



Universite Catholique de Louvain
Faculté d'Ingénierie biologique, agronomique et environnementale
Earth and Life institute

Water and nutrient use efficiency and the vertical leaching losses in urban vegetable cropping systems in Bobo–Dioulasso (Burkina Faso)

Sheick Ahmed Khalil S. B. SANGARE

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Jury members:

President : Prof. Jacques Mahillon (UCL, Belgium)

Supervisors : Prof. Charles L. BIELDERS (UCL, Belgium)

: Prof. Michel P. SEDOGO (INERA, Burkina Faso)

: Prof. Marnick VANCLOOSTER (UCL, Belgium)

Readers : Prof. Andreas Buerkert (UNIKASSEL, Germany)

: Prof. Bernard TYCHON (ULg, Belgium)

: Prof. Stefaan De NEVE (UGent, Belgium)

To my family

« Là où s'abat le découragement s'élève la victoire des persévérants. »

Thomas SANKARA

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Abstract

This thesis aimed at a comprehensive characterization of water and nutrient use and nutrient leaching losses in vegetable production systems in Bobo Dioulasso (Burkina Faso) in view of contributing to the development of more rational advice regarding water and nutrient management. For this purpose, three treatments were compared: farmer's normal fertilization practice (T100), a 30% reduction in fertilization rates (T70), and unfertilized plots (T0). Crop yield, irrigation water and fertilizers management practices as well as plant nutrient uptake were closely monitored. In addition, drainage was collected using zero-tension pan lysimeters at 30 cm depth and analyzed for total N, P, and K content. Sites were equipped with weather stations and TDR probes. Furthermore, sites were also equipped with anion/cation exchange resin cartridges for monitoring the leaching of NO_3 , NH_4 , PO_4 , and K. Four vegetable crops were evaluated: tomato, cabbage, carrot and lettuce.

As elsewhere in West Africa, vegetable production in Bobo Dioulasso is characterized by high fertilizer inputs. Indeed, 109 to 2,012 kg N, 66 to 450 kg P and 0 to 393 kg K were applied in excess of plant uptake in both gardens. Free drainage occurred mainly during rainy season, although some drainage occurred during the dry season at Kodené. The high nutrient inputs combined with periods of high drainage resulted in sometimes high rates of NO_3 and PO_4 leaching, and on the other hand in strong positive nutrient balances in the soil of both sites. Large amounts of NO_3 (236 to 990 kg ha⁻¹ year⁻¹) and to a lesser extent PO_4 (28 to 75 kg ha⁻¹ year⁻¹) and K (54 to 214 kg K ha⁻¹ year⁻¹) were thus leached every year beyond the rooting depth. Using a simple fertilizer reduction strategy (T70) allowed to significantly increase the PFP of N, P and K by about 20 to 50% at Dogona and 20 to 45% at Kodené. It also helped reduce both the amount of nutrients leached as well as the nutrients accumulated in the soil. The reduction in leaching losses ranged from 20 to 90% for NO_3 , 29 to 74% for PO_4 and 14 to 39% for K. Given the sometimes excessive application rates for N and P in the two gardens studied here, reducing nutrient application rates by 30% may help reduce the environmental impact of vegetable cropping systems and lower the costs of investment in fertilizers without adverse effect on yields. Special attention should however be paid to maintaining the K balance.

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List of acronyms and symbols

APUGEDU	: Potential for Development of Urban and Peri-urban Agriculture in Relation to Urban Waste Management in West Africa
BUNASOLS	: Bureau National des Sols
C	: Carbon
CEC	: Cation Exchange Capacity
CENCOSAD	: Centre for Community Studies, Action and Development
CPCS	: Commission de Pédologie et de Cartographie des Sols
CO	: Compost
CREPA	: Centre Régional pour l'Eau Potable et l'Assainissement
CV	: Coefficient of Variation
D	: Drainage
DM	: Dry Matter
EC	: Electrical Conductivity
Eq	: Equation
ETCrop	: Actual Crop Evapotranspiration
ET0	: Reference Evapotranspiration
Ex-K	: Exchangeable Potassium
FAO	: Food Aid Organization of the United Nations
FYM	: Farm Yard Manure
GEau	: projet Gestion de l'Eau
GDP	: Gross Domestic Product
H	: Height
HCl	: hydrochloric acid
I	: Irrigation
IAGU	: Institut Africain de Gestion Urbaine
ICRISAT	: International Crops Research Institute for the Semi-Arid Tropics
IER	: Ion Exchange Resin
IERC	: Ion Exchange Resin Cartridge
IN	: Input
INERA	: Institut de l'Environnement et de la Recherche Agricole
INSD	: Institut de la Statistique et de la Démographie
IMF	: International Monetary Fund
IRD	: Institut de Recherche pour le Développement
IRDC	: International Development Research Centre
K	: Potassium
kc	: Crop Coefficient
L	: Length
LA	: Leaf Area
LAI	: Leaf Area Index
MDGs	: Millennium Development Goals
MW	: Municipal Waste
N	: Nitrogen
NaCl	: Sodium Chloride
N/A	: Non available
NH ₄	: Ammonium
NO ₃ -N	: Nitrate

NUE	: Nutrient Use Efficiency
OUT	: Output
P	: Phosphorus
PD	: Poultry Dropping
PFP	: Partial Factor Productivity
PO ₄	: Phosphate
PVC	: Poly–Vinyl Chlorid
R	: Rainfall
R ²	: Square of the linear coefficient of correlation
SD	: Standard Deviation
SOC	: Soil Organic Carbon
SOM	: Soil Organic Matter
SSA	: Sub–Saharan Africa
SSF	: Soil Solution Fluxemeter
SSS	: Soil Solution Sampler
RUAF	: Resource centre on Urban Agriculture and Food security
TDR	: Time Domain Reflectometry
UA	: Urban Agriculture
UN	: United Nation
UNFPA	: United Nations Population Fund
UNPD	: United Nation’s Population Division
UPA	: Urban and Peri–urban Agricutlture
USD	: United State Dollar
VWC	: Volumetric Water Content
W	: Width
WAVE	: Water and Agrochemicals in soil, crop and Vadose Environment
WHO	: World Health Organization
WUE	: Water Use Efficiency
Y	: Yield
z	: depth
ΔS	: Storage variation
2IE	: Institut International d'ingénierie de l'eau et de l'environnement
θ	: Volumetric moisture content
ρ	: Density
Q ₁₀	the proportional increase in soil respiration when soil temperature increases by 10 °C

Chapter 1

Introduction and Objectives

1.1. Context and justification

1.1.1. Urban population growth is a challenge for food security in Sub-Saharan Africa

According to the United Nation's Population Division (UNPD) projections, the world's population will grow from 6 billion currently to more than 9 billion by 2050 (UN, 2008). Most of this increase is expected to occur in the developing world. Indeed, the developing world's population is currently expanding at a rate of nearly 800 million per decade, and its size was expected to increase from 4.1 billion to about 8.6 billion between 1990s and 2050 (Bongaarts, 1994). Africa is projected to experience a nearly twofold increase of its population between 2010 and 2050.

The population growth rate is strongly unbalanced between rural and urban areas, and between developed and developing countries. Currently, about half of the world's population lives in urban centres (Bettencourt and West, 2010), yet by 2050 6 billion of the 9 billion of world's population are expected to live in urban areas. By 2030, each of the major regions of the developing world will hold more urban than rural dwellers, and by 2050 more than two-thirds (about 69 %) of their inhabitants are likely to live in urban areas (Montgomery, 2008; UN, 2008). At 3.7% per year (between 2000 and 2010), the current urban population growth rate in Sub-Saharan Africa (SSA)

is almost twice the worldwide average (2% during the same period) (Drechsel and Dongus, 2010). The same growth rate applies to West Africa where the urban population will rise rapidly as some West African's cities already have an annual growth rate (averaged over the last 10 years) of 3.8 % (Niamey), 3.9 % (Kano), 4.3 % (Sikasso) and 5.1 % (Ouagadougou). This population increase is mainly driven by people migrating from rural areas to cities (UNPD, 2004). Indeed, Bloom (2008) estimated empirically that migration contributes on average to 50 % of the total urban population growth.

A major consequence of the population growth is an increase in demand for food (Tilman et al., 2002; Godfray et al., 2010). Huang et al. (2002) estimated that food and feed production must continue to rise annually by 1.2 % to satisfy the increasing demand of the fast growing world population. Concerns about the adverse effects of rapid population growth on human welfare in developing countries were already expressed several decades ago by authors who predicted that population growth would rapidly exceed their food supply capacity (e.g. Bongaarts, 1994; Sanchez, 2002). In SSA particularly, the rising demand for food due to population growth has driven the upward trend in food insecurity, and self-sufficiency in food production remains so far a distant target (Matson et al., 1997). Currently, the proportion of chronically undernourished people remains high (30 % of the population in 2010; FAO, 2010). The biggest challenge in SSA, especially West Africa, is therefore to achieve the Millennium Development Goals (MDGs) of cutting by half the number of undernourished people by 2015 (Sanchez and Swaminathan, 2005).

1.1.2. Limits of rural agricultural systems

In SSA countries, about 60% of the economically active population lives of agriculture (Gollin, 2011). Agriculture in many of these countries has a long–

standing extensive tradition and has mainly been localized in rural areas. At least 75 % of the cultivated areas are used for subsistence cereal cropping (Wang et al., 2009). However, although global world cereal production has doubled in the past 40 years (Tilman et al., 2002), in SSA it has remained either stagnant or declined over the years (Sanchez and Swaminathan 2005; Vitousek et al., 2009). This decline in production has long been ascribed to the combined effect of poor soils and erratic climatic conditions (Lal, et al., 2004; Bostick et al., 2007). Indeed, the scientific literature is replete with references demonstrating that agricultural production in West Africa suffers from intrinsically nutrient-poor soils (Stoorvogel et al., 1993; Drechsel et al., 2001, Bationo et al., 2006). This, along with recurrent problems of pest and diseases, are considered as the major biophysical limitations of crop productivity (Sanchez, 2002).

Increasing food production in such conditions could be achieved either by expanding the land area under cultivation or by increasing yields per unit area through intensification of cultivation (Tilman et al., 2002; Sanchez and Swaminathan, 2005). However, the demography has led land availability for crop production to become increasingly scarce in this region, especially in West Africa. Furthermore, the remaining uncropped land is of increasingly marginal quality. Hence, some form of intensification of cropping practices is needed, to maintain productivity level. Such intensification tightly relies on soil fertility replenishment through the building up of soil organic carbon (SOC) and nutrient stocks, together with efficient water management practices (Lal, 2004; Sanchez and Swaminathan, 2005). However, cereal crop production in these regions is characterized by low fertilizer inputs that are inadequate to sustain high productivity (Vitousek et al., 2009), owing to the scarcity of organic resources (Bationo et al., 2008) and mineral fertilizers which are often not affordable for farmers (Sanchez, 2002). This has led some researchers to state that rainfed rural cropping areas, that are also often structurally

disadvantaged, will not be able to achieve alone the challenge of food security (e.g. [Schlecht et al., 2006](#)). This is, therefore, alarming for West Africa which hosts most of the world poorest countries, such as Burkina Faso, where the population that depends on agricultural production accounts for ca. 80% ([Ingram et al., 2002](#)).

1.1.3. UPA is an opportunity for feeding the urban population.

Fortunately, over the last few decades, a market-oriented intensive urban and peri-urban agriculture (UPA) has emerged as a substantial solution to achieve the MDGs, particularly in eradicating extreme urban poverty and hunger (MDG 1; [van Veenhuizen and Danso, 2007](#); [Drechsel and Dongus, 2010](#)). UPA activities include crop and livestock agriculture, fisheries, forestry and non-wood forest production, processing and marketing within and around cities ([FAO, 2010](#)). In contrast with the subsistence farming systems that prevail in the rural zones, UPA is characterized by a much higher productivity ([Graefe et al., 2008](#); [De Bon, 2009](#)).

Despite the fact that the scale of urban food production is poorly known, conservative statistics suggest that urban agriculture is a widely practiced activity involving more than 20 million people in West Africa and 800 million worldwide ([UNPD 2004](#); [Drechsel et al. 2006](#)). UPA provides significant livelihood for several millions of people in both rural and urban areas ([van Veehuizen and Danso, 2007](#); [Thornton, 2008](#)). According to the [UNDP \(1996\)](#), 80% of families in Libreville (Congo), 68% of urban dwellers across six Tanzanian cities, 45% in Lusaka (Zambia), 37% in Maputo (Mozambique), 36% in Ouagadougou (Burkina Faso), 35% in Yaounde (Cameroon) were involved in urban agriculture. A global estimate is that urban agriculture, which occupies less than 10 % of the country's cultivated areas, provides about 15 to 20 % of the world's food ([Drechsel and Dongus, 2010](#)). Some research on specific cities

and products yield the following estimations: Dakar supplies 60% of the national vegetable consumption ([Niang, 1998](#)); in Accra, 90% of the city's fresh vegetable consumption is produced within the city ([CENCOSAD, 1994](#)); in Dar es Salam, urban agriculture forms at least 60% of the informal sector ([Mougeot, 1994](#)).

1.1.4. Risks associated with UPA.

Intensification in UPA vegetable production areas comes primarily from higher nutrient application rates ([Zhu and Chen, 2002](#); [Agele et al., 2011](#)). The intensive market-oriented character of this type of agriculture stimulates investment in such high inputs. Furthermore, the difficulties in estimating accurately the effective crop nutrient requirements often led to a supra-optimal use of fertilizer in order to guarantee maximum yield. The intensive nutrient input in UPA is also partly related to the possibility of using a wide spectrum of by-products generated by urban activities (solid waste, compost, sludge and agro-industrial waste), whose quantities increase in proportion to the population growth ([Eaton and Hilhörst, 2003](#); [Drechsel et al., 2005](#); [Akegbejo-Samsons, 2008](#); [Kabore et al., 2010](#); [Kiba et al., 2012](#)). Moreover, UPA is characterized by the intensive recycling of nutrients through the use of domestic and industrial wastewaters with sometimes very high nutrient loads ([Sou, 2009](#); [Akponikpe et al., 2011](#)), as an alternative to overcome water shortage.

Such overuse of fertilizers in the urban and peri-urban areas usually has led to strongly positive nutrient balances in soils, as reported by many studies ([Keraita and Drechsel, 2002](#); [Hedlund et al., 2003](#); [Drechsel, et al., 2004](#) ; [Diogo et al., 2009](#)). Therefore, UPA can bear risks of soil contamination by excess nutrient accumulation and groundwater contamination through nutrient leaching losses; especially nitrate ([Tamini and Mermoud 2003](#); [Qadir](#)

et al., 2007; Predotova et al., 2010). Nutrient leaching losses through the soil is particularly a considerable human, environmental and economical problem (Matson et al., 1997; 1998; Djodjic et al., 2004; WHO, 2011) and may severely undermine the sustainability of these systems. Additionally, although the use of solid waste and sewage may indeed contribute to alleviate the pressure on organic materials and fresh water resources, they have been shown to introduce pathogens and heavy metals in soils and in the food chain (Akponikpe et al., 2011; Abdu et al., 2011; Kiba et al., 2012), which is likely to affect consumers' and farmers' health.

Urban and peri-urban areas in developing countries are among the most polluted of the world. This is especially so in West Africa where treatment of solid waste (through sorting and/or composting) and wastewaters (treatment in macrophyte ponds) is very limited, thus raising concern about pathogen and heavy metal contamination. As cities continue to expand and urban populations continue to increase, the situation is growing worse and the need for safe, sustainable and affordable water and nutrient management practices is becoming even more critical. Besides the health and environmental benefits, promoting greater nutrient use efficiency may also help improve the economic returns for UPA farmers. Reconciling the needs for increased food production (MDG 1) with greater protection of the environment for a sustainable development (MDG 7) thus remains a major challenge for research and development.

1.1.5. Contribution of research to UPA sustainability in Burkina Faso.

In Burkina Faso, UPA traditionally received far less attention from research than rural rainfed cropping systems. Indeed, attempts by agricultural scientists to increase agricultural sustainability have long focused on issues relative to the improvement of soil productivity in the low-input rural cropping

systems (e.g [Zougmore et al., 2004](#); [Ouedraogo et al. 2007](#); [Bado et al., 2010](#)) or in the cotton (*Gossypium hirsutum*) production systems ([Ouattara et al., 2007](#)). In recent years, however, there have been significant scientific and public concerns about UPA activities, and promoting UPA sustainability has become henceforth prominent within the political agenda. This shift is explained to a large extent by the confluence of key factors such as the need to feed the growing population in cities, the need to dispose of the increasing waste production and the wish to prevent the negative externalities of UPA.

Most of the works in Burkina Faso have been done by Higher Education Institutions (e.g., University of Ouagadougou and Bobo), by research institutes or have been funded by development projects and agencies in view of promoting the use of organic resources and the safe recycling of urban waste. Much of the results generated by this research has remained as project reports and thesis with limited diffusion (e.g. [Eaton and Hilhorst, 2003](#); [Sou, 2009](#)), although an increasing number of research papers has been recently published regarding the agronomic performance of urban waste ([Kiba et al., 2011 and 2012](#)), composting of municipal solid wastes and slaughterhouse wastes ([Hien et al., 2010](#); [Kaboré et al., 2010](#)), the treatment and re-use of grey waters ([Akponikpè et al., 2011](#)), the healthy valorization of human urine ([Bonzi et al., 2009](#)), the socio-economical issues surrounding UPA ([Freidberg, 1996](#)) as well as livestock issues ([Thys et al., 2005](#)). Some existing studies have highlighted the negative impact of UPA in Burkina Faso, which range from risks of nitrate leaching to the introduction of heavy metals in the soil and food chain ([Tamini and Mermoud, 2002](#); [Nafiu et al., 2011](#), [Kiba et al., 2012](#)).

In order to establish a rational policy for the protection of the environment and for planning of soil and groundwater resource use in UPA systems, an in-depth analysis of nutrient flows has been advocated ([Drechsel](#)

et al., 1999). Although several studies reported the relatively high horizontal¹ nutrients inflow (Eaton and Hilhorst, 2003; Drechsel et al., 2004; Kiba et al., 2012) few studies, if any, have addressed their reduction in UPA systems. Furthermore, all the studies performed hitherto on the behaviour of nutrient surplusses in the soil were focused on on–station quantification of nitrate leaching process (Tamini and Mermoud, 2002). Consequently, solid quantitative and scientific data are still needed regarding the nutrient fluxes in soil, which would allow making informed decisions on how to effectively improve the water and nutrient use efficiency and output quality of the typically high–input UPA systems, while reducing its negative externalities. The Urban Food Project: “Challenges and Opportunities for Nutrient Efficient Agriculture in West African Cities”, which includes the present Ph.D. research, strives to contribute to filling such knowledge gaps regarding UPA in West Africa.

1.1.6. Overview of Urban Food Project framework

The Project Objective

The Urban Food project² aims at a consistent and comprehensive characterization of urban agriculture (UA) externalities in three secondary cities of the countries Mali (Sikasso), Burkina Faso (Bobo Dioulasso) and Nigeria (Kano). The ultimate goals of this process–oriented research are (i) to minimize the negative side effects of UA on food safety and environmental health and (ii) to develop scientifically sound recommendations at the producers’ level to enhance the resource use efficiency and productivity of the UA production systems.

¹ Horizontal nutrient inflows refers to all nutrient inputs through organic and mineral fertilizers and as well as the other sources of inputs such as irrigation water and deposition.

² <http://www.agrar.uni-kassel.de/UrbanFood/?c=8>

Organizational framework of the project research

The project couples process-oriented biophysical research and the use of bio-economic models with a north-south transfer of knowledge in the quantification and modeling of nutrient fluxes and a south-south transfer of expertise on soil and product contamination with fecal pathogens, pesticides and heavy metals. It involves 4 European institutions and 4 West-African Institutions through a team of 5 PhD students and 1 post-doctoral fellow who address specific topics. A schematic overview of the Urban Food Project framework is available in [Fig. 1.1](#).

The horizontal flows of nitrogen (N), phosphorus (P), potassium (K) and organic carbon (C_{org}) was determined in different types of UA vegetable crop enterprises with special emphasis on their seasonal and spatial variation at all three locations. In contrast, the determination of the vertical fluxes of nutrients and heavy metals and the contamination of agricultural produce requires a more elaborate setup and was therefore restricted to a single city. In Burkina Faso, in-depth studies of vertical nutrient losses through leaching (N, P, K) and volatilization (N, C) were undertaken. To improve nutrient use efficiency and reduce environmental and human health risks linked to UA, alternative nutrient management strategies were tested experimentally. In-depth analyses of agricultural produce contamination by faecal pathogens and agro-chemicals that might originate from inappropriate use of inputs in UA was undertaken in Mali. In Nigeria, with its typically higher level of industrialization, the contamination of the soil–water–plant continuum with heavy metals was studied in more detail. These data provided the input parameters for the calibration and validation of integrated biophysical and socio-economic modelling tools. The country-specific upscaling and cross-country comparison of resource management in UPA is being dealt with by the post-doc student.

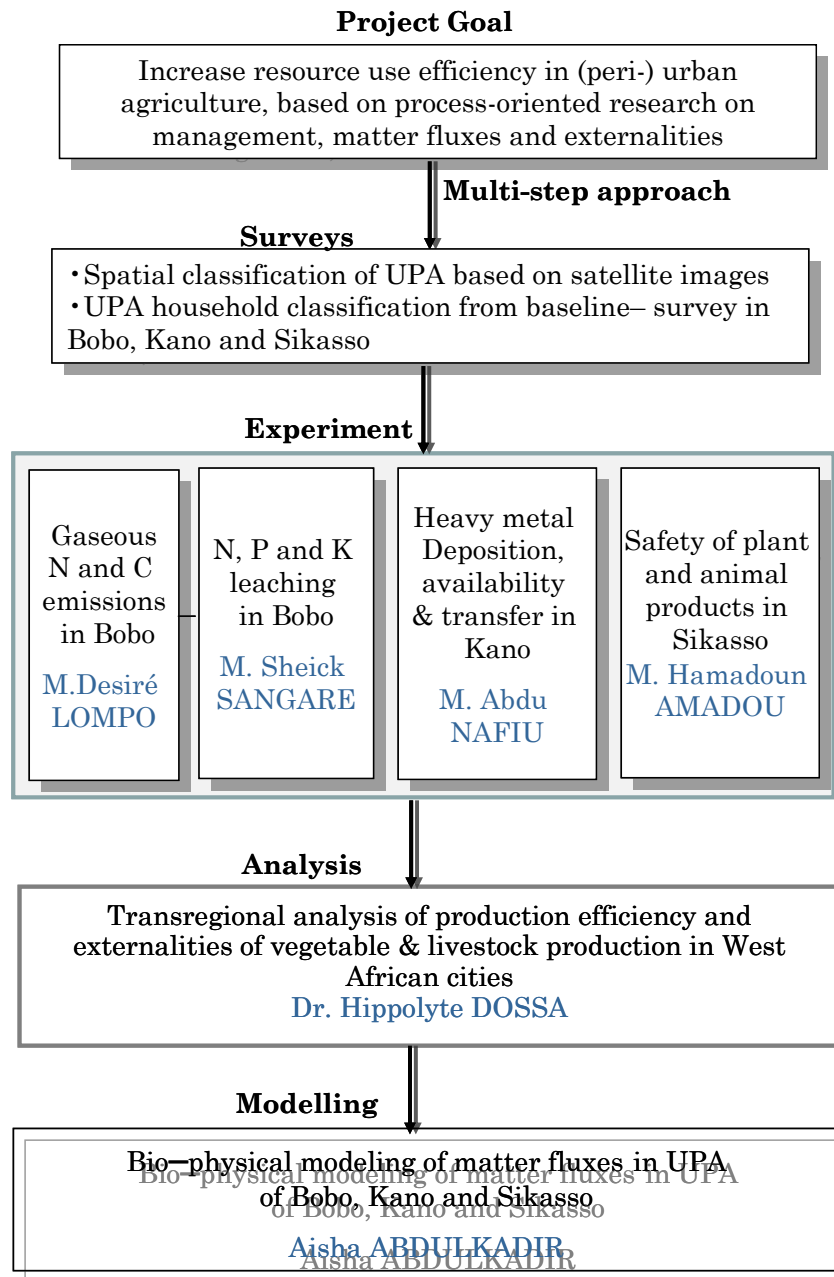


Figure 1.1.: Framework of the Urban Food Project

1.2. Research Hypotheses

It is hypothesized that:

Vegetable cropping in Bobo Dioulasso currently operates under ecologically critical conditions due to high water and nutrient inputs, leading to lowered nutrient use efficiency and potential contamination risks for ground water;

Given the soil and climatic conditions in Bobo Dioulasso, current water and nutrient management practices induce a potential risk of leaching for N but also P and K. Reducing current fertilization levels will significantly reduce the nutrient losses through leaching;

A significant reduction of the gardeners' normal fertilization practice could help improve nutrient use efficiency in vegetable cropping without adverse effects on yields and water use efficiency.

1.3. Research Objectives

1.3.1. Main objective

The main goal of the research is to identify opportunities for improving water and nutrient use efficiency in urban agriculture in Burkina Faso and reduce its potentially negative impact on groundwater through better water and nutrient management practices.

1.3.2. Specific research objectives

In this study we specifically seek to:

Evaluate the plot-level water and nutrient use efficiency as a function of crop type and location in UPA in Bobo Dioulasso;

Quantify the vertical leaching of N, P and K in urban vegetable production at the plot level as a function of location, crop type and nutrient input levels by means of different measurement techniques;

Evaluate the opportunities to increase nutrient efficiency while maintaining crop yields through a reduction in nutrient inputs as a function of crop type and location, by means of field experiments.

1.4. Outline of the thesis

This thesis is made up of 6 inter-dependant sections presented in chapter format. The first three chapters are devoted to general aspects, including a general introduction, study site description and an overview of the general methodological approach. The following three chapters are devoted to specific issues related to the experiments results. A schematic overview of the structure of the thesis is presented in Fig. 1.2.

Chapter 1 is introductory and presents the context and justification of the subject. It subsequently underlines the hypotheses as well as the general and specifics objectives of the study.

The study area is described hereafter in **Chapter 2**. This chapter deals with the biophysical characteristics of the country of Burkina and more specifically of the city of Bobo Dioulasso. It also provides a brief description of the population, the agro-climatic features, the physico-chemical characteristics of soils and their constraints. It also provides a general overview of the vegetable production system in the city of Bobo Dioulasso.

Because the methodology is transversal to all the parts, an overview of the general methodological issues is described in **Chapter 3**. In this section both gardens and the experimental layout are described. Crop management, irrigation and fertilization schedule, soil sampling, crop growth as well as soil solute monitoring methods are discussed.

The last three parts present the main outcomes of the study and discuss the specific objectives highlighted above. They are presented in article format, each including an abstract, introduction and objectives, the specific methodology, the results, a discussion and conclusions. The bibliographical references have been gathered at the end of the thesis.

Chapter 4 explores the efficiency of field scale water and nutrient uses for vegetable production. Firstly, it examines the water flux at plot scale and the impact of the gardener's water management practice on the water balance components, with special emphasis on drainage. Subsequently, the gardener's nutrient management practices and their effects on crop production and partial factor productivity are quantitatively interpreted.

Chapter 5 investigates the impact of a 30% reduction in the gardener's nutrient application rates on the improvement of the nutrient use efficiency in this agricultural system. Then it discusses the effect of the fertilizer reduction treatments on crop production and partial soil nutrient balances. It also analyses the consequences of such reductions of several soil chemical parameters and the buildup of soil nutrient stocks.

Chapter 6 is devoted to the study of the plot-scale drainage and nutrient leaching through the rooting depth. It concentrates on the determination of the drainage level and the nutrients therein and how it can be related to the nutrient inputs (treatments). Drainage water and nutrient leaching estimates derived from different monitoring methods are reported and statistically compared. The last part is a **General Conclusion** which consists in a synthesis of the results along with a sketch of perspectives for future research.

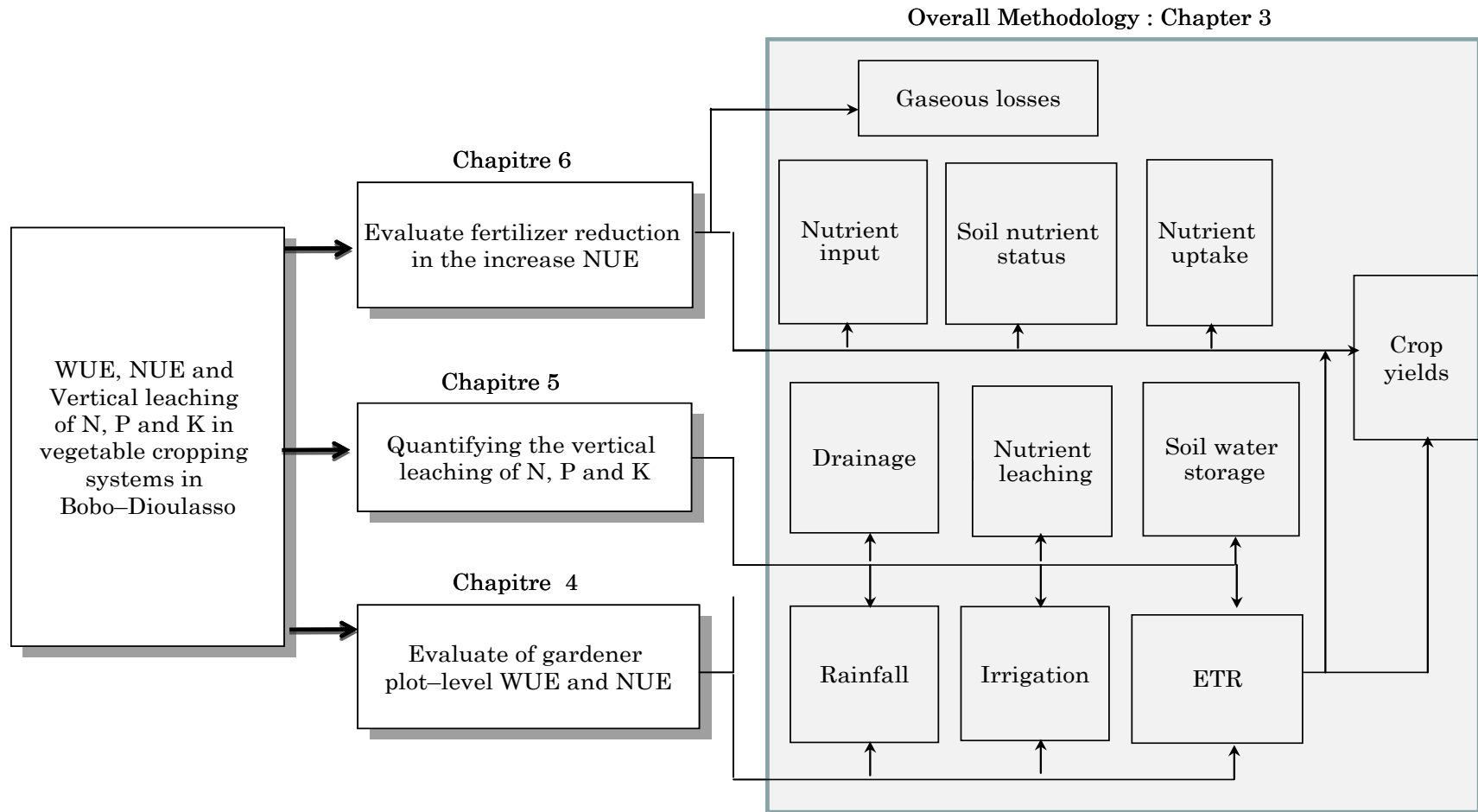


Figure 1.2.: Framework of our study

Chapter 2

Study Area

2.1. General overview of Burkina Faso

2.1.1. Localization, demography and economy

Burkina Faso is a landlocked Sahelian country in West Africa stretching between 9°20' and 15°05' latitude North, 5°20' longitude West and 2°03' longitude East ([Sedogo, 1993](#)) and covering 274 200 km². The main part of the territory is a lateritic, relatively flat plateau lying between 250 and 450 m above sea level (mean of 300 m) and sloping from the north-east to the south-west ([Derouane and Dakouré, 2007](#)).

According to the latest general population census ([INSD, 2008](#)), the country had a population of about 14 million inhabitants in 2006, with 51.7% women and 48.3% men. The population density was 51.8 inhabitants / km² and about 26 % of the population was living in the urban zones during the year 2010 ([United Nation Statistics Division, 2010](#)). Based on an annual growth rate of 3.1 % (between 1996 and 2006), it is estimated that the population will double by 2035. Burkina Faso is one of the poorest countries in the world, with an annual per capita gross domestic product (GDP) of 577 USD ([IMF, 2010](#)). Approximately 86 % of the population lives below the poverty line of 2 USD per day ([UN, 2008](#)) and about 90 % is engaged in the primary sector of the economy. The country has virtually no natural resources, and its economic development depends essentially on agriculture (cotton is the main export product) and livestock farming.

2.1.2. Climatic features

Burkina Faso is a tropical country with Sudano-Sahelian climate. Overall, rainfall is unevenly distributed and increases from North to South and South–West. The annual average rainfall varies from less than 250 mm in the North and Northeast to ca 1100 mm in the South. Three climatic zones can be defined (Figure 2.1): 1) the Sahel is a relatively dry savannah in the North with less than 600 mm average annual rainfall, 2) the Sudan–Sahel is a transitional zone with regards to rainfall and temperature and is located in the central part and further to the South, and 3) the Sudan zone receives more than 900 mm of rain on average per year and has cooler average temperatures.

The seasons are conditioned by the movement of the Intertropical Convergence Zone that governs the monomodal annual rainfall pattern ([Thackway, 1998](#)). The seasons are strongly contrasted and characterized by alternating dry and wet rainy seasons, the latter lasting approximately 5 months (May/June to October) in the South, and 3 – 4 months (June to September) in the North. The region is marked by recurrent droughts, especially since the 1970's.

During the hot dry period (March to April), the average maximum temperatures may reach 37°C in the south and central parts, and 41°C in the northern part of the country. The average minimum temperature may drop to 24°C, 25°C and 26°C for the southern, central and the northern regions, respectively. During the cold season (December to February), the maximum temperature reaches 34°C, 36°C and 38°C, and the minimum temperatures drop to 19°C, 17°C and 14°C for the same three regions, respectively. Overall, severe wind and water erosion mainly occur towards the end of the dry season (wind) and in the first half of the rainy season (wind and water), which

coincides with the occurrence of high intensity thunderstorms often preceded by violent winds.

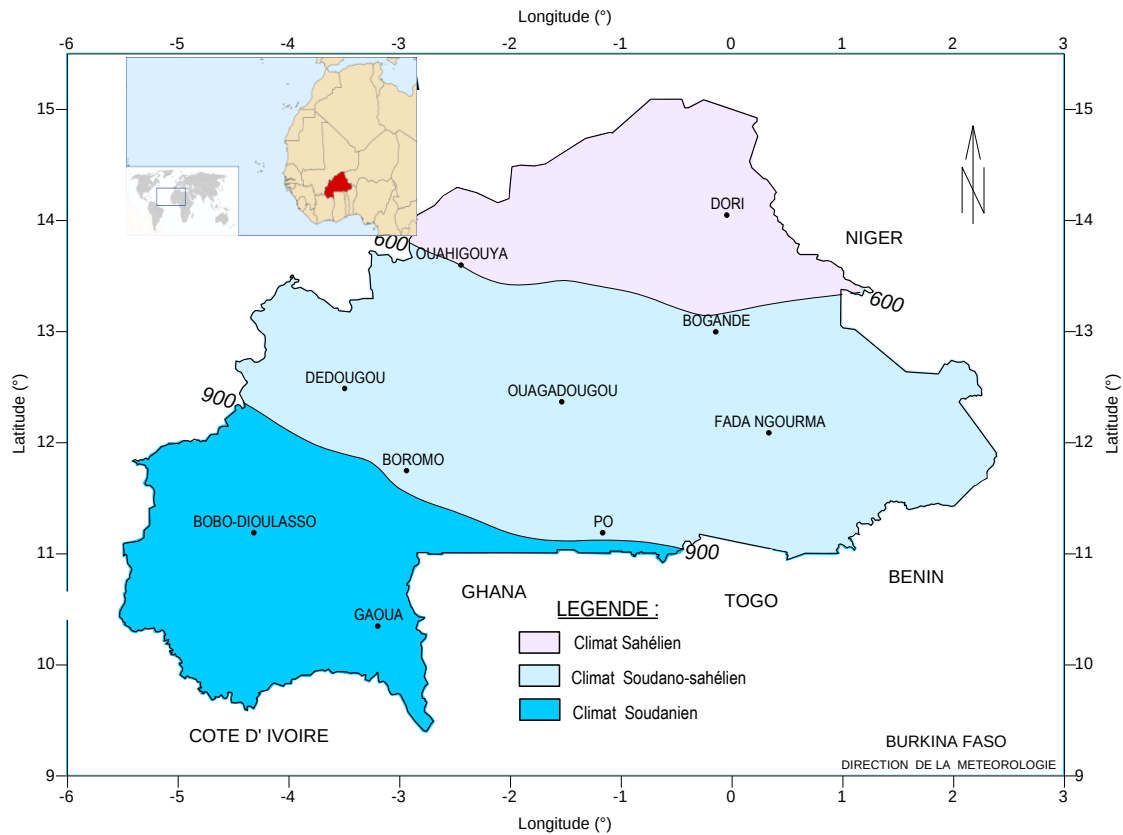


Figure 2.1: Location and climatic zones of Burkina Faso (Source: Direction de la Météorologie Nationale)

2.1.3. Soils and soil constraints

The country is characterized by a large heterogeneity in soil types (Fig. 2) due to the diversity of geology and geomorphologic evolution, including the type of alteration of primary rocks. Essentially derived from acid rock material (sandstone, granite) rich in iron and manganese oxides and hydroxides, the soils are mainly acidic and dominated by kaolinitic clay. This weathering has

resulted in weakly leached or leached Ferruginous Tropical Soils ([CPCS, 1967](#)) which cover more than half of the country's surface and which are generally associated with other soil types, particularly the regical soils on schists.

The other main soils are:

- Lithosols on various rocks, corresponding to outcrops of sandstone, granites and laterite, and having no agronomic value;
- Ferrallitic soils, composed of sandy-clay materials developed on parent material rich in clay and sand. These strongly weathered soils are only found in the Houet, Kénédougou and Comoé provinces and are acidic, permeable and have a low chemical fertility;
- Hydromorphic mineral to pseudogley soils found in bands fringing the main drainage axes and in the broad lowland plains. They generally are associated with Brown Eutrophic tropical soils;
- Brown Eutrophic tropical soils are less compact and have a greater porosity than the other soils. They are the best soils in the country and are well suited to growing crops and vegetables but represent only a small acreage.
- Vertisols characterized by high clay content and the predominance of swelling clays. Their mineral content is high but restrictive physical factors (high bulk density, rugged surface relief...) renders non-mechanized tillage difficult. High yields could be obtained with appropriate farming methods;
- Poorly-developed weathered soils cover large areas in the centre and the east in the form of plateaus and hills and are associated with the tropical ferruginous soils. Their shallowness, their limited water reserves and their deficiency in main nutrients makes these soils unsuitable for farming. They are cultivated, however, in densely populated areas such as the Mossi region.

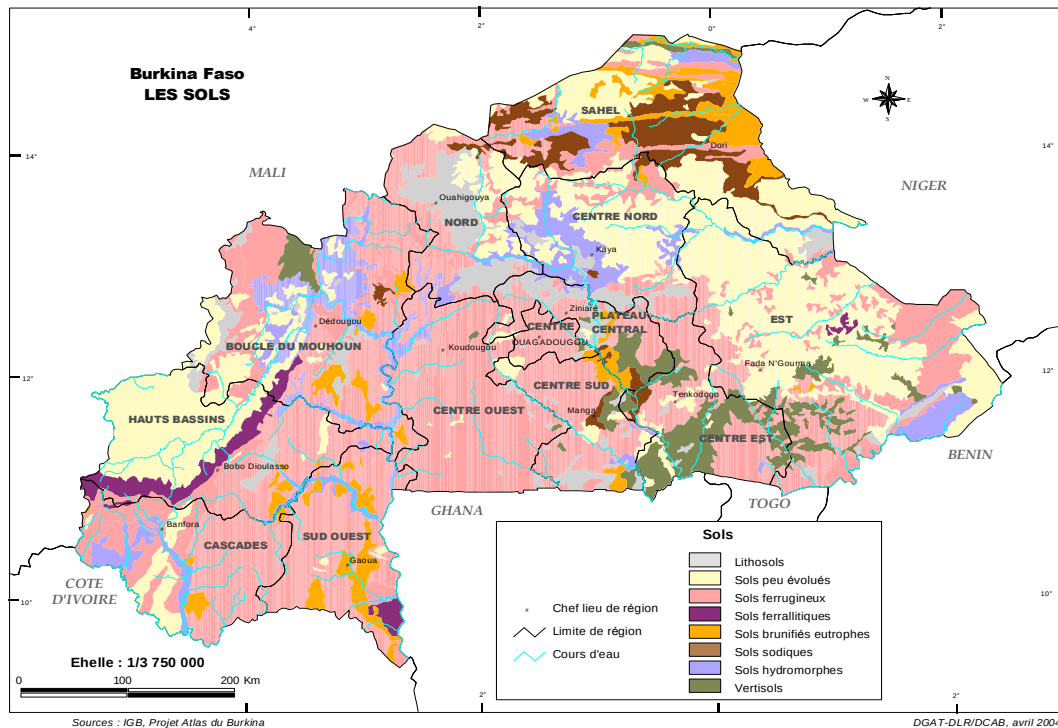


Figure 2.2: Soil map of Burkina Faso (Source: DGAT-DLR/DCAB, 2004).

The low fertility of most soils is recognized as a fundamental cause of declining food security in Burkina Faso (Bado et al., 2010). Indeed, it has been shown that soils in Burkina Faso are poor to moderately poor in organic matter (Ouattara et al. 2006), nitrogen (Sedogo, 1993; Zougmore et al., 2004), and potassium (FAO, 2006) and extremely poor in phosphorus (Lompo, 2009; Bado et al., 2010). In this region, soil phosphorus (P) is one of the main nutrients limiting crop production in the absence of water stress (Bationo and Mokwunye, 1999). The soil organic matter and fertility decline very quickly under continuous cultivation (Sedogo, 1993; Bado et al., 2007; Ouattara et al., 2006). Managing the soils' organic matter content is of particular importance in agriculture in order to maintain the soils' nutrient retention capacity and availability to crops (Ouattara et al., 2006).

Furthermore, most soils are prone to crusting due to their low structural stability caused by low soil organic matter content (< 1%). The presence of a highly developed soil crust limits infiltration and increases runoff, which is enhanced by the lack of vegetation or mulch cover (particularly in the Northern regions). Hence, soils are sensitive to both wind and water erosion, which causes serious and rapid decline in fertility of the already low fertile soils (Visser et al., 2005; Zougmore et al., 2004). The low surface coverage with plants during dry season and beginning of the rainy season enhances the deleterious effects of wind and water erosion on topsoil productivity and further contributes to negative nutrient balances in sub-Saharan West Africa (Buerkert et al., 2001). In the Sahelian zone, Visser et al. (2005) estimated that up to 78 % of the N inputs through organic and mineral fertilizers may be carried away through wind erosion in one cropping season.

Human-induced degradation due to improper land use, particularly continuous tillage (Hoogmoed, 1999; Spaan et al., 2005; Ouedraogo et al., 2006), insufficient returns of exported nutrients (Bationo et al., 2004) and inadequate erosion control (FAO 2006) have exacerbated the soil fertility decline. The low absolute level of plant available nutrients and the low cation retention makes recurrent fertilizers inputs a precondition for continuous cultivation in most soils (Driessen et al., 2001).

2.1.5. Agriculture

Agriculture drives economic growth in Burkina Faso and accounts for 37.1 % of the Gross Domestic Product (World Bank database, 2003). In Burkina Faso, 80.4 % of the population (INSD, 2008) depends upon self-subsistence agriculture for its livelihood (Ouattara et al. 2006). Only 2 % of the arable lands are irrigated, which means that rainfed agriculture is the main source of food (Zougmore et al. 2004). Both the amount and distribution of rainfall

during the growing season markedly determine the agricultural productivity (Sivakumar and Gnoumou, 1987).

