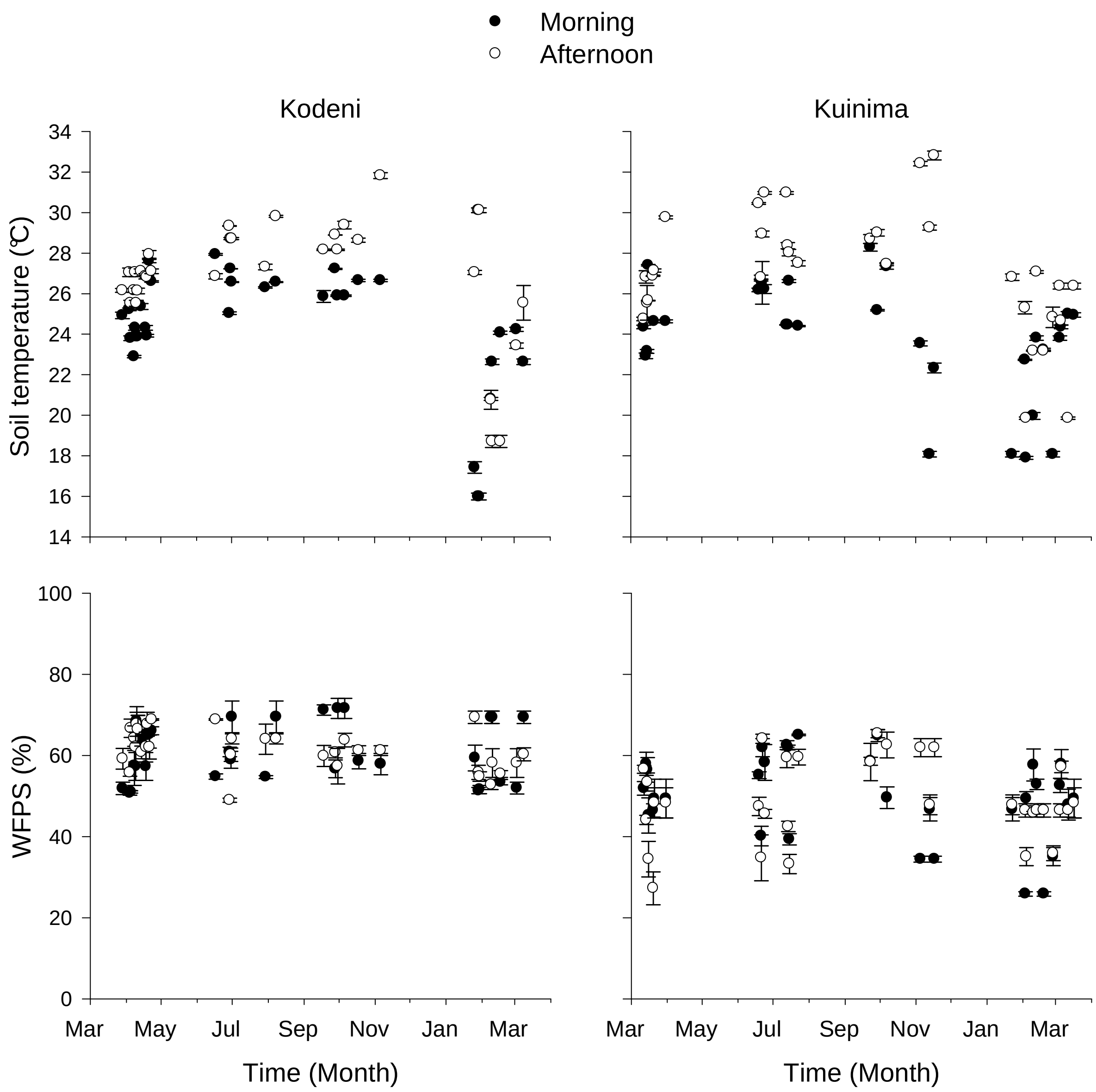


Figure 3.2. Soil temperature (℃) and WFPS (%) during morning and afternoon sampling times from March 2008 to March 2009 at Kodéni and Kuinima in Bobo Dioulasso (Burkina Faso). Data show the mean and the standard error of six measurements.