Cereal crops such as sorghum (*Sorghum bicolor*); millet (*Pennisetum glaucum*) and maize (*Zea mays*) are the main staple foods and are grown on about 80 % of the cultivated area (Zougmore et al. 2004; Ouattara et al. 2006). Because of the inter-annual variability of rainfall, the choice of crop species is restricted to short-cycle varieties. Cotton is the first cash crop, followed by groundnut. Vegetable production has increased within and at the outskirts of the cities due to the strong need for food in urbanized areas. The main production cities are Ouagadougou, Bobo Dioulasso and Ouahigouya in descending order.

2.2. Biophysical characteristics of Bobo Dioulasso

2.2.1. Geographic localization and demography

The Houet Province is located in the Western region of Burkina Faso and Bobo-Dioulasso is its administrative centre. Bobo-Dioulasso lies at Lat. 11°10'N, Long. 4°19'W, and has an altitude of 432 m above sea level. The city area covers about 160,000 ha, with a constructed area of about 5000 ha (Abdel-Rahman et al., 2008), and the annual increase in urbanization was estimated at 5.2 %. The population of the Houet province increased from 308 thousand in 1975 to slightly over 1 million in 2009 (INSD, 2009). According to the projections, it will reach 1.5 million by 2020. The population of Bobo Dioulasso was estimated at 500 thousand inhabitants in 2006, which means that roughly 50% of the population of the Houet province was living in the city of Bobo.

2.2.2. Main climatic feature

The climate is characteristic of the southern Sudan region, a transition zone between the Sudanese and Guinean environments. During the last 40 years (1967 – 2007), the mean annual rainfall was 1024 ± 167 mm (Mean $\pm$ SD).

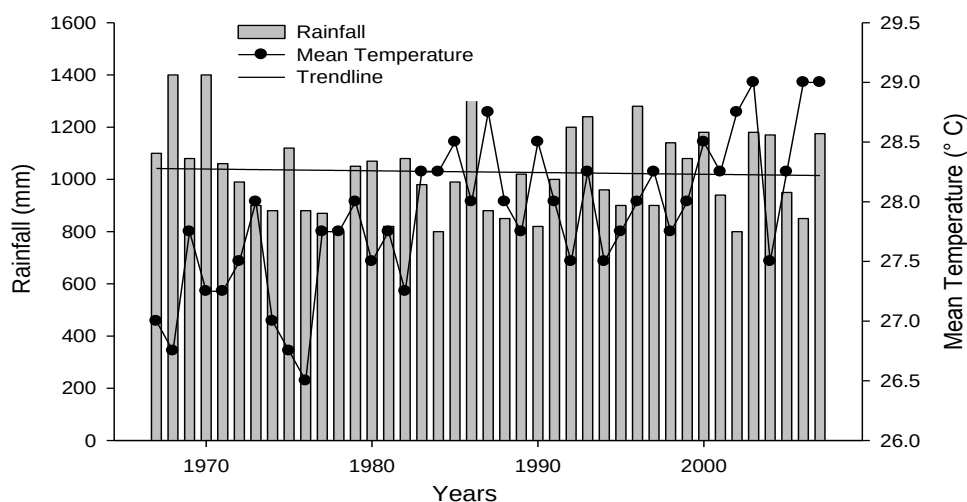


Figure 2.3. : Bobo Dioulasso's annual rainfall and mean temperature between 1967 and 2007 (Data from the National Meteorology Service)

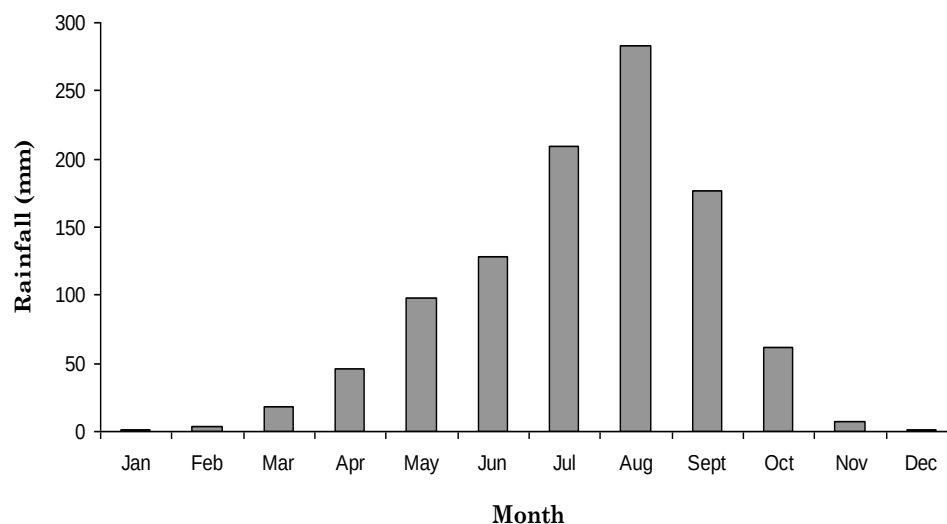


Figure 2.4. Bobo Dioulasso's average monthly rainfall and temperature between 1967 and 2007 (Data from the National Meteorology Service)

Inter-annual variations in rainfall are large but since the 1970s the tendency has been towards the lower end of the range (Figure 2.3). Since the 1960s, it has been estimated that annual rainfall declined on average by 3 mm year⁻¹ (Somé, 1996).

Rainfall is characterized by the alternation of one short rainy season (June to October) and a longer dry season (November to May; Sivakumar and Gnoumou, 1987). The average maximum temperature increased from 32 °C to 35 °C between 1967 and 2007 and the average minimum temperatures increased from 21°C to 24°C. Data from the same period show a significant increase in the average annual temperature (Fig. 2.3). Average monthly temperature for the same period was $27.9 \pm 0.7^{\circ}\text{C}$ (Mean $\pm$ SD).

On average, rainfall starts in May and stops approximately in September/early October (Figure 2.4), causing late sown crops to suffer from water stress at the end of the season (Sivakumar, 1990). Rahmnan et al. (2007), based on data from 1963–2003, showed that supplemental irrigation is required during occasional dry spells in the rainy season and regularly at the end of rainy season. Their estimation of supplemental irrigation requirements with the FAO CROPWAT model amounted annually to an average of 133 mm for cotton production. It has been shown that supplemental irrigation during dry spells can help increase sorghum harvest by 41 % (Fox and Rockstrom, 1999).

2.2.3. Main soil units

According to the soil map drawn by ORSTOM (Boulet, 1968), the main soil units found in the Bobo–Dioulasso areas are: Lithosols, Tropical ferruginous soils, and Ferrallitic soils (cf. § 2.1.3). These soils are characterized by a low organic matter content (< 1.4 %; Sedego, 1993), low available phosphorus

content (P–Bray I < 5 mg kg⁻¹; [Lompo et al., 2009](#)), low–activity clay ([FAO, 2006](#)) and low cation exchange capacity (< 8 meq/100g clay).

It has been shown that soils are particularly prone to nutrient leaching ([Bado et al., 2010](#)). Combined with the high rainfall, the high temperatures lead to the quick turnover of soil organic matter (SOM; [Manlay et al., 2004](#); [Bationo et al., 2006](#)). [Pieri \(1989\)](#) estimated that on sandy soils of West Africa (which are common in Bobo Dioulasso), the loss in soil organic matter (SOM) mineralisation can be over 5 % per annum. In these soils, nitrogen and phosphorus are the plant nutrients most limiting crop production ([Ouédraogo, 2006](#)). Phosphorus is one of the least available nutrients in many soils of Burkina Faso including all soils of Bobo Dioulasso ([Bado et al., 1997](#); [Lompo, 2009](#)). The availability of P for plants is limited by both the inherent P deficiency and the high P fixation capacity of the acidic soils ([Bado et al., 2010](#)).

2.2.4. Land use and agricultural farming systems

The main concerns related to land use and farming systems are the spatial and temporal variability of rainfall and low soil fertility, which govern the types of uses and land management. The South–Sudanian zone of Burkina Faso is undoubtedly the region where the agricultural potential is highest. Production is based on an agro–pastoral system dominated by agriculture. Production centres on rainfed food crops, i.e., sorghum (*Sorghum bicolor*), millet (*Pennisetum americanum*), maize (*Zea mays*), or rice (*Oryzae sp*), in rotation or intercropped with other food crops (e.g., yam, sweet potato, groundnut and millet) or with cash crops (e.g., cotton (*Gossipium hirsutum*), groundnut (*Arachis hypogea*) and sesame (*Sesamum indicum*). Production systems in the Houet province are fairly diversified. Cereals occupy 67% of the cultivated area, cash crops 30% (twice the national average), and irrigated and rain–fed rice

account for the rest of the area. Mixed cropping is a strategy for the farmers' profit maximization and risk minimization (Bationo et al., 2004).

Three types of fields can be found in the Houet province (Rahmnan et al., 2007): 1) compound fields, surrounding the homesteads, where maize, red sorghum and vegetables are grown. They represent 22.4% of all cultivated land. They are given particular care and fertilized with manure and household waste; 2) permanent fields (13%) or village or hamlet fields, where maize, groundnut, sorghum and millet are grown, forming a parkland savannah environment, dominated by *Parkia biglobosa* and *Vitellaria paradoxa*, and 3) the bush fields (64.4%) which include a constellation of plots scattered near the limits of the village territory and planted with sesame, “fonio” (*Digitaria exilis*), sorghum, maize, and other crops.

In rainfed cropping systems, the use of agricultural inputs remains low, being restricted to the commercial crops. “Slash and burn” is the main means of land clearing, which allows the transfer of the rich store of nutrients locked up in the vegetation to the ensuing crops. Tillage is used across the region to control weeds and prepare the seedbed for optimum growth (Ouedraogo et al., 2005), and for soil water conservation (Hoogmoed, 1999). Use of farm equipment is among the highest in the country, owing to the cotton production. The hand-held hoe (“daba”) is used for sowing, hoeing, de-stumping and loosening the soil. “Manga hoes” and ploughs are used for ploughing and ridging in this region (Ouattara et al., 2007). To cope with soil degradation, monoculture of fonio or crop rotation (sesame-groundnut–fonio–millet) is practiced. Intercropping involves sorghum, cowpea, sesame and groundnut (Bado et al., 2006). Soil erosion control focuses on farming practices, such as planting on ridges.

Intensive urban vegetable gardening is present in the inner city and some urban and peri-urban gardening and maize and sorghum farming occurs on the fringe of the town (cf. red dots in Fig. 3.1).

Privatization of the land was catalyzed by the development of agro-forestry, particularly in the southern areas of the province. Accordingly the modalities of land use are changing, with the allocation of compound fields and permanent fields among indigenous social units and the opening of bush land to all.

2.2.5. Soil fertility management practices

The low fertility of soils is recognized as a fundamental cause of decline in crop yields in sub-Saharan Africa. In this region, maintaining or restoring soil fertility is a constant challenge for crop production. Thus, most soil management practices for agricultural systems are geared towards maintaining or even improving soil fertility.

Traditional agricultural practices have been characterized as extensive, which involves increased production through expansion of crop land. Owing to the rapid decline of soil organic matter under cultivation (e.g., [Ouattara et al., 2006](#)), the traditional soil fertility management originally relies on short cultivation periods (2–3–years) followed by long term fallow (more than 20 years). As a result of demographic pressure and increasing need for land, fallow duration has decreased during the past decades to less than 6 years ([Bilgo et al., 2006](#)). Despite, the development of strategies to improve short fallows, e.g., by introducing *Andropogon gayanus* ([Bilgo et al., 2006](#)) or leguminous plants such as *Mucuna cochenchinesis* ([Segda et al., 1996](#)), the potential of short-term fallows to reverse soil organic C losses due to continuous cropping under tropical conditions remains uncertain.

As land becomes scarcer due to rapid population growth, the cropping area has expanded to more marginal lands and fallowing practices are tending to disappear from the agricultural landscape. Hence, the fertility of cultivated land declined fast. It is now well known by farmers and researchers that

recurrent input of organic matter is a precondition for continuous cultivation (Driessen et al., 2001).

In the Sudano-Sahelian zone of West Africa, compost, animal manure and crop residues are organic sources of nutrients that are known to greatly increase crop growth and yields, particularly in the low fertility soils of smallholder farming system (Bationo et al., 1998; Roose et al., 2001). However, the actual fluxes of organic matter in agro-ecosystems are in fact highly dependent on the ways crop residues and animal excreta are managed. In many cases, these organic materials are destined for other uses, and so only a small fraction is returned to the cultivated plots. Additional sources of organic amendments have appeared as a result of urbanization, namely solid waste and sewage. Nevertheless, the low nutrient content of organic tropical soils (Sedogo, 1981) has favoured the use of large quantities of mineral fertilizers for cash crops, especially in the cotton area of Bobo Dioulasso (Ouattara et al., 2006).

In this western region, agroforestry systems are well developed, which implies the growth of fruit trees such as *Anacardium occidentale*, *Mangifera indica* and other indigenous trees. Agroforestry is the practice of growing staples and vegetables between rows of valuable timber trees, woody legumes, and young tree crops, and it is known to contribute to soil protection and restoration in Sub Saharan Africa. For instance, the work of Bayala et al. (2004), in this region showed, that the decomposition of leaves of *Vitellaria paradoxa* and *Parkia biglobosa* in agroforestry systems may return to the soil about 40% of the N and P removed by cropping.

2.2.6. Overview on urban vegetable production of Bobo Dioulasso

In Bobo Dioulasso, UPA is characterized by a wide spectrum of production systems ranging from household subsistence to large-scale commercial

farming. The vegetable production database from the latest census (DGPSA, 2006) shows that there were 80 vegetable production sites in the Houet province during 2004/2005, among which 84 % have been permanently cultivated and 16 % remain uncultivated during the rainy season.

Ten sites among the most important of the province are present within the city of Bobo Dioulasso and its surroundings. During the period 2004/2005, 3 845 dwellers (compared to 89 942 dwellers at the national level) was directly involved in vegetable cultivation, among which 94% (3 626 inhabitants) were men and 0.06% of women. The number of women involved in vegetable production in the Houet province was low compared to 33 % at the national level. In fact, women are more occupied in products selling rather than production. About 83 % of gardens are individual gardens, whereas 17 % are managed by cooperatives. The market-oriented vegetable production is dominated by mostly exotic³ crop species such as lettuce (*Lactuca sativa* L.), onion (*Allium cepa*), cabbage (*Brassica oleracea* L), tomato (*Solanum lycopersicum* L), African eggplant (*Solanum aethiopicum* L), amaranth (*Amaranthus ssp*) and carrot (*Daucus carota* L.).

In 2004 – 2005, cabbage, tomato, lettuce, carrot and onion were the most cultivated crops in terms of number of sites, cultivated area and production, in decreasing order. During this period tomato was found on 51.3 % of the sites, followed by onion (13.80 %), lettuce (11.3 %) and cabbage (11 %). The [Table 2.1](#) give the acreage of each of the main vegetable crop species at the Houet province and at national level (Burkina Faso) provided by the National Statistical service [C](#)) during the last census (2004–2005).

³ Most were introduced in Africa in colonial times.

Tableau 2.1: Acreage (ha), production (t) and incomes generated by the main crop cultivated in the Houet province (compared to national level) during the campaign 2004 – 2005.

Parameters	Level	Cabbage	Lettuce	Tomato	Carrot	Onion
Acreage (ha)	Houet	124	50	76	28	38
	National	732	242	2080	125	3681
Total production (t)	Houet	4175	1420	1439	765	659
	National	20734	5373	50158	3014	34959
Total production sold (t)	Houet	4045	1146	1369	753	641
	National	27911	5162	47844	3187	31637
Incomes generated (Euros)	Houet	171806	63553	66451	10730	67017
	National	1400951	52102	811245	294377	458124

(Source : MAHRH/DGPSA/Direction des Statistiques Agricoles: 2006).

Where irrigated, urban cropping systems commonly consist of a rotation of several crops per year, like for example 4 – 6 lettuce harvests interrupted by 1 – 2 cabbage crops, all on the same beds, or six spring onion harvests after 1 tomato crop. According to the [DGPSA \(2006\)](#), 56 % of vegetable production sites in the Houet province use river water for irrigation and 38 % use well water. The Houet River is the major riverbed which crosses the town in a south–west to north–east direction ([Freidberg, 2001](#)). Most of the gardening activities in Bobo Dioulasso are located along this river which drains wastewater from factories, hospital and military camp. The most common irrigation practice is to irrigate with hand watering cans, but 38 % of UPA farmers, mostly located near the river, use pumps.

Chapter 3

Study sites, experimental design and monitoring

3.1. Study gardens selection

Two locations in the city of Bobo Dioulasso were selected for this study: Dogona and Kodení. At each location, the monitoring was carried out in one representative garden was selected based on a clustering classification of urban and peri-urban agricultural systems in Sudano-Sahelian West African cities, including Bobo Dioulasso (Dossa et al. 2011; Abdulkadir et al. 2012). These studies revealed that gardeners who combine a commercial gardening activity with semi-commercial field cropping are the most represented in Bobo Dioulasso. Hence, the two experimental sites were selected so as to be representative of that system. The location and the main features of the two selected sites are detailed in (Fig. 3.1 and Table 3.1). The intensity and the heaviness of the monitoring that was conducted imposed a limited choice of the number of sites to be investigated.

The site of Kodení was selected because irrigation at this site relied on well water as opposed to river water at Dogona, which were expected to have different chemical composition. Gardens were also selected based on the willingness of the farmers to participate. In addition, the farmers used a variety of organic and inorganic amendments, which is also typical of local practices.

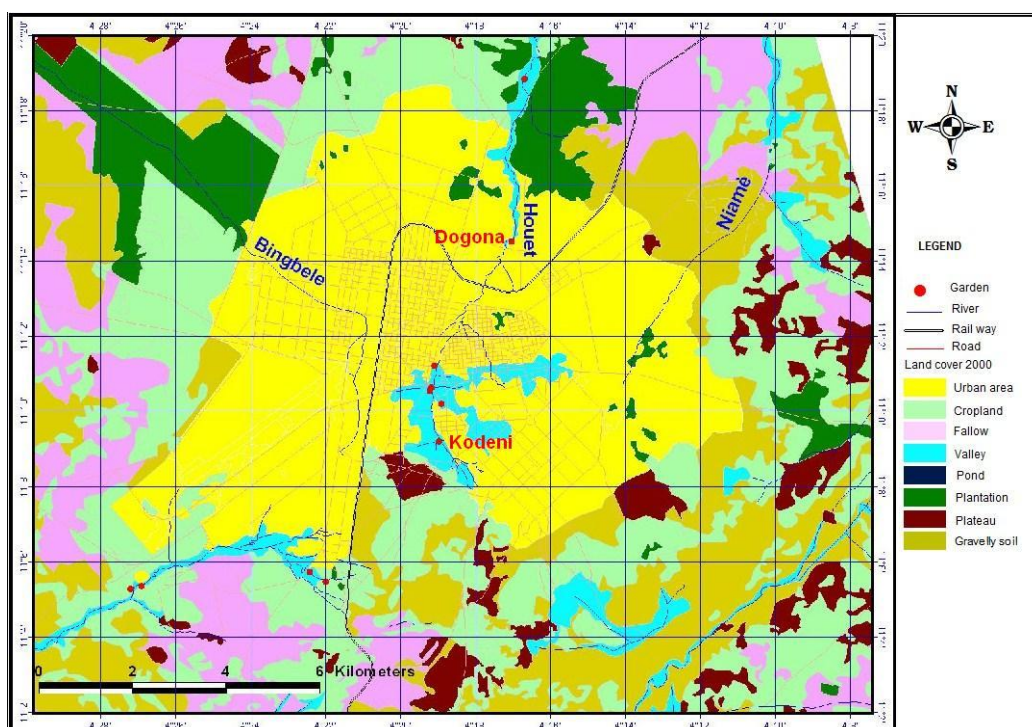


Figure 3.1. Land use at Bobo Dioulasso and study sites locations

(Source: Urban Food, 2008)

Table 3.1. Main characteristics of the selected gardens at the 2 study sites in Bobo Dioulasso during the study period

Parameters	Dogona	Kodeni
Garden location	11°13'3.82"N, 4°16' 51.58" W	11° 08' 17.12 N, 4° 19' 39.52" W
Site acreage (ha)	80	15
Water table level (m) [†]	15 m	18 m
Garden size	4130 m ²	2280 m ²
Monitoring period	April 2008 – February 2010	April 2009 – March 2010
Total rainfall		
2008	1117 mm	N/A
2009	890 mm	902 mm
Crop rotation	crop sequence : 2008:tomato-cabbage-carrot-lettuce 2009:tomato-lettuce-cabbage-carrot	1-year continuous lettuce
Irrigation water	Houet River	Well water

3.2. Main features of study gardens

Dogona is located 7 km to the north-east of the city center of Bobo Dioulasso. This site is characterized by intensive gardening that takes place throughout the year due to the proximity of the Houet River. Gardeners at this site exclusively use water from this river for irrigation. Kodené is located 5 km to the South–West of the city centre. This site is also characterized by year–round intensive vegetable production. The site is located near a river, smaller than the Houet River, whose flow is low and which is dry most of the year. Hence, the main source of irrigation water comes from wells. At these two sites, drinking water is almost exclusively supplied by water from boreholes and wells. This, together with the fact that the two sites are also typical of intensive vegetable production, have predominantly sandy soils and shallow groundwater (Table 3.2.), make them especially relevant for studying the impact of UPA on groundwater resources.

Garden locations and sizes were determined using a hand–held differential Global Positioning System (GPS; Trimble GeoExplorer II, Sunnyvale, CA, USA) (Fig 3.2). Based on the baseline surveys, both gardens were cultivated long before the start of the experiment (over 20 years); the selected gardeners were indigenous to the area and were using privately–owned gardens.

The groundwater table is about 15 m and 18 m below ground surface at Dogona and Kodené, respectively (according to GEau). Soils were classified as Ferruginous Tropical Soils, (FAO = ferric lixisols : USDA = Oxic Paleustalf) according to the World Reference Base for Soils Resources (Driessen et al., 2001; FAO, 2006) which is representative of large tracts of the Sudanian zone in Burkina Faso (Pallo et al. 2008).

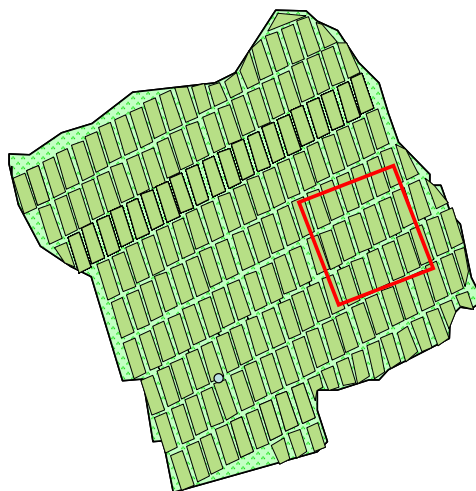
DOGONA



20 0 20 40 Meters

- Green beans
- Lettuce
- Fallow
- Tomato
- Well
- Plot boundary
- Experiment location

KODENI



20 0 20 Mètres

- Lettuce plots
- Plots Boundary
- Experiment location
- Well

Figure 3.2: Field maps of the selected garden at Dogona and Kodeni before the onset of the experiment.

The 0–30 cm depth was considered as the maximum rooting zone in our study. Therefore all measurements undertaken in this study were performed within this 0–30 cm depth. This rooting zone determination was done thanks to the root profile description whose method is described in detail in [Appendix 1](#). The results shown that for all crops considered in this study, between 95 and 99% of active roots were found in the 0–30 cm depth (data not shown).

Three soil samples were taken at three different spots within each experimental plot at the onset of each experimental year at depths 0–7.5 cm, 7.5–15 cm and 15–30 cm. These samples were subjected to a set of physical and chemical analyses to determine the soils' initial properties ([Table 3.2](#)).

Dogona's soils had a predominantly sandy–loam texture in the 0–30 cm layer, with sand being the dominant textural fraction accounting for about 76% by mass. Kodení's soil also has sand–rich topsoil (0–15 cm) with about 50% sand, but clay–rich (49% clay) subsoil (15–30 cm). Both soils had moderate nutrient contents, significantly decreasing with depth ([Table 3.2](#)).

Table 3.2. : Soils initial properties at the two sites (mean $\pm$ standard deviation; n = 18 per depth)

Site	Properties	Soil profile		
		0 – 7.5 cm	7.5 – 15 cm	15 – 30 cm
Dogona	Bulk Density (g cm ⁻³)	1.44 $\pm$ 0.01	1.43 $\pm$ 0.04	1.62 $\pm$ 0.07
	Textural class (USDA)	Loamy–Sand	Loamy–Sand	Loamy–Sand
	Sand (%)	76.9 $\pm$ 1.3	77.3 $\pm$ 1.1	74.6 $\pm$ 2.5
	Silt (%)	13.9 $\pm$ 0.4	13.9 $\pm$ 0.3	14.4 $\pm$ 0.6
	Clay (%)	9.1 $\pm$ 1.0	8.8 $\pm$ 0.9	10.9 $\pm$ 2.3
	Bulk density (g cm ⁻³)	1.44 $\pm$ 0.01	1.43 $\pm$ 0.04	1.62 $\pm$ 0.07
	Organic C (g kg ⁻¹)	15.45 $\pm$ 0.25	14.42 $\pm$ 0.37	8.9 $\pm$ 0.49
	Total N (g kg ⁻¹)	1.72 $\pm$ 0.16	1.67 $\pm$ 0.17	1.05 $\pm$ 0.07
	Total P (g kg ⁻¹)	1.31 $\pm$ 0.01	1.05 $\pm$ 0.05	0.54 $\pm$ 0.04
	Total K (g kg ⁻¹)	2.60 $\pm$ 0.14	2.30 $\pm$ 0.17	2.31 $\pm$ 0.30
	P–Bray I (g kg ⁻¹)	0.25 $\pm$ 0.01	0.23 $\pm$ 0.00	0.17 $\pm$ 0.01
	Ex–K (g kg ⁻¹)	0.25 $\pm$ 0.00	0.17 $\pm$ 0.01	0.09 $\pm$ 0.01
	CEC (cmol kg ⁻¹)	6.8 $\pm$ 0.2	6.8 $\pm$ 0.3	5.9 $\pm$ 0.5
	pH H ₂ O	6.5 $\pm$ 0.2	6.5 $\pm$ 0.2	6.7 $\pm$ 0.2
Kodeni	Bulk Density (g cm ⁻³)	1.33 $\pm$ 0.04	1.62 $\pm$ 0.03	1.58 $\pm$ 0.04
	Textural class (USDA)	Clayey–Sand	Clayey–Sand	Sandy–Clay
	Sand (%)	50.2 $\pm$ 2	49.8 $\pm$ 1.1	30.5 $\pm$ 0.4
	Silt (%)	19.4 $\pm$ 0.1	19.6 $\pm$ 0.8	21 $\pm$ 0.5
	Clay (%)	30.4 $\pm$ 2.0	30.6 $\pm$ 3.0	48.8 $\pm$ 0.6
	Bulk density (g cm ⁻³)	1.33 $\pm$ 0.04	1.62 $\pm$ 0.03	1.58 $\pm$ 0.04
	Organic C (g kg ⁻¹)	21.56 $\pm$ 1.38	21.23 $\pm$ 0.81	4.70 $\pm$ 0.48
	Total N (g kg ⁻¹)	1.66 $\pm$ 0.07	1.62 $\pm$ 0.08	0.35 $\pm$ 0.05
	Total P (g kg ⁻¹)	1.15 $\pm$ 0.07	1.14 $\pm$ 0.06	0.45 $\pm$ 0.05
	Total K (g kg ⁻¹)	2.94 $\pm$ 0.15	2.93 $\pm$ 0.018	2.86 $\pm$ 0.06
	P–Bray I (g kg ⁻¹)	0.39 $\pm$ 0.02	0.30 $\pm$ 0.01	0.11 $\pm$ 0.01
	Ex–K (g kg ⁻¹)	0.31 $\pm$ 0.02	0.30 $\pm$ 0.01	0.15 $\pm$ 0.01
	CEC (cmol kg ⁻¹)	7.9 $\pm$ 0.2	7.8 $\pm$ 0.1	6.4 $\pm$ 0.3
	pH H ₂ O	6.4 $\pm$ 0.2	6.3 $\pm$ 0.1	5.8 $\pm$ 0.6

[†] Data sources: GEau (2009).

Initial soil organic C content was 12.92 ± 3.52 g C kg⁻¹ on average at Dogona, whereas at Kodení it was slightly higher but also more variable with depth (15.83 ± 9.64 g C kg⁻¹). In general, N, P (total and available) and K content at both sites were relatively high compared to the values generally reported for ferruginous soils (e.g. [Driessen et al., 2001](#)). The initial N, P, K, available phosphorus (P Bray I) and exchangeable potassium (Ex-K) content in the soil 0–30 cm depth were 1.48 ± 0.37 g N kg⁻¹, 0.97 ± 0.39 g P kg⁻¹, 2.40 ± 0.17 g K kg⁻¹, 0.22 ± 0.05 g P kg⁻¹ and 0.17 ± 0.08 g K kg⁻¹, respectively at Dogona and 1.21 ± 0.75 g N kg⁻¹, 0.91 ± 0.40 g P kg⁻¹, 2.91 ± 0.04 g K kg⁻¹, 0.27 ± 0.14 g P kg⁻¹ and 0.25 ± 0.09 g K kg⁻¹, respectively at Kodení ([Table 3.2](#)). The pH H₂O was slightly acid at both sites, with pH = 6.5 and 6.2 at Dogona and Kodení, respectively.

3.3. Experimental design and crop management

3.3.1. Experimental design

At each garden, the experiment followed a randomized design with 3 treatments (referred to as T100, T70 and T0) representing 3 fertilizer management strategies laid out as depicted in [Fig. 3.3](#). The T100 treatment represented the farmer's normal practice, meaning that the gardener applied fertilizers following his own decisions. In T70 plots, fertilizers were arbitrary reduced by 30 % of the amount of fertilizer applied in treatment T100. The T0 treatment corresponded to unfertilized plots. Neither manure nor N, P or K fertilizers were applied to the plots under T0 treatment at Dogona. But at Kodení, because yields declined rapidly in the T0 treatment, it was decided to apply fertilizer for the 3rd and 7th cycles at the same rate as for T100. The type and volume of irrigation water was the same in all treatments (gardener's practices).

Each treatment was replicated 6 times at Dogona and 4 times at Kodení. Individual plot size was 3.5 x 1 m² separated by a guard row of 0.5 m, which is the standard size of the beds made by farmers for vegetable cropping. Beds were 0.1 m high.

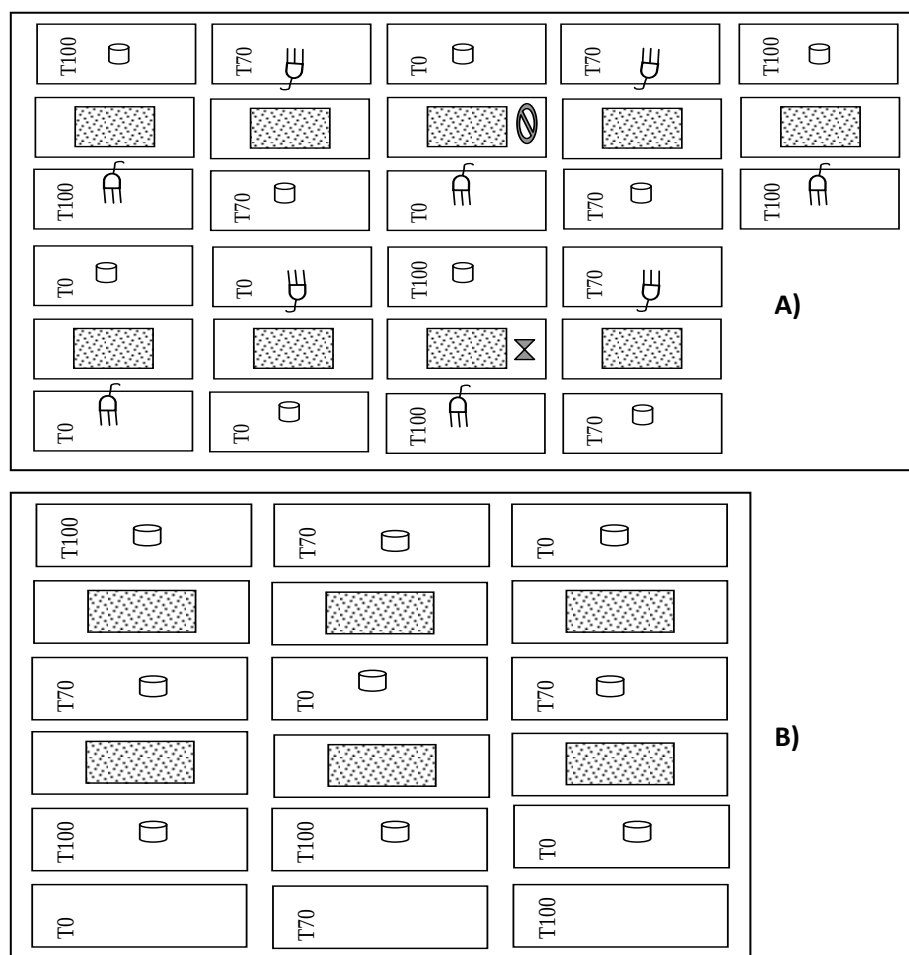
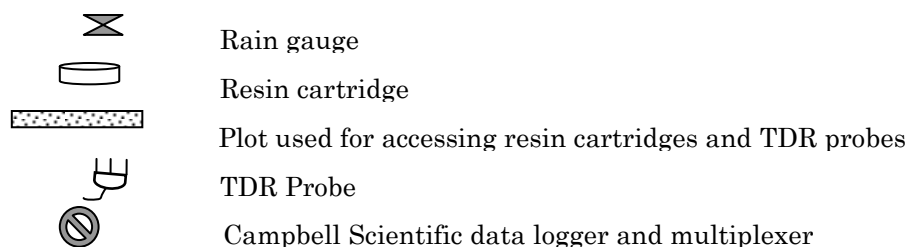


Figure 3.3. Layout of the field experiment at A) Dogona in 2009 (in 2008, the T0 treatment was not implemented); and B) at Kodení in 2009.



3.3.2. Crop management

All crop management practices are detailed in [Table 3.3](#). Different types of UA crops were monitored. Two complete crop rotations were monitored at Dogona over a period of 2 years. A 1-year rotation was composed of a succession of tomato, cabbage, lettuce and carrot. These crops were selected on the basis of their importance in terms of cultivated surface area and yields recorded at Bobo Dioulasso between 1997 and 2005 ([DGPSA 2006](#)) and because market demand for these products is high. Furthermore, the crop rotation that is generally practiced in this area includes these dominant vegetable crops. F1 seeds of tomato (*Lycopersicon esculentum* Mill. cv. Mongal), carrot (*Daucus carota* L. var. *sativa* L. cv. Touchon), butterhead lettuce (*Lactuca sativa* L. var. *capitata* L. cv. Divina) and white headed cabbage (*Brassica oleraceae* var. *capitata* cv. KK Cross) were cropped at Dogona.

A continuous rotation of lettuce was studied at Kodené over a period of one year. Continuous lettuce growth is common at this site and lettuce can be cropped continuously over a one-year period without significant adverse effects on yields ([Hamilton and Bernier 1976](#)). This also allowed focusing on seasonal variations of water and nutrient use, without interference from different crop species. Furthermore, lettuce is by far the most important leafy vegetable crop in terms of frequency in Bobo Dioulasso. At Kodené, the lettuce cultivar Divina was used for the 1st to 6th crop and Batavia for the 7th and 8th crop. This change in lettuce cultivar was caused by shortage of Batavia seeds on the local market.

All cultivar seeds were purchased from TECHNISEM® and were well adapted to tropical conditions. The reader may refer to [Rubatzky and Yamaguchi \(1997\)](#) and [Grubben and Denton \(2004\)](#) for detailed description of these species and cultivars. Tomato, cabbage and lettuce were sown and grown for 3–4 weeks on nursery beds without any fertilizer application prior to transplantation (at the 3- to 4-leaves stage) into the experimental plots, while

carrot seeds were directly broadcast onto the plots. Ploughing at both sites was exclusively done with hand tools, the maximum tillage depth not exceeding 15 cm. The planting densities were 7 plants m⁻² for tomato, 16 plants m⁻² for cabbage and 23 plants m⁻² for lettuce at Dogona and 35 plants m⁻² for lettuce at Koden. Given the sowing method of carrot, it was not possible to determine initial seedling density but the number of tubers at harvest was about 226 ± 72 tubers m⁻². About 1-week after transplanting, dead seedlings were replaced with fresh seedlings to obtain uniform stands.

The management of all raised beds as well as fertilization scheduling (Table 3.3) was fully decided by the gardeners. During the study period, both mineral and organic fertilizers were applied as 1 to 3 split applications by top-dressing (Table 3.3). The mineral fertilizers are mainly applied through urea and compound NPK. Generally manure or municipal urban waste combined with urea / NPK was applied within the first ten days after sowing or planting. When applicable, additional mineral or organic fertilizer was added approximately at the middle of the growth cycle or at the fruit or head initiations. Organic fertilizers were broadcast over the entire plot, whereas mineral fertilizers were side-dressed (placed at the side of plants). Fertilization was preceded or followed by manual hoeing and then followed by irrigation. Irrigation was performed by using watering cans. At Dogona, the gardener used a pump to bring water from the river into watering tanks before using cans.

All plots were manually weeded during the plant cycle. The non-selective herbicide Gramoxone®, whose active ingredient is *Paraquat (1, 1' dimethyl-4, 4' bipyridinium)* was used for weed control before the first cabbage cycle and the second lettuce cycle at Dogona. Depending on potential pest prevalence, pest controls were also performed once or twice during tomato, cabbage and carrot. *Profenofos + Cypermethrin* (Cypercal 50 EC®, Cigogne P 186 EC®) was diluted in water and sprayed on tomato, *Endosulfan + Cypermethrin* (Rocky C

386EC) was sprayed on cabbage. Carrot seeds and plots were treated with *Carbofuran* (Furadan) prior to sowing. No pest control was performed during lettuce at both sites.

Table 3.3. Summary of the chronology of crop management during the study period at the two sites

Site and Season	Species	Sowing / planting date	Fertilizer applications		Harvest date
			First application	Other applications	
Dogona (2008 –2009)	Tomato-1	25-04-08	07-05 NPK ^a	20-05 Urea ^b + NPK	10-08-08
	Cabbage-1	18-08-08	14-09 Urea + NPK ^c	29-09 PD [†] ; 20-10 Urea	13-11-08
	Carrot -1	23-11-08	24-12 CO ^{††}	–	10-02-09
	Lettuce-1	20-02-09	05-03 MW ^d	24-03 Urea + NPK	07-04-09
Dogona (2009–2010)	Tomato-2	24-04-09	24-05 Urea + NPK	–	04-07-09
	Lettuce-2	12-07-09	22-07 Urea + NPK	–	18-08-09
	Cabbage-2	21-08-09	19-09 Urea + NPK	22-09 FYM ^{†††}	30-10-09
	Carrot-2	05-11-09	16-11 NPK	–	08-02-10
Kodeni (2009 – 2010)	Lettuce-1	07-04-09	19-04 FYM ^e + Urea	03-05 Urea	06-05-09
	Lettuce-2	13-05-09	24-05 FYM + Urea	04-06 Urea	10-06-09
	Lettuce-3	15-06-09	26-06 FYM + Urea	–	14-07-09
	Lettuce-4	17-07-09	09-08 FYM + Urea	–	30-08-09
	Lettuce-5	05-09-09	21-09 MW	21-09 Urea + NPK	11-10-09
	Lettuce-6	13-10-09	25-10 FYM + NPK	09-11 Urea	23-11-09
	Lettuce-7	03-12-09	14-12 FYM + Urea	27-12 Urea	07-01-10
	Lettuce-8	09-01-10	20-01 Urea	01-02 FYM ; 08-02 Urea	24-02-10

^a NPK: Compound fertilizer composed of a mix of nitrogen, phosphorus and potassium with various formulations (14-23-14; 15-15-15), ^b Urea: commercial formulation with 46 % N; ^c a mix of NPK and urea; ^d MW: municipal solid waste; ^e various farm-yard manure of cattle and small ruminants and pig excreta. FYM: farm-yard manure, [†] Poultry droppings; ^{††} Compost of cattle manure + leaves from the garden; ^{†††} Cattle manure mixed to cotton residue. FYM at the site of Kodeni was a mix of cattle, sheep and goat manure.

3.4. Characterization of soil water dynamics

Assuming runoff to be negligible because of the relative weak slope (< 1.2 %) and repeated manual weeding which hampers crust formation, the following simplified water balance equation was considered for the top 30 cm of the soil for daily time intervals:

$$P + I = ET_c + D + \Delta S \quad (\text{Eq. 3.1})$$

where P (mm) is the cumulative rainfall; I (mm) is the cumulative amount of applied irrigation water; ET_c (mm) is the cumulative maximum crop evapotranspiration; D = drainage below the 30 cm rooting depth (mm). ΔS represent the change in soil water storage in the top 30 cm over a given time interval (1 day). All factors of this relation were directly measured or deduced following the methods described below.

3.4.1. Measurement of water input (rainfall, irrigation)

Rainfall (mm) was recorded with an automatic ARG100 tipping-bucket rain gauge (Campbell Scientific, Logan, Utah, USA) at 1 m above ground at Dogona and by a WatchDog tipping-bucket rain gauge (Model 115 of Spectrum Technologies Inc.) at same height for Kodení. The ARG100 was connected to a CR1000 data logger (Campbell Scientific, Logan, Utah, USA) and the WatchDog tipping-bucket was connected to a WatchDog data logger. Both rain gauges had a resolution of 0.2 mm tip⁻¹ and cumulative rainfall data were stored every 5 min.

Applied irrigation water was quantified twice a week by counting the number of applied watering cans applied per plot per day and weighing the water that each watering can holds. For the remaining days, the gardeners themselves were asked to register the number of cans applied per day. Then the total amount of water applied per week was estimated by multiplying the total number of cans applied per week by the mean volume of water of a

single can. The total irrigation during a cropping cycle was calculated from the quantity applied per week and the duration of the cropping cycle.

3.4.2. Measurement of water output (ETCrop, drainage)

The potential evapotranspiration of crop (ETCrop; mm) grown under optimal soil water and fertility conditions was derived from the Penman–Monteith/FAO ET₀ model (Eq. 3.2; [Allen et al., 1998](#)), by multiplying the potential evapotranspiration of a reference surface (ET₀) with crop coefficient (K_c) for a given crop and growth stage (Eq. 3.3).

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e^0 - e)}{\Delta + \gamma(1 + 0.34u_2)} \quad 3.2$$

$$ETCrop = k_c.ET_0 \quad 3.3$$

with ET₀ the reference evapotranspiration (mm d⁻¹), Δ the slope of the vapour pressure curve (kPa °C⁻¹), R_n the net radiation (MJ m⁻² d⁻¹), G the soil heat flux (MJ m⁻² d⁻¹), γ the psychrometric constant (kPa °C), T the dry temperature (°C), U₂ the wind speed measured at 2m height (m s⁻¹), e⁰ and e the saturated and the actual vapour pressure (kPa), respectively.

Throughout the cropping season, the plant growth (from emergence to maturity) was measured and the phenological stages and duration were noted. These different phenological stages and their durations have served to assign the values of K_c using the table given by Allen et al. (1998). The different K_c values used in this study are presented in [Table 3.4](#). Because it was assumed that crops did not suffer from water stress as crops were regularly irrigated twice a day, no water stress coefficients were applied to Eq. 3.3.

Table 3.4.: Time course of the crop Kc factor values

Crop type	Bare Soil	Initial Stage	Development Stage	Mid-Season Stage	Late-Season Stage
Tomato	1	0.85	1.05	1.05	0.60
Cabbage	1	0.70	1.05	1.05	0.95
Lettuce	1	0.70	1.00	1.00	0.90
Carrot	1	0.70	0.95	0.95	0.95

The Penman–Monteith/FAO model uses climatic variables such as dry and wet temperature, relative air humidity, solar radiation and wind speed. Therefore, the air temperature and air humidity were recorded at 5 min intervals using a HYGROMER® MP100A air temperature and relative humidity probe (Rotronic AG Instrument, Bassersdorf, Switzerland) at Dogona, and with a small weather station (HOBO PRO, Watchdog 2700, Onset Corp., Bourne, MA, USA) at Kodení. Other required daily weather data were collected from the Airport Meteorological Services (11° 10' N, - 4° 19' W, altitude: 460 m) located at approximately 5 km and 2 km from Dogona and Kodení, respectively.

Zero–tension pan lysimeters were used as a low cost and direct method for monitoring the free drainage (D) below the rooting depth (30 cm) (Weihermueller et al., 2007). Pan Lysimeters were adapted from that published by Van der Velde et al. (2005) (Fig. 3.5.). The seepage water was collected and quantified on a weekly basis or after each heavy rain events (< 20 mm). Some lysimeters were equipped with a tipping spoon gauge, which allowed recording of the drainage volume every 5 min.

3.4.3. Change in soil water storage (0 – 30 cm depth)

Change in soil water storage within the 0 – 30 cm depth was assessed on the basis of volumetric water content measurements made by Time Domain Reflectometry (TDR) (Kelleners et al., 2005). Because of logistical constraints, this could be done only at Dogona. Triple–rod TDR probes (CS610 probes of Campbell Scientific, Logan, Utah, USA) were horizontally

inserted into the soil. In 2008, probes were installed at 7.5; 15 and 30 cm depth. In 2009, due to the introduction of T0 treatment, it was decided to remove probes of the 15 cm depth in order to use them for this new treatment. The 7.5 cm probes were maintained as they record greater moisture fluctuations and the 30 cm probes were maintained as they correspond to the depth of installation of the lysimeters. TDR probes were inserted in 3 replications per treatment (total of 18 probes) adjacent to the plots used for embedding resin cartridges (Fig. 3.4).

Probes were connected to a TDR100 (Campbell Scientific, Logan, Utah, USA). Soil water content was measured every 5 min and automatically stored by a CR1000 data logger. The polynomial calibration relationship of Topp et al. (1980) was used to relate the measured bulk dielectric constant to the volumetric water content (m water m⁻³ soil). The TDR had been calibrated in order to analyze the reliability of the Topp relationship for our soils. The calibration curve, i.e., the relation between the apparent dielectric constant (Ka) and the soil water content ($\theta_{\text{Gravimetric}}$) achieved a R² of 0.92 and a Root Mean Square Error (RMSE) of 0.038.

Soil moisture data were not available from April 24, 2008 to August 18, 2008 due to equipment failure associated with wire damage. Therefore, during this period soil moisture data were determined gravimetrically as described further on in this section for Koden's site. Moreover, data were occasionally lost (< 12 h) as a result of some TDR probe malfunctions or battery failure.

Based on the TDR volumetric moisture content measurements, the soil water storage held within the soil profile between the soil surface and a given depth z can be calculated following Equation 3.4.

$$S = \int_0^z \theta(z) dz \quad (\text{Eq. 3.4})$$

Different integration techniques exist to calculate the soil water storage. In our study we used the trapezoidal method as follows:

$$S = \theta_1.z_1 + \sum_{i=2}^3 1/2(\theta_{i-1} + \theta_i).(z_{i-1} - z_i) \quad (3.5)$$

with θ_i = volumetric moisture content at depth i ($\text{cm}^3 \text{cm}^{-3}$); with $i=1$ for $z = 7.5$ cm, $i = 2$ for $z = 15$ cm (2008) or $z = 30$ cm (2009), and $i = 3$ for $z = 30$ cm (2008); z = depth of TDR probe (mm). Eq. 3.4 assumes moisture content to be constant in the top 7.5 cm.

In addition to TDR measurements at Dogona, changes in soil water storage were determined gravimetrically twice a week taking soil cores at three depths (0 – 7.5 cm, 7.5 – 15 cm and 15 – 30 cm). This was done from April 2009 to February 2010 only. Sampling was done twice a week at 3 locations per plot in all replications from April to September 2009 before irrigations, and in 3 replications from October 2009 to February 2010 before and after irrigations. Samples were immediately weighed and subsequently dried in an oven at 105° C for 24 h. At Kodení, water content was exclusively measured gravimetrically during the whole experiment following the same method as at Dogona.

Gravimetric water content was converted to volumetric water content using the soil bulk density data (Table 3.2.) determined from undisturbed soil core samples taken in the middle of the 0 – 7.5 cm, 7.5 – 15 cm and 15 – 30 cm layers at harvest (Eq. 3.6). Soil bulk density in each layer was determined following Dane and Topp (2002). Soil bulk density was determined as the ratio of the dry weight of the soil to the bulk volume of the soil. Water storage within the 0 – 30 cm soil profile was calculated from Equation 3.7.

$$\theta_i = w \times \frac{\rho_b}{\rho_w} \quad (3.6)$$

$$S = \sum_{i=1}^3 \theta_i . z_i \quad (3.7)$$

where θ_i = volumetric moisture content of layer i ($\text{cm}^3 \text{cm}^{-3}$); with $I = 1$ for $z = 0 - 7.5$ cm, $i = 2$ for $z = 7.5 - 15$ cm and $i = 3$ for $z = 15 - 30$ cm; ρ_b is the bulk density of the soil (g cm^{-3}); ρ_w is the density of water (1 g cm^{-3}); w is gravimetric moisture content (g g^{-1}); S = Soil water storage (mm) and z = thickness of soil layer (mm). At Dogona, these volumetric water content data were used to compare and calibrate the TDR data.

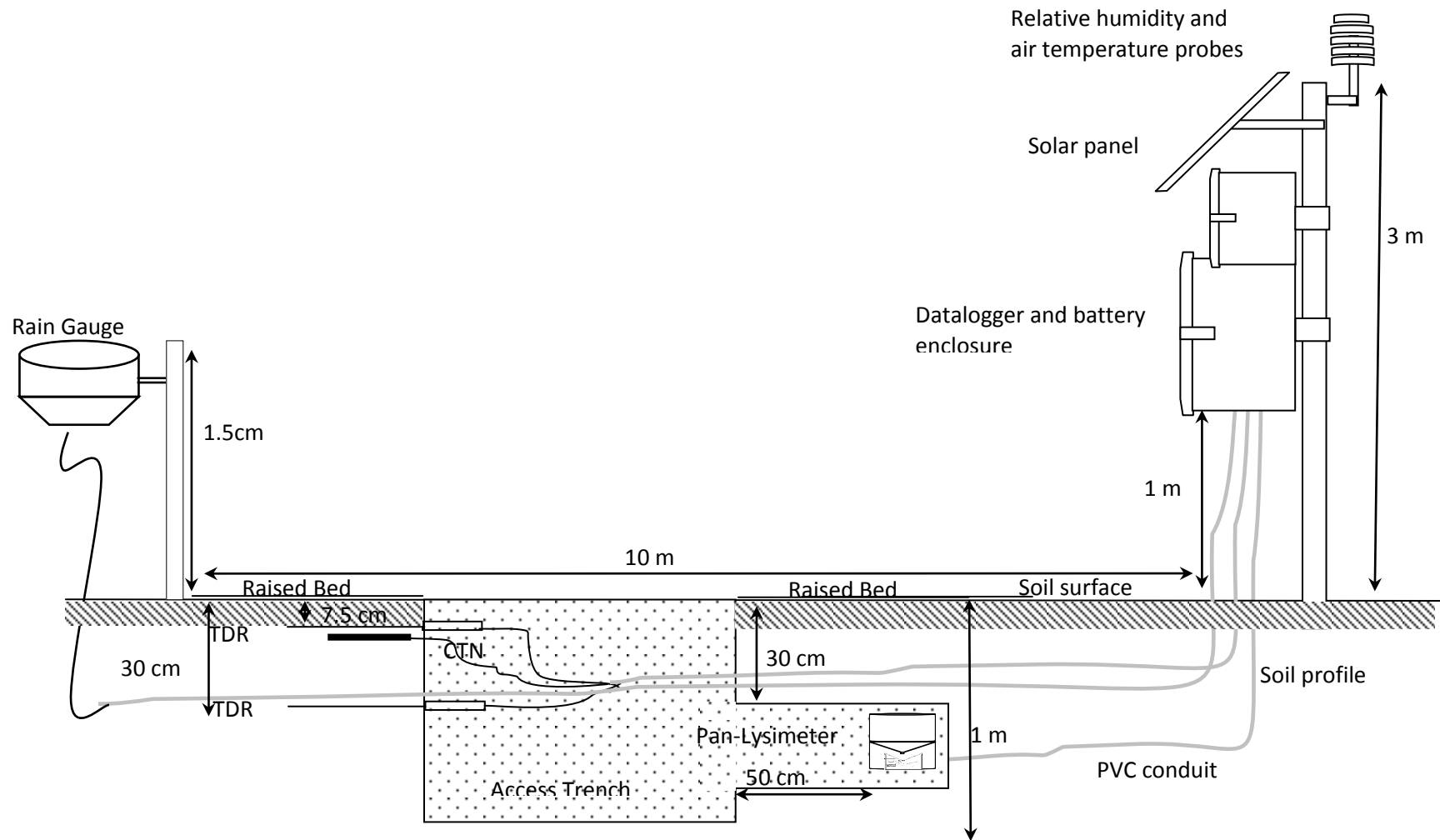


Figure 3.4. Detailed cross sectional view of the experimental equipment for the monitoring of water balance en nutrient leaching at Dogona

3.5. Crop growth and yield

3.5.1. Plant growth and development

Growth and development from emergence to ripening stages were recorded every week on 10 representative plants per pot, taken from the two central rows of each plot. Plant height measurements were made, twice a week, by measuring plant height and leave dimensions with a ruler. For tomato, cabbage and lettuce, plant growth dynamics were assessed by measuring plant height (H) from soil surface to the tip of the highest leaf. During the whole elongation stage, five representative leaves (of varying sizes and fully expanded) per plant were measured to determine the length (L) of the main vein without leafstalk and the width (W) of widest part of the leaf. Empirical regressions were used to estimate the actual individual leaf area (LA) based on linear measurements of leaf length and width (independent variables). The linear relationships used here exhibited high accuracy and precision in estimating the individual leaf area of cabbage ($R^2 = 0.95$; [Olfati et al. 2010](#)), lettuce ($R^2 = 0.97$; [Yoshida et al., 1997](#)) and tomato ($R^2 = 0.98$; [Blanco and Folegatti, 2003](#)).

For the 3 crops, leaf appearance dynamics were also recorded by counting twice a week the total number of leaves. The total leaf area (m^2) of individual plants was estimated by multiplying the mean area of measured individual leaves by the total number of leaves of each plant. These data allowed computing the leaf area index (LAI; m^2m^{-2}) dynamics by dividing the total leaf area of each plant by the area of the soil occupied by a single plant ([Koller and Upadhyaya, 2005](#)). The area occupied by one plant was obtained by dividing the area of the plot by the number of plants therein.

For carrot, which has highly dissected leaves, the above procedure could not be applied. Hence, the “Point Quadrat method” ([Jonckheere et al., 2004](#)) was applied to monitor both plant growth and total leaf area. The LA was estimated by the modified vertical Point Quadrat relationship of [Groeneveld \(1997\)](#). The method consists of piercing the leaf canopy with a

long thin (3 mm diameter) graduated (in cm) steel needle (“Point Quadrat”) under known elevation and azimuth angles and counting the number of contacts of the point quadrat with plant canopy elements. The needle was pushed vertically (90°) at regular 0.05 m intervals along a horizontal transect 3.5 m long, through the leaf canopy. The total numbers of leaf contacts, as well as the number of non-contacts and the height of touching, were recorded. At least 2 transects were done per plot.

3.5.2. Yield measurements

All harvested fresh biomass (leaves, storage organs and stems) was separately weighed at harvest time, bed by bed, by sampling and weighing all material removed from two or three 1m² areas per bed, depending on crop type. The yield of a single bed was then obtained by multiplying the mean yield of the 2 – 3 replicate sampling areas by the total plot area, and expressed in kg ha⁻¹. Samples were pooled per bed for a given crop.

3.6. Design and installation soil solute flux measurement methods

3.6. 1. Ion exchange resin (IER)

The Ion Exchange Resin (IER) method was used to monitor soil nutrient leaching ([Lehmann et al. 2001](#)). The technology relies on the chemical interaction between reactive entities to form stable bonds between a sorption material and a functional group possessing negative/positive charges ([Xu et al., 2011](#)).

For this study, PVC cartridges (10 cm high and 12 cm inner-diameter, with a nylon mesh at the bottom) were filled with a mixture of sand + Na-saturated cation exchange resins, and Cl-saturated anion exchange resin ([Amberjet™, ROHM and HAAS Company, 2007, Philadelphia, PA, USA](#)) at a ratio of 2:1:1, respectively. The total weight of mixture by cartridge was 1 kg and was inserted beneath the plots at 30 cm soil depth. Before use, the

IER was thoroughly washed once with deionised water (Fernandez and Warren, 1996; Lehmann et al., 2001). The main characteristics of the resins are listed in Table 3.5.

Table 3.5. Technical properties of the anion and cation exchange resins

Characteristics	Anion exchange resin	Cation exchange resin
Resin name	Amberjet™ 4200 Cl	Amberjet™ 1200 Na
Producer description	Strong basic anion exchanger	Strong acid cation exchanger
Matrix	Styrene divinylbenzene copolymer	
Functional group	Trimethyl ammonium (– N ⁺ (CH ₃) ₃)	Sulfonate (– SO ₃ [–])
Ionic – form	Cl [–]	Na ⁺
Shipping weight	670 g l ^{–1}	850 g l ^{–1}
Total exchange capacity	≥ 1.30 eq l ^{–1} (Cl [–] form)	≥ 2.0 eq l ^{–1} (Na ⁺ form)
Moisture holding capacity	49 to 55 % (Cl [–] form)	43 to 47 % (Na ⁺ form)
Specific gravity	1.06 to 1.08 (Cl [–] form)	1.2 to 1.30 (Na ⁺ form)
Particle size		
Uniformity Coefficient	≤1.25	≤1.2
Mean grains size	600 to 800 µm	620 ± 50 µm
Fines content	< 0.425 mm	< 0.300 mm

Source: Rohm & Haas (2007), Frankfurt Main, Germany

These resin types have been previously shown to satisfactorily remove the targeted nutrients from soil solution (Lehmann et al., 2001; Predotova et al., 2010; Siegfried et al., 2011). Five mixed-bed IER cartridges (12.5 cm inner diameter and 10 cm height) were placed in three replications per treatment, for a total of 45 cartridges per site before the onset of the experiment. For the installation of cartridges in each replication, three adjacent plots were selected according to the guidelines of TerrAquat Consultancy (Stuttgart, Germany), the patent holder of this method. A 1-m deep trench was dug in the plot in between the two other plots.

At Dogona, TDR probes were installed in one side of the trench and cartridges were laterally embedded in the same trench but on the opposite side from the TDR probes (Fig. 3.4., 3.5a.). A lateral hole was excavated at the 30 cm depth in the trench wall until the middle of the targeted plot. Therefore, the overlying soil was undisturbed. At Kodení, resin cartridges

were installed on the two sides of the tranches, given the fact that no TDR was used at this site (Fig. 3.3.b). During installation, the cartridges were gently pressed into the lateral hole and held in place by filling the volume underneath the cartridge with sand (Lehmann et al., 2001). After installation, the horizontal tunnels were tightly backfilled with the same sand and subsequently the trenches were closed. Plots were, thereafter, cultivated over a period of 12 months and cartridges were unearthed after this period. The subsequent extraction of nutrients from the exchange resins in the laboratory allowed estimation of nutrient fluxes.

3.6.2. Soil solute collection methods

The resins are suited for estimating the cumulative amount of nutrients leached during one full rotation, but not for monitoring the temporal dynamics and concentration of leached solution (Lehmann et al., 2001; Lang and Kaupenjohann, 2004). For monitoring the year-round water and nutrient flux dynamics, the above-mentioned pan lysimeters were used. The greatest advantage of these devices is the possibility of simultaneously measuring water and solute fluxes and study the chemical composition of leachate (Jemison and Fox, 1992; Zhu et al., 2002).

Three methods were used as pictured in Fig. 3.5.: 1) resin cartridge with solute flux meter (IERC + SSF), further referred to as SSF; 2) resin cartridge with soil solute sampler (IERC + SSS_r) further referred to as SSS_r; and 3) sand-filled cartridge with solute sampler (Sand + SSS_s) further referred to as SSS_s. The SSF consisted in a calibrated (which a sensitivity of 5 ml tip⁻¹, equivalent to a resolution of 0.44 mm tip⁻¹) plastic tipping spoon-gauge (Rain-O-Matic, Pronamic® Co. Ltd, Sikeborg, Denmark) that continuously monitored the drainage flux at the bottom of the cartridges (measurement accuracy with maximum deviation of $\pm 2\%$). The total number of tips measured was stored at 5-min time intervals by the CR1000 datalogger via an 8 channel SDM-SW8A switch Closure Input module (Campbell Scientific Inc., Logan, Utah, USA). SSS consisted of a simple PVC

container housed at the bottom of the resin cartridges and was intended for periodical sampling of the soil solution which percolated through the resin. A hand vacuum pump was connected to the container via flexible polyethylene tubing (Fig 3.5). The goal was to determine the drainage volume and the effect of the cartridge filling material (sand or sand/resin mixture) on the nutrient concentration. For SSS_r , the objective was also to determine the effectiveness of the resins to capture all incoming ions.

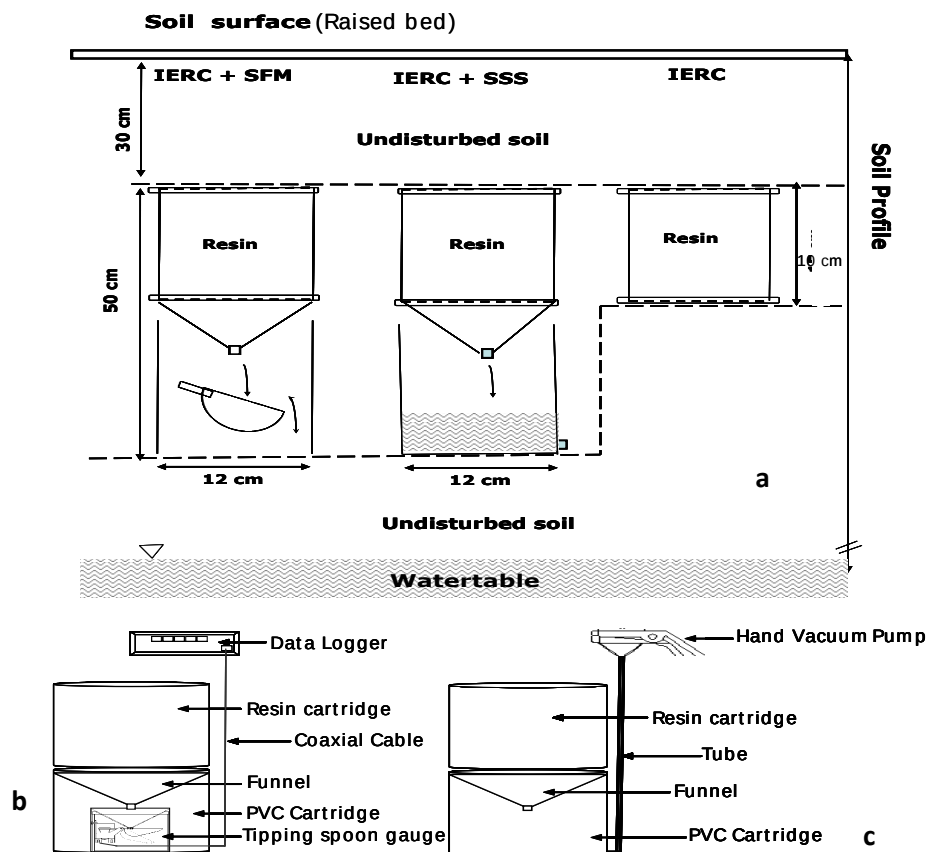


Figure 3.5. a) Schematic cross section of the design and installation of the devices used for nutrient leaching measurement in the soil. IERC: Ion Exchange Resin Cartridge. All devices correspond to non-suction lysimeters; b) Matter fluxes (water and nutrient) can be continuously measured with the solute flux meter (SSF) by means of tipping-spoon gauges; c) Soil solution samples are extracted from soil solute sampling (SSS) devices, which are filled with pure sand (SSS_s) or with a mixture of sand and IER (SSS_r).

All three devices were installed at Dogona, whereas only SSS_r and SSS_s were placed at Koden, again because of logistical constraints. Duplicates of each device (SSS_r and SSS_s) were installed in 3 replications (2 x 2 x 3) per treatment at each site. Leachates accumulated at the bottom of SSS_r and SSS_s (of ~1 liter capacity) were extracted on a weekly-basis during the entire season or after every heavy rainfall event (≥ 20 mm), whichever occurred first, using a hand operated vacuum pump. Total leachate volume was determined using a graduated bottle (Nalge Nunc International Rochester, NY). Thereafter sub-samples (100 ml) were immediately acidified with 0.1 M HCl and deep-frozen until chemical analysis. The amount of leached nutrients for a given collection period was calculated from the product of the drainage volume and the nutrient concentration.

During the period of frequent solute sampling, leachate sub-samples from a given week were pooled based on their corresponding total sample volumes (volume-weighted average) before analysis. For the remainder of the data collection period, leaching losses for each plot were determined as the product of the weekly average nutrient concentration and the respective weekly drainage volume. In case of low leachate volumes (< 10 ml), the volume were recorded but analyses could not be performed due to insufficient sample volume.

Flow-weighted average ion concentrations over multiple sampling events for multiple samplers within the same treatment were computed as:

$$C_t = \frac{\sum_{t=1}^N \sum_{i=1}^{n_t} C_{i,t} V_{i,t}}{\sum_{t=1}^N \sum_{i=1}^{n_t} V_{i,t}} \quad (3.6)$$

with C_t the flow-weighted mean concentration (mg l^{-1}) over N sampling events and n_t SSS devices, $C_{i,t}$ is the concentration (mg l^{-1}) measured by SSS sampler i during event t , and $V_{i,t}$ is the volume (ml) of leachate measured by SSS sampler i during event t .

The cumulative mass flux of ions over multiple sampling events averaged over multiple samplers was computed as:

$$M = \frac{\sum_{t=1}^N \frac{1}{n_t} \left(\sum_{i=1}^{n_t} C_{i,t} V_{i,t} \right)}{A} \quad (3.7)$$

with M the cumulative mass flux (mg cm^{-2}); A is the surface area of SSS (113.04 cm^2) and N is the number of sampling events.

3.7. Soil, plant, water and fertilizer sampling

Organic and mineral fertilizers inputs were quantified throughout the cropping cycle each time they were applied by weighing the amounts applied in each plot. Organic fertilizer sub-samples were collected, air-dried until constant weight and used to determine the effective dry matter applied. Subsamples (100 g) were ground to 2 mm particle size and stored before analysis.

Total nutrient input through irrigation water was obtained by multiplying irrigation volume by the mean nutrient concentration in the water over a given period. Samples of irrigation water were collected twice a week throughout the year. Because it was assumed that water quality during the dry season remained fairly constant, water samples from the dry season were pooled on a monthly basis (by taking into account the amount applied per event). Samples from the rainy season were pooled on a weekly basis. All samples were stored in a freezer before analysis.

Per replication, one representative sub-sample of harvested plants (stem, leaves and fruits) was air-dried until constant weight, ground in a mill and passed through a 2 mm sieve and a thoroughly mixed 10 g portion of each sample was stored until further analyses of their total C, N, P and K contents. Nutrient exports through plant uptake were determined by multiplying the total dry matter weight of plants tissues by the corresponding C, N, P and K concentration. A complete description of all analysis procedures is provided in the section 3.8.2.

Soil samples were collected in each replicate before the experiment, after each crop cycle and at the end of the study periods at 3 depths (i.e., 0–7.5; 7.5–15 and 15–30 cm) with a hand-auger. Samples from the onset and the end of the trial were analyzed for each replicate and depth separately, whereas those from the end of each crop cycle were pooled (v:v) for budgetary reasons, giving one composite sample for the layer 0–30 cm per replication. All soil samples were air-dried within a few hours after sampling, crushed and passed through a 2 mm sieve.

3.8. Chemicals analyses

3.8.1. Ions extraction from resin and chemical analyses

Each resin cartridge was separated into four equally thick layers of about 2.5 cm each from which the adsorbed nutrient were extracted in the laboratory (Fig. 3.6). All layers were weighed, labelled and stored at 4°C until analysis. Sub-samples (5 ± 0.5 g) from each layer were used for dry weight determination (65 °C for 24h).

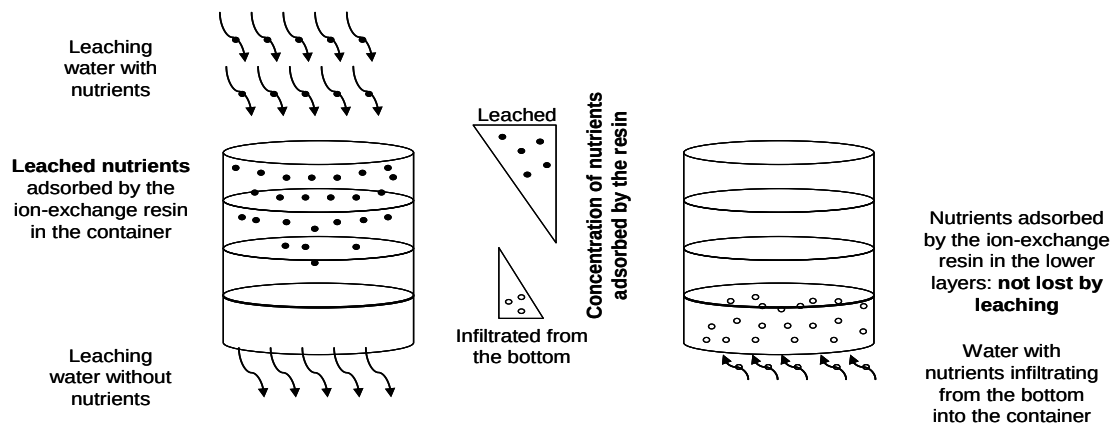


Figure 3.6: Functional diagram of ion adsorption by the resin cartridges (after [Predotova et al., 2010](#))

For ion extraction, about 30 g of the resin mixture of each layer was placed in a 250 ml plastic bottle, and horizontally shaken for 1 h in 100 ml

of 0.5 M NaCl as extractant (purity > 99.8 %) to displace nutrients from the IER into the extract. The extract was passed through an ashless filter and poured into glass jar and the left resin–sand mixture was washed again with the same 0.5 M NaCl. This extraction process was repeated 8 times with the same subsample. The first four extractions were mixed together and about 25 ml subsamples taken and frozen until analysis. The 5th and 6th extractions were also mixed as well as the last 7th and 8th, subsamples were subsequently also collected and frozen.

The K, PO₄, SO₄, Fe, Mg, Mn, Al, Ca and SiO₄ in the solution were analyzed with inductively coupled-plasma Spectrometer (ICP, Model Spectro–Flame, Spectro Analytical Instruments GmbH & Co. KG, Germany; [Heinrichs 1989](#)), whereas NO₃–N was analyzed spectrophotometrically according to a modified Chromotropic acid method ([West and Ramachandran, 1966](#)). A calibrated UNICAM 8625 UV–visible spectrophotometer (Unicam Analytical System, Cambridge, U.K.) was used for the determination of NO₃–N at a maximum absorbance of 410 nm after elimination of critical interferences due to oxidizing agents, nitrite, chloride and iron with solutions of Natrium Sulfite (Na₂SO₄), Urea and Antimony (Sb) in presence of concentrated Sulfuric acid (H₂SO₄), respectively. This method can mask up to 2000 mg Cl l⁻¹ ([West and Ramachandran, 1966](#)), while Cl concentration in our samples after dilution was ≤ 1800 mg l⁻¹. Analysis of the samples from the second year was confined to NO₃–N because NH₄⁺N from the previous year constituted < 10% of the total mineral N content of the resins. Three samples of the sand used in the resin mixture were also extracted following the same procedure. The data from the analysis of pure anion– and cation–exchange resins have been used as blanks to correct for potential initial contamination of the resins ([Predotova et al, 2010](#)).

The total resin–derived nutrient mass was computed from the exact weight of each layer and the nutrient concentration therein after subtracting the nutrient mass contained in the blank resin and the blank sand ([Lehmann et al., 2001](#)). The retrieved total masses of elements from

each layer were then normalized by the cross-sectional area of the resin cartridge to give the cumulative solute fluxes in mg / m² (Weihermueller et al., 2007).

3.8.2. Prerequisites to estimate resin– based element fluxes

The separation into layers allowed assessment of possible saturation of the resins cores by checking the nutrient concentration profile for each cartridge (Bischoff et al., 1999; Weihermueller et al., 2007). The concentration profile was also used to check for possible disturbance of the resin core (Lehmann et al., 2001) or a contamination of the bottom layer due to capillary rise or temporary water logging (Fig. 3.6).

For the analysis, the nutrient concentration gradient of each cartridge was examined in order to determine the suitability of data from each cartridge. Data from a given cartridge was retained if a consistent decrease in nutrient concentration with depth was observed and / or if a “zero layer” existed, i.e., a layer with negligible nutrient content. Because the bottom layer concentration of a substantial number of cartridges presented much larger concentration than the overlying layer, suggesting contaminations from capillary rise, it was decided to only consider the three upper–most layers of all cartridges for greater consistency. Such treatments of resin layers have been commonly performed in several previous studies (e.g. Lehmann et al., 2001; Predotova et al., 2010; Siegfried et al., 2011).

3.8.3. Soil, plant, fertilizer and organic matter analyses

All soil, plant, fertilizer and water analyses were performed at the ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) laboratory at Sadoré (Niger). Regarding chemical analysis, soils samples from the outset and the end of each complete rotation were analysed for pH, cation exchange capacity (CEC), total carbon (C), nitrogen (N), phosphorus (P) and potassium (K), exchangeable bases (EB) and available phosphorus

(P Bray I). The other soil samples, i.e., those sampled at the end of each crop cycle within a given rotation, were analysed only for pH, CEC, EB and P Bray I, because of financial constraints.

Soil particle size was determined following [Gee and Orr \(2002\)](#) after wet oxidation of organic matter with H_2O_2 , followed by dispersion with Calgon solution (NaPO_3)₆. Sieving was performed for the particles with size $> 50 \mu\text{m}$ (sand) and the pipette method (Stokes law) was used for particles $< 50 \mu\text{m}$ (silt and clay fraction).

Soil $\text{pH}_{\text{H}_2\text{O}}$ was determined in a mixture of 1:2.5 soils: distilled water volumetric ratios using a glass electrode pH meter. Electrical conductivity (EC) of soil/water suspensions was measured electrical conductivity meter in a mixture 1:2.5 soil: distilled water volumetric ratio.

Organic carbon content in soil, plant and organic amendments was determined by the wet chemical digestion procedure of [Walkley and Black \(1934\)](#) by wet oxidation of the organic matter (OM) with a mix of H_2SO_4 and $\text{K}_2\text{Cr}_2\text{O}_7$ and titration of the remaining $\text{K}_2\text{Cr}_2\text{O}_7$ with ferrous sulphate.

The CEC and EB of soils were measured by the silver–thiourea (AgTU) method based on extraction (4h shaking) of a soil sample with an unbuffered 0.01M solution of AgTU at the prevailing soil pH. This method is thought reliable for CEC estimation in Ferric Lixisols ([Oorts *et al.*, 2003](#)). CEC–Ag is determined by measuring residual silver in the solution using an atomic absorption spectrophotometer (AAS). Exchangeable Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry, while Na^+ and K^+ were determined using flame emission photometry. Available P (P–Bray I) in soils was determined colorimetrically according to [Bray and Kurtz \(1945\)](#) method based on the phosphomolybdate complex and using ascorbic acid as reductant after extraction with HCl 0.25N and NH_4F 0.03 N. This method is suitable for the available P determination on weakly acid soils of West Africa ([Bationo *et al.*, 1991](#)).

Before total N, P and K determination, soil, manure and plant samples were digested with H_2SO_4 + salicylic acid + H_2O_2 + selenium. Total P was determined colorimetrically based on the phosphomolybdate complex

method of [Lowry and Lopez \(1946\)](#) again using ascorbic acid as reductant. The total N was detected also colorimetrically using the Bertholet reaction ([Chaney and Marbach 1962](#)) with an N–autoanalyzer (TECHNICON AAI, Ontario, Canada) at 630 nm. K in plant and organic amendments was determined by flame emission spectroscopy (Varian ICP–OES, Varian Inc., Palo Alto, California). The total N, P and K concentrations in irrigation water and drainage water were measured as for total soil N, P and K following prior digestion with H_2SO_4 + salicylic acid + H_2O_2 + selenium.

Detailed description concerning analysis methods of organic carbon, pH, CEC, and exchangeable bases are given in [van Reeuwijk \(1993\)](#), whereas, the total N, P and K extraction procedure are described by [Houba *et al.* \(1995\)](#).

3.9. Monitoring of soil nutrient fluxes and plot–scale mass balance calculation

Establishing nutrient balances provides insight into the flows of nutrients over one or more cropping cycle and is a first step in designing efficient fertilizer advice system. We adopted the so called *Soil System Budget* approach ([Oenema *et al.*, 2003](#)) to study the fate of nutrient in our study gardens. This approach expresses the net change in soil nutrients stocks (surplus or deficit) by summing all inputs and outputs of nutrients for a predefined spatial–temporal scale and soil boundaries (Eq 3.7.; [FAO, 2003](#)).

$$\Delta S_i = IN_i - OUT_i \quad (3.7)$$

where ΔS_i , IN_i and OUT_i stand for the nutrient balance (change in nutrient stocks), the total input and the total output of element i , respectively. All the terms were expressed in $\text{kg ha}^{-1}\text{year}^{-1}$.

Only nutrients derived from organic and mineral fertilizers and irrigation water were recorded as inputs as they constitute the major sources of nutrients entering in these systems ([Smaling *et al.*, 1996](#); [FAO,](#)

2005; Titonell et al., 2006). The other potential sources of inputs (atmospheric rainout and fallout, N fixation) are difficult to quantify accurately under field conditions (Dilkes et al. 2004), and it was assumed that their contribution may be negligible compared to the aforementioned sources (FAO, 2005).

It was also assumed that losses by wind erosion are negligible as the soil was maintained wet (through one or two irrigations per day) for most of the year. Moreover, dissolved nutrient losses through runoff was not accounted for as plots were located on a relatively flat site and were frequently tilled for weeding and /or fully covered by a dense vegetation, which restricts surface sealing and allows fast water infiltration. As a consequence, nutrient exports through crop uptakes were considered as the major process by which nutrients leave the system. The other losses were considered to occur through leaching and gaseous emissions. Losses through gaseous emissions have been measured in a companion study by M. Lompo J. P. Desiré. The reader is referred to Lompo's thesis (Lompo, 2012) for further details regarding the measurements of gaseous emissions.

By taking into account these components for each element i , the plot-based balance can then be written as follows:

$$\Delta S_i = (\text{FERT}_i + \text{IRR}_i) - (\text{HARV}_i + \text{LEACH}_i + \text{GAS}_i) \quad (3.8)$$

In this relation, i stands for each considered element (N, P or K); ΔS is the net change in the soil nutrient stock; FERT: nutrient input through organic and/or mineral fertilizers; IRR: input through irrigation water; HARV: nutrient export through harvested products and crop residues; LEACH: leaching losses; GAS: gaseous emissions of nitrogen (NH_3 and N_2O). All data was expressed in $\text{kg ha}^{-1} \text{ year}^{-1}$.

Nutrient fluxes (input and output) were calculated following Eq. 3.9.

$$F_i = \sum_{j=1}^n Q_{i,j} C_{i,j} \quad (3.9)$$

with F_i being total nutrient flow (input or output) for element i over the period of measurement; n : the number of input or output events; $Q_{i,j}$: the oven-dry mass of raw material i at event j ; $C_{i,j}$: nutrient concentration in the raw material i at event j .

Soil carbon stocks (C_s ; kg C ha⁻¹) up to 30 cm depth were calculated following [Batjes \(1996\)](#):

$$C_s = 10^4 \cdot \sum_{i=1}^3 \rho_i C_i Z_i (1 - S_{2mm,i}) \quad (3.10)$$

where ρ_i is the soil bulk density (kg m⁻³) of layer i , C_i is the organic carbon concentration (kg kg⁻¹), Z_i is the thickness (m) of the layer i , and S_{2mm} is the relative proportion of the fraction of particles ≥ 2 mm in this layer. The factor 10^4 converts m² to ha.

Stocks in soil total N, P and K (kg ha⁻¹) were computed in a similar way. Subsequently, variations in soil nutrient stocks were computed as the difference between stocks from the end minus stocks from the onset of each cropping year.

3.10. Quantifying water (WUE) and nutrient use efficiency (NUE) at garden scale

At plot level, the water use efficiency (Gibberd et al., 2003; Lovelli et al., 2007) was calculated as the ratio between total saleable biomass produced at harvest (kg ha⁻¹) and total water applied to each crops (mm).

$$WUE = Y / (RAIN + IRR) \quad (3.11)$$

where Y (kg ha⁻¹) refers to fresh matter yield of the saleable parts (part of economic interest e.g., fruit, leaves or tuber); RAI+IRR (mm) is the total amount of water supplied during the cropping cycle through irrigation and rainfall.

A set of simples indices, frequently used in agronomic research to assess the efficiency of applied fertilizer (Cassman et al., 2002), have been implemented to evaluate the short-term crop nutrient use efficiency under field conditions. The partial factor productivity (PFP) that emphasizes crop response (yield) to each applied nutrient (N, P and K) is the broadest index used for measuring field scale NUE (Olk et al, 1999; Dobermann, 2007). In the case of nitrogen PFP_N (kg kg⁻¹):

$$PFP_N = Y / N \quad (3.12)$$

where Y refers to fresh or dry yields of the plant parts of economical interest (kg ha⁻¹); N (kg ha⁻¹) is the amount of nitrogen input during each cropping cycle. The PFP of P and K are calculated similarly.

PFP is an aggregate efficiency index that includes the contributions to crop yield of nutrients taken up by the plants which were initially present in the soil or supplied through additional fertilizer input, nutrient uptake efficiency, and the efficiency with which nutrients acquired by the plants are converted to yield (Cassman et al., 1996). Hence, PFP may be a useful

indicator of fertilizer use efficiency and strategies for maintaining maximum vegetable yields and help promote reduction of applied fertilizers.

3.11. Soils physical and hydrodynamic properties: the water retention curve

The sand box and pressure chamber apparatus allows determination of the retention curve (Dane and Hopmans, 2002). Water retention curves were determined on core samples collected in 100 cm³ Kopecky rings. The soil cores were collected at both sites at the onset of the field experiment at three depths (0–7.5 cm, 7.5–15 cm and 15–30 cm) and five replications per depth. Samples have then been saturated during 5 days prior to the experiment. Then water contained in the soil samples was submitted to increasing suction (pF 0 to pF 4.2) during periods between 5 and 7 days for each step. Retention values between –1 and –70 cm suction were obtained from undisturbed soil cores with the hanging water column method using the sand– and kaolin boxes apparatus (Eijkelkamp agri–equipment, Giesbeek, the Netherlands). For higher suctions, pressure chambers were used (Soil Moisture Equipment, Santa Barbara, CA). For pressure potentials between –0.1 and –1 bar, retention values were obtained using undisturbed sample cores whereas for pressure between 3.1 bar to 15.8 bar, disturbed subsamples of 20 cm³ were used.

The water retention function of Van Genuchten (1980) was fitted to the desorption data:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha|h|)^n\right]^m}$$

3.15

where θ_r and θ_s are the residual and the saturated soil water content, respectively (cm³ cm⁻³), h is the soil pressure head (cm), and a , n and $m=1-1/n$ are parameters obtained by fitting Eq. 3.15 to measured water retention data.

Table 3.6.: Summary of measurements by site

Activities	Data Recorded	Equipement and measurements scheduling	
		Dogona (2008-2010)	Kodeni (2009-2010)
Input	Irrigation	- Weighing cans twice a week - Counting the number of cans every day	- Weighing cans twice a week - Counting the number of cans every day
	Rainfall	ARG 100; data recorded every 5 mn	Spectrum 115 ; data recorded every 5 mn
Soil water profile	Soil moisture content (0-7.5cm; 7.5-15cm; 15-30cm)	- 18 TDR probes; data recorded every 5 mn - Gravimetric method twice a day and twice a week	- Gravimetric method twice a day and twice a week
Meteorological data	Relative Humidity	MP100; data recorded every 15 mn	HOB0 Pro ; data recorded every 15 mn
	Air temperature	MP100; data recorded every 15 mn	HOB0 Pro; data recorded every 15 mn
	Other Climate data	Meteorological service	Meteorological station
Nutrient Leaching	Resins	45 cartridges	45 cartridges
	SSF	2 per replication	-
	SSS	2 per replication	2 per replication
	Total Soil salinity	18 TDR probes + 4 Thermocouples	-
Crop Management	Cropping systems	Rotation of Tomato-cabbage-lettuce-carrot	Continuous lettuce
	Fertilization practices	Monitored at each event	Monitored at each event
	Pesticides	During tomato	-
Crop data	Plant growth	Measured twice a week during the two years	Measured twice a week during one years
	Yields	Monitored at the end of each cropping cycle	Monitored at the end of each cropping cycle
	Root profile	Monitored at the end of each cropping cycle	Monitored at the end of each cropping cycle
Samples for laboratory analysis	Soils	Before and after each cropping cycle	Before and after each cropping cycle
	Plants	Samples of each replication and each cycle	Samples of each replication and each cycle
	Irrigation water	Collected twice a week	Collected twice a week
	Soil solute	Sampled one a week and after heavy rainfall	Sampled one a week and after heavy rainfall
	Fertilizer samples	Sampled at each fertilization event	Sampled at each fertilization event

Chapter 4

Field-scale analysis of water and nutrient use efficiency for vegetable production in a West African urban agricultural system⁴

Abstract

Urban agriculture increasingly supplies food and non-food services to the rapidly growing West African cities. However, with its typically heavy use of fertilizers and uncontrolled use of water, it bears severe risks of soil and groundwater pollution. This study was carried out in Bobo Dioulasso (Burkina Faso, West Africa) at two commercial gardening sites. It aimed at performing a detailed characterization of farmer's water and nutrient management strategies. Four vegetable crops were monitored (tomato, cabbage, carrot and lettuce). Water inputs (rainfall and irrigation), nutrient inputs (organic and mineral fertilizers and nutrients in irrigation water) and crop uptake were monitored over a 1–2-year period. In addition, pan lysimeters allowed monitoring drainage. Depending on the site, 3–8% of the input water was lost by drainage, i.e., as much as 259 mm/year at one of the sites. During the dry season, when the farmer has full control over the water supply, water application exceeded plant requirements by as much as 40%, which reveals inefficient water use. Up to 800 kg N ha⁻¹, 140 kg P ha⁻¹

⁴ Adapted from: Sangare, S. K., Compaore, E., Buerkert, A., Vanclooster, M., Sedogo, M.P., Biélders L. C. 2012. Field-scale analysis of water and nutrient use efficiency for vegetable production in a West African urban agricultural system. *Nutr Cycl Agroecosyst.* 92:207–224.

and 500 kg K ha⁻¹ were applied for a single crop cycle. With few exceptions, crops tended to be strongly over-fertilized, except for K at one of the two sites. Nutrient supply exceeded crop requirements by 109 to 2,012 kg N, 66 to 450 kg P and 0 to 393 kg K per year. These results, in combination with the large observed rates of drainage, are indicative of a high risk of nutrient leaching and groundwater contamination. The partial factor productivity of nutrients tended to be low. These results therefore suggest that there is scope to substantially reduce nutrient application rates in these systems without adverse effects on yields, which would be beneficial for groundwater resources and improve the economic returns.

Keywords: Urban agricultural systems; Resources management; Water and nutrient use Efficiency; West Africa.

4.1. Introduction

Very high application rates of nutrient and water in vegetable production systems, leading to large positive nutrient surpluses, have been widely referred to in the scientific literature ([Zhu et al. 2005](#); [Khai et al. 2007](#); [Thompson et al. 2007](#)). In Hanoi (Southeast Asia), [Khai et al. \(2007\)](#) have reported an annual surplus of 85 to 882 kg N ha⁻¹, 109 to 196 kg P ha⁻¹ and 20 to 306 kg K ha⁻¹ for small-scale peri-urban vegetable farming systems. In southeast Spain, [Thompson et al. \(2007\)](#) have shown that irrigation water used for vegetable production often exceeded 150 % of crop water requirement. Equally high inputs have been observed in some West African countries such as Benin, Ghana and Niger ([Drechsel et al. 2004](#); [Graefe et al. 2008](#); [Diogo et al. 2010](#)). For instance, excessive fertilizer applications have led to an annual positive nutrient balance of 843 kg N ha⁻¹, 70 kg P ha⁻¹ and 200 kg K ha⁻¹ in urban and peri-urban agricultural (UPA) systems in Niamey, Niger ([Diogo et al. 2010](#)).