Table 3.4. Selected soil physical and chemical characteristics of the two studied UPA gardens (Kodéni and Kuinima) in Bobo Dioulasso, Burkina Faso. Data show the average values of 3 subsamples with the standard error of the mean or the range in brackets

<table>
<tr><th rowspan="2">Garden</th><th rowspan="2">pH-H_2O</th><th rowspan="2">Corg (g kg^{-1})</th><th rowspan="2">Total N (mg N kg^{-1})</th><th rowspan="2">C/N</th><th rowspan="2">Sand (%)</th><th rowspan="2">Silt (%)</th><th rowspan="2">Clay (%)</th><th colspan="2">Soil temperature (℃)</th><th colspan="2">WFPS (%)</th></tr>
<tr><th>Morning</th><th>Afternoon</th><th>Morning</th><th>Afternoon</th></tr>
<tr><td>Kodéni</td><td>6.7 ± 0.2</td><td>26 ± 1</td><td>2096 ± 125</td><td>13 ± 0.5</td><td>38</td><td>19</td><td>43</td><td>24 (16-28)</td><td>27 (19-32)</td><td>61 (50-72)</td><td>61 (49-69)</td></tr>
<tr><td>Kuinima</td><td>5.8 ± 0.8</td><td>14 ± 0.8</td><td>1061 ± 79</td><td>13 ± 0.5</td><td>67</td><td>10</td><td>23</td><td>24 (18-28)</td><td>27 (20-33)</td><td>50 (26-65)</td><td>49 (27-65)</td></tr>
</table>

3.3.3. Gaseous emission rates of N and C

At Kodéni emission rates of NH_3-N reached 595 and 1,140 g ha^{-1} h^{-1} in the morning and afternoon hours, respectively, while at Kuinima they were about 500 and 880 g ha^{-1} h^{-1}. N_2O-N flux rates reached maxima of 155 and 110 g ha^{-1} h^{-1} during the hottest period of the day at Kodéni and Kuinima (Figure 3.3).