The positive nutrient balance observed in urban vegetable production systems is in sharp contrast with the low inputs and the negative N, P and

K balances that generally prevail in West African rural cropping systems, and in particular in Burkina Faso (Stoorvogel et al. 1993; Lesschen et al. 2007). The tendency towards positive nutrient balances in UPA systems has been attributed to their income-generating and market-oriented nature which allows investments in inputs (Drechsel and Dongus 2010). In addition, urban vegetable cropping benefits from the widespread availability of urban wastes as alternative sources of nutrients (De Bon et al. 2009; Kiba et al. 2011). However, such positive nutrient balances suggest low nutrient use efficiency in UPA systems, which may reflect unnecessary economic losses. This may also lead to negative environmental externalities such as groundwater pollution by leached nutrients (e.g. Predotova et al. 2011). For instance, as part of an evaluation of gardeners' irrigation and fertilizer management practices for an onion crop in an on-station trial, Tamini and Mermoud (2002) measured leaching of $17.6 \pm 7.5 \text{ kg NO}_3\text{-N ha}^{-1}$ through a loamy soil over a 3.5-month period in Ouagadougou (Burkina Faso) following the application of 35 t ha^{-1} of bovine manure and 83 kg ha^{-1} of mineral N, with an average irrigation rate of 8 mm day^{-1} .

Besides nutrient use efficiency, water use efficiency (WUE) is also an important issue for vegetable production in arid and semi-arid countries, where rainfall is a limiting factor yet water resources for irrigation are lacking or diminishing. Low WUE due to excessive water application would reflect poor management of this scarce resource, but may also increase the risk of nutrient losses by leaching. Competition for water resources between urban centres and UPA irrigation is becoming a growing concern and further justifies looking into the WUE of vegetable production. As a matter of fact, the shortage of fresh water has stimulated the use of alternative, low quality water resources such as sewage water (Van der Hoek et al. 2002). For instance, Kinané et al. (2008) estimated that one third of households involved in urban agriculture in Bobo Dioulasso (Burkina Faso) use waste water for vegetable crop production. Although this may indeed alleviate the pressure on fresh water resources, the nutrient content of waste water is not necessarily taken into account by vegetable growers, generally by lack of

knowledge (Keraïta and Drechsel 2002). For instance, Sou (2009) showed that untreated waste water in Ouagadougou may supply annually up to 300, 100 and 200 % of the N, P and K required for eggplant (*Solanum melongena*) production, respectively. This may further exacerbate the nutrient imbalance and the risk of groundwater contamination by leached solutes as well as contribute to soil and food contamination by pathogens (Qadir et al. 2010) or heavy metals (Abdu et al. 2011).

While there are strong indications of inadequate nutrient use in urban cropping systems in Burkina Faso, and despite the obvious economic and environmental implications, very little, if any, reliable data exist on the extent of the problem. So far, studies that have dealt with water and nutrient management and use efficiencies in West African vegetable production systems are still very limited, and most of them have been either qualitative or based on on-station trials (Tamini and Mermoud 2002; Eaton and Hilhorst 2003; Mermoud et al. 2005; Akponikpè et al. 2011) which may not be representative of UPA vegetable gardens. Most of the aforementioned studies were also restricted to only part of the year, even though vegetable cropping is a year-round activity and climatic variables that govern crop growth, evapotranspiration and leaching present seasonality. Hence, continuous studies over at least one year are essential to get a complete picture of gardener's management practices and water and nutrient efficiency in vegetable cropping systems.

The shortage of information regarding garden-level water and nutrient use efficiency in vegetable cropping systems in African cities hampers the development of strategies for better matching water and nutrient supply with crop requirements, reducing the negative externalities and increasing its profitability (Drechsel et al. 1999). Therefore, this study aimed at quantifying in detail farmer's water and nutrient (N, P, K) management practices for selected crops and urban vegetable gardens, in view of evaluating water and nutrient use efficiency. The study was performed in Bobo Dioulasso (Burkina Faso). To our knowledge, this is the first study in West Africa and especially in Burkina Faso based on 2-years

of continuous monitoring. Moreover, all previous studies in Burkina Faso were conducted in Ouagadougou, whereas the region of Bobo Dioulasso may be more sensitive to the problem of nutrient leaching because of its 50% higher annual rainfall.

4.2. Materials and methods

4.2.1. The related dataset

This chapter is based on the gardener's water and nutrient management practices (treatment T100) as described in Chapter 3. It makes use of the dataset regarding the gardener's water application rates described in section 3.4.1 as well as the rainfall data and the weather station needed to compute the crop evapotranspiration (see detailed description in section data 3.4.2). Zero-tension pan lysimeters were used for monitoring free drainage (see 3.4.1 and 3.5.2). In the present study, no distinction is made between the lysimeter types, as the collection system is identical and only weekly cumulative data are reported. Because the amount of seepage water collected from the lysimeters showed very high variability (CV = 118 %), seepage water collected from additional raised beds was used to better estimate the mean drainage rate. These additional raised beds corresponded to plots with reduced levels of fertilization which are not representative of farmer's practices and hence are not discussed here. Prior to pooling the data, it was checked through an ANOVA that there was no effect of the reduced fertilization rate on the drainage rate, irrespective of the season (and crop). In total, 18 lysimeters of each type were used to estimate the weekly drainage rate at each site. Data relative to fertilizer application, plant developpement stage, plant height, leaf area and fresh and dry matter yield are described in 3.4.4. All plant, fertilizer and water samples were analyzed as described in section 3.7.3. The efficiency of gardeners' irrigation and fertilization practices was evaluated by means of the agronomic indices described in section 3.9.

4.2.2. Statistical analysis

All data were analysed using SAS® 9.2 software (SAS Institute Inc., Cary, North Carolina, USA). Data distribution was described using univariate descriptive statistics. When applicable, linear regression analysis was performed to test the relationship between variables.

4.3. Results

4.3.1. Climate features

As expected in this region, rainfall varied markedly over the 2 years of experimentation (Fig. 4.1). Total rainfall recorded during the study period was representative of the 1967 – 2007 long-term annual average (1028 ± 167 mm; mean $\pm$ SD). A total of 81 and 89 rainy days (≥ 0.2 mm) were recorded during 2008 and 2009, respectively. Fifteen and thirteen days had rainfall events exceeding 20 mm during 2008 and 2009, respectively, most of them occurring between July and September.

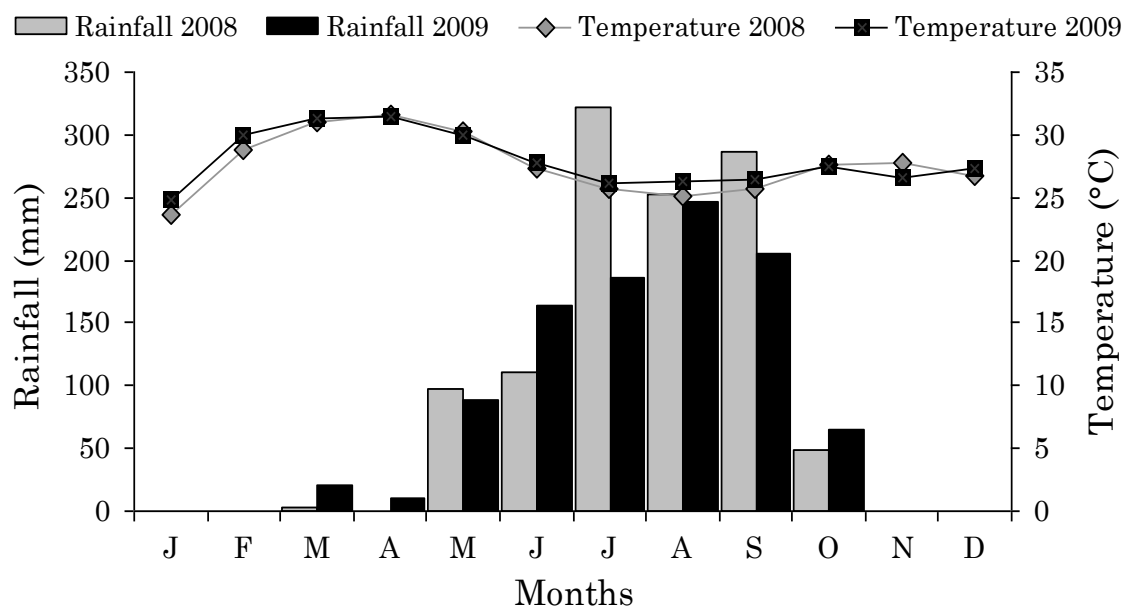


Figure 4.1. Cumulative monthly rainfall and average temperature during 2008 and 2009 at Bobo Dioulasso (Burkina Faso).

Monthly rainfall reached maximum values in July (321 mm) in 2008 and in August (246 mm) during 2009. Mean monthly maximum and minimum temperatures were 31.6 ± 1.6 °C and 23.6 ± 1.7 °C (mean $\pm$ SD). Air temperature occasionally dropped to 19 °C, whereas the daily maximum reached 35 °C during the hottest months (March–April).

4.3.2. Crop water balance

At Dogona, on average 43 mm and 35 mm of rainfall were recorded per week between May and October 2008 and 2009, respectively (Fig. 4.2). At Kodení, this amount was about 36 mm per week over the same period in 2009. As weekly rainfall fluctuated greatly during the rainy seasons, additional irrigation was applied by gardeners to mitigate the water deficit, especially at the onset and towards the end of the rainy season, but also during rain-free periods. Hence, 20 mm and 24 mm of irrigation water were applied on average per week at Dogona during the 2008 and 2009 rainy seasons, respectively (Fig. 4.2). The farmer at Kodení tended to apply more water: he applied on average 44 mm of irrigation water per week during the rainy season.

During the dry season, crop water supply relied exclusively on irrigation. Thus at Dogona, 35 mm and 40 mm of irrigation water per week were provided on average to crops during this period in 2008 and 2009, respectively. At Kodení, 90 mm of irrigation were applied per week on average during the dry season, twice the amount applied at Dogona.

Crop evapotranspiration (ETCrop) showed seasonality at both sites (Fig. 4.2). It was lowest during the second half of the rainy season, coinciding with low temperatures (Fig. 4.1) and high relative humidity. During the cold dry season (November to February), despite somewhat lower temperatures, ETCrop was high because of the low relative humidity (< 50 %). During the hot dry season from March till the start of the rainy season (June–July), the rise in temperature compensated for the rise in relative humidity in maintaining high ETCrop values. The average weekly

ETCrop at Dogona was about 34 mm during the rainy season (June–October) and up to 60 mm during the dry season. At Kodení it was about 35 mm / week during the rainy season, but reached 55 mm per week during the dry season.

In general, the amount of water supplied (irrigation + rainfall) amply satisfied the crop evapotranspiration needs during the rainy season at both sites (Fig. 4.2). During the dry season, however, ETCrop was about 15 % higher than the irrigation water supply at Dogona, whereas at Kodení the quantity of irrigation water applied was on average 40% higher than ETCrop.

Free drainage below 30 cm depth was observed at Dogona exclusively during the rainy season, whereas at Kodení some drainage occurred also during the cold dry season from November to February (Fig. 4.2). Drainage started around mid–June, early–July each year. The total cumulative drainage volume collected at Dogona was on average 102 mm and 113 mm during the first and second rotation, respectively, which represented 3 % and 5 % of the total water input. At Kodení the total drainage water amounted to 260 mm during the 1–year cropping season, i.e., 7 % of the total water input.

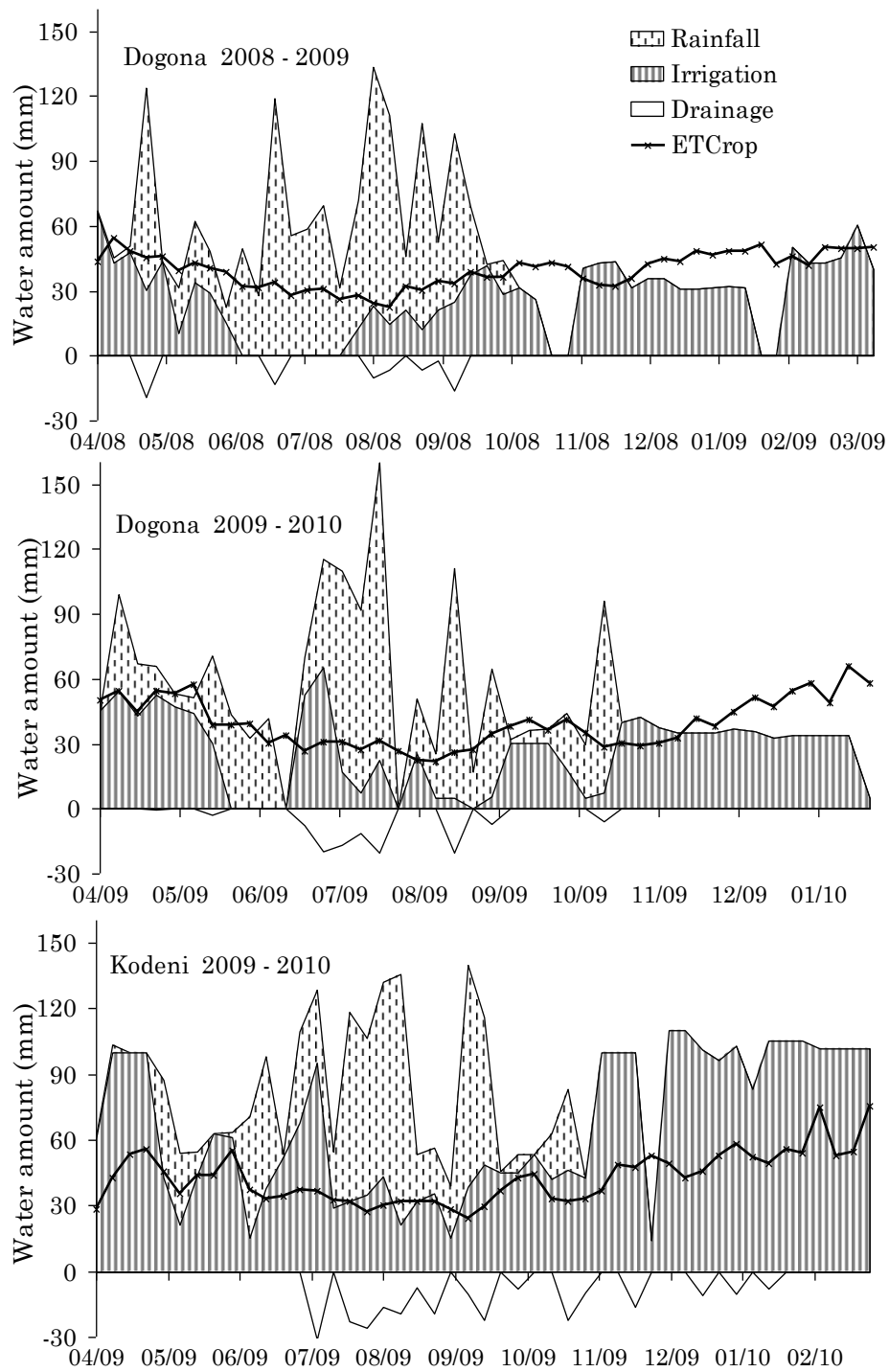


Figure 4.2. Weekly water fluxes (irrigation, rainfall, crop maximum evapotranspiration and drainage) at Dogona (2 years) and Koden (1 year). Irrigation and rainfall values are cumulated.

At both sites, no drainage was observed when the difference between the weekly amount of applied water and ETCrop was < 18 mm (Fig. 4.3). At Dogona, drainage was positively correlated with the amount of water input ($R^2 = 0.42$). At Koden, even though there was also a general tendency towards increasing drainage as water input in excess of ETCrop increased, there was no correlation between the variables (Fig. 4.3.B). Overall, peaks in drainage rates generally coincided with high rainfall periods (Fig. 4.2). Much higher amounts of weekly cumulative drainage volumes were recorded either during the rainy season in between two successive crops when the soil was left bare, or coincided with the early development stages of lettuce when plant transpiration was still low.

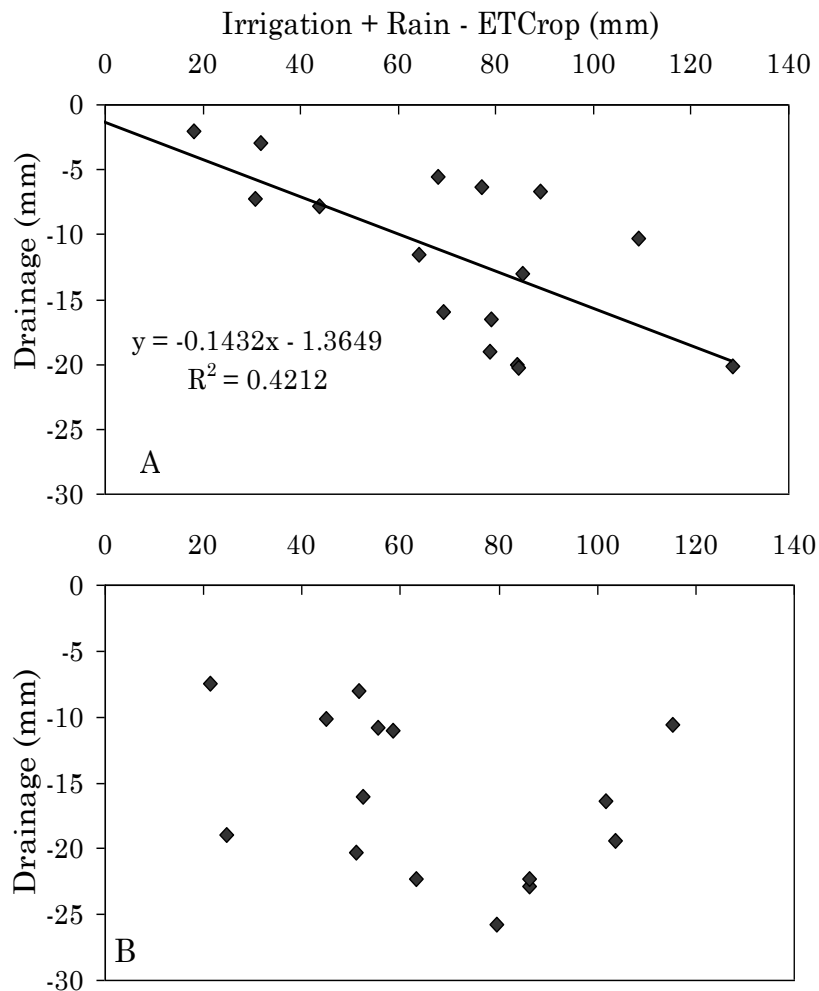


Figure 4.3. Relationship between weekly drainage and the difference between input water (rainfall + irrigation) and ETCrop, A) during the 2–years at Dogona and B) during the 1–year continuous lettuce at Koden.

4.3.3. Crop yields and water use efficiency

At Dogona, average marketable yields recorded over the two years were 43, 51, 36 and 48 t ha⁻¹ for fresh matter (FM) and 1.9, 16, 2.8 and 8 t ha⁻¹ for dry matter (DM) of tomato, cabbage, lettuce and carrot, respectively ([Table 4.1](#)). At Kodení, the average yield of lettuce across the 8 cycles was 49.9 ± 16.1 t FM ha⁻¹ and 4.5 ± 1.2 t DM ha⁻¹. The strong yield increase observed during the 7 and 8th lettuce cycle at Kodení was due to a change in the variety used by the farmer, which was caused by a shortage of seeds of the same variety on the local market.

At Dogona, WUE (FM basis) varied, between 56 ± 15 and 124 ± 12 kg ha⁻¹ mm⁻¹ depending on the crop cycle. The greatest WUE values were registered for carrots and cabbage. Lettuce-2 yielded the lowest WUE values but it rivalled with other crops on a fresh matter basis. The low WUE values often coincided with high rainfall periods, such as for tomato-1, cabbage-1, tomato-2 and lettuce-2. At Kodení, WUE (FM basis) varied between 52 ± 6 and 186 ± 14 kg ha⁻¹ mm⁻¹. The lowest WUE was recorded for the lettuce-4 which was grown during the peak of the rainy season at Kodení. The highest WUE efficiency was observed for the high yielding lettuce variety grown during the 7th cycle, yet similarly high WUEs were also achieved during the 2nd and 3rd cycles when a lower yielding variety was grown yet rainfall and irrigation were limited.

Table 4.1. Water input (Irrigation and Rainfall), marketable fresh matter (FM) and dry matter (DM) yields (mean $\pm$ SD) and water use efficiency (WUE) for fresh matter (WUE_{FM}) and dry matter (WUE_{DM})

Site and Season	Species	Water input (mm)		Yield (kg ha ⁻¹)		WUE _{FM}	WUE _{DM}
		Irrig.	Rain	F M	D M	(kg ha ⁻¹ mm ⁻¹)	
Dogona (2008 –2009)	Tomato–1	320	573	57942 $\pm$ 13553	2642 $\pm$ 618	65 $\pm$ 15	0.6 $\pm$ 0.1
	Cabbage–1	298	558	49357 $\pm$ 5066	15152 $\pm$ 2673	58 $\pm$ 6	18 $\pm$ 3
	Carrot–1	406	0	50200 $\pm$ 4832	10370 $\pm$ 1679	124 $\pm$ 12	26 $\pm$ 4
	Lettuce–1	302	27	35580 $\pm$ 8477	2455 $\pm$ 1024	108 $\pm$ 26	7 $\pm$ 3
Dogona (2009 –2010)	Tomato–2	317	180	28007 $\pm$ 7322	2455 $\pm$ 334	56 $\pm$ 15	0.5 $\pm$ 0.3
	Lettuce–2	175	402	36580 $\pm$ 4575	3080 $\pm$ 460	75 $\pm$ 8	5 $\pm$ 0.8
	Cabbage–2	155	294	51914 $\pm$ 5969	16956 $\pm$ 1799	116 $\pm$ 13	38 $\pm$ 4
	Carrot–2	482	0	45816 $\pm$ 3330	5994 $\pm$ 485	95 $\pm$ 7	12 $\pm$ 1
Kodeni (2009 –2010)	Lettuce–1	346	38	38344 $\pm$ 6471	3470 $\pm$ 308	100 $\pm$ 17	9 $\pm$ 0.8
	Lettuce–2	175	104	46625 $\pm$ 3750	4830 $\pm$ 220	167 $\pm$ 13	17 $\pm$ 0.8
	Lettuce–3	212	29	44500 $\pm$ 5582	3910 $\pm$ 920	185 $\pm$ 23	16 $\pm$ 3.8
	Lettuce–4	184	538	37750 $\pm$ 4573	3330 $\pm$ 450	52 $\pm$ 6	5 $\pm$ 0.6
	Lettuce–5	194	85	38750 $\pm$ 6062	3890 $\pm$ 650	139 $\pm$ 22	14 $\pm$ 2.3
	Lettuce–6	359	80	42057 $\pm$ 4452	3904 $\pm$ 435	96 $\pm$ 10	9 $\pm$ 1
	Lettuce–7	412	0	76700 $\pm$ 5858	5940 $\pm$ 316	186 $\pm$ 14	14 $\pm$ 0.8
	Lettuce–8	598	0	74333 $\pm$ 2081	6589 $\pm$ 430	124 $\pm$ 3	11 $\pm$ 0.7

4.3.4. Soil fertility management practices and nutrient supply

A wide range of amendments was used by the gardeners to enhance soil fertility, namely urban solid waste, animal manure, compost, urea and compound mineral fertilizers (NPK) of various formulations (Table 4.2). Application rates were highly variable depending on the crop, site and amendment used, but regardless of season. Organic and mineral fertilizers were systematically combined for each lettuce cycle at Kodení.

Table 4.2. Type and rate of organic (dry weight) and inorganic fertilizers applied at both sites.

Site and Season	Species	NPK	Urea	NPK + Urea [†]	Manure	Solid Waste
kg ha ⁻¹						
Dogona (2008 – 2009)	Tomato–1	980	–	765	–	–
	Cabbage–1	†–	875	877	7309	–
	Carrot–1	–	–	–	12930	–
	Lettuce–1	–	–	538	–	75858
Dogona (2009 – 2010)	Tomato–2	–	–	920	–	–
	Lettuce–2	–	–	1468	–	–
	Cabbage–2	–	–	1086	9777	–
	Carrot–2	897	–	–	–	–
Kodení (2009 – 2010)	Lettuce–1	–	450	–	22500	–
	Lettuce–2	–	424	–	19458	–
	Lettuce–3	–	426	–	39866	–
	Lettuce–4	–	446	–	29200	–
	Lettuce–5	–	–	437	–	44101
	Lettuce–6	629	425	–	19440	–
	Lettuce–7	830	–	–	19400	–
	Lettuce–8	–	511	–	21000	–

[†] NPK and Urea were mixed and applied together. ^{††} Not applied.

The average application rate of manure at Dogona was 2– to 3–fold lower than at Kodení. Sorted municipal wastes were used only once at both locations, but at very high rates. Up to three different types of amendments were used for a single crop cycle such as in cabbage–1 at Dogona (Table 4.2). The combination of NPK with urea was the most common practice at

Dogona, whereas at Kodení, urea was by far the most used mineral fertilizer.

Mixing of compound NPK fertilizer with urea resulted in a dilution of P and K concentrations and in a high variability in N concentrations as attested by the high SD values in Table 4.3. Organic amendments were characterized by a lower nutrient concentration than mineral fertilizers. Farm yard ruminant manure contained about 2 and 4 times more P and N than solid waste, respectively. Poultry manure was richer and contained 2 to 10 times more N, P and K than the other organic amendments.

Table 4.3. Average carbone (C), nitrogen (N), phosphorus (P) and potassium (K) content of organic and mineral fertilizers applied to garden plots at Kodení or Dogona (Mean $\pm$ SD). n= number of samples analyzed, which corresponds to the number of inputs during the study period.

Type	Source	n	C	N	P	K	C/N
					(%)		
Manure	Poultry	1	15.2	2.3	1.5	2.7	6.6
	Ruminant	9	9.0 $\pm$ 3.4	1.0 $\pm$ 0.3	0.3 $\pm$ 0.1	1.7 $\pm$ 0.4	8.6 $\pm$ 1.6
Waste	Solid Waste	2	2.54	0.28	0.15	0.58	9.5
Mineral	Urea	12	–	47.5 $\pm$ 1.4	–	–	–
	NPK	3	–	14.3 $\pm$ 1.7	5.93 $\pm$ 2.14	13 $\pm$ 4.0	–
	NPK+ Urea	7	–	28.3 $\pm$ 12.7	5.37 $\pm$ 1.25	6.57 $\pm$ 0.9	–

Overall, N concentrations in the irrigation water were fairly constant and ranged between 5 and 10 mg total N l⁻¹, except at Kodení during the rainy season when very large fluctuations were observed in the well water and the mean concentration was about 3 times higher than during the dry season (Fig. 4.4 A and B). Total phosphorus concentrations were generally low, below 0.3 mg P l⁻¹, the highest values being observed in the river water at Dogona during the dry season (Fig. 4.4 C). There was no seasonal effect on P concentration in well water (Fig. 4.4 D) or on K concentration in river water (Fig. 4.4 E). In well water at Kodení total K concentrations were on average 3 times lower than in river water at Dogona. For well water there

was also a seasonal effect on K concentrations, with total K being about twice as high in the rainy season compared to the dry season.

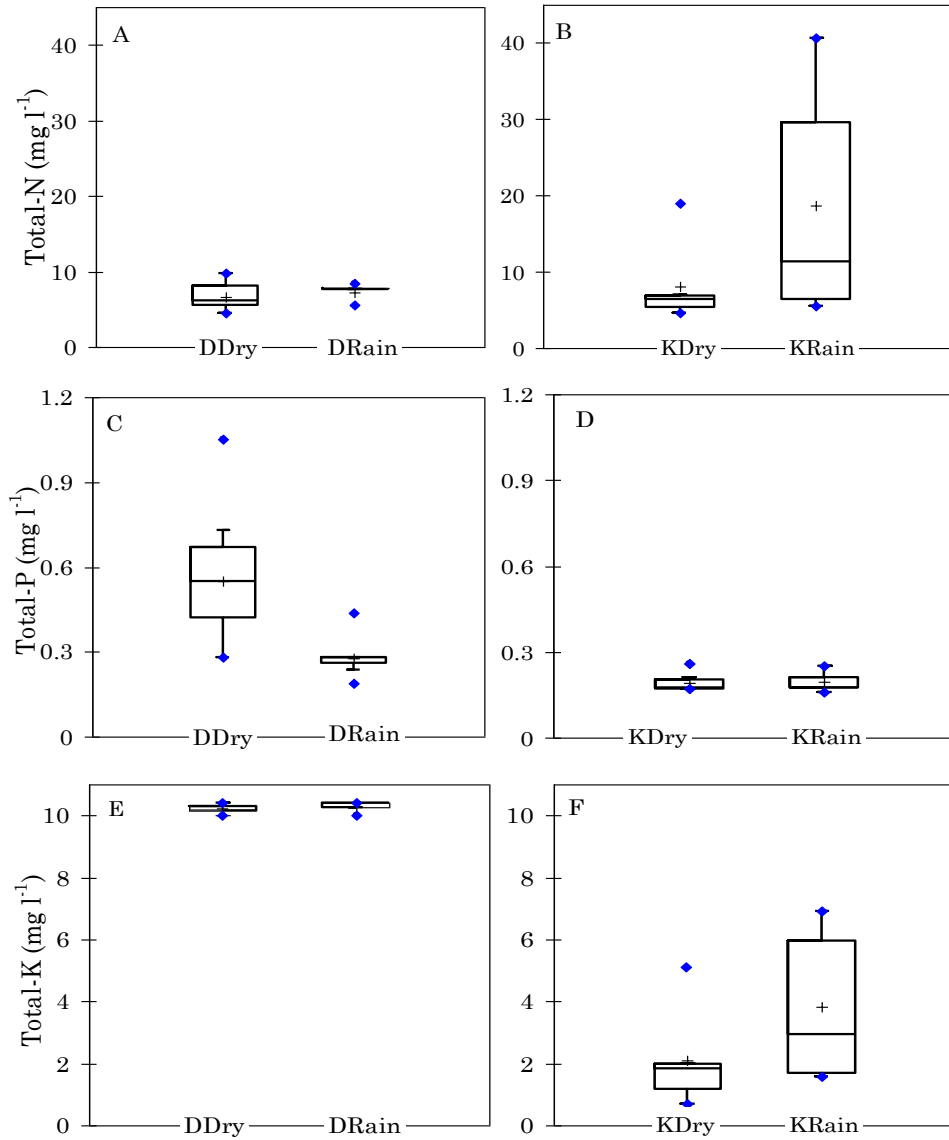


Figure 4.4.: Box and whisker plots of the total N, P and K (mg l^{-1}) concentration in river water during the dry season (DDry) and rainy season (DRain) at Dogona (A, C, E), and in well water during dry season (KDry) and rainy season (KRain) at Kodeni (B, D, F). The horizontal line represents the median, the cross represents the mean, the box covers the region from the 25th and 75th percentiles, whiskers delineate the 5th and 95th percentiles, min and max values are plotted with a $\blacklozenge$.

The total amounts of N, P and K applied per crop were calculated based on water and fertilizer application rates (Table 4.2) and their nutrient concentrations (Table 4.3; Fig. 4.5). Mineral fertilization appears to be the cornerstone of the soil fertility management strategies at Dogona as far as N and P are concerned, though not for all crop cycles (Fig. 4.5 A, C and D and Table 4.4). Based on the total nutrient input through organic and / or mineral fertilizers and irrigation water, the nutrients were applied at a rate equivalent to 416 ± 223 kg N ha⁻¹, 88 ± 48 kg P ha⁻¹ and 230 ± 138 kg K ha⁻¹ per crop cycle averaged over the two years. Over the two years, mineral fertilizers supplied 75%, 57% and 33% of all N, P and K inputs, respectively. At this site, the total annual amount of N applied was similar in both years, yet for the same crop, the rates varied widely across the two years. Annual P and K amounts were 40 and 60% lower in the second year compared to the first year. Overall, organic amendments supplied 20%, 42% and 53 % of the total N, P, and K, respectively, over the 2 years. Irrigation water from the Houet river supplied in total 166 kg N ha⁻¹, 12 kg P ha⁻¹ and 253 kg K ha⁻¹ during the two years of experimentation at Dogona, which represented 5%, 1% and 14 % of the total N, P and K applied to crops, respectively.

As opposed to Dogona, fertilization at Kodení relied heavily on organic amendments, especially regarding P and K (Fig. 4.5 B, D and F and Table 4.4). Overall, organic amendments supplied 49%, 83% and 90% of the total N, P, and K, respectively. Each lettuce cycle received on average 437 ± 102 kg N ha⁻¹, 92 ± 31 kg P ha⁻¹ and 409 ± 52 kg K ha⁻¹. Well water at Kodení provided more N (247 kg N ha⁻¹) in a single year than river water during the two years at Dogona (169 kg N ha⁻¹). Nutrient supply by well water accounted for 7 %, 1% and 2 % of the total N, P and K input at Kodení, respectively.

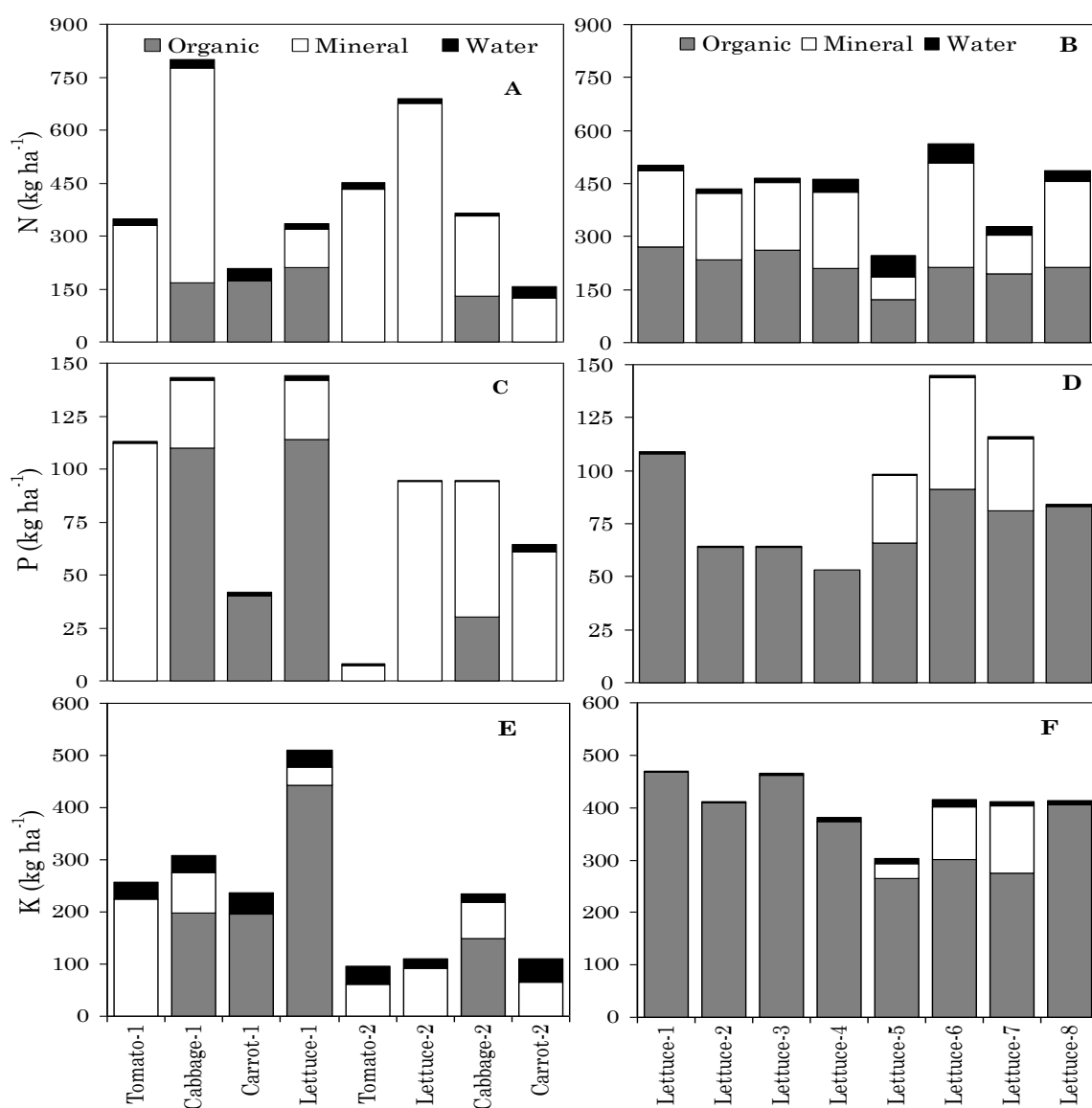


Figure 4.5. Average contribution of organic and mineral fertilizers and irrigation water to total N, P and K input at Dogona during the 2 years (Fig. 5 A, C, D) and Kodení during 1 year (Fig. 5 B, C, E).

4.3.5. Nutrient use and partial factor productivity

At Dogona, 12 to 201%, 12 to 188% and 29 to 410% of the total applied N, P and K, respectively, was taken up and stored in the above ground biomass depending on the cropping cycle (Fig. 4.6). With few exceptions, vegetable crops were substantially over-fertilized in terms of N (Fig. 4.6 A) and P (Fig. 4.6 B). In the case of K, both under (carrots, cabbage and lettuce–2 cycles) and over fertilization (both tomato cycles, lettuce–1) were observed (Fig. 4.6 C).

Over the 2 years, 1123 kg N and 331 kg P ha⁻¹ were supplied by the farmer in excess of plant uptake, whereas there was an application deficit of 1122 kg K ha⁻¹. The amount of nutrients exported was always highest for cabbage.

At Kodení, nutrient application rates generally exceeded nutrient uptake by lettuce, except for K for which some crop cycles received less K than was taken up by the crop (Fig. 4.6). Nutrients removed by lettuce at Kodení accounted for 14 to 110%, 18 to 68% and 50 to 141% of the total N, P and K applied, respectively. In a single year, 2012 kg N, 379 kg P and 738 kg K ha⁻¹ were supplied by the farmer in excess of plant uptake.

Given the wide range of yields and fertilizer application rates, the PFP of N, P and K varied markedly across cropping cycles at both sites (Table 4.4). Values of PFP were lowest for PFP–N and to a lesser extent for PFP–K compared to PFP–P.

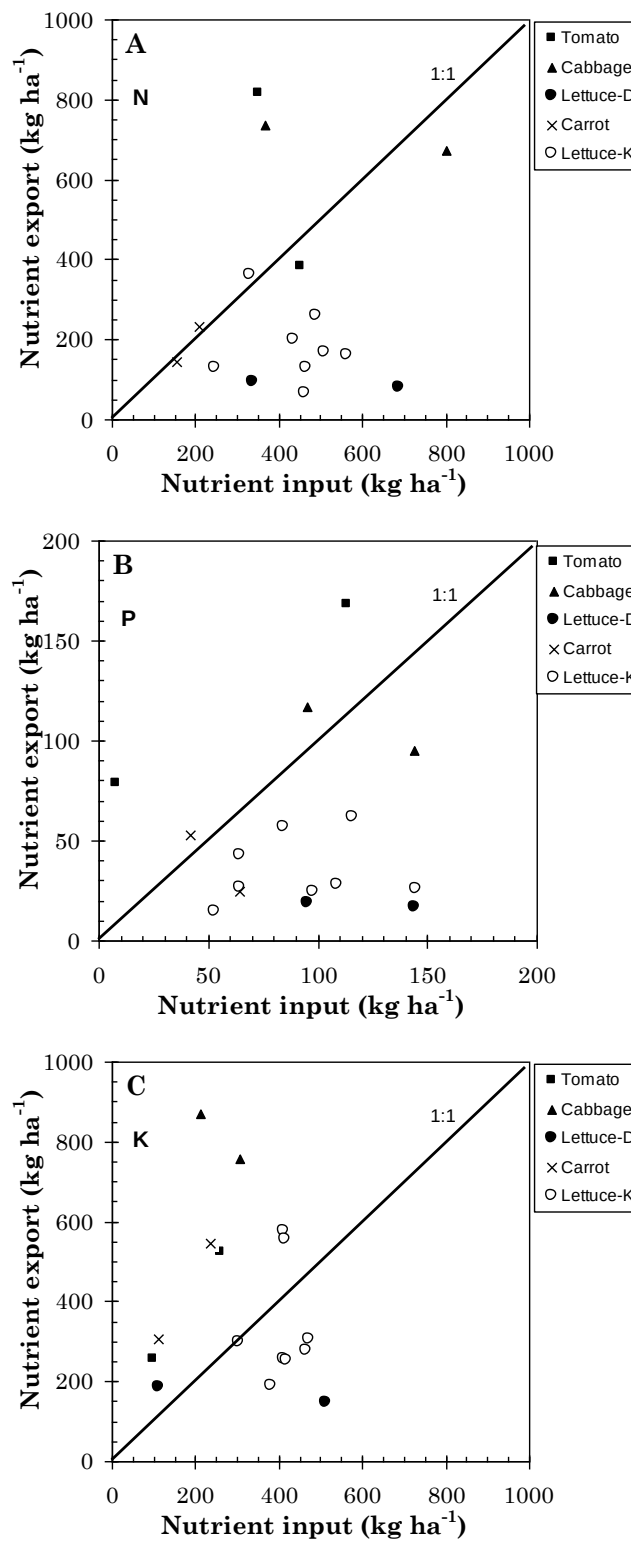


Figure 4.6. Comparison between total nutrient input (organic and mineral fertilizer and irrigation water) and nutrient uptake by aboveground plant parts. Lettuce–D= lettuce at Dogona, Lettuce–K=lettuce at Koden.

Table 4.4. Contribution (%) of the organic (OM) and mineral (MF) sources of fertilizers used to the total N, P and K input, and Partial factor productivity (PFP; Mean $\pm$ SD) of N, P and K.

Site and Season	Crops	OM (%)	MF (%)	PFP-N (kg kg ⁻¹)	OM (%)	MF (%)	PFP-P (kg kg ⁻¹)	OM (%)	MF (%)	PFP-K (kg kg ⁻¹)
Dogona (2008 –2009)	Tomato-1	0	100	175 $\pm$ 41	0	100	517 $\pm$ 121	0	100	560 $\pm$ 258
	Cabbage-1	23	77	66 $\pm$ 7	77	30	345 $\pm$ 35	71	29	179 $\pm$ 18
	Carrot-1	100	0	290 $\pm$ 28	100	0	1255 $\pm$ 120	100	0	257 $\pm$ 25
	Lettuce-1	66	314	87 $\pm$ 27	80	20	195 $\pm$ 60	93	7	58 $\pm$ 18
Dogona (2009 –2010)	Tomato-2	0	100	65 $\pm$ 17	0	100	455 $\pm$ 103	0	100	451 $\pm$ 118
	Lettuce-2	0	100	39 $\pm$ 7	0	100	279 $\pm$ 49	0	100	286 $\pm$ 50
	Cabbage-2	37	63	146 $\pm$ 17	40	60	552 $\pm$ 63	67	33	265 $\pm$ 30
	Carrot-2	0	100	373 $\pm$ 27	0	100	751 $\pm$ 55	0	100	705 $\pm$ 51
Kodeni (2009 –2010)	Lettuce-1	56	44	78 $\pm$ 13	100	0	355 $\pm$ 60	100	0	82 $\pm$ 14
	Lettuce-2	55	45	110 $\pm$ 9	100	0	729 $\pm$ 59	100	0	114 $\pm$ 9
	Lettuce-3	57	43	98 $\pm$ 12	100	0	695 $\pm$ 87	100	0	96 $\pm$ 12
	Lettuce-4	51	49	88 $\pm$ 10	100	0	712 $\pm$ 86	100	0	101 $\pm$ 12
	Lettuce-5	66	34	209 $\pm$ 32	67	33	395 $\pm$ 61	90	10	132 $\pm$ 21
	Lettuce-6	42	58	83 $\pm$ 9	63	37	292 $\pm$ 31	75	25	105 $\pm$ 11
	Lettuce-7	64	36	252 $\pm$ 19	70	30	667 $\pm$ 52	68	32	190 $\pm$ 15
	Lettuce-8	47	53	163 $\pm$ 5	100	0	885 $\pm$ 25	100	0	184 $\pm$ 5

At Dogona, the lowest PFP–N was recorded for lettuce–2 and the highest values were observed for the two carrot cycles. The lowest PFP–K was found for lettuce–1 due to the high amount of solid waste used and the relatively high K concentration therein. The highest PFP–K values were registered for carrot–2 and tomato–2.

Similar trends were observed at Kodení, where N and K showed lower partial factor productivity than P. PFP of N and K varied greatly for the same crop species at Kodení (lettuce) as a result of the variable amount of nutrients applied and differences in crop response. N and K were most efficiently used during the first, sixth, fourth and third lettuce cycles in comparison to the other cycles at this site.

4.4. Discussion

4.4.1. Field–scale water flow

At both sites, irrigation was performed year around, even during the rainy season. This may be required because of the shallow rooting of vegetable crops and because successive rainfall events can be separated by several days or even weeks. The total annual amount of irrigation water applied at Kodení (2480 mm) was almost twice that applied at Dogona (1228 mm). When comparing lettuce at similar dates, it appears that irrigation rates were similar at both locations during the rainy season (175 and 184 mm), but twice as high at Kodení (lettuce–8: 598 mm) than at Dogona (lettuce–1: 302 mm) during the dry season ([Table 4.3](#)). At both sites, water application rates were reduced by approximately 40 to 70% during the rainy season compared to the dry season ([Fig. 4.2](#)). These differences in water management reflect differences in farmers' appreciation of crop water needs and may affect crop productivity as well as the rate of water losses through deep drainage.

During the dry season, the fact that no drainage water was collected at Dogona seems to indicate that water was applied at a rate smaller or

equal to ETCrop. Indeed, during the cold dry season (November to February) irrigation provided less than the maximum evapotranspiration of lettuce-1 and carrot-2 grown during this period (Fig. 4.2). Likewise, the amount of irrigation + rainfall during both tomato cycles (62 mm / week on average) was lower than the optimum water requirements for tomato during hot periods (April – May), which is reported to be around 70 mm / week in tropical Africa (Grubben and Denton, 2004). Again, the lack of measured percolation below 30 cm depth during this period seems to confirm that water supply was less than ETCrop. Nevertheless, the occurrence of a significant water stress during these periods can be ruled out as yields of lettuce-1 and carrot-2 were within the high production range recorded between 1997 and 2005 in the city (DGPSA 2006). It would be of interest, however, to test whether the farmer may achieve higher yields at this site by increasing slightly the water supply to crops.

The lack of water collected in the lysimeters during certain periods of the year is not in itself proof that drainage beyond 30 cm depth is nil. Indeed, the efficiency of passive lysimeters has been reported to be of the order of 12 to 58% depending on the soil matric potential status (Gee et al. 2009). This is supported by Fig. 4.3, which indicates that lysimeters collect drainage only when rainfall + irrigation exceed ETCrop by 18 mm / week. This difference may in part be due to an underestimation of ETCrop, but may also indicate that when excess water supply is < 18 mm / week, drainage occurs through strongly unsaturated flow and is not properly trapped by the passive lysimeters. Note, however, that the design of the lysimeters ensures that the matric head at the top of the lysimeters is at least -10 cm (height of the cartridge).

At Kodení, the comparison of water supply with ETCrop as well as the occurrence of drainage during a large fraction of the year provides evidence that irrigation may be substantially reduced during much of the rainy season and the cold dry season. Indeed, irrigation during these periods was about 30% above ETCrop. Furthermore, the amount of water applied exceeded on average by 4 mm day⁻¹ the evapotranspiration rates reported

for lettuce during the full growth stage by [Grubben and Denton \(2004\)](#) for tropical African countries. Consequently, the total drainage volume at Kodení was more than 3 times higher than at Dogona, implying a lower WUE and a much higher risk of nutrient leaching and groundwater contamination at Kodení.

Even in case of perfect matching of irrigation to ETCrop, some drainage would still be expected each year. Indeed, high drainage events were to a large extent induced by heavy rainfall events ([Fig. 4.2](#)), especially at Dogona where the drainage occurred solely during the rainy season. This agrees with previous experimental vegetable production studies in arid and semi-arid regions (e.g. [Mermoud et al. 2005](#); [Predotova et al. 2011](#)). The cumulative drainage collected at Dogona was within the range of the 55 to 104 mm year⁻¹ of drainage water (representing 13% of water applied) collected between 1999 and 2001 by [Mermoud et al. \(2005\)](#) when evaluating gardeners' irrigation practices on onion cropping.

4.4.2. Vegetable production and water use efficiency (WUE)

Overall, at both sites, saleable FM yields were in the medium to high range of yields reported for carrots (9 – 52 t ha⁻¹), tomatoes (5 – 55 t ha⁻¹) and lettuce (7– 48 t FM ha⁻¹) for the period 1997 – 2005 at the national level by the agricultural statistics services ([DGPSA 2006](#)). Cabbage FM yields were fairly high but were consistent with the optimum range (40 – 60 t FM ha⁻¹) reported for tropical regions ([Grubben and Denton 2004](#)), yet far below the 97 t ha⁻¹ obtained in some high input gardens in Niamey ([Diogo et al. 2010](#)). Slightly lower FM yields of lettuce (35 t ha⁻¹) and tomato (35.2 t ha⁻¹) were obtained by [Sou \(2009\)](#) and [Akponikpè et al. \(2011\)](#), respectively, when applying waste water together with recommended mineral fertilization in Ouagadougou (Burkina Faso). Lettuce DM yields at both sites were of comparable magnitude as the 2.5 t DM ha⁻¹ recorded in Niamey and the 4.6 ± 1.2 t DM ha⁻¹ recorded in similar intensive vegetable production systems in tropical regions ([Khai et al. 2007](#); [Diogo et al. 2010](#)).

As WUE is expressed on a yield basis, the higher the crop yield, the greater the WUE. Crops grown during the rainy season showed lower WUE, which can be attributed to the high cumulative amount of water during this period. Conversely, WUE was relatively high during the dry season, especially at Dogona. A slight water deficit at this site during the dry season may in fact have led to higher WUE than for optimal irrigated crops (Zotarelli et al. 2009). Overall, WUE at Kodené may be increased by reducing water supply and better matching water supply with ETCrop, possibly in combination with higher yielding lettuce varieties such as the one used in the 7th and 8th cropping cycles.

4.4.3. Fertilization practices and partial factor productivity

Nutrients were supplied to crops through a variety of organic amendments and mineral fertilizers (Table 4.2). The organic amendments had low P and N content (generally < 1.3 %) and were often very heterogeneous in terms of concentration (Table 4.5), which is consistent with previous studies (e.g. Palm et al. 2001; Harris 2002). The variability of nutrient content in manure results partly from it being mixed with other organic biosolids (e.g. cotton seeds and crop residues). Despite its low quality, the use of municipal solid waste as an alternative organic resource has gained in importance in the region in response to the low availability of conventional organic amendments and the need to dispose of increasing amounts of domestic urban wastes (Eaton and Hilhorst 2003; Kiba et al. 2011). Mixing NPK and urea is also a common practice due to the unavailability of NPK formulations specifically designed for vegetable crops. Besides its diluting effect on P and K, mixing compound NPK fertilizer with urea also results in a highly variable N concentration (Table 4.3), which would make it more difficult for farmers to follow recommendations, if any.

Wastewater used at Dogona had lower N and K concentrations than those reported by previous studies in Ouagadougou. For instance, Akponikpe et al. (2011) found nutrient concentrations in treated wastewater

(from macrophyte ponds) of about 28 to 54 mg N l⁻¹ and 10 to 19 mg K l⁻¹ between 2001 and 2003. These authors also observed low P concentrations in wastewater. On the other hand, nutrient concentration in wastewater from Niamey reached 150 mg N l⁻¹ , 19 mg P l⁻¹ and 66 mg K l⁻¹ during the dry season (Diogo et al. 2010), that is 18 (N), 38 (P) and 6 (K) times higher than at Dogona. High concentrations in wastewater have led to a yearly nutrient input from waste water up to 200 kg N, 130 kg P and 470 kg K ha⁻¹ at Kumasi (Ghana) (Keraïta and Drechsel 2002). Nevertheless, despite the fairly low nutrient concentrations, irrigation water at Bobo Dioulasso supplied about 20% of the total N and K taken up by crops, except for cabbage which has substantially higher requirements (Fig. 4.5). Phosphorus supply through irrigation water represented no more than 5 to 10% of crop uptake. Future fertilization recommendations should therefore take into account the N and K supplied by irrigation water, even though this will require site specific knowledge regarding water quality and will be made complex in view of the sometimes high temporal variability in N and K concentrations in well water (Fig. 4.4 B and 4.4 F).

Combining organic and mineral fertilizers is a widespread practice in sub-Saharan Africa UPA systems (Drechsel et al. 2004; Graefe et al. 2008) and allows exploiting their well-known synergetic effects (Gentile et al. 2009). Overall, results have shown that fertilizer management at both sites resulted in N and P inputs well in excess of crop uptake (Fig. 4.5) and advices, which is in agreement with other studies in sub-Saharan Africa. Recently, for similar input rates, Diogo et al. (2010) reported annual positive balances of N (1,133 kg ha⁻¹) and P (223 kg ha⁻¹) in Niamey. Furthermore, Khai et al. (2007) also reported that less than 50% of the N applied to soils is taken up by crops in vegetable production systems in Asia. These excessive application rates indicate that gardeners do not rigorously follow the blanket recommendations provided by extension agencies. These high nutrient inputs have led to low NUE as reflected by sometimes very low PFP values (Table 4.6). The PFP values were overall lowest for N as a result of the continuous and high N supply from both organic and N fertilizers,

especially with urea at Kodení. Such low N use efficiency is commonplace within intensive vegetable production elsewhere (Zhu et al. 2005; Khai et al. 2007; Drechsel and Dongus 2010). On the other hand, our results agree with the conclusions of Zhang et al. (2010) who argued that the application of K is generally neglected in many developing countries and that K fertilizer supply in vegetable cropping systems seldom matches crop requirement. This results in high PFP–K. PFP values were generally highest for P despite the fact that P inputs generally exceeded crop uptake. Because crop P requirements are always lower than N and K, it is normal for PFP–P to be higher than for K and N. Carrot showed particularly high PFP–P values. This results from high FM yields (Table 4.1) and low P application rates (Tables 4.2 and 4.3). The high carrot yield despite low P application rates may be explained by a carryover effect of P applied to previous crops as well as low P requirement of carrot.

At Kodení, it appears that the gardener's fertilization practices primarily focused on satisfying lettuce N requirements as attested by the recurrent and high urea inputs. Given the continuous lettuce rotation, this seems justified as P and K uptake was entirely satisfied through the nutrient inputs from organic amendments. In contrast, at Dogona, even though N supply was also favored, efforts were made by the gardeners to supply P and K by regularly combining NPK + Urea. The resulting supply of P exceeded crop uptake, but K input still remained deficient, mostly as a result of the high K requirements of carrot and especially of cabbage (Fig. 4.5). Additional K applications through mineral fertilizers would therefore be well advised for high K-demanding crops.

Both from an economic and environmental point of view, applying excess nutrients cannot be justified since all amendments, except for the waste water, have to be paid for. It is likely that farmers underestimate the residual effect of previously applied fertilizers as well as the amount of nutrients present in irrigation water. High nutrient input is worrying since, considering the occurrence of periods of excess water application, excess nutrients may be subject to losses by leaching (Predotova et al. 2011).

Consequently, water and nutrient (especially N and P) use efficiency deserve careful attention in order to alleviate the potential nutrient burden on groundwater.

Furthermore, fertilizer application practices could increase the nutrient use inefficiency. For instance, we noticed that fertilizers were directly broadcast to plants and generally followed by irrigation. As urea hydrolyzes rapidly following its application (Marvi, 2009) it may immediately result considerable losses by volatilization (Predotova et al. 2010) and consequently reduce the nutrient use efficiency.

4.5. Conclusions

As opposed to subsistence rainfed agriculture in sub-Saharan Africa for which economic factors prevent the excessive use of both water and fertilizers, in intensive UPA gardening systems, economic arguments as well as the wide-spread availability of different fertilizer sources provide incentives for irrigation and over-fertilization. Our study showed that about 3 to 6 % of water input in UPA was lost by drainage at Dogona and 8 % (293 mm) at Kodení. This occurred mostly during the rainy season, yet at Kodení drainage was also recorded during the cold dry season (November to February) as a result of heavy irrigation, up to 40% in excess of crop requirements. Therefore, irrigation rate could be reduced by this extent during the cold dry season to match more closely the crop requirement. Given the limited water resources in semi-arid areas, there is therefore a need to better instruct farmers regarding crop water needs. This would allow them to save on labour, but would also reduce the risk of nutrient losses by leaching as well as reduce nutrient inputs through irrigation water. Indeed, irrigation water supplied a substantial amount of total N and K, irrespective of the source of water (well or surface water).

Our study also highlighted the excessive nutrient application rates and hence the need to better match nutrient application rates (especially N and P) to the crop requirements. Indeed, gardeners generally applied 30 to

50 % more nutrients than taken up by the crops. This likely results from a poor knowledge of nutrient content of the great variety of nutrient sources used by farmers as well as incomplete knowledge regarding crop needs. Nutrient supply did not seem to follow a crop-specific strategy, such that they were sometimes supplied in large excess (e.g., N for some lettuce crops) or in deficit (e.g., K for cabbage). Overall, it is expected that the partial factor productivity of N and P could be strongly improved by substantially reducing application rates, which is not expected to impact yields given the current strong over fertilization. Based on the partial nutrient balances observed in the present study, a reduction in nutrient application rates of 30% seems reasonable. This would lead to a greater sustainability of UPA systems, by reducing the risk of groundwater contamination, but it may also lead to better economic returns for farmers by saving on fertilizers. Further studies therefore need to be undertaken in order to evaluate to what extent fertilizer application rates can be reduced without adverse effects on yields, and the associated reduction in nutrient losses by leaching within commercial urban gardening systems.

Chapter 5

Vertical leaching of soil nutrients as affected by water and fertilizer management in urban vegetable production systems of West Africa.

Abstract

Optimization of water and nutrient use in agriculture requires reliable quantification of vertical nutrient fluxes through the soil. However, the quantification of soil water and solute fluxes under field conditions remains a challenge. In this research, three devices have been used to monitor water flow and solute transport at the plot scale. The study was carried out within two vegetable production gardens in Bobo Dioulasso (Burkina Faso). The objectives were to: (i) characterize water drainage and the vertical leaching of nutrients below the root zone; (ii) investigate the impact of a reduction in fertilizer application rates on the nutrient leaching pattern; (iii) and to compare the relative efficiency of the different methods. In both gardens, vegetable crops were evaluated under 3 treatments: gardener's fertilization practice; 30% reduction in fertilizer input, and no fertilization, during 12 to 24 months. At each site, ion exchange resin cartridges and two types of pan lysimeters were installed at 30 cm soil depth in order to monitor soil solute leaching. Furthermore, the sites were equipped with weather stations and TDR probes to compute the soil water balance over 24 months concurrently with the drainage measurement. Under farmer management conditions,

between 74 and 113 mm/year of drainage was collected at Dogona and about 250 mm/year at Kodení. For the same treatment (T100), based on the IERC, between 236 and 990 kg NO₃ ha⁻¹ year⁻¹, 28 and 75 kg PO₄ ha⁻¹ year⁻¹ and 54 and 214 kg K ha⁻¹ year⁻¹ may be lost by leaching beyond the rooting depth. Reducing the amount of fertilization by 30% significantly reduced the concentration of total N and K in soil solute samples at 30 cm depth. The magnitude of the reduction ranged from 20 to 90% for NO₃, 29 to 74% for PO₄ and 14 to 39% for K. Results also showed that the pan lysimeters consistently collected much less water ($\leq 10\%$) than the potential drainage estimated from water balance calculations. This is attributed to the disturbance in water flow introduced during device installation and the hydraulic functioning of the devices (e.g., free drainage lower boundary condition). In terms of nutrient leaching, the IERC were more effective ($> 65\%$) in trapping ions than the pan lysimeters (SSF and SSS), which may be due to less soil disturbance during installation and more realistic boundary conditions. Nevertheless, the devices used in this study can be seen as valuable tools to estimate root zone drainage, subject to a better evaluation of their efficiency.

Keywords: Urban Agriculture, Ion Exchange Resin, Pan Lysimeters, Drainage, Vertical nutrient leaching, Devices efficiency.

5.1. Introduction

Excessive use of chemicals in agriculture is viewed as a global threat, due to the potential contamination of the aquifers (Tilman *et al.*, 2001; Djodjic *et al.*, 2004; Jahangir *et al.*, 2011; Zupanc *et al.*, 2011). This applies to conventional cropping but also to vegetable cropping (Cho *et al.*, 2007; Li *et al.*, 2007; Nyenje *et al.*, 2010). For instance, Thompson *et al.* (2007) reported studies that have shown, in the province of Almeria (South–East Spain), concentrations in excess of 100 mg NO₃ l⁻¹ in shallow aquifers under greenhouse–based vegetable production, whereas the threshold value in

drinking water is set to 50 mg NO₃ l⁻¹ or 11.3 mg NO₃-N l⁻¹ (WHO, 2011). In northern China, Zhao et al. (2010) reported that nitrate concentrations exceeded the WHO standard in about 45% of 600 wells sampled between 2007 and 2009, the highest recorded NO₃ concentration being 113 mg l⁻¹. Most of these wells were located in intensive vegetable farming areas typically using more than 1,700 kg N ha⁻¹ year⁻¹.

West Africa also experiences groundwater NO₃⁻ contamination from agricultural sources. For instance, Sall and Vanclooster (2009) in Senegal reported that wells from about 74 out of 131 sites presented nitrate concentration > 50 mg NO₃ l⁻¹, with a median value of 65 mg NO₃ l⁻¹, 84% of them being located in vegetable production areas. In the Northern region of Burkina Faso, 15% out of 168 boreholes drilled during 1984 – 1986 revealed water nitrate concentrations much higher than 45 mg l⁻¹, which was closely related to agricultural activities (Groen et al., 1988). More recent investigations compiling nitrate concentration data from 1800 wells and 510 boreholes spread across 27 sites in the city of Ouagadougou (Burkina Faso) have shown that about 50% of them presented nitrate levels > 50 mg l⁻¹ (Yaméogo et al., 2006). Besides the risks to human health (Addiscott and Benjamin, 2004), nitrate leaching losses through the soils poses considerable environmental and economical concerns.

Although subsurface P transport is not the predominant loss pathway, there is increasing evidence of vertical P movement in soils when P application rates exceed crop P removal over extended periods (e.g. Heckrath et al., 1995; Sinaj et al., 2002 and references therein). Such potential P leaching toward groundwater is worrying since it can contribute to the eutrophication of the connected surface water.

While N leaching, and to a lesser extent P leaching, towards groundwater has received special attention, little attention is being paid to K leaching, mainly because its leaching does not result directly in serious groundwater degradation (Alfaro et al., 2004; Kolahchi and Jalali, 2007). Nevertheless, K leaching beyond the rooting depth may result in significant economic losses for the farmers (Goulding et al. 2008).

Groundwater water provides about 65 – 85% of the water for human consumption and economic activities in Burkina Faso ([Derouane and Dakouré, 2007](#)). These figures are much higher than the world average ($\leq 50\%$; [UN, 2003](#)) and thus illustrate the need to preserve the aquifers both for quantitative and qualitative reasons. Efforts must therefore be put into developing and implementing strategies to curtail water degradation by preventing the transport of nutrients through the soil towards the groundwater.

Nutrient leaching refers to nutrients moving vertically downwards with water through the soil matrix to depths beyond the reach of growing plants ([Sigunga et al., 2008](#)). It is governed by a wide range of factors, depending on the nutrient involved, but it is strongly linked to soil physical properties ([Alfaro et al., 2004](#); [Kolahchi and Jalali, 2007](#); [Zotarelli et al., 2007](#)), and the soil moisture status () which determine the volume of drained water ([Warrick, 2002](#); [Thompson et al., 2007](#)). Since NO_3^- is very soluble in water and virtually not adsorbed on soil colloids, it can easily be carried away from the rooting zone as rain or irrigation water percolate towards the groundwater ([Havlin et al., 2005](#)). Consequently, intensive vegetable production, with its high nutrient inputs coupled with excess watering, has the potential to be a major source of nutrient leaching and groundwater contamination. Due to the high buffering capacity of most soils for P, phosphate mobility is low and its leaching is of lesser importance compared to the N. Nevertheless, the existence of preferential flow paths or soils with low P sorption (as in sandy soils) could result in substantial and fast transport of phosphate into deep soil layers and groundwater ([Sinaj et al., 2002](#); [Djodjic et al., 2004](#)). The K leaching has been shown to be positively related to the proportion of coarse sand and to an increase in annual rainfall amount ([Alfaro et al., 2004](#)). Being a cation, some K can be held on the exchange complex of the soil, but the amount of exchangeable K will depend on the characteristics of the exchange complex (CEC, mineralogy) as well as on the pH and the competition with other cations (mainly Ca and Mg) for the exchange sites.

There is also a consistent correlation whereby nutrient leaching increases significantly as the nutrient content at soil surface increases beyond the agronomic optimum range (Djodjic *et al.*, 2004; van Es *et al.*, 2004 and 2006; Barnard and Leadley, 2005; Li *et al.*, 2007; Zhao *et al.*, 2010). For instance, Zotarelli *et al.* (2009) stressed that N input beyond 224 kg N ha⁻¹ in some tomato trials increased the likelihood to trigger nitrate leaching towards groundwater in California. Furthermore, Heckrath *et al.* (1995) have shown a linear increase of P concentration in drainage water to more than 2 mg l⁻¹ when available P (Olsen-P) in soil exceeded 60 mg kg⁻¹ in England. This is of special concern for vegetable cropping, given that numerous studies have reported strong positive nutrient balances in West African UPA soils (Dreschsel *et al.*, 2004; Assogba-Komlan *et al.*, 2007; Graefe *et al.*, 2008; Diogo *et al.*, 2010).

A full identification of the factors underlying the occurrence and the magnitude of field-scale nutrient leaching within these systems can provide a basis for site-specific soil water and nutrient management and for rational combined nutrient application rates. Optimization of water and nutrient use in agriculture requires reliable estimates and quantification of vertical matter fluxes through the soil (Gee *et al.*, 2009). Knowledge of the fate of solutes into the soil can lead to better fertilizer application strategies, resulting in both economic and ecological benefits (van der Velde *et al.*, 2005).

Although the body of knowledge pointing to large excesses in nutrients applied at the soil surface in SSWA UPA systems is appreciable, the fate of these surpluses remains little studied hitherto (Tamini and Mermoud, 2002; Predotova *et al.*, 2010) yet it is crucial to both our understanding and management recommendations. Studies that have attempted to measure the vertical leaching of nutrients within Burkina Faso UPA systems have so far focused exclusively on nitrate leaching (Tamini and Mermoud, 2002). However, attention must also be paid to the losses of other macronutrients because of the pivotal role they play on the fertility of the inherently nutrient deficient soils of West Africa (Bado *et al.*,

2010). Moreover, these previous studies provided only a snapshot during a part of the year, and no leaching studies were long enough to reliably estimate annual losses and seasonal variations.

Relevant published data with regard to the vertical leaching of nitrogen, phosphorus and potassium into soils under intensively managed UPA systems remain currently unavailable for Bobo Dioulasso (the second largest city of Burkina Faso). However, high fertilizer application rates as reported in Chapter 4 can be conducive to rapid leaching of applied nutrients, especially when over-irrigated or during the short rainy season with often intensive rainfall events. This is exacerbated by the predominantly sandy-textured soils of Bobo and predominance of low activity clay (of kaolinitic type) with low nutrient holding capacity and small buffering capacity.

The use of appropriate methods to measure leached nutrients is critical to the study of their movement to the groundwater (Zhu et al., 2002). Recently, thorough reviews and comparative studies of soil solute sampling and nutrient flux monitoring methods have been published by Weihermuller et al. (2007) and Meissner et al. (2010). However, although many methods are available, no single technique has been proven to be suitable under all conditions (Barzegar et al., 2004). Furthermore, the practical nature of our study as well as the limited resources available call for the use of methods that are both inexpensive and easy to handle. Zero-tension pan lysimeters (Gee et al., 2009) and ion exchange resins (IER; Lehmann et al., 2001) can be used for this purpose. Both have advantages but also potential problems that cause errors in the measured drainage and nutrient fluxes (Jemisson and Fox, 1992; Masarik et al., 2004). For instance, both are very useful for determining solutes rapidly draining in macropores (Zhu et al., 2002; Meissner et al., 2010) but fail to properly sample matrix water which can bypass these devices (Jemisson and Fox, 1992; Schmidt and Lin, 2008). This, therefore, adversely affects the collection efficiency of these devices. Nevertheless, despite their well known weaknesses, collection efficiency data may prove useful to correct measured percolated volumes and masses

of percolated constituents into actual fluxes under field situation ([Jemisson and Fox, 1992](#); [Zhu et al., 2002](#); [Van der Velde et al., 2005](#); [Gee et al., 2009](#)).

Nitrate leaching in Burkina Faso has been assessed so far mainly by using porous ceramic suction cups ([Tamini and Mermoud, 2002](#); [Zougmore et al., 2004](#)). However, this method is more expensive than zero-tension lysimeters. Furthermore, it has been speculated that porous cups have an inherent bias, for instance because of its small contact area ([Barzegar et al., 2004](#)) and the unknown volume of soil being sampled when acquiring leachate, which may induce large uncertainties in calculating nutrient losses ([Lord and Shepherd, 1993](#); [Zotarelli et al., 2007](#)). Although the number of zero-tension lysimeter and IER-related papers published in soil and environmental journals has increased steadily over the years worldwide, they have seldom been investigated up to now under West African tropical condition (e.g. [Agbenin and van Raij, 2001](#); [Predotova et al., 2010](#)). In view of the above, this research aims at (i) characterizing the soil water balance; (ii) quantifying the vertical leaching losses of N, P and K beyond the rooting depth; (iii) comparing the efficiency of different methods used herein to monitor nutrient leaching under field conditions (iv) and investigating the impact of a reduction of applied fertilizers on the leaching of nutrients through the soils.

6.2. Material and Methods

6.2.1. Dataset considered

In this chapter, the drainage was estimated based on the dataset collected for soil water balance purposes and whose components are described in detail in sections 3.4 and its sub-sections. The solute flux measurement methods are those described in section 3.5 and comprise the ion exchange resins and the solute sampling devices.

6.2.2. Statistical analysis

Statistical analyses were conducted for a completely randomized experimental design with six and four replications for Dogona and Koden, respectively. The leaching data was not normally distributed according to the Shapiro–Wilk’s W–Test and this restriction could not be removed through any transformation. Therefore, we used the non–parametric Kurskal–Wallis Test to test for the difference between treatments and sampler type of the cumulative leachate volumes collected at both sites.

The examination of the residuals of the nutrient leaching data obtained from ion–exchange resins associated or not with sampler type did not indicated significant deviations from the normal distribution. Therefore, data were compared using ANOVA of the nutrients trapped by each type of resin. When the F value was significant, a multiple means comparison was performed using Duncan Multiple Range Test at a P value of 0.05. All Statistical analyses were performed using the PROC GLM procedure of SAS release 9.2 software (SAS Institute Inc., Cary, North Carolina, USA).

6.3. Results

6.3.1. Drainage flux estimates

No technical problems with the SSF components (i.e. tipping bucket) occurred during the growing season. Furthermore, no single lysimeter systematically yielded higher or lower water volumes.

Treatments had no significant effect on the total annual volume of water collected, irrespective of the type of lysimeter (Table 5.1). However, the amount of water collected differed significantly from one type of lysimeter to another. Indeed, the result of the non parametric analysis of the drainage volume collected by SSS and SFM during each growing season showed that the differences between lysimeters were highly significant (Table 5.1). On average at Dogona, the drainage volume recovered by SSF

over a one-year period were 102 and 113 mm in 2008–2009 and 2009–2010, respectively, whereas the corresponding drainage values for SSS were 74 and 89 mm. At Kodení, an average of 260 mm was collected by SSS during 2009–2010.

Table 5.1: *p-values* of the Kruskal–Wallis analysis of the cumulative annual drainage volumes collected at 30 cm depth at both sites, as a function of treatment and lysimeter type.

Source	Dogona (2008–2009)	Dogona (2009–2010)	Kodení (2009–2010)
Treatment	0.568	0.1325	0.258
Sampler type	0.02	0.001	N/A [†]

[†] N/A: not applicable. At this site only one type of sampler (SSS) was used see section

At Dogona, the cumulative drainage patterns reflected mostly the rainfall pattern, whereas at Kodení it reflected also the irrigation practice (Fig. 5.1). Indeed, drainage events at Dogona occurred mainly during periods of rain, which also coincide with the lowest evapotranspiration rates (Fig. 5.1). At Kodení on the contrary, drainage continued to occur beyond the rainy season till January 2010 which may be attributed to the high weekly irrigation rate (~100 mm per week) applied at this site as off the end of October.

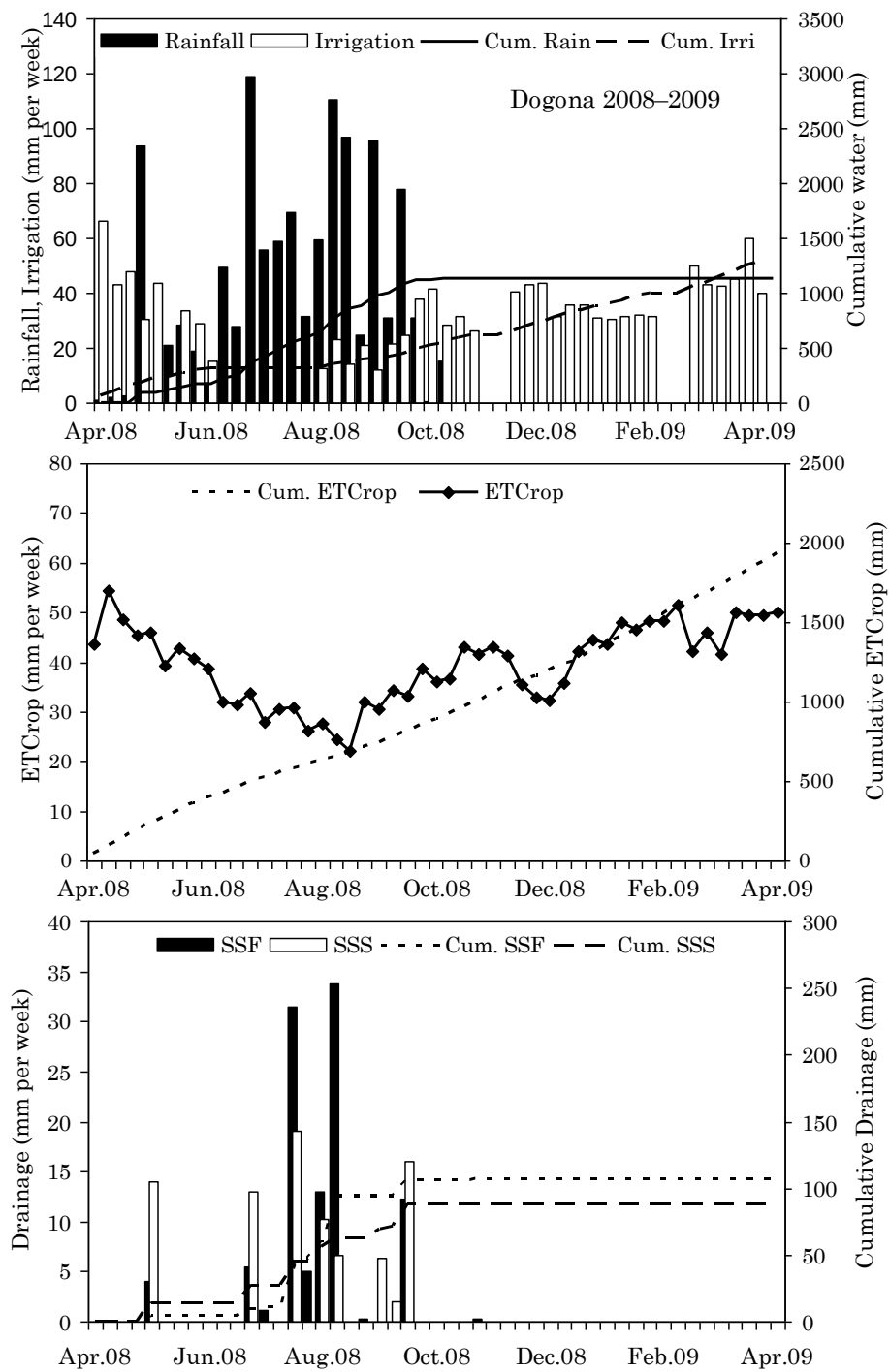


Fig. 5.1A: Weekly and cumulative irrigation and rainfall (top), ETCrop (T100 treatment, middle) and drainage (bottom) data during 2008–2009 at Dogona. Cum. = Cumulative values. SSS and SSF: drainage collected from SSS and SSF sampling devices.

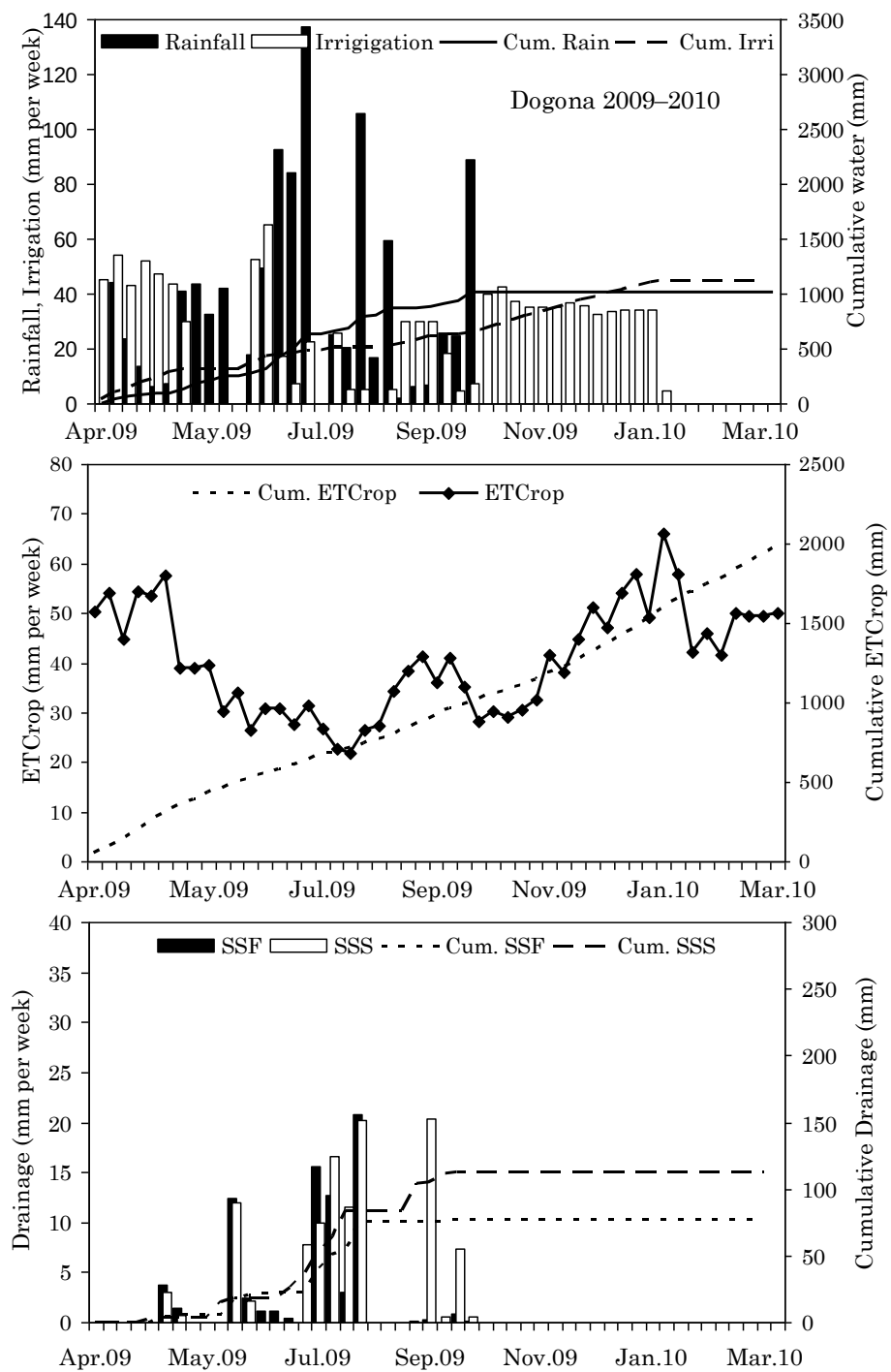


Fig. 5.1B: Weekly and cumulative irrigation and rainfall (top), ETCrop (T100 treatment, middle) and drainage (bottom) data during 2009–2010 at Dogona. Cum. = Cumulative values.

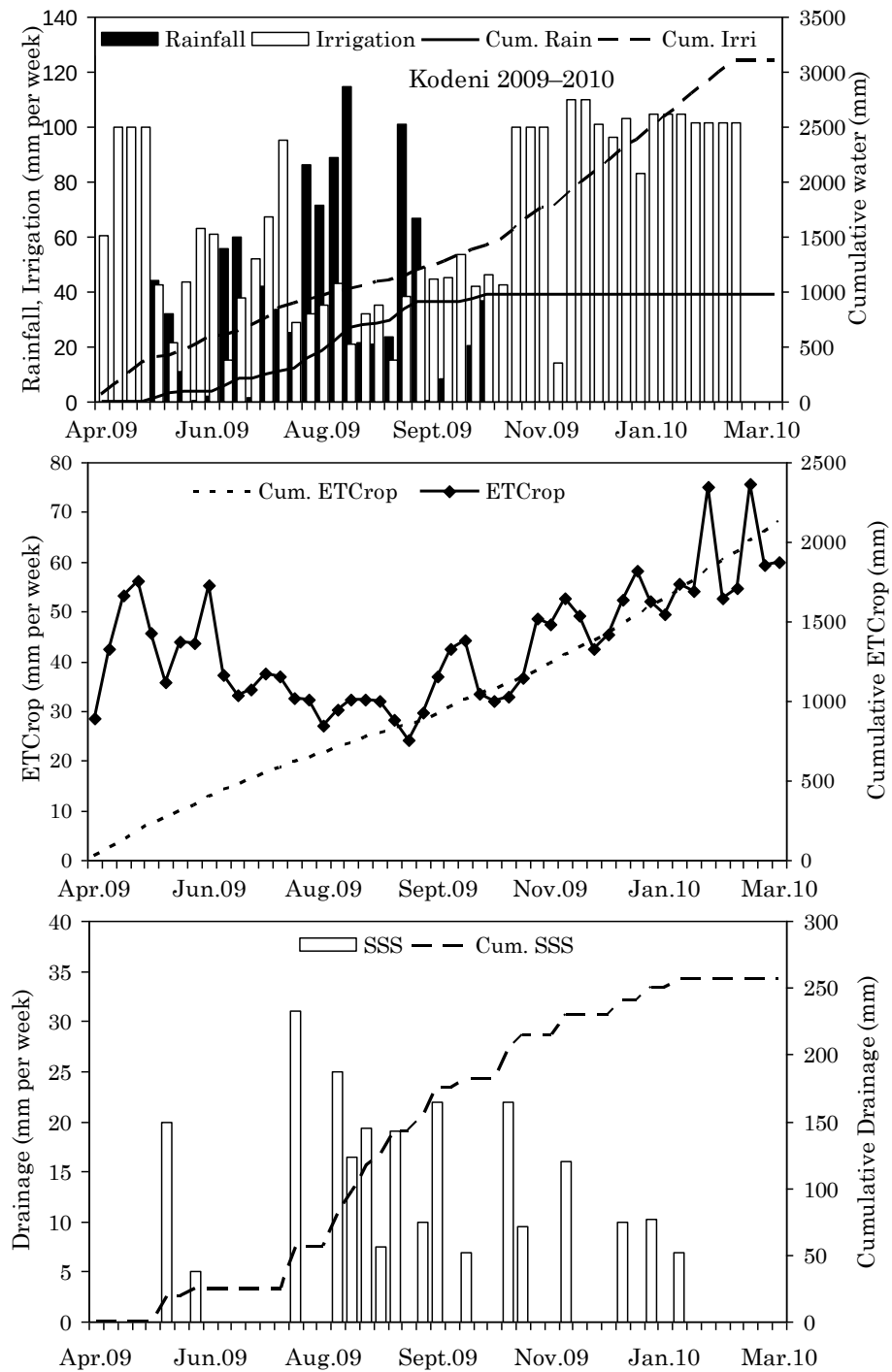


Fig. 5.1C: Weekly and cumulative irrigation and rainfall (top), ETCrop (T100 treatment, middle) and drainage (bottom) data during 2009–2010 at Kodení. Cum. = Cumulative values.

The weekly drainage volumes as measured by SSF and SSS were compared to the drainage values calculated via the water balance (Fig 5.2). It appears that both lysimeter devices systematically under-estimated the drainage water when compared to the water balance-derived drainage. On average, at Dogona, the drainage calculated through the water balance model was 8 to 10-fold greater than the drainage collected by both types of lysimeters.

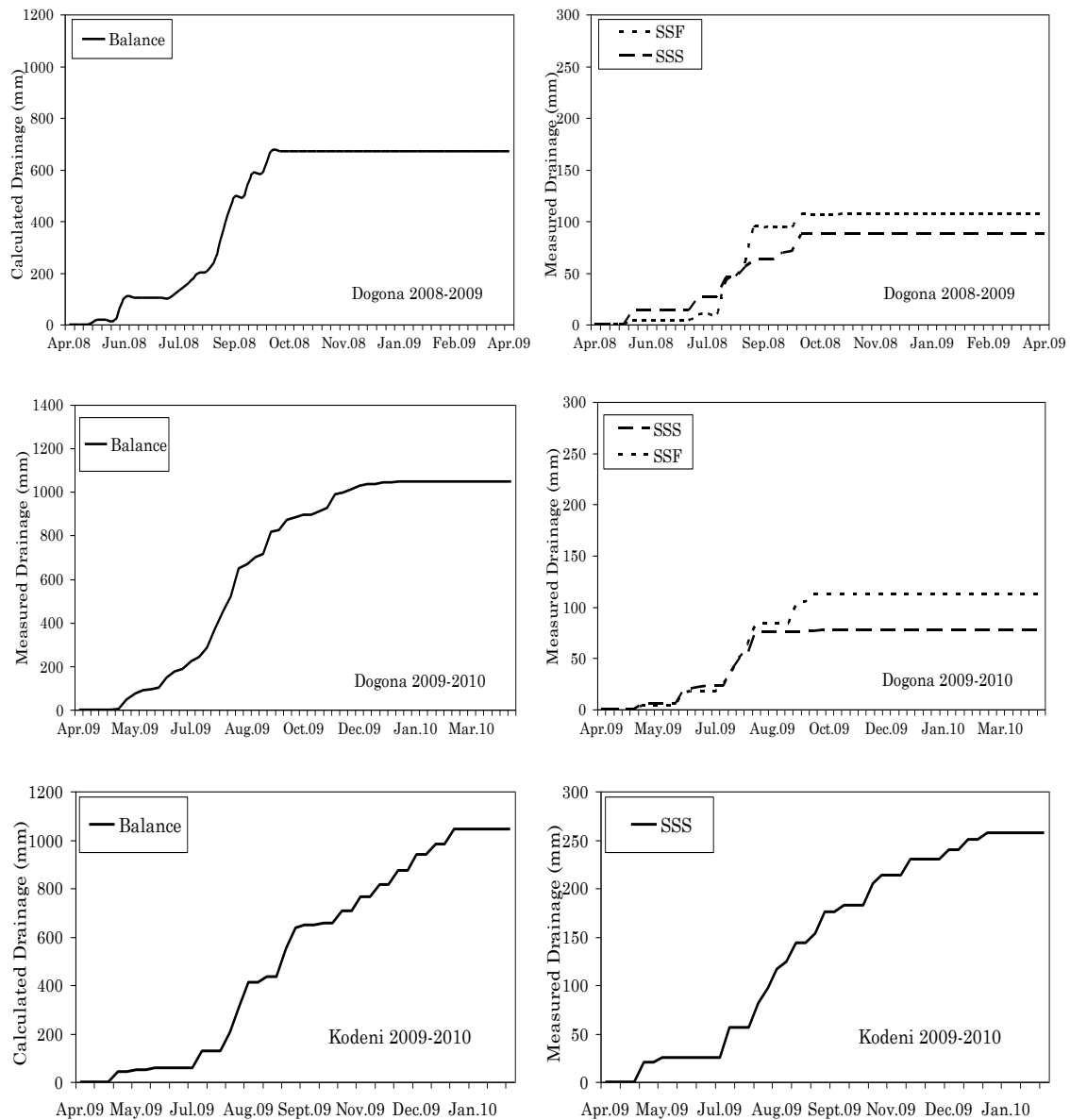


Figure 5.2: Cumulative weekly drainage at 30 cm depth calculated using a simple water balance compared to cumulative measured drainage using the two types of lysimeters (SSS and SSF) at Dogona and Kodení. At Kodení, only the SSS device was used for monitoring drainage.