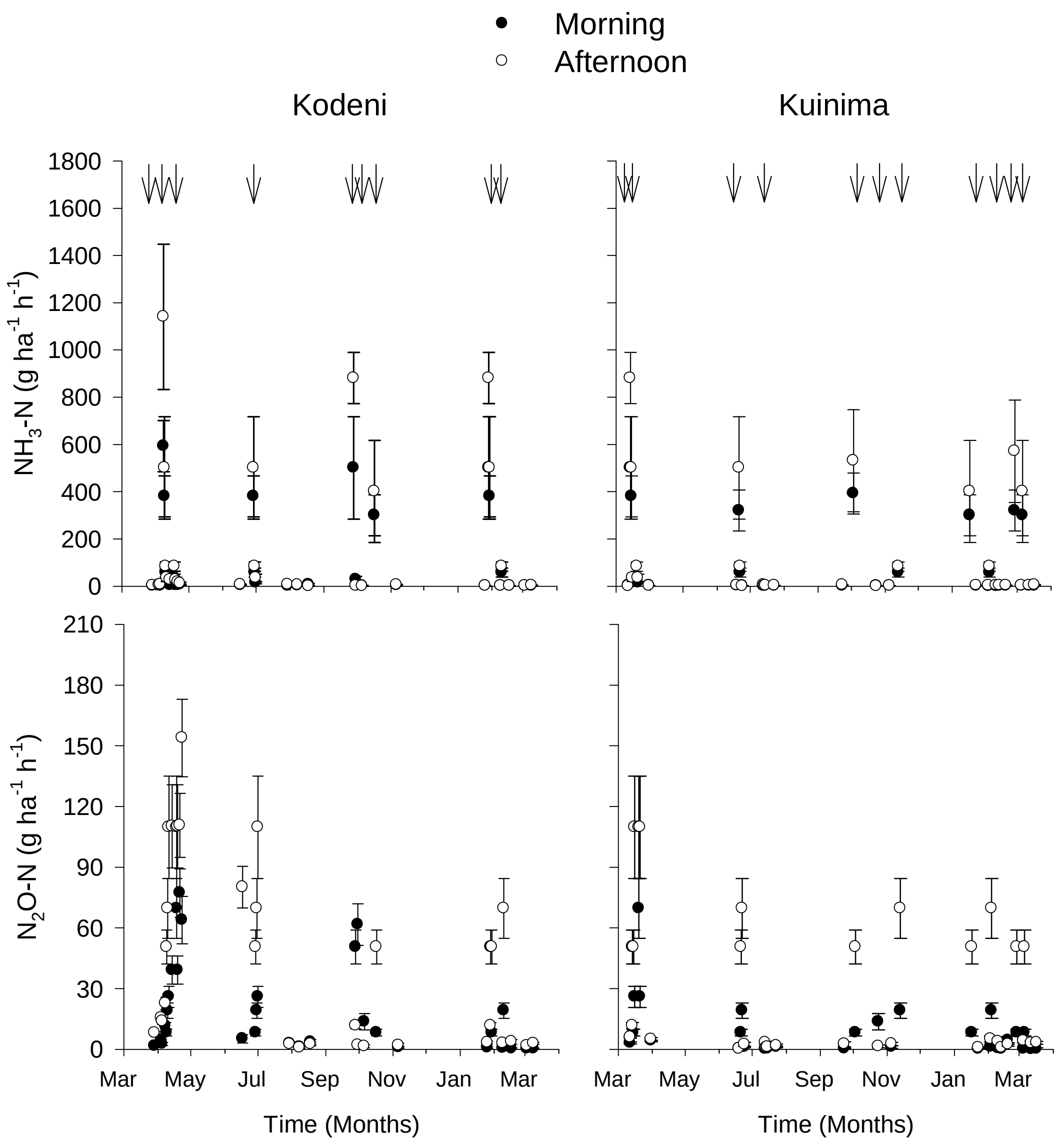


Figure 3.3. NH_3-N and N_2O-N flux rates during morning and afternoon hours from March 2008 to March 2009 at Kodéni and Kuinima in Bobo Dioulasso (Burkina Faso). Data show the mean and the standard error of six measurements. Arrows indicate days of fertilizer application.

Emission rates of CO_2-C at Kodéni reached maxima of 10,540 and 12,990 g ha^{-1} h^{-1} in the morning and afternoon hours, respectively, exceeding those of Kuinima which were about 8,700 and 9,770 g ha^{-1} h^{-1}. Emission rates of CH_4-C peaked at 410 and 370 g ha^{-1} h^{-1} at Kodéni and Kuinima during the hot period of the day and were thus 1.3 and 1.2 times higher than those of the cool period (Figure 3.4).