During the cropping year 2009–2010, the SSF stopped to yield drainage in August 2009 whereas the SSF continued until October 2009 and the water balance results show that drainage occurred until November–December 2009. The collection efficiencies of the lysimeters, calculated as the ratio between the total collected leachate and the total water balance–derived drainage volume, were low. They are equal to 8% (SSS) and 12% (SSF) at Dogona, and 25% (SSS) at Kodení.

5.3.2. Mass of leached nutrient trapped by the mixed-bed ion exchange resin cores

Regardless of treatment and device type, NO_3^- was by far the most important nutrient trapped onto the resins during the second cropping year (2009–2010) at both sites (Fig. 5.3), followed by Calcium (Ca), Potassium (K), Magnesium (Mg) and Phosphate (PO_4) in descending order, whereas during the first cropping year (2008–2009), Ca was the main nutrient, followed by NO_3^- .

During the first year, the NO_3^- trapped by resins was always 10 times larger than those of NH_4^+ , which was almost always consistently below the detection limit of 0.1 mg l^{-1} . Therefore, it was concluded that NO_3^- is the main pathway by which mineral N is leached out of the system, and only NO_3^- was monitored in the second year. Furthermore, during the first year, K always exhibited erratic vertical concentration profiles inside the resin cartridges (see Appendix 9) as well as unreliable analytical results. Consequently, K concentrations are not presented for the first year.

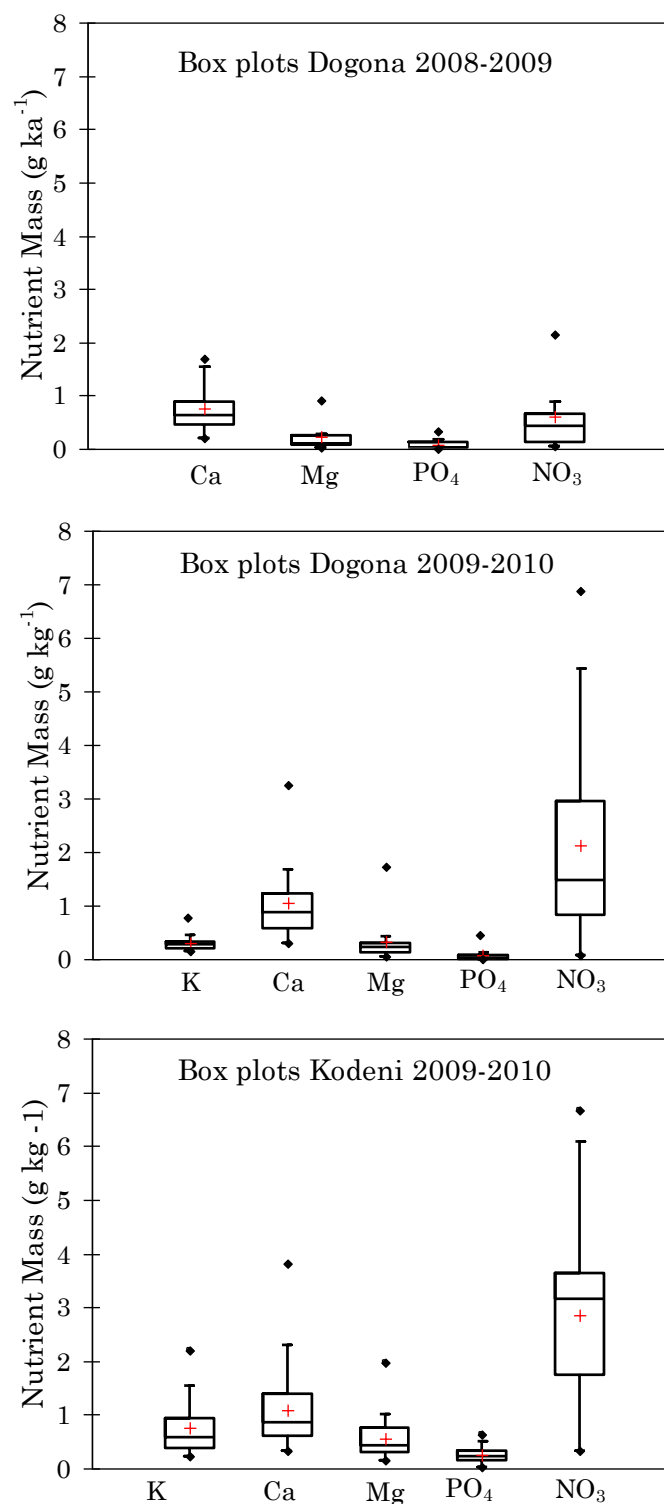


Figure 5.3: Box and whisker plot comparing resin-derived mean mass of mineral nutrients (Ca, Mg, K, PO₄ and NO₃) per kg of mixed-bed resin, regardless of treatments and device type. The horizontal line represents the median, the star represents the mean, the box covers the region from the 25th and 75th percentiles, whiskers delineate the 5th and 95th percentiles, min, max and extremes values are plotted with a ♦.

Statistical analyses performed on the mass of nutrients retained by the resins are presented in [Table 5.2](#). There was a significant treatment effect on the mass of NO_3 , PO_4 or K trapped by the resins at both sites and for both years. With few exceptions, at all sites and for all devices used, the T100 treatment tended to have higher nutrient losses, followed by T70 and T0 ([Table 5.3](#)). Furthermore, the statistical results showed that the lysimeter type significantly affected the mass of leached nutrients.

Table 5.2: Analysis of variance (*p-values*) regarding the mass of NO_3 , PO_4 and K leached at 30 cm depth as a function of treatment and type of lysimeter (IERC, SSSr or SSF) at Dogona and Kodení.

Site year	and Source	Df	NO_3^-	PO_4	K
Dogona (2008–2009)	Treatment (T)	1	<.0001	<.0001	N/A [†]
	Lysimeter Type (L)	2	<.0001	<.0001	N/A
	L x T	2	<.0001	<.0001	N/A
	Error	12			N/A
Dogona (2009–2010)	Treatment (T)	2	<.0001	<.0001	<.0001
	Lysimeter Type (L)	2	<.0001	<.0001	<.0001
	L x T	4	<.0001	<.0001	<.0001
	Error	18			
Kodení (2009–2010)	Treatment (T)	2	<.0001	<.0001	<.0001
	Lysimeter Type (L)	1	<.0001	<.0001	<.0001
	L x T	2	<.0001	<.0001	<.0001
	Error	12			

[†] K was not considered during this cropping season at Dogona

Regardless of treatment and type of device, NO_3 was by far the most important nutrient trapped onto the resins during both cropping years, compared to potassium (K) and phosphate (PO_4) ([Table 5.3](#)). At Dogona, up to 774 kg NO_3 , 29 kg PO_4 and 90 kg K per hectare were lost in T100 in the second year according to the IERC resins. The corresponding values at Kodení were 991 kg NO_3 , 75 kg PO_4 and 214 kg K per hectare. The mass of nutrients leached at Kodení was always higher than at Dogona. At this

latter site, leaching of NO_3^- was much higher in 2009–2010 than in 2008–2009, whereas PO_4 leaching was comparable across both years.

Table 5.3: Summary of the cumulative mass of NO_3 , PO_4 and K collected at 30 cm depth (mean $\pm$ SD) as affected by treatments and lysimeter type (IERC, SSSr or SSF) at Dogona and Kodení.

Site and year	Type	Source	NO ₃ [−]	PO ₄	K
		kg ha ^{−1}			
Dogona (2008–2009) [†]	IERC	T100	236 ± 4a	65 ± 13a	N/A [†]
		T70	43 ± 3b	18 ± 3b	N/A
	SSSr	T100	26 ± 3a	10.8 ± 0a	N/A
		T70	5 ± 1b	3.6 ± 1b	N/A
	SSF	T100	59± 2a	14 ± 1a	N/A
		T70	6 ± 0b	8 ± 1b	N/A
Dogona (2009–2010)	IERC	T100	774 ± 25a	29 ± 3a	90 ± 10a
		T70	718± 71a	21 ± 0b	63 ± 4b
		T0	213 ± 16b	12 ± 0c	61 ± 3b
	SSSr	T100	384 ± 15a	6 ± 0a	55 ± 3a
		T70	198 ± 9b	4 ± 0b	48 ± 3b
		T0	107 ± 3c	3 ± 1c	26 ± 3c
	SSF	T100	450 ± 2	12 ± 1a	58 ± 3a
		T70	331 ± 51b	8 ± 1b	57 ± 5a
		T0	190. ± 13c	6 ± 0c	43 ± 4b
Kodeni (2009–2010) ^{††}	IERC	T100	991 ± 9a	75 ± 14a	214±11a
		T70	790 ± 10b	54 ± 2.b	197±3b
		T0	569 ± 17c	41 ± 1c	153±1c
	SSS	T100	519± 6a	53 ± 2a	196±0a
		T70	411± 11b	60 ± 4a	159±2.b
		T0	183±18c	30 ± 3b	90±1c

Mean within columns followed by the same lowercase letters are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test. [†] K was not considered during this cropping season at Dogona; ^{††} at this site, only SSS devices were associated to the resin cartridges.

IERC consistently yielded higher nutrient masses than the other collection devices at both sites and during both cropping seasons. The method relying on a collection vessel (SSSr) yielded fewer nutrients than the one associated with a tipping bucket (SSF) (Table 5.3). At Dogona during 2008–2009, IERC yielded 89% and 88% more NO_3 than SSSr and SSF, respectively. During the second year (2009–2010), these corresponding differences were 60% (for SSSr) and 43% (for SSF). At Kodení, IERC trapped 54% more NO_3 compared to SSSr. The PO_4 trapped onto resins followed a similar pattern. Indeed, the IERC collected 83% (SSSr) and 74% (SSF) more PO_4 at Dogona during 2008–2009, 80% (SSSr) and 62% (SSF) more at Dogona during 2009–2010, and 16% more (SSSr) at Kodení. During the second year, the IERC yielded 40% and 36% (average over all treatments) more K than SSSr and SSF at Dogona, respectively. At Kodení, the corresponding value is 32% when comparing the K collected by IERC to that collected by SSSr.

For all nutrients, treatments also significantly interacted with the lysimeter type at both sites and for both cropping years (Table 5.2). At Dogona, fertilizer reduction by 30% significantly reduced NO_3 leaching by 82% (IERC), 80% (SSSr) and 90% (SSF). The corresponding reduction values for PO_4 were 74% (IERC), 67% (SSSr) and 41% (SSF). During the second year (2009–2010), no significant difference was detected between T100 and T70 in IERC but the T70 treatment yielded 49% and 44% less NO_3 than T100 in SSSr and SSF devices, respectively. The corresponding values for PO_4 were 29% (IERC), 40% (SSSr) and 31% (SSF). Except in SSF devices, the same behavior was observed with K, whose amounts were reduced by 31% (IERC) and 14% (SSSr) when fertilizer input was reduced by 30%.

At Kodení, the same pattern in treatment effect prevailed as at Dogona. Indeed, and except for PO_4 in SSSr, the T100 always exhibited the highest nutrient leaching rates. Fertilizer reduction (by 30%) allowed reducing NO_3^- leaching by 21% (IERC) and 20% (SSSr). Concerning PO_4 , this value was 29% (IERC). Regarding K, leaching was reduced by 9% (IERC) and 19% (SSSr). For all elements and all devices, the T70 presented

nutrient leaching values significantly higher than T0, except for K in the IERC (Dogona 2009–2010) for which no difference was found between T70 and T0.

5.3.3. Leachate collected from sand or mixed-bed ion exchange resin cores

Overall, the nutrient concentration in collected leachate was significantly influenced by fertilizer treatment and sampler type (SSSr and SSSs), except for P at Kodení (Table 5.4). However, there were no significant interactions between treatments and the type of device.

Table 5.4: Statistical analysis (*p-values*) of the flow-weighted concentration (mg l⁻¹) of total N, P and K occurred at the bottom of the resin and sand cartridges (SSS devices) as affected by treatments and sampler type.

Site and year	Source	Df	N	P	K
Dogona (2009–2010)	Treatment (T)	2	0.0011	0.0036	0.0001
	Sampler Type (S)	1	0.0003	0.0105	<.0001
	T x S	2	0.1548	0.0878	0.2414
	Model	5	<.0001	0.0014	<.0001
	Error	30			
Kodení (2009–2010)	Treatment (T)	2	0.0116	0.0035	0.0015
	Sampler Type (S)	1	0.0024	0.088	<.0001
	T x S	2	0.3494	0.7557	0.053
	Model	5	0.005	0.0122	<.0001
	Error	51			

Overall, the leachate collected under the T100 treatment was more concentrated than T70 and T0, regardless of the collection period and type of device (SSSs or SSSr) (Fig. 5.4). The reduction of fertilizer input by 30% led to a reduction of the cumulative mass of leached N by 47% compared to T100 at Dogona. At this site, the cumulative N mass collected at the bottom of the cartridges was reduced by 75% when comparing T0 to T100. The

reduction in the amount of P leached from T70 compared to T100 was less pronounced ($< 10\%$), whereas it was stronger for K, as K losses were reduced by approximately 45% after reducing fertilization by 30%. Similar observations could be made at Kodení where the T70 treatment yielded about 50% less N than T100. Again, the P did not noticeably vary during the sampling period between treatments (Table 5.4). But fertilizer reduction by 30% resulted in a reduction by 17% of the cumulative K mass collected. The extent of P and K reduction in leachate, as induced by T0 treatment (compared to T100), was somewhat lesser (60% and 74% for P and K, respectively) than for N.

When considering the SSS devices, overall a significant difference could be observed between SSSr and SSSs as nutrient concentrations were much lower in SSSr compared to SSSs. Even at the onset of the drainage period, some N and K and to a lesser extent P were collected in the lysimeters below the resin cartridges (SSSr). At Dogona, the amounts collected below the resin cartridges (SSSr) represented about 19%, 17% and 12 % of the total mass of N, P and K that passed through the sand cartridge (SSSs), respectively. At Kodení, the total mass of N collected in T70 under resin cartridges (SSSr) were about 76% less compared to SSSs. Much stronger reduction (about 86%) was observed for the P and K.

The data did not exhibit any clear trend towards an increase in the concentration of nutrients that passed through the resin with time. For instance, at Dogona, during some periods (e.g. 28 September 2009) about 4 mg l⁻¹ of N occurred in the vessels under T100 plot but during the next period the solute concentration in the same treatment dropped to < 1 mg l⁻¹.

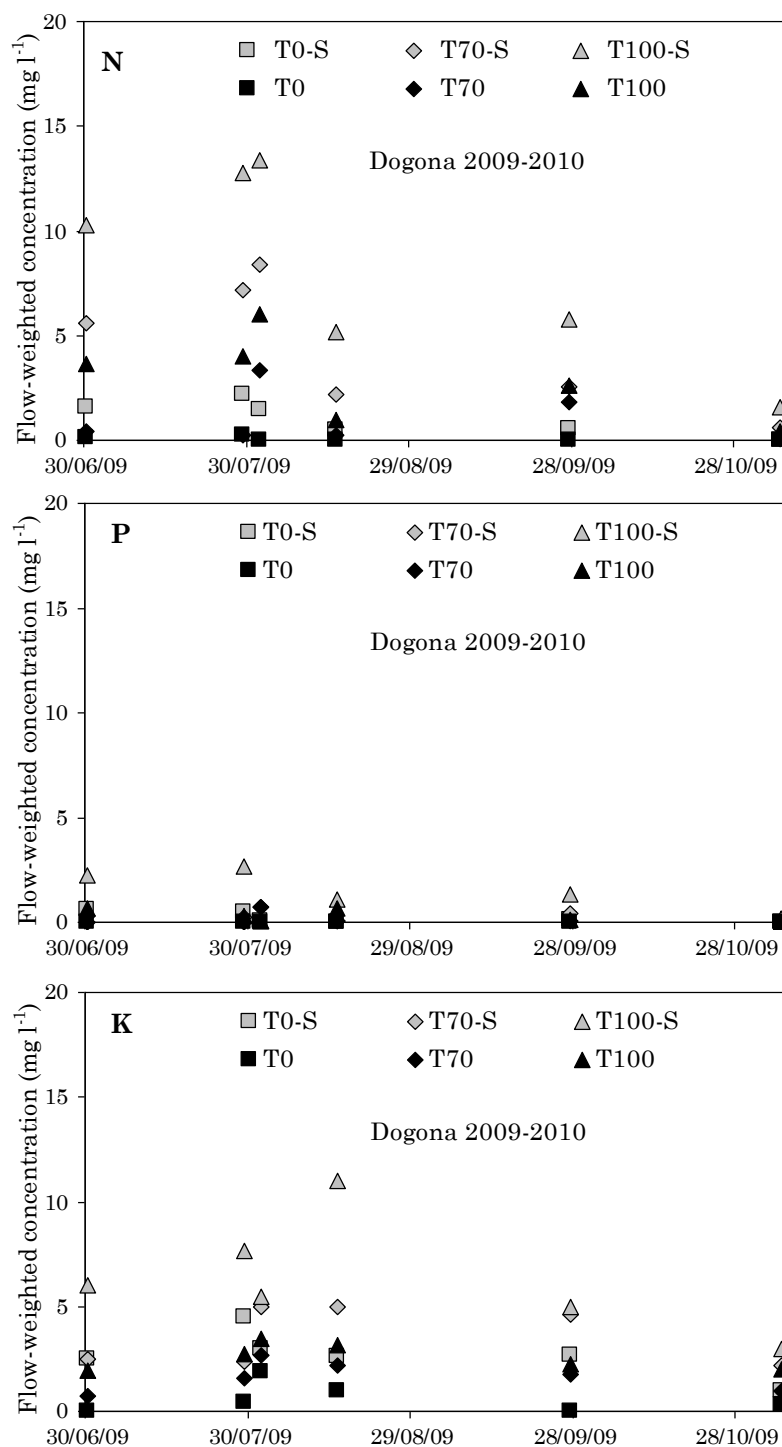


Figure 5.4.A. Effect of fertilizer application rate on volume-weighted mean total N, P and K concentration (mg l⁻¹) in leachate collected at the bottom of the resin and sand cartridges (SSSs and SSSr) at Dogona. T100, T70 and T0 = samplers associated to resin cartridges; T100-S; T70-S and T70-S = samplers associated to cartridges filled with pure sand.

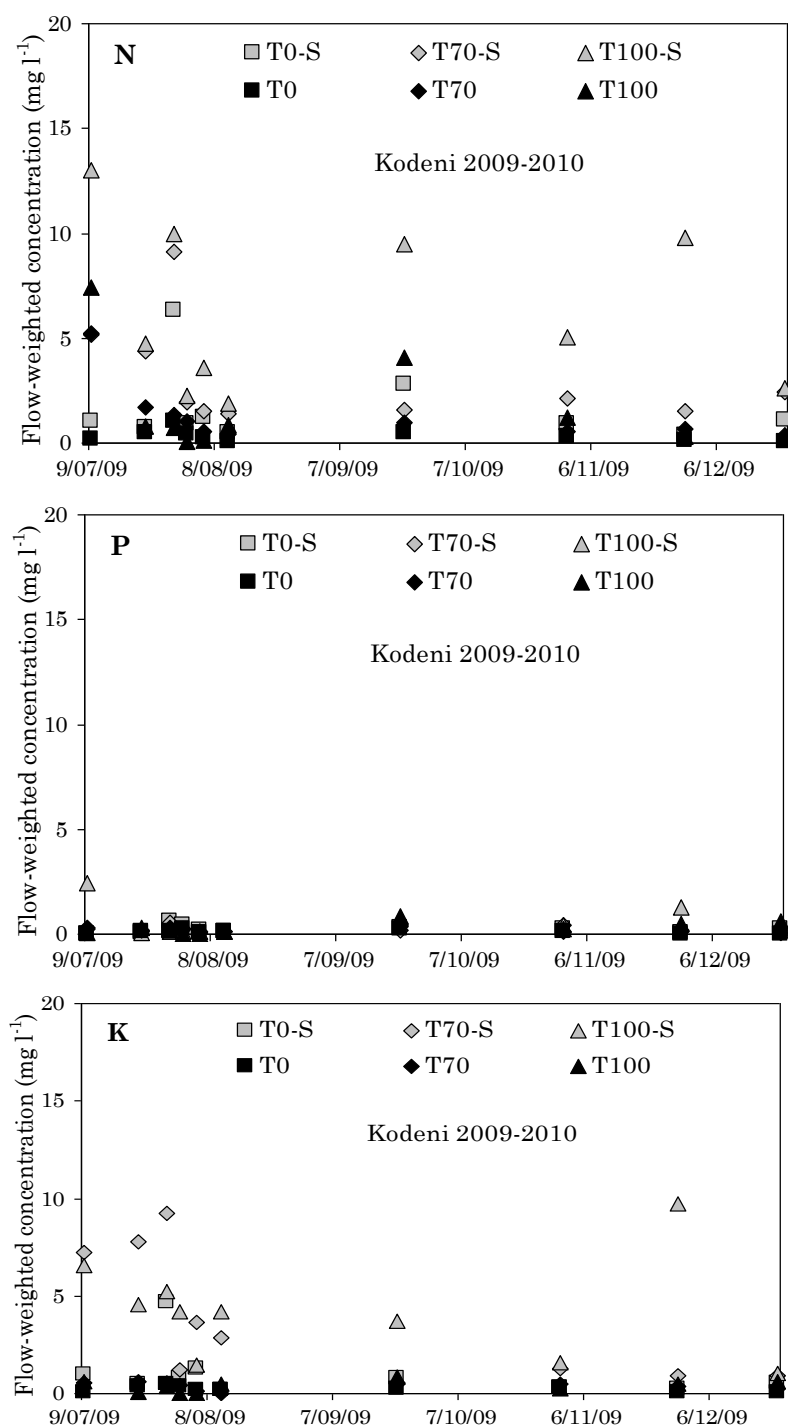


Figure 5.4.B. Effect of fertilizer application rate on volume-weighted mean total N, P and K concentration (mg l⁻¹) in leachate collected at the bottom of the resin and sand cartridges (SSSs and SSSr) at Kodeni. T100, T70 and T0 = samplers associated to resin cartridges; T100-S; T70-S and T70-S = samplers associated to cartridges filled with pure sand.

5.4. Discussion

5.4.1. Drainage measurement and drainage collection efficiency

At both sites, fertilization treatment had no significant effect on the total leachate volume collected for either lysimeter types (Table 5.1). Such findings have been made by other studies (e.g. Gehl et al., 2005). The lack of difference between T100 and T70 is not surprising since plant development was generally not significantly affected by the 30% reduction in fertilization (see Chapter 6). LAI and soil cover, and hence evapotranspiration, were therefore probably not different between T100 and T70. Crop development in T0 was substantially lower compared to T100 and T70. It may therefore be expected that LAI, and hence transpiration losses, must have been lower in T0 compared to the two other treatments. However, this may have been partially compensated for by a higher evaporation due to lower soil cover. Besides these effects, the high variability of drainage amounts, resulting in a large standard deviation, could have masked a possible treatment effect.

The performance of pan lysimeters has been critically evaluated several times under various soil and climatic conditions. In general, lysimeter collection efficiencies have been evaluated by dividing the collected leachate volume by the drainage volume estimated by means of a water balance model (Zhu et al., 2002; van der Velde et al. 2005). By doing so, our results show that the collection efficiency of our devices was very low (about 10%) yet consistent with that of several studies reporting pan lysimeters collection efficiencies ranging from 10 to 58% (Jemison and Fox, 1992; Zhu et al., 2002; Barzegar et al., 2004). For instance, collection efficiencies ranging between 4 to 20% have been reported by Zotarelli et al. (2002) based on drainage lysimeters under pepper and tomato trials in Florida (USA). Therefore, the majority of drainage water seems to have bypassed the pan lysimeters devices. This could be explained by the fact that pan lysimeters collect gravitational water as they require a zero-tension boundary condition (seepage face) for drainage to occur (Barzegar et

al. 2004; Mertens et al., 2006). However, soil water potentials measured in our vegetable gardens were most often less than zero (unsaturated). Indeed, the mean volumetric water content was about $0.29 \pm 0.08 \text{ m}^3 \text{ m}^{-3}$ and $0.32 \pm 0.09 \text{ m}^3 \text{ m}^{-3}$ at Dogona and Koden, respectively. These values seldom approached the saturated volumetric water content which amounted on average to $0.39 \text{ m}^3 \text{ m}^{-3}$ and $0.42 \text{ m}^3 \text{ m}^{-3}$ in the top 0 – 30 cm of the soil at Dogona and Koden, respectively⁵. Saturated conditions occurred essentially during the rainy season at Dogona but also during the dry season at Koden. Therefore, unsaturated soil conditions result in water flowing away from the sampler due to local gradients in matric potential (Jemison and Fox, 1992). This may also explain why the pan lysimeters collected drainage mainly during the rainy season when evapotranspiration was low and when more water was available for transport. At Koden, this period extended into the dry season as a result of the much higher irrigation rates.

The extent of bypass flow depends on the size (Jemison and Fox, 1992; Lehmann et al., 2001) and the number of pan lysimeters used (Zhu et al. (2002)). For instance, a collection efficiency rate of about 40% has been reported by Zhu et al. (2002) based on pan lysimeters of 76 by 61 cm in size. van der Velde et al. (2005) have shown that the collection efficiency of pan lysimeters could be improved when they are equipped with a pipe of 20 to 60 cm length that extends from the top of the funnel and filled with the same soil to minimize divergence. This allowed them to obtain collection efficiencies ranging between 92 and 129% with pan lysimeters of 31.5 cm diameter. In our devices, the length of the pipe extends for 10 cm above the free seepage face and was filled with sand, which reduces the contact with the top soil compared to those lysimeters of van der Velde et al. (2005) filled with repacked soil.

⁵ The water retention curves of both sites are presented in Appendix C.

5.4.2. Nutrient leaching

In the first year at Dogona, the resins trapped on average 10 times more NO_3 than NH_4 (Data not shown). This agrees with several previous studies which showed significantly lower amounts of ammonium ions in soil solution than nitrate (Kjonaas, 1999a, b; Lehmann et al., 2001; Predotova et al., 2010, Zhao et al., 2010). In our case, this may be linked to the rapid nitrification of ammonium into nitrate, given the well-drained soils and high temperatures. The lower concentration of ammonium entering the resin cartridges could also be linked to the fact that ammonium ions are positively charged and hence adsorb to the negatively-charged exchange complex of the soil; while nitrate virtually does not adsorb to the complex (Jalali, 2000; Wilcke and Lilienfein, 2005). Some ammonium may also be lost by volatilization in the form of ammonia gas (e.g. Predotova et al. 2011). Furthermore, the preferential adsorption of polyvalent cations (especially Ca^{2+} in our soils) onto the ion exchange resin can reduce adsorption of monovalent cations such as NH_4^+ (e.g. Skogley and Dobermann, 1996)

The N leaching values under gardeners practices (T100) in this study ($53 - 223 \text{ kg N ha}^{-1}$) by far exceeded the 5.9 kg N ha^{-1} measured by Predotova et al. (2011) in similar intensive vegetable gardens of Niamey (Niger) that the authors suggested more related to the low rainfall and the low irrigation intensity during their study period. Furthermore, Tamini and Mermoud (2002) observed $17.6 \pm 7.5 \text{ kg N ha}^{-1}$ leaching under gardeners managed onion field typically using $90 \text{ kg NPK ha}^{-1} + 20 \text{ t FYM ha}^{-1}$ and applying average irrigation amount of 8 mm d^{-1} . These differences with our results reflect the variability of practices from one site to another; they also depend on the performance of the tools used to monitor the leaching.

The performance of the various nutrient leaching monitoring devices has often been tested by comparing the results obtained with different devices (e.g. Siemens and Kaupenjohann, 2004; van der Velde et al., 2005). The statistical comparison of devices used in this study showed that there were significant differences in the mass of trapped nutrients between

devices (Table 5.2). Resin associated to pan lysimeters (SSF and SSSr) consistently yielded significantly lower amounts of nutrients than the IERC. The lower mass of nutrients trapped in SSF and SSSr could be, partly, linked to the lower volumes of drainage water that passed through the SSS devices compared to SSF (Table 5.1, Fig 5.1 and Fig. 5.2). Furthermore, Flury et al. (1999) demonstrated through a numerical evaluation that the saturated zone above the sampler not only had a large effect on the sampled flux but also influenced the solution concentration (dilution of the solution) of the sampled leachate. Finally, the total mass of leached nutrients trapped by the resins were lower than what could be expected based on the large excess fertilization observed for both gardens in T100 as reported by Sangare et al. (2012). Indeed, the surpluses amounted to 1123 kg N and 331 kg P ha⁻¹ at Dogona and 2012 kg N, 379 kg P and 738 kg K ha⁻¹ at Kodení. A share of this nutrient surplus contributed to the soil's enrichment (see Chap. 6) and a substantial amount of nitrogen (e.g. NH₃-N and N₂O-N forms) may have been lost through gaseous emission. For instance, Predotova et al. (2010) reported about 92 to 101 kg N ha⁻¹ year⁻¹ emission (from NH₃-N and N₂O-N sources) in vegetable gardens in Niamey typically receiving between 781 and 3800 kg N ha⁻¹ year⁻¹. This is especially applicable to the garden in Kodení where a lot of urea (average 447 kg ha⁻¹) was applied throughout the cropping season. Nevertheless, one would still expect larger losses than what has been measured. All of these conclusions tend to show that the pan lysimeters underestimate the true extent of the nutrient leached in our study.

The IERC seems to be more effective at trapping ions from soil solution than SSSr and SSF. Indeed, significantly higher nutrient masses were trapped onto the resin compared to SSF and SSSr. This suggests that more solution passed through the IERC cartridges. These three devices differed in terms of the boundary conditions at the bottom of cartridges. In fact, during installation, the top and bottom of the IERC cartridges were filled with sand in order to ensure a good contact between the soil and the extremities of the resin cartridges. This procedure is critical to minimize

flow disturbance and to increase the similarity of hydraulic properties between resin core and the surrounding soil (Hagedorn et al., 1997). On the contrary, the bottom of the SSF and SSSr devices was isolated from the underlying soil (see Fig. 3.5) and therefore, water has to overcome the soil matric potential to enter the collector. In contrast, the IERC does not necessarily require a seepage face before solute can drip into the cartridge. Furthermore, under our study conditions, most drainage occurred during the rainy season when soil was saturated or nearly saturated (Fig. 5.1). Under such conditions, the difference in water suction between the resin–sand mixture and the surrounding soil may be small and hence have little effect (Lehmann et al., 2001).

Given the high exchange capacity of the resin, it is generally assumed that almost no ions percolate through the resin cores (e.g. Wilcke and Lilienfein, 2005). Whereas Schnabel (1983) found that 99% of added nitrogen (N) was adsorbed by ion exchange resins, Wyland and Jackson (1993) reported an 85% average adsorption rate of nitrogen (N) percolated through the resin cores. Our results are more in line with the latter study. Indeed, some amount of N and K and to a much lesser extend P were detected very early in the collection vessels fixed at the bottom of the resin cartridges (Fig. 5.4). This occurred at a period when the exchange sites of the resin were not supposed to be saturated. As a matter of fact, layer by layer analysis of the resins indicated that the resin was never fully saturated, i.e., the concentration profiles in the resins showed a strong decrease with depth over the first 7.5 cm of resin. This leads us to hypothesize that the leached nutrients not retained by IER may have been predominantly in organic form.

At our study sites, soils are characterized by a low clay content dominated by low–activity clay (kaolinite). Consequently, K^+ does not interact strongly with the soil matrix, and the relatively high concentrations of Ca^{2+} as a competing ion result in an increase in K^+ concentration in the soil solution (Kolahchi and Jalali, 2006; Jalali et al., 2010). This, in conjunction with the higher affinity of resin for Ca^{2+} compared to K^+

(Skogley and Dobermann, 1996), could explain the high and early occurrence of K in the solution collected by the SSS devices (Fig. 5.4). Furthermore, the examination of Fig. 5.4 shows that there was no trend towards a gradual increase in the leachate's nutrient concentration that could suggest any progressive exhaustion of the resin's adsorption capacity. The occurrence of nutrients in the leachate below the resin seems to be more related to high drainage periods and possibly high nutrient concentrations therein (following fertilization events) rather than a progressive saturation of the resin's exchange sites. This is supported by the study of Siegfried et al. (2011) which showed that the adsorption rate of $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$ and K onto resins is significantly constrained by water flow rate and the ion concentration in the solution.

Although these losses of nutrients at the bottom of the resin represent a small part of the nutrients effectively retained by the resin, the total mass that could effectively have leached through the resin is strongly underestimated. Indeed, our results from Fig. 5.2 showed that the drainage volume collected in SSS devices represents less than 10% of the effective drainage that may have occurred at these sites (comparison with water balance data). In addition, the analyzed samples represent about 65% of the total sample volume collected given that some drainage events did not deliver a sufficient volume of water for chemical analysis.

The high nutrient leaching observed under farmer management (T100) raises serious concerns about possible groundwater contamination. However, reducing fertilization by 30% may be an efficient means of reducing this potential threat. Indeed, leaching losses in T70 were significantly lower than in T100. Therefore, fertilizer reduction could significantly reduce the potential nutrient leaching and therefore reduce the potential threat involved in urban vegetable production.

5.5. Conclusions

Nutrient losses from agriculture can cost farmers dearly and pose a serious threat to receiving water bodies. Several authors stressed that root zone nutrient leaching measurements are needed to improve fertilizer management in areas where agricultural may be impacting groundwater supplies. To quantify leaching of nutrients, simultaneous measurements of both water flux and nutrient concentration therein are required. To do so, a consistent quantitative characterisation of the vertical leaching of nitrogen (N), phosphorus (P), potassium (K) in the soil of two types of vegetable cropping system was performed at Bobo Dioulasso. In this research, two approaches have been used to monitor the water flow and solute transport at the field scale. The first approach was based on the measurement of drainage using two types of pan lysimeters (SSS and SSF). The results from these devices were compared with data generated by simple soil water balance relationship. The second approach was performed concomitantly to the first approach and consisted in the monitoring of nutrient leaching by using ion exchange resin cartridges (IERC) in addition to the analysis of solution collected by the SSS devices.

Our results suggest that a fraction of the drainage water was diverted from the samplers, resulting on very low collection efficiency (about 10%). The diversion magnitude was more pronounced for Pan Lysimeter than for IERC due to the difference hydraulic functioning of these devices. Nevertheless, based on results from SSS and SSF one can notice that gardener's management practices resulted in the leaching of 25 to 519 kg $\text{NO}_3 \text{ ha}^{-1} \text{ year}^{-1}$, 6 to 65 kg $\text{PO}_4 \text{ ha}^{-1} \text{ year}^{-1}$ and 54 to 214 kg $\text{K ha}^{-1} \text{ year}^{-1}$ across both sites. Results also suggested that IERC performed more efficiently than pan lysimeters devices, as IERC collected much more nutrients (>65 %) than pan lysimeters. The amount of NO_3 collected by IERC during one year reached up to 10-times the mass of nutrients collected in SSF devices. Some leaching of nutrient occurred at the bottom of SSSr devices, possibly under organic form. Based on the observations, the

treatment that consisted in a reduction of fertilization rate by 30% significantly reduced the amount of nutrients leaching below the rooting zone. Such reduction would mean a lower risk of groundwater pollution by these nutrients.

While our results provide evidence that the efficiency of pan lysimeters was very low, the current study lacks details to correctly evaluate the hydrological functioning of the devices used to monitor nutrient leaching in order to improve their efficiency. Therefore, for future studies, it would be useful to confront the results obtained with field measurement methods with those generated by a hydrological model.

Chapter 6

Reduced fertilization as an option for improving nutrient use efficiency in urban vegetable production systems in West Africa

Abstract

With its typically heavy use of agrochemicals, untreated municipal waste and sewage as inputs for crop and vegetable production, UPA bears severe risks of soil and ground water contamination. Therefore, efficient nutrient management strategies are needed to enhance the sustainability of this type of agriculture. This study aimed at investigating the impact of a reduction in fertilizer application rates on crops yield, water use efficiency and NUE as well as on soil chemical properties and soil nutrient balances. In two representative gardens of Bobo Dioulasso, vegetable crops were evaluated under three treatments: gardener's fertilization practice (T100), 30% reduction in fertilizer input (T70), and no fertilization (T0), during 12 to 24 months. The results suggest that nutrient inputs may be reduced by 30% (T70) without significant ($P < 0.05$) adverse effect on yields and that the initial nutrients in soil can support at least one cropping cycle before fertilization is required. Indeed, fresh matter (FM) yields in T70 were not significantly different from yields achieved in T100 at both sites. On the contrary, FM yields in T0 were significantly lower than T100. WUE was not

affected by a 30% reduction in nutrient application rates since the same amount of irrigation water was allocated to T100 and T70 and yields were unchanged. On the contrary, reducing fertilization by 30% (T70) significantly increased partial factor productivity of N, P and K by about 20 to 50% at Dogona and 20 to 45% at Kodení depending on crop type and period, compared to T100. Both T100 and T70 favoured positive N and P balances in soil, but reducing the input rate by 30% (T70) allowed a significant reduction of soil N and P surpluses. Indeed, a reduction of 23% of N, 39% P was found for T70 at Dogona compared to T100 during the first year. At this site, during the second year (2009 – 2010), T70 reduced the K negative balance by about 48% compared to T100. Such a reduction had significant repercussions on soil nutrient status. For instance, at Dogona, the 30% fertilizer reduction allowed to reduce N accumulation in soil by about 673 kg N ha⁻¹ compared to T100, during the second cropping year (2009–2010). Furthermore, the fertilizer reduction significantly reduced the available PO₄, K⁺ and N in soil. It appears therefore that in the two gardens studied here, reducing nutrient application rates by 30% could lead to reduced environmental impact and lower costs of investment in fertilizers without adverse effect on yields.

Key words: urban horticulture, resource management, nutrient leaching, soil and groundwater pollution, production quality.

6.1. Introduction

The multipurpose role of urban and peri–urban agriculture (UPA) as an alternative livelihood strategy favored by the fast growing urbanization worldwide is well acknowledged (FAO, 2007; van Veehuizen and Danso, 2007; De Bon et al., 2009). However, concerns have been raised regarding the sustainability of this agricultural production system. These concerns relate to health issues (food contamination by pathogens or heavy metals)

(Qadir et al., 2010; Nafiu et al., 2011 and references therein) as well as negative environmental externalities (surface and groundwater pollution by agro-chemicals) (Ju et al., 2009; Nyenje et al., 2010). For instance, there is an abundance of scientific references highlighting nutrient management practices that are not agronomically and environmentally sound within most intensive UPA areas (Matsumoto et al., 2000; Zhao et al., 2010). In particular, the use of large amounts of organic and inorganic fertilizers, well in excess of crop recovery, has become an integral part of conventional vegetable production areas, among others in West African cities (Dresch et al., 2006; De Graefe et al., 2008; Diogo et al., 2010).

Summarizing results from several countries worldwide it may be considered that currently only 40 to 80% of the N and 45 to 60% of the P applied within intensive UPA areas are used by plants (e.g. Ju et al., 2009; Nyenje et al., 2010; Widowati et al., 2011). Furthermore, nutrient input data from several studies worldwide suggest that gardeners' fertilization practices generally bear no relationship with inherent soil fertility (e.g. Widowati et al., 2011; Sangare et al., 2012 and references therein). Because of the lack of extension advice for fertilization of vegetable crops and difficulties for farmers in estimating accurately the effective crop nutrient requirements (Ju et al., 2007) as well as the nutrient content of the amendments that are being used (Sangare et al., 2012), gardeners are inclined to apply excessive quantities of fertilizers as a rule of thumb to obtain maximum yields, thereby avoiding the risk of yield loss (Zotarelli et al., 2007; Ju et al., 2009).

As elsewhere in Sub-Saharan Africa, UPA is a key agricultural sector in Burkina Faso and occupies an increasing part of the cities' landscape. For instance, Kedowide et al. (2010) reported that vegetable cultivation areas increased by 225% from 1996 to 2009 in the capital city Ouagadougou. A high economic value is also attached to UPA activities as UPA products rank second in terms of export after cotton (*Gossypium hirsutum*) (FAO, 2011). And as elsewhere, vegetable production in Burkina Faso is characterized by the use of excessive amounts of fertilizers manure or

compost ([Eaton and Hilhorst, 2003](#); [Kiba et al., 2012](#); [Sangare et al. 2012](#)), domestic solid wastes ([Kabore et al. 2010](#); [Kiba et al. 2011](#)) and wastewater ([Akponikpe et al. 2011](#)). Furthermore, the occurrence of deep drainage below the rooting depth has been reported during the rainy season, and sometimes also during the dry season depending on irrigation practices ([Tamini and Mermoud, 2002](#); [Sangare et al. 2012](#)). Consequently, despite the semi-arid climate, the excess application of nutrients in this region is likely to cause undesirable human and environmental impacts from nutrient leaching toward groundwater.

The UPA's sustainability is therefore being questioned in this region and a major challenge is to promote production practices that could help optimize the trade-offs between agronomic benefits and environmental protection through better nutrient management. However, in Burkina Faso, owing to the predominance of the rural low input rainfed cereal production systems and to the informal character of the UPA, most efforts have been put into designing cropping systems and fertilization strategies which enhance cereal crop productivity (e.g. [Bonzi et al. 2003](#); [Zougmore et al. 2004](#)). Few, if any, attempts have been made to reduce fertilizer input within the intensive UPA systems.

During the past decade, the concept of nutrient use efficiency (NUE) has been considered as the best way to improve the sustainability of agricultural systems ([Tilman et al., 2002](#); [Dobermann et al. 1996](#); [FAO, 2006](#)). NUE can be defined in many ways depending on the perspectives, but the general principle is to ensure that maximum yield is achieved per unit mass of each nutrient applied ([Tilman et al., 2001](#)). Frequently, fairly complex fertilizer scheduling strategies ([Cassman et al., 1998](#)) are being promoted. However, the diversity of vegetable crops being grown in UPA as well as the variety of amendments used and the low level of education of most UPA farmers undoubtedly calls for simpler approaches.

One such approach would be to exploit the residual nutrients stored in the soil in combination with a reduction in fertilization. This has been studied, for instance, in cereal cropping systems (e.g. [Sorensen, 1993](#); [Ju et](#)

al. 2009). However, the issue of reducing fertilization rates or even of exploiting the residual soil nutrients in UPA does not seem to have been addressed so far in West Africa and particularly in Burkina Faso. The main objective of this paper was therefore to explore the potential of reducing or interrupting fertilization in UPA so as to improve on-farm nutrient use efficiency, while maintaining vegetable yields and reducing the negative externalities. As a consequence, this study aimed at investigating the impact of a reduction, or even an outright interruption, in fertilizer application rates on crops yield, water use efficiency and NUE in a farmer-managed vegetable cropping system. The effect of the fertilizer reduction strategies on soil chemical properties and soil nutrient balances was also investigated. The monitoring was carried out at two sites with different crop rotation and over a period of one to two years.

6.2. Materials and Methods

6.2.1. The related dataset

In this chapter, the gardener's fertilization practices (T100) was compared to the reduced fertilization practices (T70 and T0) (see Chapter 3). It makes use of the fertilization and yield data from these three treatments. Data relative to crop yield and fertilizer input were collected as described in section 3.8. However, the comparison of treatment effects on the soil nutrient status focused especially on the T100 and T70 treatments because some nutrients were added in the T0 treatment at Dogona as described in section 3.3.1. Details about the methods of analysis of soil, plant and fertilizer nutrient content can be found in section 3.7.