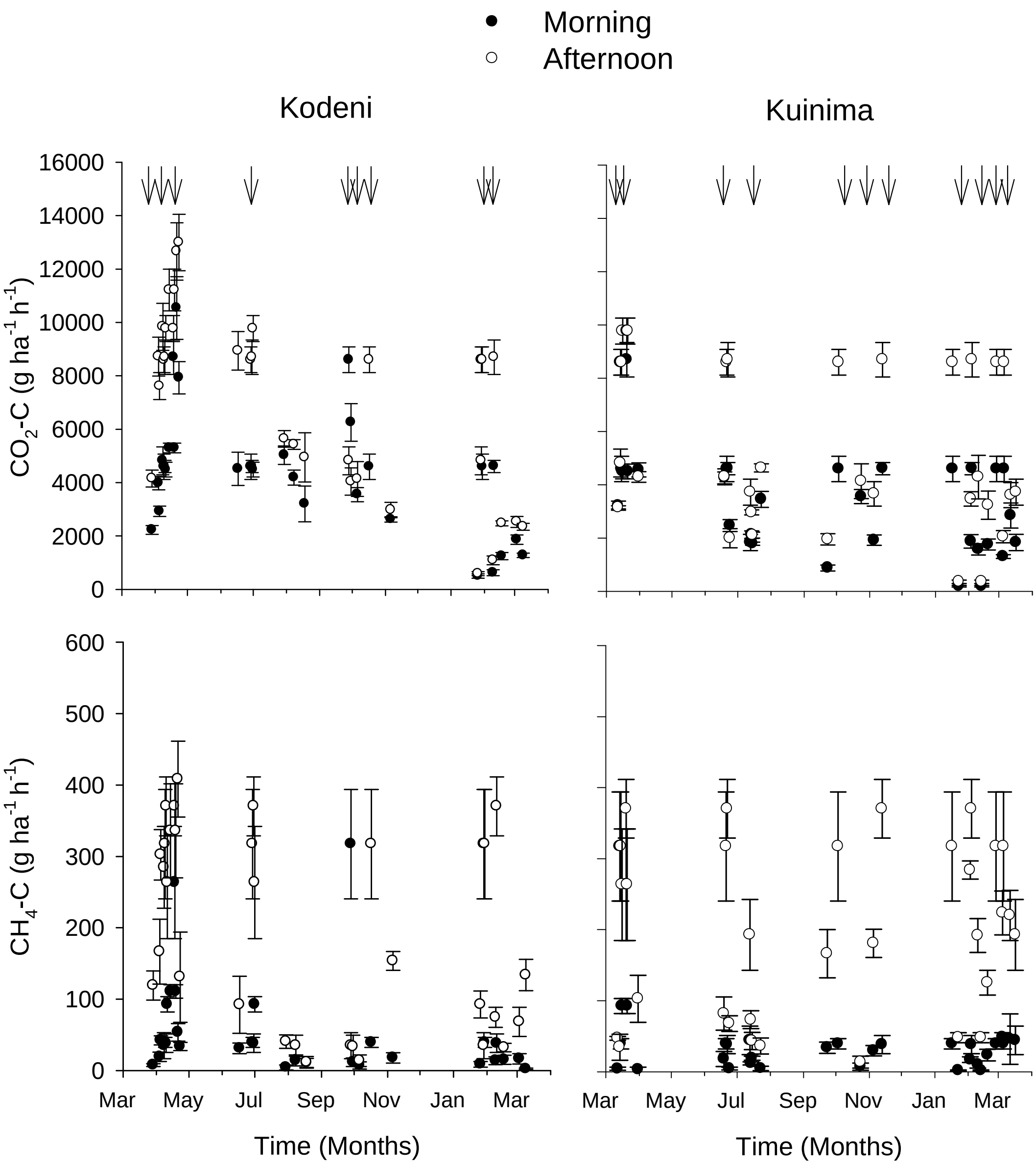


Figure 3.4. CO_2-C and CH_4-C flux rates during morning and afternoon hours from March 2008 to March 2009 at Kodéni and Kuinima in Bobo Dioulasso (Burkina Faso). Data show the mean and the standard error of six measurements. Arrows indicate days of fertilizer application.

3.3.4. Cumulative emission rates of N and C

Annual cumulative losses of NH_3-N reached 310 kg N ha^{-1} at Kodéni and 270 kg N ha^{-1} at Kuinima, accounting for 14% and 16 % of total applied N. Annual cumulative losses of N_2O-N were about 113 and 80 kg N ha^{-1} at Kodéni and Kuinima, representing for both gardens 5% of total applied N. In both gardens, cumulative NH_3-N losses were higher than of N_2O-N and accounted for 73% and 77% of total estimated N losses for Kodéni and Kuinima gardens. Total N losses (NH_3 + N_2O) reached 420 and 350 kg N ha^{-1} yr^{-1} at Kodéni and Kuinima (Figure 3.5) and represented 20% of the N input in the two gardens (Table 3.2).

Estimated annual total CO_2 emitted amounted to 36 and 22 t C ha^{-1} yr^{-1}, accounting for 57% and 50% of total C inputs at Kodéni and Kuinima. Estimated annual CH_4-C emitted reached 527 and 467 kg C ha^{-1} yr^{-1} at Kodéni and Kuinima, respectively, accounting both gardens for 1% of total C input. CO_2 losses accounted for up to 98% of total gaseous C losses in both gardens (Figure 3.5). The estimated annual C loss (CO_2-C + CH_4-C) was 60% of the total C input at Kodéni and 52% at Kuinima (Table 3.5).

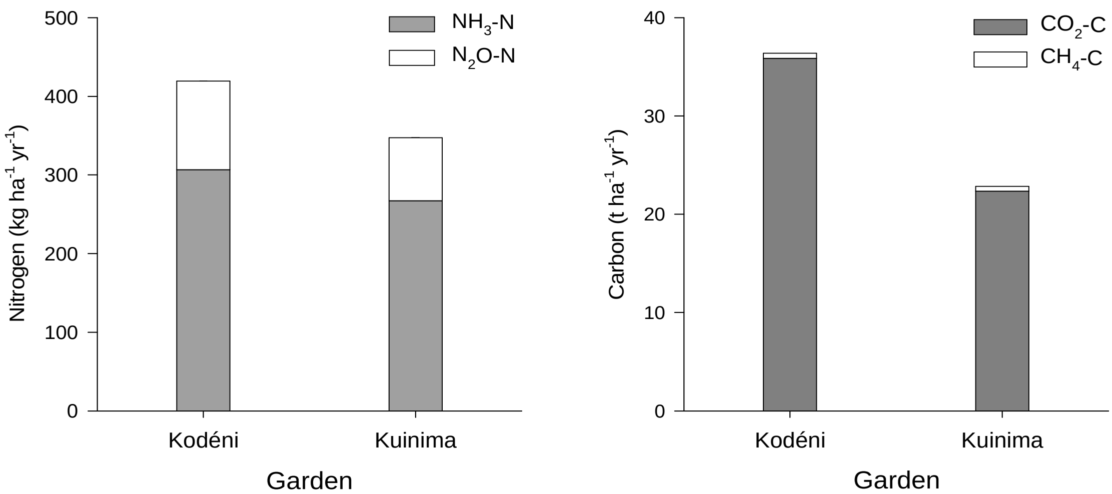


Figure 3.5. Cumulative annual fluxes of NH_3-N, N_2O-N, CH_4-C and CO_2-C at Kodéni and Kuinima vegetable gardens during March 2008-March 2009 in Bobo Dioulasso, Burkina Faso.

Table 3.5. Amounts of N and C inputs and the respective estimated gaseous losses in Kodéni and Kuinima vegetable gardens during March 2008-March 2009 in Bobo Dioulasso (Burkina Faso).

Garden	N input	N gaseous loss	N gaseous loss	C input *	C gaseous loss	C gaseous loss
	kg ha^{-1} yr^{-1}		% of N input	t ha^{-1} yr^{-1}		% of C input
Kodéni	2225	419.3	19	63.1	36.4	59.6
Kuinima	1729	347.2	20	45.1	22.8	52.2

* : Input from manure + estimated C input via photosynthesis

3.4. Discussion

In both gardens emission rates were highest during the hottest period of the day indicating the effect of temperature on gas emissions from soil. It is well known that N and C mineralization increases with temperature due to the physiological adaptation of soil organisms to their soil habitat (De Neve et al., 1996; Sierra, 1997). Similar results have also been reported recently by Agehara and Warncke (2005), Mkhabela et al. (2009) and Predotova et al. (2010).

Similarly, NH_3 emission is affected by factors such as fertilizer type, application rate and method, weather and field conditions (Huijsmans et al., 2003). Annual N input rates of up to 2,060 kg ha^{-1} were recorded at Kodéni, exceeding the 1,730 kg ha^{-1} yr^{-1} recorded at Kuinima (Chapter 2). This may be the reason why the highest emission rate at Kodéni (1,140 g NH_3-N ha^{-1} h^{-1}) exceeded that recorded at Kuinima (880 g NH_3-N ha^{-1} h^{-1}). Ma et al. (2010) also observed increased flux rates of NH_3 with increasing N levels.

Our maximum NH_3-N emission rate of 1,140 g ha^{-1} h^{-1} (Figure 3.3) was comparable to the 1,200 g NH_3-N ha^{-1} h^{-1} recorded by Rochette et al. (2009) in a laboratory study on NH_3 volatilization following surface application of urea to tilled and un-tilled soil. However, our flux data by far exceeded the flux maxima of 83 and 333 g NH_3-N ha^{-1} h^{-1} recorded by Asing et al. (2008) and Ma et al. (2010), respectively, probably because of the higher N input rate used in our study.

In our study relative annual cumulative NH_3–N losses (14% and 16 % of total applied N at Kodéni and Kuinima, respectively), were higher than those of 2.8% to 11% reported by Asing et al. (2008) for lettuce. However, they were in good agreement with those of Sommer et al. (2004) who stated that NH_3-N losses may reach 50% of the applied N, depending on fertilizer type and environmental and soil conditions.