The nutrient leaching data are those measured with the IERC resin cartridges (see §3.5.1), given that this method appears to yield the most representative leaching data. In order to estimate the mass of leached nutrients during each crop cycle, it was assumed that leaching into the

IERC occurred exclusively during periods of free drainage as recorded by the soil solute collection devices (SSF and SSS, see §3.5.2).

The total amount of nutrient leached during each cropping year as determined from the IERC was then divided by the total volume of drainage, which yielded a mean concentration. Subsequently the mean concentration was multiplied by the volume of drainage occurred during each crop cycle to obtain the total mass of nutrients leached during each cropping cycle.

In this chapter we also use the gaseous N losses dataset of [Lompo \(2012\)](#), performed within the same gardens, to complete the field-scale nutrient balance. Statistical inferences about the effects of changing fertilization rate on crop yields, nutrient balance and soil nutrient storage are finally drawn.

6.2.2. Mineralization model description and assumptions

The mineral fertilizers are mainly applied under urea and compound NPK. It has been assumed that 100% of the nutrients input through mineral fertilizers become immediately available for plant uptake, whereas organic matter-derived nutrients are released through decomposition and mineralization of the organic matter. To predict the release of nutrients from organic matter, we considered a simple mineralization model ([Fig. 6.1](#)).

The release of nutrients from the soil organic pool was assumed to occur from two sub-pools (manure and humus) and the transfer between these sub-pools is controlled by first-order rate degradation constants (referred to as k_{man} and k_{hum} respectively). The soil litter pool is not considered here. Before solving the mineralization equation, the initial soil organic matter pool was distributed over these two pools. As for [Paul and Juna \(1981\)](#), we assumed that 92% of the initial soil organic matter is situated in the stable humic pool (stable fraction) ([Fig. 6.1](#)). The remaining soil organic matter is in the manure pool (labile fraction). The organic amendment inputs enter the system through the soil labile carbon pool.

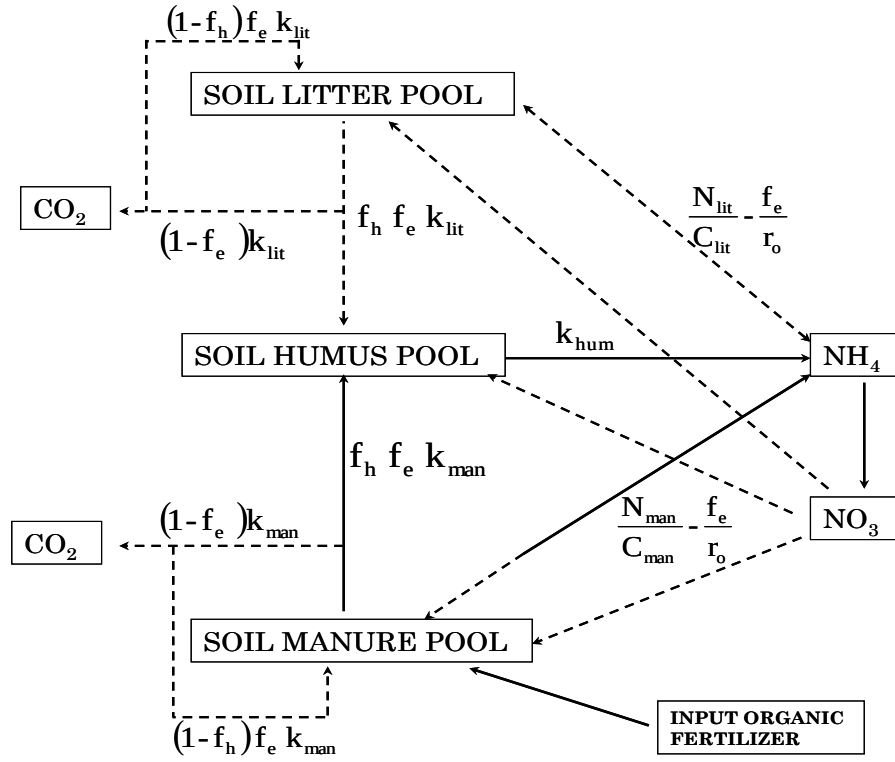


Figure 5.1. Organic matter turnover concept as applied to the nitrogen fate module in the WAVE model. Only the lower loop is concerned by our study. The continuous lines represents the processes considered in this study. Adapted from [Vanclooster et al. \(1995\)](#).

The fraction of C in a specific pool which is turned over during a specified period of time, t (day) is expressed by a first order decay model as given in Eq. 6.1.

$$\frac{\partial C}{\partial t} = -kC \quad 6.1$$

in which C is the carbon content of the targeted pool (kg C ha⁻¹ soil) and k is the mineralization rate constant of the concerned soil organic matter (day⁻¹).

From Eq. 6.1, it follows that the fraction of the soil humus pool which is turned over during a specified period of time, t (day) can be written as:

$$\frac{\partial C_{hum}}{\partial t} = -k_{hum}C_{hum} \quad 6.2$$

with C_{hum} the carbon content of the humus pool (kg C ha^{-1} soil) and k_{hum} is the decomposition (mineralization) rate of the humus pool (day^{-1}).

The turnover of the carbon in the soil manure pool is represented by the lower loop in Fig. 6.1. The turnover efficiency f_e (–) determines which fraction of the manure is effectively transformed into new organic matter through the biomass and which fraction is decomposed into CO_2 . A part of the soil manure which is turned over goes to the humus pool of the soil. This fraction is controlled by the humification coefficient (f_h). Hence the net change of C in the manure pool is written as:

$$\frac{\partial C_{man}}{\partial t} = [(1 - f_h)f_e - 1]k_{man}C_{man} \quad 6.3$$

where C_{man} is the C content (kg C ha^{-1}) in the manure pool and k_{man} is the decomposition rate of the manure pool (day^{-1}). In this study, it is assumed that $f_e = 0.6$ (Dendooven, 1990) and the $f_h = 0.2$ (Vanclooster et al. 1995).

From Fig. 6.1, it can be seen that the net rate of change of the C in the humus pool is written as:

$$\frac{\partial C_{hum}}{\partial t} = f_h f_e (k_{man}C_{man}) - k_{hum}C_{hum} \quad 6.4$$

In this study, we assumed average daily k_{hum} (mineralization rate of the stable pool) of $0.0000682 \text{ day}^{-1}$ (corresponding to 2.5% per year) as proposed by several studies for tropical soils (e.g. FAO, 2003). The k_{man} –

values (mineralization rate of the labile pool) were derived from several studies of soils incubation (at 30°C). The synthesis of these results yields an average k_{man} -value of $0.033 \pm 0.013 \text{ day}^{-1}$ (e.g. [Sedogo, 1993](#); [Bacyé et al., 1998](#); [Pallo et al. 2008](#)). Like all chemical and biochemical reactions, the mineralization process is moisture and temperature-dependent. In order to account for the effect of soil temperature on the organic matter turnover, each k was corrected using a nonlinear temperature dependence equation ([Das et al. 1995](#)). The temperature sensitivity of the mineralization rate k is often expressed as a Q_{10} coefficient (Eq. 6.5), where Q_{10} expresses the change in a constant associated with a 10°C change in temperature.

$$\frac{k_T}{k} = Q_{10}^{\left(\frac{T-T_{30}}{10}\right)} \quad (6.5)$$

where k_T is the modified rate constant adjusted for field soil temperature T (°C); k is the rate constant at the reference temperature T_{30} (30°C).

A widely accepted rule of thumb is that the rate of decomposition of SOM tends to double or triple for every 10°C rise in soil temperature, that is, the Q_{10} for decomposition is of the order of 2 to 3 (e.g., [Davidson and Janssen 2006](#)). In our calculation a $Q_{10} = 2$ was considered for an average soil temperature of 30 °C, as reported in several studies (e.g. [Stanford et al. 1973](#); [Van Keulen, 2001](#); [Davidson and Janssen, 2006](#)).

At Dogona, the field soil temperature measurements were obtained with four thermocouples (Thermocouples 105T of Campbell Scientific, Logan, Utah, USA) embedded at 7.5 cm depth. Average soil temperature data were measured and saved every 5-min with the CR1000 (Campbell Scientific Inc., Logan, Utah, USA). At Koden, a multi-digital thermometer (Carl ROTH GmbH & Co, Karlsruhe, Germany) was used to record the soil temperature at 0.10 m depth twice a day, during the cool morning hours (5:00–7:00 am) and in the hot afternoons (1:00 – 3:00 pm).

Furthermore, the nutrient mineralization rate was adjusted for soil water content by the relationship between relative nutrient mineralization and relative available soil water content as described below (Mikha et al. 2006):

$$y = bx + (1 - b)x^2 \quad (6.6)$$

where y is the net mineralization expressed as a fraction of the maximum rate; b is a coefficient considered equivalent to 1 according to Myers et al. (1982).

The water-related correction factor x is written as follows (Paul et al. 2003):

$$x = \frac{(M - M_0)}{(M_{\max} - M_0)} \quad (6.7)$$

where M is the actual soil moisture content ($\text{m}^3 \text{m}^{-3}$); $M_{\max}$ and M_0 are the maximum and minimum soil moisture content ($\text{m}^3 \text{m}^{-3}$), respectively.

For this study $M_{\max}$ and M_0 were derived from the moisture retention curve (see description in section 3.10). For the 0–30 cm depth, average $M_{\max} = 0.39 \text{ m}^3 \text{m}^{-3}$ and $M_0 = 0.10 \text{ m}^3 \text{m}^{-3}$ at Dogona, and $M_{\max} = 0.42 \text{ m}^3 \text{m}^{-3}$ and $M_0 = 0.16 \text{ m}^3 \text{m}^{-3}$ at Koden. The actual soil moisture at 7.5, 15 and 30 cm depth content data were obtained from TDR and gravimetric water content measurement as described in section 3.4.3.

The nutrient demand for the internal cycling of C and for instance N in the different pools is regulated by a constant C/N ratio which is identical for the soil biomass and the metabolization products (Duwig et al., 2006). This C/N ratio controls the soil mineral nitrogen release from the two organic pools (manure and humus) of the soil. The release of P and K is controlled by their C: P or C: K ratios. The values of the C: N, C: P and C: K

ratios used for each of the organic amendment sources used in the model are presented in Appendix 4a.

6.2.3. Data treatment and statistical analysis

All statistical analyses were performed using SAS® 9.2 software (SAS Institute Inc., Cary, North Carolina, USA) based on a complete randomized experimental design. The Shapiro–Wilk W test was used to test significant deviation from normality of the data set. The yield and WUE from the T100 treatment were compared with the reduced fertilization treatments T70 and T0, whereas the PFP of T100 was compared to T70 only. Since these data did not always meet the hypotheses underlying the ANOVA, non-parametric analyses were performed with the Kruskal–Wallis rank sum test. A modified [Elliot and Hyman \(2011\)](#) SAS® macro for Dunn’s pair-wise comparisons, with T100 set as control, was implemented to compare treatments in case of significant ($P < 0.05$) treatment differences. A Mann–Whitney–Wilcoxon Test was used to compare PFP values between T100 and T70.

The relationship between the amount of each applied nutrient (N, P and K) and crop yield was fitted by a generalized linear fixed-effects model using the PROC GLM procedure in SAS ([Davis, 2002](#)). As nutrient inputs were very often in excess of plant uptake ([Sangare et al., 2012](#)), a carryover (residual) effect due to previous fertilizer applications could act in conjunction with the nutrients applied during the cropping cycle to determine yield response ([Park et al., 2011](#)). The model used, therefore, allows drawing inference about yield considering the direct and carryover effects of fertilizers. It was written as:

$$Y_{i,j} = \mu + \tau_{i,j} + \rho_{i-1,j} + \lambda_{(i,j)(i-1,j)} + \varepsilon_{i,j}, \quad (6.8)$$

where $Y_{i,j}$ represents the yield; μ stand for the overall mean, τ_i denotes the direct effect of the treatment assigned during i th period

to the j th plot; $\rho_{i,j}$ indicates the first-order carry-over effect of the treatment applied in the previous period ($i-1$) to the j th plot and $\rho_{1-1,j} = 0$ for $i=1$; $\lambda_{(i,j)(i-1,j)}$ captures the interactions produced by direct and carryover effects. The $\varepsilon_{i,j}$ are independent and identically distributed Gaussian random error terms.

Only the T100 and T70 treatments were considered and the model was run separately for each treatment. At Dogona, the model was run taking into account data from the two years of experimentation. For a given crop cycle, the amount of nutrient carried over from the previous cycle was determined on the basis of the nutrient balance from the previous cycle as explained in section 6.2.1.

For the repeated measures of soil pH, CEC, exchangeable K (Ex-K) and P Bray I, analysis of variance was used to determine whether the fertilization affected the dynamics of these soil parameters over time (GLM procedure with ordinary least squares estimation; Davis, 2002). The Least Square Means of fixed effects was pair-wise compared. The significant p -values were adjusted with Bonferroni α -level adjustment for 3 pairwise comparisons. Analysis of variance was carried out for soil nutrient stocks and nutrient content in the soil profile data using the GLM procedure. Welch's correction was made where the homogeneity of the variance assumption was violated, according to Levene's test. Treatment averages were separated using Duncan's multiple range tests considering differences to be significant at $P \leq 0.05$.

6.3. Results

6.3.1. Crop yields, water use efficiency (WUE) and partial factor productivity (PFP)

With few exceptions, FM yield did not exhibit significant differences between T100 and T70 according to the statistical analysis. The significant

differences occurred during cabbage–1 (T100 > T70) and carrot–2 (T100 < T70) at Dogona (Fig. 6.1A) and during lettuce–7 and lettuce–8 (with T100 yield being higher than T70 by 10% and 14%) at Kondeni (Fig. 6.1B).

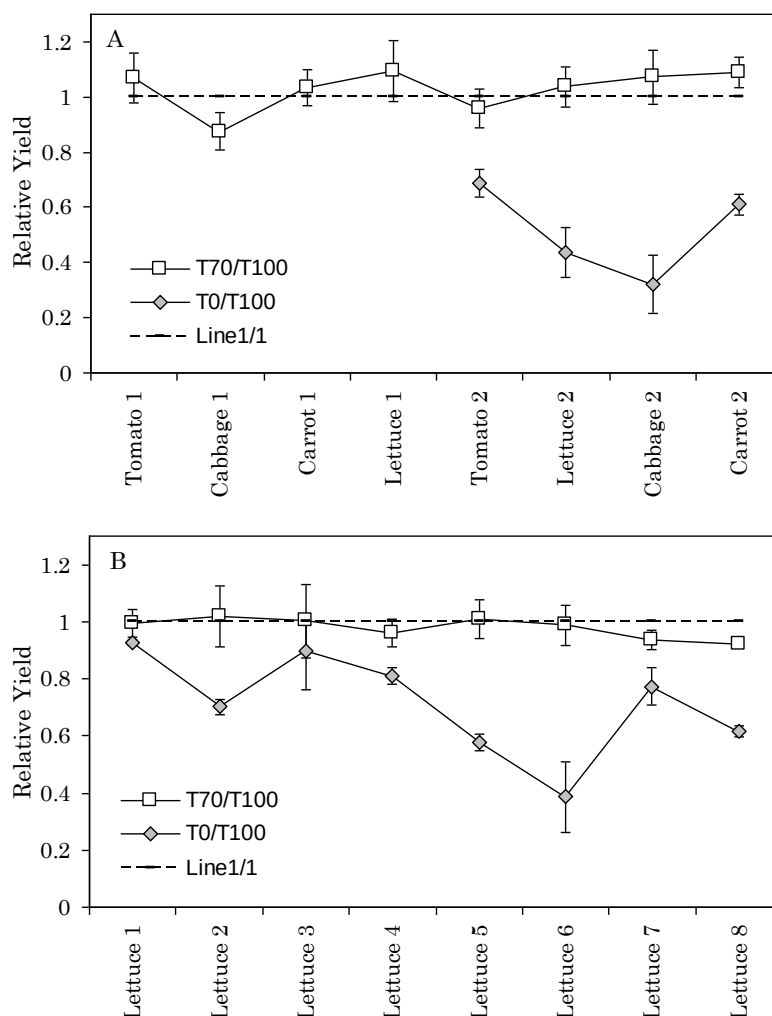


Figure 6.1. Fresh matter yields of T70 and T0 relative to T100 for the crops at Dogona (A, 2 years) and Kondeni (B, 1 year). Vertical bars denote standard deviation.

At Dogona, interrupting fertilization (T0) immediately resulted in a severe yield loss of crops which ranged from –35% for tomato–2 to about –70% for cabbage–2 (Fig. 6.1A). Lettuce yield dropped by 42% as off the second lettuce crop compared to T100 (Fig. 6.1B). This yield loss being unacceptable for the farmer, it was decided to apply fertilizers for the third lettuce crop at the same rate as T100. This allowed yields to recover within

nearly 85% of the T100 treatment. Thereafter, yields again dropped sharply and reached < 50% of T100 for lettuce–6. Again, fertilizer was applied and yields reached up to 80% of the yield achieved with T100. In the absence of fertilization, the next lettuce crop (lettuce–8) again showed significantly lower yields (– 40%) than T100. Overall, FM yield values in T0 were significantly lower than T100, except during the first lettuce cycle after interruption (lettuce–1) and during the lettuce–3 cycle when yields in T0 were statistically similar to T100 (Fig. 6.1B).

Table 6.1. Results (*p-values*) of the non-parametric comparisons between treatments with T100 as control, based on Dunn’s method for fresh matter (FM) yield and water use efficiency (WUE) and the Mann–Whitney–Wilcoxon test for the partial factor productivity (PFP).

Site and Season	Crops	FM yield or WUE		PFP
		T70 – T100	T0 – T100	T70 – T100
Dogona (2008 – 2009)	Tomato–1	0.076	N/A [†]	0.004
	Cabbage–1	0.010	N/A	0.004
	Carrot–1	0.261	N/A	0.003
	Lettuce–1	0.106	N/A	0.003
Dogona (2009 – 2010)	Tomato–2	0.916	0.008	0.002
	Lettuce–2	0.911	0.013	0.003
	Cabbage–2	1.000	0.008	0.005
	Carrot–2	0.003	0.013	0.004
Kodeni (2009 – 2010)	Lettuce–1	1.000	0.062	0.030
	Lettuce–2	1.000	0.013	0.021
	Lettuce–3	1.000	0.191	0.030
	Lettuce–4	0.625	0.010	0.021
	Lettuce–5	1.000	0.008	0.020
	Lettuce–6	1.000	0.001	0.020
	Lettuce–7	0.038	0.026	0.030
	Lettuce–8	0.028	0.016	0.032

[†]N/A = not applicable. T0 treatment was not implemented in 2008 – 2009.

The results for WUE were identical to those of crop FM yields (Table 6.1). Since the same amount of irrigation water was allocated to all treatments and WUE is calculated on a FM basis, differences in WUE

directly reflect differences in FM yields. No statistically significant differences were observed between the T100 and T70 treatments for most crops regarding total above ground FM biomass. The PFP values and statistics directly reflected the differences in nutrient input rates between these two treatments (Table 6.2; Fig. 6.2). Therefore, for similar yields, treatments that received less nutrients exhibit higher PFP values. Moreover, given the fact that each element had been reduced by 30%, the relative changes in PFP values between T100 and T70 are the same for N, P or K. Therefore, the trend of the relative PFP values depicted in Fig. 6.2 is valid for each of these 3 elements.

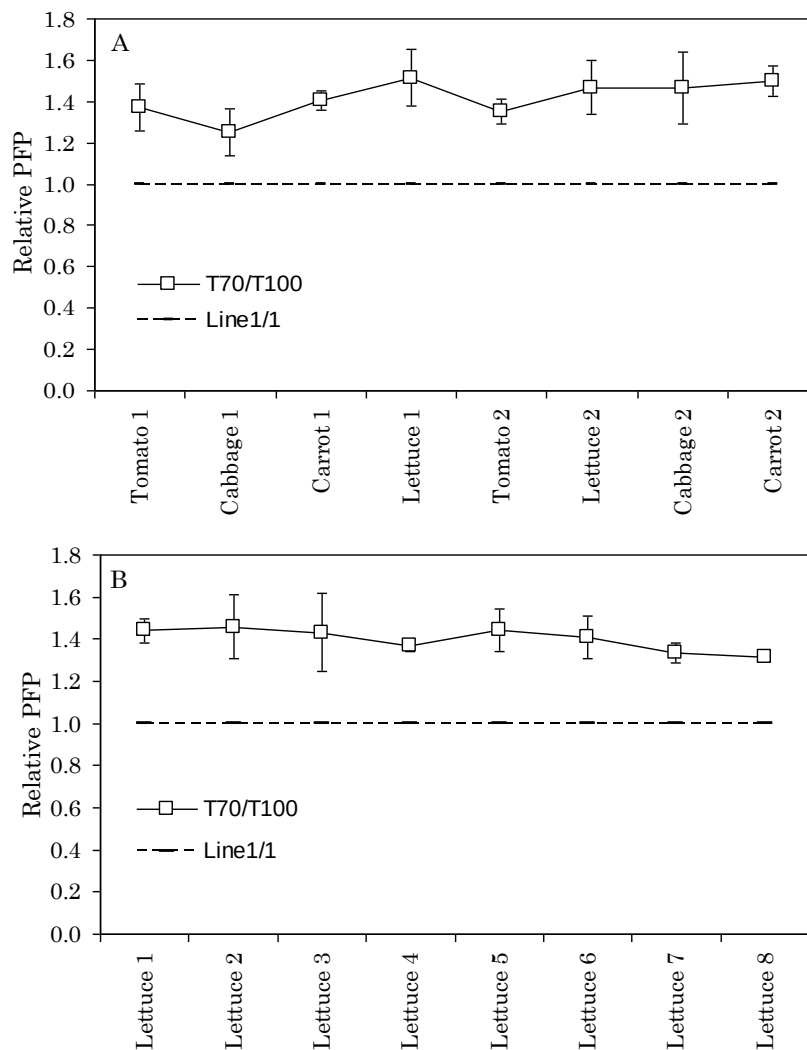


Figure 6.2. Partial factor productivity (PFP) of N, P and K in T70 relative to T100 (PFP = 1) for the crops at Dogona (A) and Kodení (B). Vertical bars denote standard deviation. Relative PFP values are identical for N, P and K.

The reduction of fertilization by 30% (T70) resulted in a significant increase in PFP of N, P and K by about 20 to 50% at Dogona ([Table 6.2](#); [Fig. 6.2A](#)) and by 20 to 45% at Kodení ([Fig. 6.2B](#)), depending on crop type and period, compared to gardeners practice (T100). At Kodení, the generally large increase in PFP in T70 relative to T100 was dampened during the last two crop cycles as a result of the slight decline in lettuce FM yields in T70 during those two cycles.

6.3.2. Contribution of direct and residual effect fertilizer on the crop yields

The [Table 6.3](#) present the amount of nutrient released during each crop cycle through the organic matter mineralization. The nutrient amount of N, P and K presented in the table are those derived from the mineralization model, i.e., from soil organic pool and applied organic matter during the study period. For each cropping cycle, ‘Di’ represents the amount of nutrients added through the mineralization of organic amendements applied during this crop cycle and ‘Res’ results from the mineralization during the crop cycle of the residual organic matter from previous crop cycles + soil organic pool. For the analysis of direct effects on yield, the nutrients added through mineral fertilizers are added to Di.

At Dogona, during tomato–1 and 2, lettuce–2 and carrot–2, the organic matter–based nutrient release resulted exclusively from the mineralization of the soil organic pool as no organic amendment was applied during these cycles ([Table 6.3](#)). On average, the nutrients released from the residual organic pools (soil humus + residual organic amendements) were the main organic source of nutrient input for a given crop cycle. Indeed, for both treatments, about 88 to 91% of the total N, 79 to 82% of the total P and 74 to 82% of the total K input from organic material during the two years of the experiment was provided by mineralization of residual organic matter.

The same applied to Kodení, where nutrients released through organic matter during each cropping cycle came primarily from the

mineralization of residual organic matter. Indeed, based on the results of our model, about 80 to 82% of the N, 79 to 81% of the P and 78 to 82% of the K supplied from organic sources during the cropping period comes from the mineralization of residual organic matter in the soil.

At Dogona, the statistical model explains a very large part of the yield variability, having $r^2 > 0.90$ for both treatments when considering N and K (Table 6.2). However, yield was found to be less related to direct P input ($r^2=0.97$ and 0.49 for T100 and T70, respectively). At this site, there was a direct N effect on crop yields for both treatments ($P<0.01$). However, the direct effect was significant in T100 only for P and for K. No significant direct effect was found for P and K at this site for treatment T70, meaning that the amount of P and K applied could not explain the level of yield obtained. As for the direct effect, the carryover effect of N was significant for both T100 and T70.

Contrary to Dogona, yields were best explained by P ($r^2 > 0.97$) for both T100 and T70 at Koden. Nevertheless, a large part of the variability could also be explained by N direct inputs ($r^2 > 0.81$). Yield was found to be less related to K input ($r^2 = 0.73$ and 0.20 for T100 and T70, respectively). Regarding N and P at this site, there was a direct effect for both treatments, whereas no direct effect was observed for K, irrespective of the treatment. Furthermore, a significant carryover effect was observed for both treatments concerning N. A carryover effect was observed for P in treatment T100 only, and for none of the treatments regarding K. Consequently, reducing K fertilization had neither a significant direct effect nor a carryover effect.

6.3.3. Effect of treatments on the temporal dynamics of soil chemical properties

Overall, pH was about 0.5 units lower at Kodení compared to Dogona, where the pH was close to neutral (Fig. 6.3 A and B). At Kodení, CEC was on average about 1 cmol kg⁻¹ higher and more stable than at Dogona (Fig. 6.3C and D). At the start of the experimental period, both sites presented similar and extremely high P Bray I values (Fig. 6.3E and F). Ex-K values were about 1.5 times higher at Kodení than at Dogona (Fig. 6.3G and H).

At Dogona, during both years, pH increased whereas CEC decreased with decreasing fertilization (Fig. 6.3A and C). There was no significant treatment effect on P Bray and Ex-K in the first year, but treatments significantly affected P Bray I in the second year at Dogona (Table 6.4). P-Bray I decreased with decreasing fertilization (Fig. 6.3E). Albeit not significant, the same trend was observed for Ex-K. There was also a significant period effect for pH in the first year and for CEC and Ex-K in both years. Soil pH was rather stable throughout the experimental period, except for a sharp decrease in cabbage-1 and a sharp rise in carrot-2. CEC showed a cyclical pattern, with highest values at the start, middle and end of the 2-year monitoring period. The Ex-K presented a first dip after carrot-1 and then declined steadily for all treatments during the second year. This decline started right after tomato-2 for T0 and T100, whereas it became noticeable only after cabbage-2 for T70.

Table 6.2: *p-values* of the predictors, together with coefficients of determination (r^2) for the model computed to examine the relationship between the amount of applied nutrients and yield, taking into account the direct and carryover effects.

Site and Season	Source	Df	N				P				K				
			T100		T70		T100		T70		T100		T70		
			p-value	r ²	p-value	r ²	p-value	r ²	p-value	r ²	p-value	r ²	p-value	r ²	
Dogona (2008–2010)	Period (P)	7	<.0001		<.0001		<.0001		0.433		0.005		0.0242		
	Direct effect (D)	7	<.0001		0.001		<.0001		0.745		0.005		0.9409		
	Carryover (C)	6	<.0001		<.0001		0.102		0.046		N/A †		N/A		
	D x C	13	<.0001		<.0001		0.104		0.212		N/A		N/A		
	P x D	14	<.0001		<.0001		0.373		0.43		N/A		N/A		
	Model	57		0.90		0.91		0.79		0.49		N/A	0.99	N/A	0.99
	Error	82													
Kodeni (2009–2010)	Period (P)	7	<.0001		<.0001		<.0001		0.005		<.0001		<.0001		
	Direct effect (D)	7	0.0136		0.0053		0.007		0.030		0.100		0.244		
	Carryover (C)	6	0.0181		0.0157		0.0002		0.000		0.001		0.019		
	D x C	13	0.005		0.0014		0.0001		0.04		0.522		0.424		
	P x D	14	0.2709		0.765		<.0001		0.730		0.185		0.287		
	Model	57		0.81		0.80		0.97		0.98		0.73		0.38	
	Error	76													

† N/A: plant uptake almost always exceeded K input; therefore carryover effect could not be included in the model

Table 6.3: Amount of N, P and K available for each crop cycle resulting from the mineralization of organic amendements applied during a given crop cycle (Di) and from the mineralization during a given crop cycle of the residual organic matter from previous crop cycles + soil organic pool (Res).

Site	Crop	Type	N		P		K	
			kg ha ⁻¹					
			T100	T70	T100	T70	T100	T70
Dogona (2008 – 2009)	Tomato–1	Res	284	284	72	71	525	525
		Di	0	0	0	0	0	0
	Cabbage–1	Res	343	343	82	82	153	153
		Di	102	72	26	18	111	78
	Carrot–1	Res	283	266	78	69	100	82
		Di	67	47	27	19	113	79
	Lettuce–1	Res	269	247	82	71	141	106
		Di	99	69	61	43	123	86
Dogona (2009 – 2010)	Tomato–2	Res	514	474	209	170	303	226
		Di	0	0	0	0	0	0
	Lettuce–2	Res	178	174	59	52	65	51
		Di	0	0	0	0	0	0
	Cabbage–2	Res	287	285	80	73	74	61
		Di	61	43	18	13	178	125
	Carrot–2	Res	288	275	80	71	147	111
		Di	0	0	0	0	0	0
Kodeni (2009 – 2010)	Lettuce–1	Res	101	101	135	116	549	339
		Di	78	55	0	0	0	147
	Lettuce–2	Res	187	161	87	81	432	360
		Di	51	35	15	11	55	39
	Lettuce–3	Res	209	372	70	61	312	252
		Di	114	80	34	24	100	70
	Lettuce–4	Res	382	308	102	81	420	321
		Di	112	111	28	20	79	55
	Lettuce–5	Res	411	382	73	55	299	222
		Di	37	26	20	14	38	27
	Lettuce–6	Res	302	199	49	37	190	22
		Di	59	41	21	15	140	105
	Lettuce–7	Res	340	228	53	39	224	73
		Di	57	40	21	15	163	98
	Lettuce–8	Res	570	388	79	58	296	187
		Di	85	60	31	22	121	85

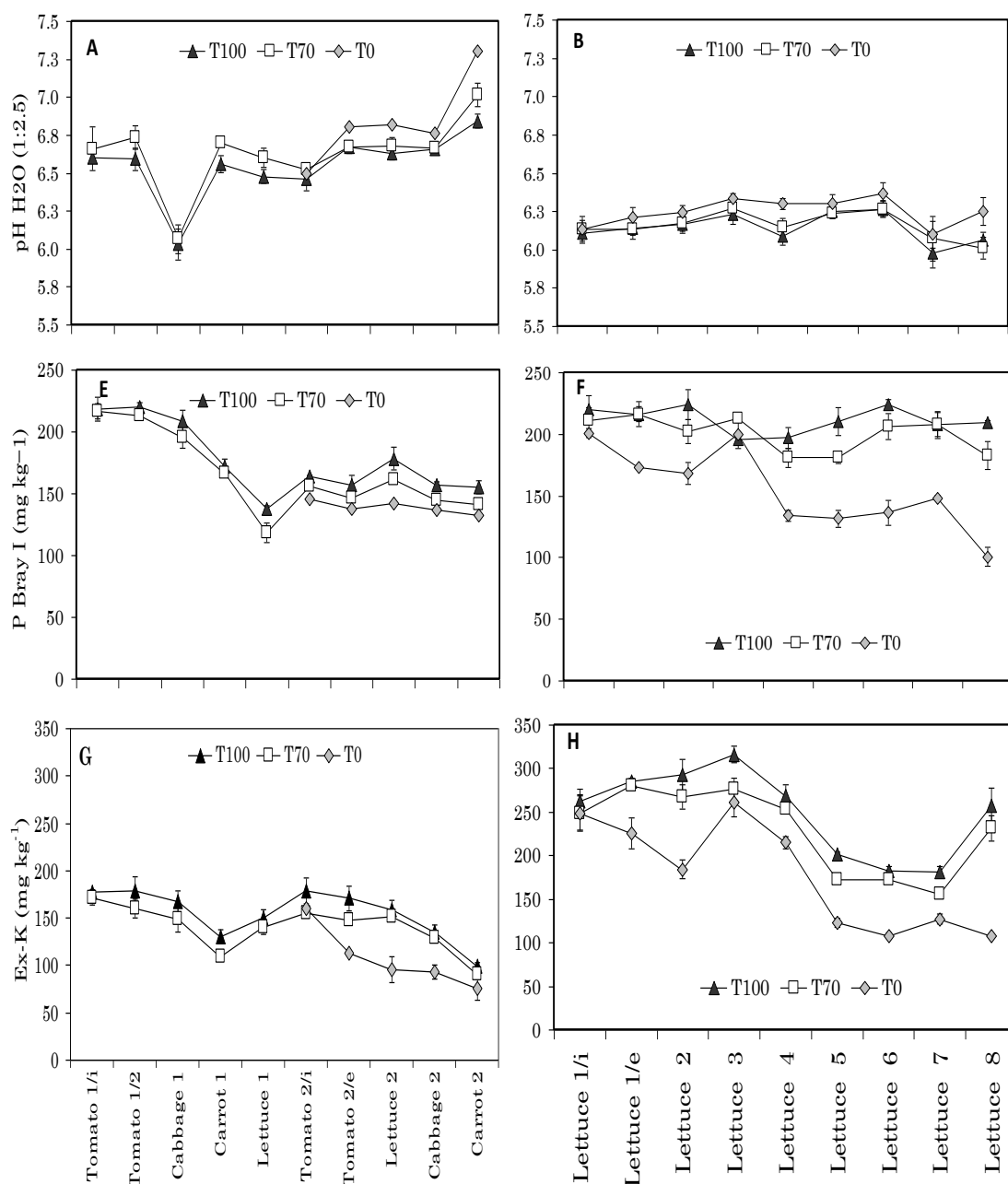


Figure 6.3: temporal dynamics of selected soil chemical parameters throughout the cropping cycle at both sites (0–30 cm). Fig. A, C, E, G relate to Dogona and Fig. B, D, F, H relate to Kodeni. Vertical bars denote standard deviation. 1/i, 1/e, 2/i and 2/e denote the beginning and the end of the first crop of each cropping year, respectively.

At Kodeni, a significant treatment effect was observed for pH and P Bray I, but not for CEC and Ex-K (Table 6.4). A period effect was observed only for available elements (P-Bray I and Ex-K). As for Dogona, pH increased as the rate of fertilization decreased (Fig. 6.3B). P Bray I

remained rather stable in T70 and T100 but declined steadily in T0, except for the periods when fertilizer was applied (Fig. 6.3F). A similar decline was observed for Ex–K in T0 (Fig. 6.3H). No significant treatment x period interaction was observed for any of the soil parameters, irrespective of the site. Throughout the cropping cycles, electrical conductivity (EC) ranged from 0.12 ± 0.01 to 0.43 ± 0.02 dSm⁻¹ at Dogona and from 0.17 ± 0.01 to 0.32 ± 0.03 dSm⁻¹ at Kodení.

Table 6.4. Results of the ANOVA (*p-value*) for testing the significance of treatment and sampling period effects on selected soil chemical properties at Dogona and Kodení for each cropping year.

Site and Season	Source	Df	pH _{H2O} (1:2.5)	CEC	P Bray I	Ex–K
Dogona (2008–2009)	Treatment (T)	1	0.045	0.0001	0.053	0.29
	Period (P)	4	0.001	0.021	0.78	0.043
	T x P	5	0.57	0.35	0.48	0.89
Dogona (2009–2010)	Treatment (T)	2	0.013	<.0001	0.035	0.273
	Period (P)	4	0.19	0.012	0.47	0.046
	T x P	6	0.351	0.635	0.432	0.053
Kodení (2009–2010)	Treatment (T)	2	<.0001	0.1221	0.0229	0.1859
	Period (P)	7	0.5954	0.3583	0.0279	0.0319
	T x P	8	0.5406	0.7324	0.5011	0.1911

6.3.4. Effect of treatments on soil nutrient concentrations and stocks

The statistical analysis summary for individual and combined effects of treatment and depth on soil chemical properties at the end of the experimental period is presented in table (Table 6.5). There was a significant depth effect at both sites and for all parameters, reflecting decreasing concentrations with depth, except for total K at Kodení. This decrease in concentration with depth was generally more marked at Kodení than at Dogona (Fig. 6.4).

A significant Treatment x Depth interaction was found for organic C (C org) and total N at Dogona and Kodení, as well as for P– Bray I and Ex–K at Kodení (Fig. 6.4). At 30 cm depth, treatments never had a significant effect on the selected soil chemical parameters, irrespective of the site. At 7.5 and 15 cm depth at Dogona however, T100 values were almost always highest and T0 values lowest, although differences among treatments were generally small in the top 15 cm. For the same depth at Kodení, the highest values were also observed for T100 and the lowest for T0, with intermediate values for T70. Overall, treatment differences were found to be much more marked at Kodení than at Dogona in the top 15 cm.

Table 6.5. Analysis of variance summary for soil organic C, total N, P and K, P Bray I and Ex–K concentration (g kg⁻¹) at the end of the experiment at both sites.

Site and year	Source	Df	P Bray I	Ex–K	C org	N tot	P tot	K tot
Dogona	Treatment (T)	2	0.011	0.0219	0.010	<0001	0.001	0.053
	Depth (D)	2	0.003	0.0101	0.013	<0001	0.115	0.030
	T x D	4	0.100	0.0969	0.0313	0.030	0.737	0.355
	Model	8	0.000	<0001	<0001	<0001	0.002	0.049
	Error	18						
Kodení	Treatment (T)	2	0.021	0.0002	0.0002	0.0294	0.030	0.759
	Depth (D)	2	0.008	<0001	<0001	<0001	<0.001	0.277
	T x D	4	0.95	0.057	0.0019	0.0250	0.415	0.571
	Model	8	0.031	<0001	<0001	<0001	<0.001	0.237
	Error	18						

The change in soil nutrient stocks between the start and the end of the experiment (0–30 cm depth) varied significantly between treatments for all sites and years, except for P–Bray I and Ex–K after the first year at Dogona (Table 6.6). Negative values indicate net soil nutrient losses whereas positive values indicate soil enrichment during the experimental period.

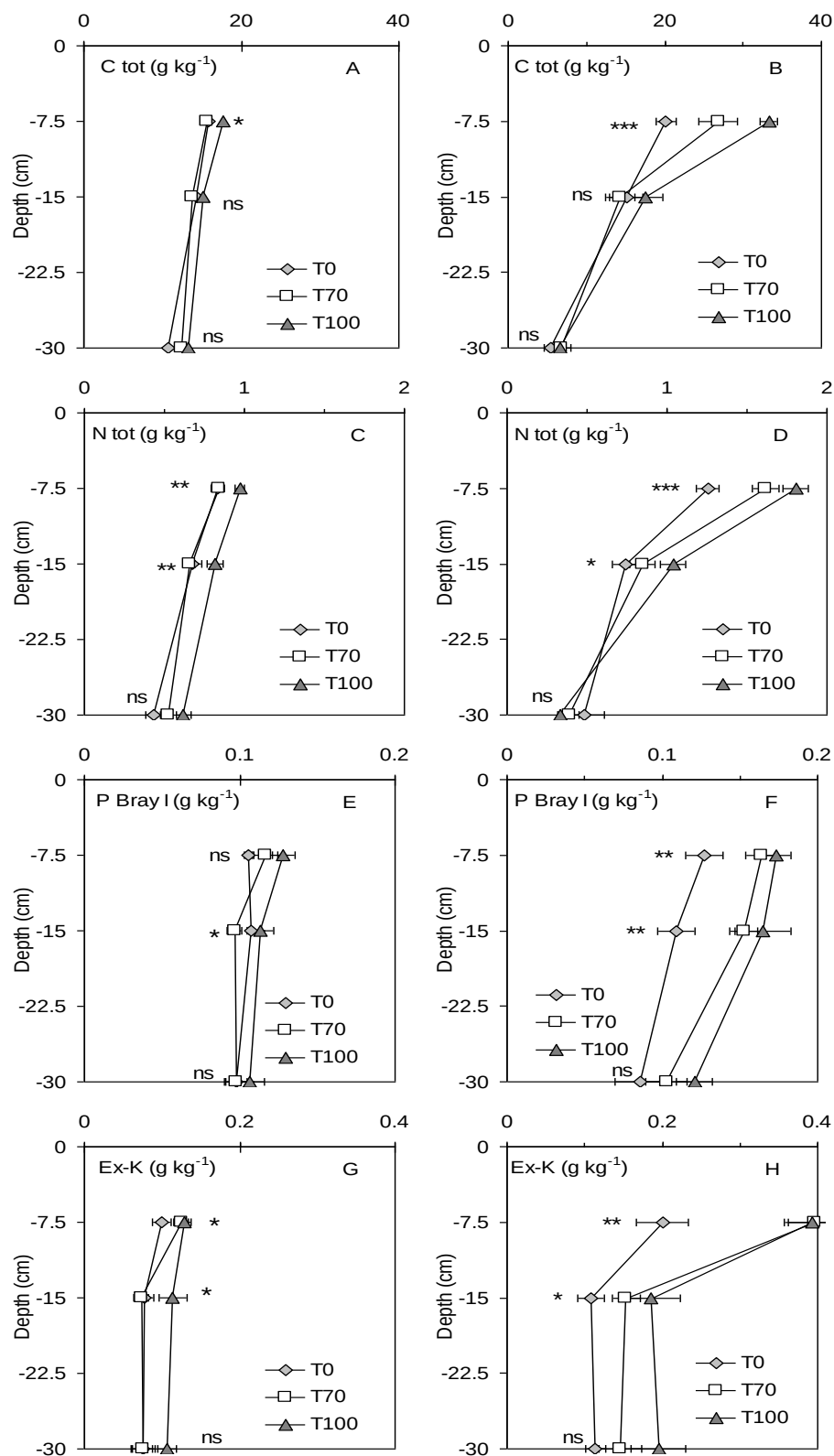


Figure 6.4: Vertical distribution of selected nutrients in the soil profile (g kg^{-1} ; Mean $\pm$ SD) at the end of the experiment. Figures A, C, E, and G relate to Dogona and B, C, F and H relate to Kodení. ns = non-significant; *, **, *** probability significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ according to Duncan's multiple range test, respectively. Horizontal bars denote standard deviation.

Table 6.6. Analysis of variance for the net change in soil organic C and total N, P, and K, P Bray I and Exchangeable K stocks (difference between the end and the onset of each experimental year; mean value $\pm$ standard errors) summed over 30 cm depth as affected by treatments at both sites.

Site and year	Source	C org t ha ⁻¹	N tot t ha ⁻¹	P tot t ha ⁻¹	K tot t ha ⁻¹	P Bray I t ha ⁻¹	Exch-K t ha ⁻¹
Dogona (2008 – 2009)	T100	1.06 $\pm$ 0.30 _a	0.65 $\pm$ 0.04 _a	0.42 $\pm$ 0.08 _a	– 3.20 $\pm$ 0.02 _b	– 0.06 $\pm$ 0.02 _a	0.00 $\pm$ 0.00 _a
	T70	– 3.15 $\pm$ 0.29 _b	– 1.03 $\pm$ 0.03 _b	0.34 $\pm$ 0.05 _b	– 2.88 $\pm$ 0.04 _a	– 0.09 $\pm$ 0.00 _a	0.00 $\pm$ 0.00 _a
	Pr > F	<.0001	0.0005	0.045	0.0004	0.134	0.098
	Signif.	***	***	*	***	ns	ns
	CV (%)	28	29	11	4	8	34
Dogona (2009 – 2010)	T100	3.89 $\pm$ 0.22 _a	0.17 $\pm$ 0.01 _a	1.11 $\pm$ 0.01 _a	– 1.40 $\pm$ 0.03 _b	0.01 $\pm$ 0.00 _a	– 0.03 $\pm$ 0.00 _b
	T70	1.96 $\pm$ 0.07 _b	0.02 $\pm$ 0.01 _b	0.31 $\pm$ 0.01 _b	– 1.42 $\pm$ 0.01 _b	– 0.04 $\pm$ 0.00 _b	– 0.02 $\pm$ 0.00 _a
	T0	1.40 $\pm$ 0.02 _c	– 0.36 $\pm$ 0.03 _c	0.27 $\pm$ 0.01 _b	– 1.24 $\pm$ 0.02 _a	– 0.08 $\pm$ 0.00 _c	– 0.01 $\pm$ 0.00 _a
	Pr > F	<.0001	<.0001	0.001	0.01	<.0001	<.0001
	Signif.	***	***	***	***	***	***
	CV (%)	58	4	11	19	11	13
Kodeni (2009 – 2010)	T100	5.37 $\pm$ 0.75 _a	0.69 $\pm$ 0.09 _a	0.71 $\pm$ 0.09 _a	1.18 $\pm$ 0.44 _a	– 0.06 $\pm$ 0.01 _a	0.01 $\pm$ 0.00 _a
	T70	1.62 $\pm$ 0.21 _b	0.68 $\pm$ 0.08 _a	0.34 $\pm$ 0.08 _b	0.12 $\pm$ 0.07 _b	– 0.12 $\pm$ 0.02 _b	– 0.01 $\pm$ 0.00 _b
	T0	– 2.7 $\pm$ 1.07 _c	– 0.93 $\pm$ 0.04 _b	– 0.02 $\pm$ 0.14 _c	– 0.98 $\pm$ 0.2 _c	– 0.23 $\pm$ 0.03 _c	– 0.04 $\pm$ 0.00 _c
	Pr > F	0.0074	0.0135	0.007	0.0035	0.0006	<. 0001
	Signif.	***	*	***	**	***	***
	CV (%)	35	10	33	16	18	13

Mean within columns followed by the same lowercase letters are not significantly different ($P \leq 0.05$) according to the Duncan's multiple range comparison of fertilization treatments within same site and same cropping year. ns = non-significant; *, **, *** probability significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively.