In our study, the maximum N_2O-N flux rate of 155 g ha^{-1} h^{-1} recorded at Kodéni by far exceeded the rates recorded by other authors, which may partly be due to the very high N inputs in the intensive urban vegetable gardens of Bobo Dioulasso (up to 320 kg N ha^{-1}; Chapter 2). For instance, an emission rate of up to 1.42 g N_2O-N ha^{-1} h^{-1} was reported by Brümmer et al. (2008) for sorghum fields in SW-Burkina Faso which received 140 kg N ha^{-1}. However, our results were comparable to flux rates of 150 g ha^{-1} h^{-1} reported for a natural savanna reserve in SW-Burkina Faso.

The higher average WFPS (61%) and the higher N input rate (2225 kg N ha^{-1} yr^{1}) at Kodéni compared to Kuinima could be the reasons of the higher N_2O emissions at Kodéni (Brümmer et al., 2008; Predotova et al., 2010). About 5% of applied N was lost as N_2O in both gardens. These values exceed those of Ma et al. (2010) who reported emission losses of < 0.2% of applied N. However, our rates were similar to the 2-5% reported by Predotova et al (2010). More studies are needed to identify the processes and the factors involved in N_2O emissions and to test approaches to effectively reduce its emissions.

Nitrogen applied to soils is mostly lost in form of NH_3 through volatilization which is the result of physico-chemical processes easier to occur in comparison to N_2O emission resulting from the microbiological processes of nitrification and denitrification (Harrison and Webb, 2001; Dalal and Allen, 2008). In both gardens, cumulative NH_3-N losses were higher than of N_2O-N and accounted for 73% and 77% of total estimated N losses for Kodéni and Kuinima. Similar results have been reported by Master et al. (2003) who observed emission rate of NH_3-N up to 3 times that of N_2O-N in an experiment testing the effect of reclaimed effluent irrigation on gaseous N losses and other N transformations in a Grumosol.

Total annual N losses (NH_3-N + N_2O-N) in the two gardens by far exceeded the 11% losses of applied N reported by Predotova et al. (2010) for the UPA vegetable gardens of Niamey (Niger), probably because of the higher N input rates recorded at Kodeni and Kuinima. The total annual N losses at Kodeni and Kuinima (Table 3.5) represented 36% and 50% of the N partial balance (Table 3.2), respectively, indicating that N emissions were an important pathway of N losses, and calling for improved management practices that help reducing N losses in UPA vegetable gardens of Bobo Dioulasso.

The particularly large CO_2-C fluxes at Kodéni that reflected rapid mineralization of organic matter were likely induced by the combination of the high amounts of C and N applied, the daily irrigation and the frequent soil tillage observed in the UPA gardens of Bobo Dioulasso. Our results by far exceed those of Konda et al. (2008) who reported emission rates of up to 1,530 g CO_2-C ha^{-1} h^{-1}, but they were still lower than the 25,000 g CO_2-C ha^{-1} h^{-1} from a loam soil reported by Sainju et al. (2008) in a study on the effects of management practices on soil surface CO_2 fluxes in Rasmussen, MO, USA. Similarly, average annual CO_2-C emissions from our gardens were with 56% of the C input substantially higher than the 24-27% reported by Ding et al. (2007) from a field study on CO_2 emission from an intensively cultivated loamy soil at Henan, China. In contrast, they were lower than the relative emission rates of 58% recorded in only 30 days by Ajwa and Tabatabai (1994) in a laboratory experiment evaluating organic C mineralization of various organic materials added to non-calcareous agricultural soils of Iowa (USA). Sainju et al. (2008) reported annual CO_2-C emission as high as 36.4 t C ha^{-1} yr^{-1} from a tilled soil following heavy rain or irrigation managed for more than 20 years.

Peak CH_4-C emission rates of 340 g CH_4-C ha^{-1} h^{-1} measured in our study by far exceeded those of 7 g CH_4-C ha^{-1} h^{-1} reported for sandy loam and clay soils by Jareki et al. (2008) in a study on the effects of soil type and N fertilization on CH_4 fluxes. Normally, rates of this magnitude are only reported from anaerobic conditions (Keppler et al., 2006). However, upland soils can also be sources of CH_4 when gas diffusivity is heavily altered by agricultural management practices such as organic matter application (Jarecki et al., 2008), tillage (Hütsch, 1998; Ussiri et al., 2009), and irrigation (Jin and Jury, 1995). In addition, inorganic N fertilization can reduce the CH_4 oxidation capacity of upland soils and therefore enhance emissions (Harrison et al., 1995; Chan and Parkin, 2001). In the urban garden of Bobo Dioulasso, the often twice-daily irrigation, frequent hoeing, and the application of organic fertilizer may have affected soil aeration and thus gas diffusivity leading to higher CH_4 emissions. Similarly, cumulative CH_4-C recorded in our study was much higher than those varying from 125-131 kg ha^{-1} yr^{-1} reported from a field study by Adhya et al. (2000) for upland rice-based cropping systems under humid tropical conditions of eastern India. However, further investigations are needed to verify these results and to provide solid data for a better understanding of CH_4 emissions from the intensive UPA vegetable gardens in Bobo Dioulasso.

3.5. Conclusion

In intensively managed UPA gardens of Bobo Dioulasso gaseous N and C emissions represent an important pathway of losses whereby NH_3 dominates N losses and CO_2 C losses. Surprisingly, N_2O emission appeared to be also important in both gardens. This study highlighted the need of improved fertilizer management practices to reduce N losses and to slow down C mineralization. Applying fertilizers during the coolest periods of the day to reduce the effect of high temperatures on gas emissions, coupled with the incorporation of mineral fertilizers to reduce NH_3 volatilization, may be good options to reduce N losses. Further investigations are needed to identify the processes involved in N_2O emissions from urban vegetable gardens of Bobo Dioulasso and to provide effective measures for their reduction. The use of low C:N organic fertilizers combined with reduced hoeing may be a good option to improve C sequestration.

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Chapter 4. General discussion, conclusion and recommendations

4.1. Horizontal matter flows and balances

Depending on the data input, the nutrient balance approach can be used at diverse scales to establish a link between nutrient use, the effects on the environment and the sustainability of soil fertility. It is more and more frequently used for describing nutrient flows and for planning nutrient management (Mikkelsen, 2005). The use of a nutrient balance approach to explore nutrient flows and balances in our study provided interesting data and allowed us to appreciate nutrient management practices in the urban vegetable production systems in Bobo Dioulasso. Recorded nutrient input rates for the two investigated production systems exceeded plants nutrient requirements and those recommended by the Extension Service for vegetables in the Soudano-sahelian zone (d'Arondel de Hayes and Traoré, 1990). As a consequence of the excessive fertilizers applications in our study site, nutrient balances were positive (chapter 1 and 2). This was also reported by Diogo et al. (2010) for urban gardens in Niamey (Niger). On average, the annual surpluses for both systems were as high as 715 kg N ha^{-1}, 281 kg P ha^{-1}, 117 kg K ha^{-1} and 31 t C ha^{-1}, suggesting substantial inefficiencies and scope for improvement by better synchronizing nutrient inputs to crop nutrient requirements. Even if we take into account leaching losses quantified by Sangaré et al. (Unpublished) and volatilization losses reported in the Chapter 3, this conclusion would remain the same except C for balance of the cGscC system indicating a need for improving organic matter use.

The weak integration between farming and animal husbandry has been indexed as one of the factors limiting soil productivity in Sub-Saharan Africa (Bationo et al., 1998). The recorded nutrient surpluses were statistically similar in the two systems, suggesting that the livestock component in the cGCL system did not have a major effect on nutrient management in urban vegetable gardens of Bobo Dioulasso.

The surpluses recorded in our study are in sharp contrast to the negative nutrient balances often reported for rural agricultural systems in sub-Saharan Africa (Stoorvogel et al., 1993; Bationo et al., 1998; Anthofer and Kroschel, 2000; De Jager et al., 2001; Haileslassie et al., 2006). This is probably due to the fact that UPA systems are largely market-oriented, allowing investments in soil amendments (Hedlund et al., 2003). Another factor is the ready availability of urban waste as effective inputs at no or only nominal cost for urban farmers (Eaton and Hilhorst, 2003). Furthermore, urban gardens are typically small in size, mostly <1ha (Dossa et al., 2011), which reduces the quantities of fertilizers required and facilitates their application.

With regards to the prevailing sandy texture of the UPA soils, the surpluses of N, P and K are leached during the rainy season, especially from July to September when rainfall is strongest (Figure 1) (Predotova et al., 2011). Excessive fertilizer application can also increase disease susceptibility and reduce the quality of vegetables (Hochmuth et al., 1991; Gruhn et al., 2000; Assogba-Komlan et al., 2007; Wang H.J. et al., 2008).

4.2. Gaseous emissions of N and C

The mineralization of N and C are influenced by temperature and rose with increasing temperatures due to the physiological adaptation of soil organisms to their soil habitat (De Neve et al., 1996; Sierra, 1997). Temperature influences microbial activity and subsequently the synthesis of enzymes that catalyze biochemical processes. For instance, urease activity changes with change in temperature thereby changing the hydrolysis rate of urea applied to soil and the subsequent release of ammonia (Tabatabai and Bremner, 1972; Moyo et al., 1989). In our study, the effect of temperature was emphasized by comparing gases emissions from soil during the day's coolest and hottest periods. The results reveal that emission rates were highest during the hottest period of the day, indicating the positive influence of temperature on gas emissions from soil (Chapter 3). Agehara and Warncke, (2005), Mkhabela et al., (2009) and Predotova et al., (2010) have reported similar results. Management options for reducing the effect of temperature on gas emissions have already been identified mostly in temperate conditions (Jarecki et al., 2008) and should be tested in semi-arid climate zones like in Bobo Dioulasso.

Gaseous N emissions represent an important pathway of N losses and NH_3-N dominated N_2O-N losses in the intensively managed UPA garden systems of Bobo Dioulasso. More attention should be paid to fertilization practices that minimize ammonia volatilization. Surprisingly, N_2O emission appeared to also be important in both gardens, suggesting the need for further investigations to identify the processes involved and to provide effective measures to reduce N_2O emissions.

Management practices have the potential to affect soil CO_2 emissions (Sainju et al., 2008). The combination of the high amounts of C and N applied (Chapter 1), combined with the daily irrigation and the frequent soil tillage observed in the UPA gardens of Bobo

Dioulasso, lead to rapid mineralization of organic matter resulting in large fluxes of CO_2-C especially at Kodéni (Chapter 2). The maximum emission rate recorded in our study (12,990 g ha^{-1} h^{-1}) exceed those of Konda et al. (2008) who reported emission rates of about 1,530 g CO_2-C ha^{-1} h^{-1} but they were still lower than the 25,000 g CO_2-C ha^{-1} h^{-1} from a loam soil reported by Sainju et al. (2008) in a study on the effects of management practices on soil surface CO_2 fluxes in Rasmussen, MO, USA.

The average annual CO_2-C emissions found from all gardens was about 28 t C ha^{-1} yr^{-1}, or 56% of C input (Chapter 2). This was higher than the 24-27% of C input reported by Ding et al. (2007) in a field study on CO_2 emission in an intensively cultivated loam. In contrast, they were lower than the relative emission rates of 58% recorded in only 30 days by Ajwa and Tabatabai (1994) in a laboratory experiment evaluating organic C mineralization of various organic materials added to non-calcareous agricultural soils of Iowa (USA). Sainju et al. (2008) reported annual CO_2-C emission as high as 36.4 t C ha^{-1} yr^{-1} from a tilled soil following heavy rain or irrigation and under a conservation reserve program management.

Nutrient management practices in vegetable gardens of Bobo Dioulasso are not depleting soil fertility but may actually lead to the improvement of soil fertility. However, they need to be improved in order to minimize nutrient and C losses.

4.3. Conclusion and recommendations

This study focuses on UPA systems in Bobo Dioulasso, especially with respect to vegetables production systems. It indicates that regardless the production system, current nutrient inputs are much higher than nutrient removal by crop uptake confirming our first hypothesis. The livestock component in the cGCL system did not seem to have a major effect on nutrient management. Gaseous N and C emissions occur during the hottest period of the day and represent an important pathway of losses, confirming the second hypothesis. NH_3 dominates N losses and CO_2 C losses.

These results suggest substantial inefficiencies. Management practices should be improved to sustain UPA in Bobo Dioulasso by:

- Coupling plant and animal husbandry
- Better synchronizing nutrient inputs with crop demands
- Better use of fertilizers to reduce NH_3 volatilization and C mineralization

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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, 10 January 2012 Désiré Jean-Pascal Lompo