During the first and second years at Dogona, Corg, total N and total P stocks increased in T100, whereas the stocks remained stable or decreased for total K, available K and available P. On the contrary, in T70 the stocks decreased for all elements in the first year, except for P_{tot}. During the second year, they increased for total C, N and P and decreased for the other elements. Changes in stocks were consistently less positive (or more negative) for T70 compared to T100. Stocks generally decreased in T0, except for Corg and total P. At Koden, C org and total N, P and K storage increased for both T100 and T70, but the increase rate was lower for T70 than for T100. They were neutral or negative for P–Bray I and Ex–K. In T0, all stocks decreased. The general tendency was for the changes in stocks to become less positive (or more negative) from T100 to T70 to T0.

6.3.5. Nutrient balance components

At Dogona, the balance was strongly positive with respect to N and P in the T100 treatment ([Table 6.7](#)). Based on our balance components, a negative K balance occurred during the second year at Dogona.

The nutrient inputs through organic matter are those derived from the mineralization model, i.e., from the soil organic pool + applied organic matter during the study period. Regarding inputs, within both sites and for both treatments, organic fertilizer supplied more nutrients than mineral fertilizer, based on our mineralisation model. Except during the second year at Dogona where the amount of nutrient supplied through organic amendment applications was reduced compared to the mineral fertilizer applications. The organic material was also the main source of P and K supplied to crops at both sites and for both treatments. Regarding losses, crop uptake is the main pathway by which nutrients leave the soil system followed by gaseous N losses at both sites and by leaching.

Table 6.7 : Soil N, P and K balance component (kg ha⁻¹ year⁻¹) after each year of tomato, cabbage, lettuce and carrot rotation at Dogona and the continuous year of continuous lettuce growth at Kodení (B).

		N		P		K	
		T100	T70	T100	T70	T100	T70
Site	Parameter	kg ha ⁻¹ year ⁻¹					
Dogona (2008–2009)	Input						
	<i>organic</i>	1447	1328	428	373	1266	1109
	<i>mineral</i>	1046	732	0	0	339	237
	<i>irrigation</i>	96	96	2	2	139	139
	Output						
	<i>harvest</i>	1722	1552	282	282	1706	1461
	<i>leaching</i>	53	10	65	10	N/A	N/A
	<i>gaseous</i>	498	348	0	0	0	0
	Balance	316	246	127	78	N/A	N/A
Dogona (2009–2010)	Input						
	<i>organic</i>	1325	1251	446	379	767	574
	<i>mineral</i>	1457	1020	119	83	290	203
	<i>irrigation</i>	73	73	3	3	115	115
	Output						
	<i>harvest</i>	794	703	176	140	1621	1124
	<i>leaching</i>	176	162	7	5	91	64
	<i>gaseous</i>	420	294	0	0	0	0
	Balance	1465	1185	363	305	-540	-296
Kodení (2009–2010)	Input						
	<i>organic</i>	3095	2587	818	649	3318	2697
	<i>mineral</i>	1602	1121	119	83	257	180
	<i>irrigation</i>	247	247	5	5	50	50
	Output						
	<i>harvest</i>	1483	1318	283	228	2723	2461
	<i>leaching</i>	224	178	33	23	215	150
	<i>gaseous</i>	350	245	0	0	0	0
	Balance	2887	2214	626	486	687	316

Reducing the input rate by 30% (T70) allowed a strong reduction of soil N and P surpluses. Indeed, the surplus was reduced by 23% (–70 kg ha⁻¹) for N and 39% (–49 kg ha⁻¹) for P in T70 at Dogona compared to T100 (Table 6.7) during the first year. Because leaching data were not available for K during the first year (see Chapter 5), the K balance was not computed. During the second year, the reduction was 20% (–280 kg ha⁻¹) for N and 16%

(-58 kg ha^{-1}) for P. At this site, during the second year (2009–2010), T70 reduced the K negative balance by about 45% ($+244 \text{ kg ha}^{-1}$) compared to T100.

At Kodení, contrary to Dogona, the K balance in both treatments T100 was positive. Nutrient surpluses were cut by 23% (-673 kg ha^{-1}) and 22% (-140 kg ha^{-1}) for N and P, respectively, when the fertilizer inputs were reduced by 30%, but the balances remained positive. The 30% fertilizer reduction resulted in a reduction of K surplus by 54% (-371 kg ha^{-1}).

6.4. Discussion

6.4.1. Effect of fertilizer reduction on yields, water and nutrient use efficiency

Overall, yields in T70 were not significantly different from yields achieved in T100 at both sites. This indicates that farmers mostly applied fertilizers in excess of what is needed to reach maximum yields, regardless of the cropping cycle (continuous lettuce cropping at Kodení or crop rotation at Dogona). Based on a comparison between T70 and T100, yield reductions as a result of fertilizer reduction were not apparent in the present study, except for cabbage–1 (Fig. 6.1). However, it is likely that the lower yield of cabbage–1 did not directly result from the reduced fertilization since the cabbage–2 achieved similar yields as the control (T100) despite the fact that the plots had been under reduced fertilization for a longer period of time than for cabbage–1.

Beyond a certain rate of fertilization, a linear increase of vegetable yield no longer exists (Greenwood et al., 1980; Johnstone et al., 2005; Zotarelli et al. 2009a). Zotarelli et al. (2009a) even reported a decrease in tomato yields with the increasing of N rate application in Florida (USA). Excessive nutrient application rates have also been reported to cause yield reductions by $\geq 10\%$ in tomato fruit in Cairo, Egypt (Badr and Talaab, 2008). Similar observations have also been made for cabbage (Rahn et al.,

1998) and hot pepper (Zhu et al. 2005). This is supported by our carrot–2 yield that was significantly lower in T100 than in T70 (Fig. 6.1). Carrot–1 already tended to exhibit higher yield values in T70 than in T100, albeit not significantly different.

In the present study, the nutrient balances confirm that N application rates are less excessive in T70 than in T100 (Table 6.7). This suggests that T70 may be closer to the optimum N fertilization rate for tomato than T100. Regarding P, the nutrient application rates recorded in the present study are less excessive. But the application rates observed at Dogona and Kodení nevertheless still exceeded plant uptake for both T100 and T70. At Kodení, the carryover effect of P observed for T100 was suppressed after reducing fertilization by 30%, which indicates that significant amounts of P remained in the soil after some crop cycles in T100 but not in T70. In combination with the lack of yield decline in T70 compared to T100; this suggests that P fertilization rates in T70 at Kodení more closely match crop requirements for maximum yields.

The fact that yields in T70 and T100 were similar seems to indicate that there were no severe limitations of major nutrients (N, P, K) in those treatments. The only major exception may be the last two lettuce crops at Kodení (lettuce–7 and –8), when yields declined in T70 compared to T100 (Fig. 6.1). These two lettuce crops (mean FM yield = 71.9 ± 4.3 kg ha⁻¹) are of a different, higher–yielding variety than the first 6 lettuce crops (mean FM yield = 41.7 ± 4.7 kg ha⁻¹). The higher plant requirements of lettuce–7 and 8 apparently could not be entirely satisfied after reducing fertilization rates by 30%. Although foliar analysis may be required to determine the exact nutritional cause of this yield decline, K deficiency seems likely given that the K balance changed from positive for T100 to negative for T70 (Fig. 6.3B). This questions the sustainability of yields at Dogona, where the partial K balances were systematically negative, irrespective of the treatment (Fig. 6.3A).

The ability of many soils to supply adequate amounts of K for many years and the non significant response of some crops to K fertilization often

leads to its under-application in vegetable production areas (Hochmuth et al. 2006; Zhang et al. 2010; Siegfried et al., 2011). The lack of knowledge by farmers regarding plant nutrition and the nutrient content of the variety of fertilizer sources used in vegetable production (inorganic fertilizers, household refuse, various animal manures, irrigation water, etc.) tends to exacerbate K deficiency as K concentrations are low in many of these sources (Sangare et al., 2012). Accordingly, K balance was negative during the second cropping year at Dogona in all treatments (Table 6.7). Many concerns have been raised about K imbalances in intensive agricultural systems as it has been shown to cause growth stagnation or a gradual decrease of tomato, cabbage and lettuce yields (Pujos and Morard, 1997; Chen et al., 2004). At Dogona, during the second year, the absence of yield decline when reducing fertilization by 30% seems to indicate that K was not a limiting. This is further confirmed by the fact that carrot-2 yielded significantly higher yield in T70 than in T100, indicating that K did not restrict yield for this crop (Fig. 6.1). This is somewhat surprising given the negative K balances (Fig. 6.3A). Besides weathering of soil primary minerals, K may be supplied through irrigation water and atmospheric dust deposition. This is corroborated by a study from Burkina Faso in which wet and dry deposition contributed to about 7.0 – 7.7 kg K ha⁻¹ year⁻¹ of the K input to cotton, groundnuts and millet (Lesschen et al., 2007). The slight carrot-2 relative yield increase in T0 probably arises from such factors (Greenwood et al., 1980; Hochmuth et al. 2006).

Our study provides strong evidence that the current N and, to a lesser extend, P fertilizer rates can reasonably be reduced by 30% without compromising yield levels. Similar results have been obtained by Widowati et al. (2011). On the other hand, the negative K balance could impede crop production and points to the need to better balance K application.

The 30% reduction in fertilization generally had no effect on water use efficiency given that the water application rates were unchanged and yields unaffected. However, it significantly increased partial factor productivity of N and P (Table 6.1 and Figure 6.2). Indeed, the ratio of crop

yield per unit N or P supplied increased significantly when comparing T70 to T100 since similar yields were achieved in T70 with lesser N and P additions. However, as opposed to N and P, the PFP of K increased with increasing fertilization. This is because fertilizer additions did not significantly increase K input levels as organic and inorganic fertilizers were generally poor in K ([Sangare et al., 2012](#)).

6.4.2. Effect of fertilizer reduction on soil nutrient balance

In sub-Saharan Africa, it is recognized that optimizing farm level nutrient balances is one of the most difficult agricultural management challenges ([Dougill et al., 2001](#)). This holds true in our case too. Indeed, the overall accumulation of N in T100 plots after the experimental period was extremely high ([Table 6.6](#) and [Fig. 6.4](#)), reflecting nutrient inputs that were well in excess of plant uptake. High positive N and P balances in vegetable production systems have been reported several times earlier ([Vasquez et al., 2006](#); [Ju et al., 2007](#); [Khai et al., 2007](#); [Zhu et al., 2007](#); [Widowati et al., 2011](#)). [Diogo et al. \(2010\)](#) measured positive balance of 1133 kg N ha⁻¹, 223 kg P ha⁻¹ in similar high input gardens in Niamey (Niger). N application rates 2- to 4-fold higher (namely 4328 kg N ha⁻¹ year⁻¹) and P application rates 3-fold higher (1337 kg P ha⁻¹ year⁻¹) than plant uptake were reported for greenhouse tomato processing by [Ju et al. \(2007\)](#) in China. The annual surpluses of 312 kg K ha⁻¹ calculated by [Diogo et al. \(2010\)](#) match well with our K balance in T100 at Kodení but contrast with the negative K balance measured at Dogona during the second year. This difference with our results could be attributed to the low K content in the mix of mineral fertilizers (Urea + NPK) used by gardeners ([Sangare et al., 2012](#)).

6.4.3. Effect of fertilizer reduction on soil nutrient status

In general, the values of the soil chemical properties at both sites ([Figs. 6.4 and 6.5](#)) were higher than those usually reported for cotton growing soils

(Ouattara et al., 2006) and cereals (Bado et al., 2010) in western Burkina Faso, thus reflecting the large fertilizer application rates. The values of P Bray I, Ex-K and CEC are slightly higher than those reported by Diogo et al. (2010) for vegetable gardens in Niamey (Niger) for a comparable intensity of fertilization, likely due to the finer texture of the soils in Bobo Dioulasso compared to Niamey.

In intensive crop production, including vegetables, soil acidification is commonly observed and attributed to the recurrent application of large quantities of mineral nitrogen fertilizers, especially urea (Zotarelli et al., 2009b; Diogo et al., 2010; Guo et al., 2010). Excessive mineral nitrogen application has been reported to induce a decrease in topsoil pH by 1.3 and 1.4 units in *Lycopersicon* and *Brassica* gardens (Stamatiadis et al., 1999; Ju et al., 2007). A limited drop (0.4 unit: from 7.1 to 6.7) in pH values has been reported by Diogo et al. (2010) after one year of intensive vegetable production in Niamey (Niger). This is ascribed to the release of H^+ through the process of nitrification of urea ($CO(NH_2)_2$) and NH_4^+ to NO_3^- . In general, the pH was more acidic at Kodené than at Dogona (Fig. 6.4), which may have resulted from the high application of large quantities of urea at Kodené. Such high urea input (about 300 kg ha^{-1}) during the cabbage-1 cycle at Dogona could have been responsible for the temporary drop in pH by 1.7 units in T100 and T70 plots (Fig. 6.4A). However, pH values remained rather constant throughout the cropping year, despite the repeated use of urea at Kodené, which may be ascribed to the increase in soil buffering capacity favoured by the concomitant application of large quantities of organic matter (Stamatiadis et al., 1999; Gentile et al., 2011). Consistent with the effect of N fertilization on soil pH, there was a systematic increase in pH as fertilization decreased, although the increase was generally small (Fig. 6.4A and 6.4B).

One possible consequence of the application of high amounts of fertilizers is the accumulation of soluble salts in soils leading to high EC values (Adviento-Borbe et al., 2006; Ju et al., 2007). Ju et al. (2007) reported several studies which showed that high N inputs caused a rise in soil EC

values by up to 4 dS m⁻¹ in greenhouses after 8 years of intensive vegetable cropping. However, despite the high nutrient surpluses, significant changes in soil EC were not observed throughout the two years of study (data not shown). The EC values observed within our intensively fertilized soils were far below the thresholds of 0.7 – 1.8 dS m⁻¹ (soil: water 1:1 ratio) above which the growth and yield of lettuce, tomato, cabbage and carrot can be significantly impaired (Smith and Doran, 1996; Shannon and Grieve, 1999). The low observed EC values seem to indicate sufficient leaching to prevent salt accumulation. Sangaré et al. (2012) reported yearly drainage below 30 cm depth of about 113 and 246 mm at Dogona and Kodení, respectively.

At Dogona, there was a tendency for P Bray and Ex-K to decline in T70 and T100, which was not apparent at Kodení (Fig. 6.4). The decline in exchangeable K at Dogona is consistent with the strongly negative K balances observed at this site (Fig. 6.3). On the contrary, P-Bray I declined despite positive P balances in T70 and T100 (Fig. 6.3). One should note, however, that both P Bray and Ex-K only represent a fraction of the total P and K present in the soil. Although these fractions are a measure of available P and K and should therefore be most sensitive to management, nothing is known regarding the rate of replenishment of the available P and Ex-K through transfers between the various soil K or P pools in our experimental sites. Across the experimental period, the net change in soil P Bray was negative whereas the net change in total P was positive (Table 6.7), which clearly reflects the fact that additions of P do not automatically translate into greater P availability. Regarding K, both soil Ex-K and total K decreased (Table 6.7), but K_{tot} decreased to a much larger extent, indicating that K not present on the exchange complex was made available to the plants during a one year crop cycle. At Kodení, the lack of temporal changes of P Bray I and Ex-K in T100 and T70 may be related to the overall higher excess (or less deficient) P and K fertilizer application rates at this site (Fig. 6.3).

As soil organic matter (SOM) is the most important contributor to the CEC in ferric Lixisol soils given that the clay minerals are dominated by

kaolinite (low activity clay), the dynamics of CEC are thought to directly reflect the SOM dynamics in SSA soils (Manlay et al., 2002; Bationo et al., 2008). Oorts et al. (2003) reported that CEC values ranging between 2.8 and 6.0 cmol⁺ kg⁻¹ are characteristic of tropical ferric Lixisols. The fact that the organic C concentration at Dogona and Kodení was at the high end of this range is probably the consequence of the recurrent applications of organic amendments. Our results show that reducing or stopping fertilization lead to a decrease in organic C content in the top 7.5 cm at both sites (Fig. 6.5). This quick decline in soil organic C is characteristic for irrigated subtropical soils with their recurrent high mineralization rates (Bationo and Buerkert, 2001; Siegfried et al., 2011).

The distribution of total N in the soil profile showed a similar trend as carbon and decreased with increasing soil depth (Fig. 6.5). At Dogona, fertilizer reduction allowed to reduce N accumulation in soil by -150 kg N ha⁻¹ compared to T100, during the second cropping year (2009–2010) (Table 6.7). On the contrary, at Kodení, despite the large difference in N balance over the 1-year study period (Fig. 6.3B), the changes in total soil N stocks at the end of the experiment period were not significantly different between T100 and T70 (Table 6.7). Poor N accumulation in soils under conditions of excess fertilization have been reported previously and may be due to the high intensity of leaching that may occurs in permeable and over-watered soils (e.g. Ju et al. 2006; Widowati et al., 2011).

6.5. Conclusions

In light of our study, it is obvious that gardeners did not apply fertilizers at optimum rates, which may question the sustainability of the UPA. Unfortunately, due to the lack of functional fertilizer recommendation systems for vegetables in Burkina Faso, at present gardeners are not aware of their low fertilizer use efficiencies. Therefore, these are compelling reasons to raise farmers' awareness regarding plant nutrient requirement and regarding the nutrient content of fertilizers and organic amendments.

Improved fertilizer management strategies should be promoted in order to improve nutrient use efficiency and reduces losses by processes such as leaching or volatilization. Practices that concomitantly address a reduction of fertilization rates and exploiting residual soil fertility would provide dual ways to improve NUE of UPA systems.

Although site-specific soil and plant properties (e.g., clay and carbon content, pH, crop species...) influence the relation between soil nutrient content and fertilizer effectiveness, the present results provide evidence of a real scope for reducing the current fertilizer use in vegetable cropping systems. Indeed, based on the results of this study, a 30% reduction of the added N and P could be recommended, while aiming at balancing the K supply. Although the fertilizer reduction in our study by 30% sometimes resulted in a positive nutrient balance in soil, it may serve as a reasonable indicator of what can be targeted in efficient fertilizer managements in UPA in these two gardens. Such reduction can yield great saving in cost as carryover effect was reduced that could lead to a “win-win” scenario because of economic and environmental benefits. Implementing such a practice is quite simple as gardeners generally use boxes or buckets of a known volume to quantify their fertilizers. Therefore, where they usually apply 3 measures, they can now apply 2. Furthermore, as our results suggest that the soil sometimes provides significant amounts of residual nutrient to the actual crop cycle; gardeners could exploit this opportunity to reduce the quantity of applied fertilizers.

Chapter 7

General Conclusions and perspectives

7.1. Review of the methodological aspect

With its typically heavy use of agrochemicals, manure, compost, untreated municipal waste and sewage as inputs for crop and vegetable production, UPA bears severe risks of soil and groundwater contamination. Therefore, efficient nutrient management strategies are needed to enhance the sustainability of this type of agriculture. This thesis contributes to this objective in Bobo Dioulasso (Burkina Faso; West Africa). The main goal of the research was to identify opportunities for improving water and nutrient use efficiency in urban agriculture in Burkina Faso and to reduce its potentially negative impact on groundwater through better water and nutrient management practices. The achievement of this goal required to :

- 1) Evaluate plot-level water and nutrient use efficiencies as a function of crop type and location in UPA in Bobo Dioulasso;
- 2) Quantify the vertical leaching of N, P and K in urban vegetable production systems at the plot level as a function of location, crop type and nutrient input levels by means of different measurement techniques;
- 3) Evaluate the opportunities to increase nutrient use efficiency while maintaining crop yields through a reduction in nutrient inputs, by means of field experiments.

The thesis attempted to gather reliable data based on simple and replicable methods in order to reach these three objectives. This experimental study relied exclusively on *in situ* field trials that were conducted between 2008 and 2010 within two gardens in Bobo Dioulasso. The gardens had been selected based on an initial characterization and

classification of UPA systems of the city. The gardeners' fertilizer as well as irrigation management practices were regularly quantified (Chapter 4). To assess the opportunities for reducing the potential leaching of nutrients towards groundwater in these systems, we tested a simple fertilizer reduction strategy: a 30% reduction of the gardener's fertilization practice and a temporary interruption of fertilization in order to exploit the residual nutrients in soil (Chapter 5). In this chapter, two methods were tested for monitoring the water and nutrient flows in soil. The first approach used ion exchange resins (IERC) and the second used zero-suction lysimeters. Finally, the effect of these different practices on the evolution of soil fertility and nutrient balances was evaluated (Chapter 6).

7.2. Summary of the main results

Our results (Chapter 4) confirm the excessive use of water and nutrients in UPA systems in Bobo Dioulasso. With the current gardener's levels of fertilization, and to a lesser extent of irrigation (Kodeni), UPA systems can not be considered sustainable. Indeed, at Kodeni, water application rates during the dry season, when the farmer has full control over the water supply, exceeded plant requirements by as much as 40%, which reveals inefficient water use. At Dogona, during the same season, water use was much more efficient as little drainage was recorded. Drainage was observed at both sites during the rainy season, but this is more difficult to avoid as it corresponds to a period when the farmer has less control over the water supply due to the erratic and sometimes high rainfall events.

Regarding fertilization, and with few exceptions, crops tended to be strongly over-fertilized, except for K at one of the two sites. Nutrient supply exceeded crop requirements by 109 to 2,012 kg N, 66 to 450 kg P and 0 to 393 kg K per year. These results, in combination with the large observed rates of drainage (between 74 and 113 mm/year of drainage was collected at Dogona and about 250 mm/year at Kodeni), point to the high risk of nutrient leaching and groundwater contamination. This was confirmed in Chapter 5

where we have shown that for the T100 treatment, based on the IERC, very high amounts of NO_3 (between 236 and 990 $\text{kg NO}_3 \text{ ha}^{-1} \text{ year}^{-1}$) and to a lesser extent PO_4 (28 to 75 $\text{kg PO}_4 \text{ ha}^{-1} \text{ year}^{-1}$) and K (54 to 214 $\text{kg K ha}^{-1} \text{ year}^{-1}$) were leached every year beyond the rooting depth.

By reducing the amount of fertilization by 30%, we noticed a significant reduction in the mass of N, P and K leached beyond the rooting depth (Chapter 5). The magnitude of the reduction ranged from 20 to 90% for NO_3 , 29 to 74% for PO_4 and 14 to 39% for K. The 30% reduction in fertilization did not have a significant ($P < 0.05$) adverse effect on yields. We also observed that the nutrients currently present in the soil can support at least one cropping cycle before fertilization is required (Chapter 6). Furthermore, reducing fertilization by 30% (T70) significantly increased partial factor productivity of N, P and K by about 20 to 30% at Dogona and 20 to 45% at Kodení depending on the nutrient, crop type and period, compared to T100. The 30% fertilizer reduction had no effect on water use efficiency as water management was unchanged and yields unaffected. Reducing the input rate by 30% (T70) allowed a strong reduction of soil N and P surpluses by 23% (-70 kg ha^{-1}) for N and by 39% (-49 kg ha^{-1}) for P. The T70 reduced the K negative balance by about 45% ($+244 \text{ kg ha}^{-1}$) compared to T100 during the second year at Dogona.

In Chapter 5 we evaluated the efficiency of the pan lysimeters in capturing drainage within our field soils, by comparing measurements with the results of a simple water balance calculation. Results indicate that the pan lysimeters consistently collected less water ($\leq 10\%$) compared to the potential drainage estimated from water balance calculations. This was attributed, among others, to the disturbance in water flow introduced during device installation and the hydraulic functioning of the devices (e.g., free drainage lower boundary condition).

A comparison of the various leaching monitoring methods (Chapter 5) revealed that the IERC were more effective ($> 65\%$) in trapping ions than the pan lysimeters (SSF and SSS), which was explained by the lesser soil disturbance during installation of the IERC and more realistic lower

boundary conditions. Both the flow rate and the nutrient concentrations of the leachate entering the IERC may therefore have been more representative of the soil conditions than in the case of SSS or SSF. IERC seems best suited for longer term monitoring but it provides information neither regarding drainage rates nor about short-term fluctuations in nutrient concentrations. An evaluation of their collection efficiency remains, however, to be done. The SSS or SSF devices underestimate the actual drainage rates and nutrient losses but are seen as valuable tools to characterize the short-term dynamics (≤ 1 day) of root zone drainage and leaching losses, provided a better evaluation of their efficiency is made. We used a simple mineralization model to predict the release of nutrients from the soil organic matter. Based on model results, both T100 and T70 favoured positive N and P balances in soil, but reducing the input rate by 30% (T70) allowed a strong reduction of soil N and P surpluses. The model also allowed estimating the direct and carry-over effects of the organic amendments applied to each crop cycle. A statistical analysis revealed that the carried over nutrient contribute significantly to crop yields.

7.3. Limitations of the study and perspectives

Some questions and limitations have been raised by this research and merit further investigation. The first limitation of this study relates to the empirical character of the fertilizer reduction strategy (-30%). Indeed, despite this reduction, N was sometimes still applied much in excess of plant requirements. On the other hand, K remained deficient, as it was already deficient in T100. It would therefore be more effective to target each nutrient independently. However, in practice, this would require knowledge by the farmer regarding the nutrient content of the large variety of nutrient sources they use, which seems illusory at this stage. The 30% reduction in nutrient application rates can be seen as a first, practical, indication of what can be targeted in nutrient reduction strategies. It should be accompanied with a recommendation to increase K applications. Other scenarios of

reducing N and P fertilization should nevertheless be tested taking into account the specific requirements of different crops.

In this study, the PFP index was used as an economic aggregate index to assess the use efficiency of the N, P and K used. However, the lack of factorial trials didn't allow gathering information regarding the use efficiency of each individual nutrient. Although in the literature the PFP is generally used the way we did, the PFP of each nutrient could be studied within the frame of further factorial field experiments.

In our study we used an empirical approach to model nutrient release through mineralization of organic matter. The model was based on several assumptions and simplifications that could have hampered the reliability of our predictions of nutrient availability. The main simplification consisted in considering that the mineralization from the soil organic pool occurred only from two pools (humus and manure pool), instead of three pools (+ litter pool). Further assumptions relate to the empirical selection of the mineralization coefficients in the humus and manure pools based on the literature. Furthermore, the model was based on predefined and fixed values of mineralization coefficients irrespective of the type of amendment type, whereas it is well known that this coefficient depends on the type of organic resource. These assumptions and limitation are likely to introduce large uncertainties in our model predictions. Therefore, there is a need for a thorough investigation of the error sources. Such an analysis may provide additional insight into the reliability of our mineralization data and the accuracy of the calculated nutrient balances. To tackle this question, an in-depth quantification of the model sensitivity to the parameters and their associated uncertainties needs to be performed. A Monte Carlo uncertainty analysis could for instance be performed to check for the response of the model to the uncertainty associated to each coefficient.

Another relevant question relates to the discrepancy that exists between drainage measured at the bottom of the root zone with pan lysimeters and the drainage derived from the water balance calculation. Indeed, the performance of the flux meters was only evaluated using simple

soil water balance calculations. These calculated drainage values include the water flowing both under saturated and unsaturated conditions. Our soil volumetric water content measurements suggested that the soil within the 0–30 cm depth remained predominantly under unsaturated conditions during the monitoring period. However, it has been shown that pan lysimeters sample water only under (near–) saturated conditions, and fail to sample unsaturated flow. They may also fail to sample preferential flows. This may explain the low efficiency of these devices when compared to the drainage obtained from water balance calculations. Therefore the evaluation of the performance of these devices by means of a numerical water and solute transport model which takes into account their operating principle would be needed. An evaluation with such model might clarify the actual seepage drainage that occurred during the study period and therefore provide an estimate of the efficiency of our pan lysimeters.

Our study was based on an intensive monitoring of water and nutrient management practices in UPA in Bobo Dioulasso. Given the intensive monitoring that was required, we were limited in the number of gardens and management practices that could be evaluated. Therefore our study is based on only two gardens. Even though these two sites were selected so as to be representative of the 111 gardens classified in the city Bobo Dioulasso by [Dossa et al. \(2011\)](#) and [Abdulkadir et al. \(2012\)](#), the limited number of gardens that were studied may raise concerns regarding the possibility of generalizing our results at the city level. Furthermore, our study was based on a continuous monitoring during 1 to 2 years. Even though this study is one of the first studies that lasted continuously for such a long period, our study is nevertheless constrained by the limited duration. Indeed, besides the inherent climatic variability, we observed high temporal variability in the management practices (e.g., types and application rates of amendments). Modelling could help overcome such limitations. As a matter of fact, the data collected in this thesis could be used to calibrate and validate a biophysical model. Among the process models that could be used for such a purpose, the integrated soil crop model Wave (Water and Agrochemicals in

soil, crop and Vadose Environment ([Vanclooster et al. 1995](#)) could be used as it has been subjected to numerous validation studies and benchmarking.

Bibilography

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Appendices

Appendix A:

Root profile description

Assessment of root characteristics was done by means of the core method on 18 plants per treatment randomly selected among the inner rows of the plots. The root profile was determined once at the end of the crop cycle. Soil cores were extracted with a 7-cm inner diameter corer in successive 10 cm increments up to 30 cm depth, since very few roots were encountered below 30 cm during the evaluation period. Two sampling positions were chosen for each selected plant: directly under the plant stem and halfway between two plants. The soil was washed manually over three sieves of different mesh sizes (2 mm; 1 mm and 0.25 mm) in order to separate roots from soil. The line intercept method, based on [Tennant \(1975\)](#), was used for estimating root length by counting the number of interceptions between roots and horizontal and/or vertical lines of a grid drawn on a glass plate ([Dechassa et al., 2003](#)). Equ. 3.9 was used to derive root length ([Bayala et al., 2004](#)):

$$R = \pi ND / 4$$

where: R (cm) = root length; N = number of counts and D (cm) = grid size (5 mm x 5 mm).

This method gives good correlation ($R^2 = 0.9998$, $P < 0.001$; Tennant, 1975) between estimated and actual root length. When samples were very small (less than 10 intercepts), direct length measurements were made using a ruler. Then root length density (RLD) was obtained by dividing root length by the soil sample volume used for root extraction. After length measurement, root samples were weighed to determine wet biomass and oven-dried at 70 °C for 48 hours and weighed again. Root weight density (RWD) was obtained by dividing root weight dry matter of each sample by the soil sampling volume.

Appendix B:

Organic and mineral fertilizers advice

Table B: Organic and mineral fertilizers advice for the different crops in tropical Africa (after [Wichmann, 1992](#); [Rubatzky and Yamaguchi, 1997](#); [Grubben and Denton, 2004](#); and [INERA](#) advices).

Crops	Data from litterature				
	t ha ⁻¹	t ha ⁻¹	kg ha ⁻¹		
	Yield	O M [†]	N	P	K
Tomato (tropical cv.) ^{††}	12-40	25	80-180	80-200	80-200
Cabbage (tropical cv.)	20-50	20-50	121-200	24-65	75-150
Lettuce (tropical cv.)	10-25	20-30	100-200	45	65-100
Carrot (tropical cv.)	10-37	10 -20	75-150	50-100	50-200
Recommendations of INERA (Burkina Faso)					
Tomato “Mongal”	25-40	20	120	120	240
Cabbage “KK Cross”	20-40	20	100	80	140
Lettuce “Augusta & Batavia”	8-15	20	100	50	100
Carrot “Touchon”	12-25	20	90	90	160

NB: the N, P and K requirement include both the OM + mineral fertilizer

[†] Animal manure or Compost; ^{††} Recommendations for all cultivar adapted for tropical zones.

Appendix C:

Ratio [-] between C and N, P and K used for the organic matter mineralization model

Site	N/C	P/C	K/C
Soil humus	0.07	0.011	0.184
Soil manure	0.07	0.011	0.184
Poultry Dropping	0.167	0.098	0.177
Farm Yard Manure	0.136	0.033	0.189
Municipal Waste	0.11	0.06	0.23
Compost	0.139	0.033	0.189

Appendix D:

Water retention curves

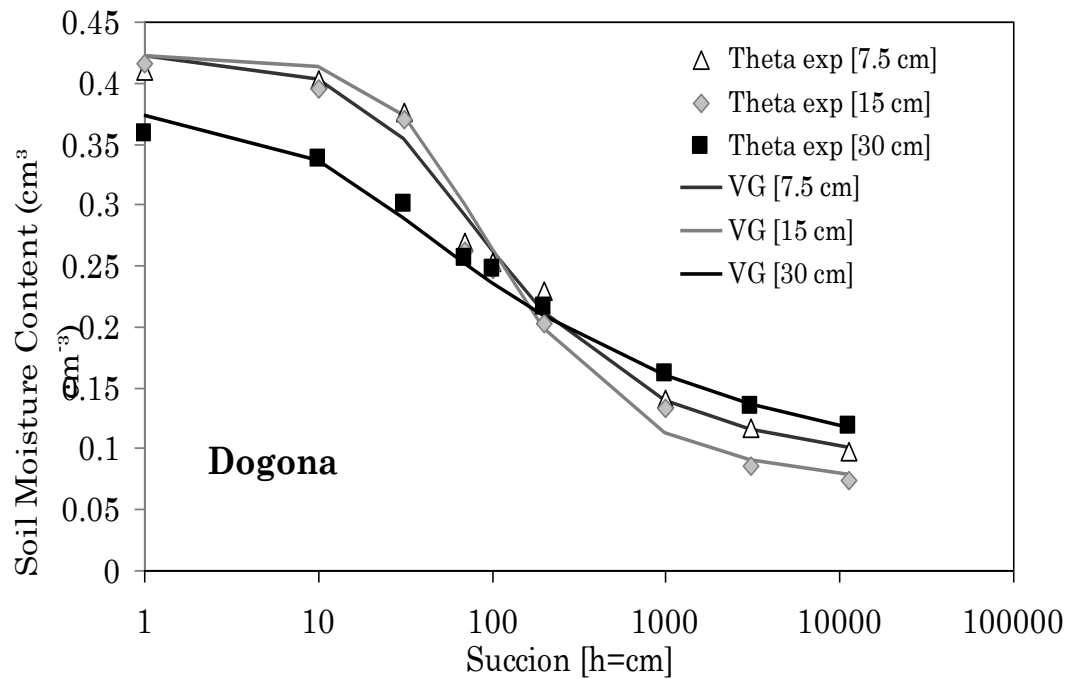


Figure D1: Measured water retention characteristics and the corresponding van Genuchten (1980) curves obtained for three soil depths at Dogona.

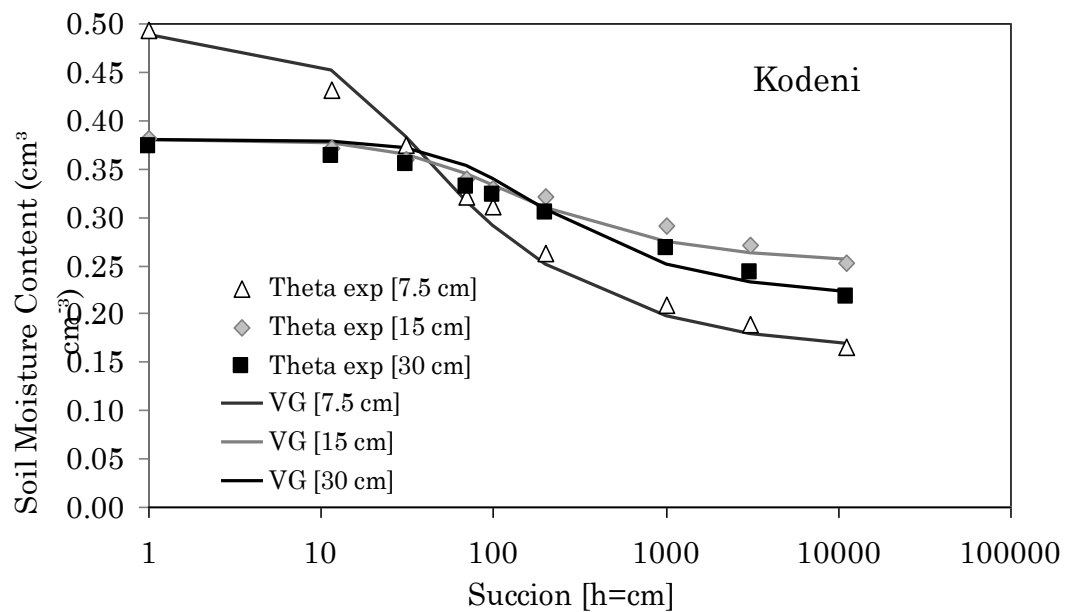


Figure D 2 : Measured water retention characteristics and the corresponding van Genuchten (1980) curves obtained for three soil depths at Dogona.

Appendix E:

Example of Nutrient distribution profile in the resin cartridges

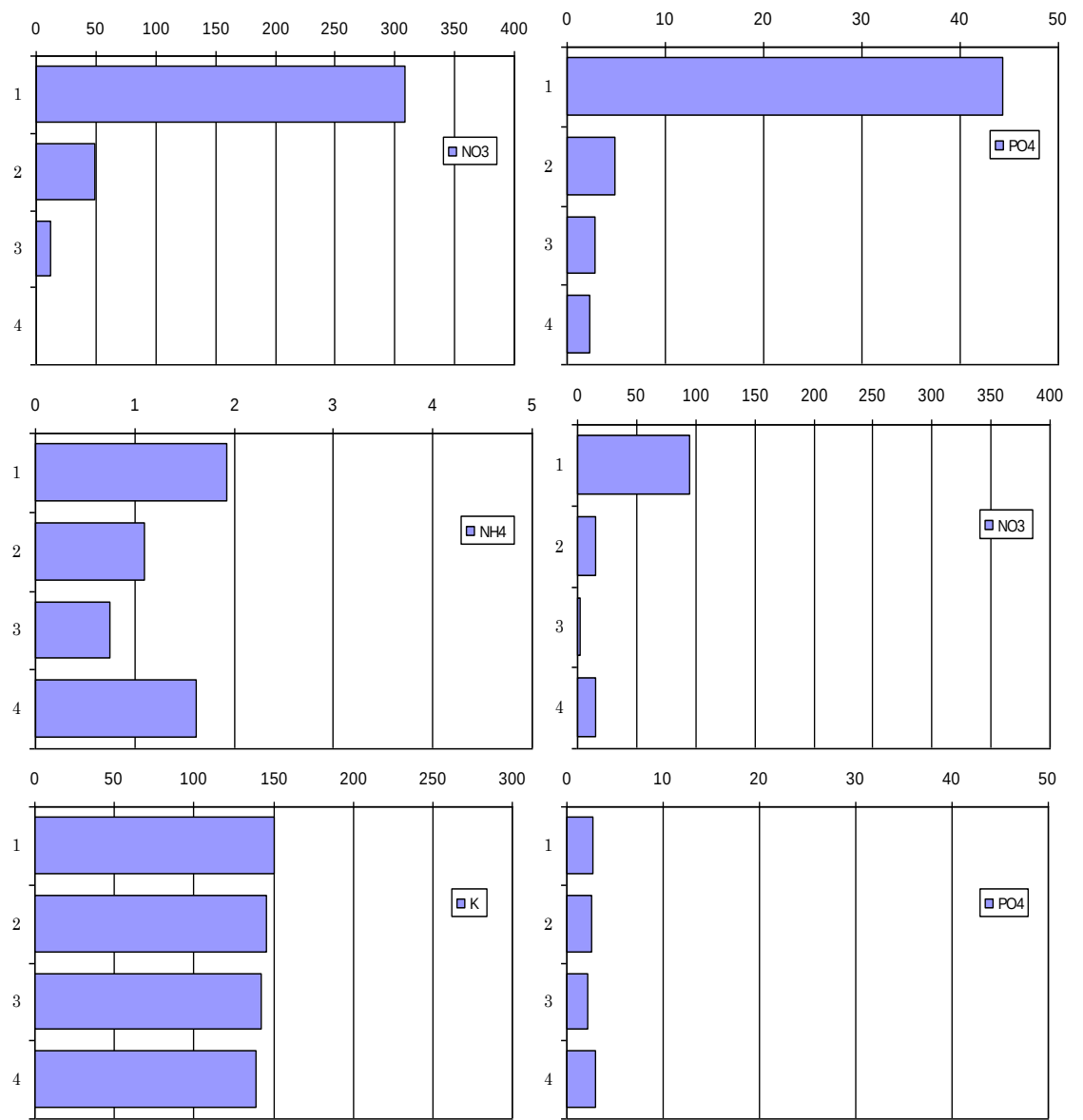


Figure E: Nutrient concentration (mg/kg) in the four layers of resin cartridges

Publications and Conferences

Conferences and workshops

Oral Presentations

- 1) **Sangaré, S. K.**, Compaoré, E., Vanclooster, M., Sédogo, P.M., Biielders, C. Vertical nutrient fluxes in soils of urban agriculture: Fiel-scale analysis of the study of nitrogen, phosphorus and potassium leaching in Bobo Dioulasso. Proceeding of the International Conference on Land and Water Degradation Processes and Management – “COMLAND 2009”. Magdeburg, Germany from 7th – 12th September 2009.
- 2) **Sangaré, S.K.**, Compaoré, E., Vanclooster, M., Sédogo, P.M., Biielders, C. 2009. Vertical nutrient fluxes in soils of urban agriculture: a study of N, P and K leaching in Bobo Dioulasso, Burkina Faso. Grantees Meeting “Resources, their Dynamics, and Sustainability: Capacity–Development in Comparative and Integrated Approaches”. Dar Es Salam; Dar Es Salaam, Tanzania.
- 3) **Sangaré, S. K.**, Bilgo, A., Hien, V., Duponnois, R. Maitrise de la symbiose mycorhizienne en vue de l’amélioration de la fertilité des sols dans les agrosystèmes et de la régénération d’arbres endémiques du Burkina Faso et de Madagascar. Atelier–Rencontre CORUS : « Conservation et valorisation de la biodiversité et des écosystèmes en Afrique ». Coopération Française, IRD/CORUS ; UCAD – Dakar 5–10 Novembre 2007.

Poster Presentation

Sangaré, S. K., Compaoré, E., Vanclooster, M., Sédogo, P.M., Biielders, C., 2010. Vertical nutrient fluxes in soils of urban agricultural systems: measuring and modeling the nitrogen, phosphorus and potassium leaching in Bobo Dioulasso (Burkina Faso). “Natural Resources Research in Africa”, Witzenhausen, Germany (20–24 September 2010).

List of Publications

Submitted or to be submitted

- 1) Lompo, D. J. P., **Sangaré, S. A. K.**, Compaoré, E., Sedogo, M. P., Predotova, M., Buerkert, A. Gaseous emissions of nitrogen and carbon from urban vegetable gardens of Bobo Dioulasso, Burkina Faso. Submitted to *Journal of Plant Nutrition and Soil Science*.
- 2) Lompo, D. J. P., **Sangaré, S. A. K.**, Compaoré, E., Sedogo, M. P., Predotova, M., Schlecht, E., Buerkert, A. Horizontal flows and balances of nitrogen, phosphorus, potassium, and carbon in urban vegetables gardens of Bobo Dioulasso, Burkina Faso. Submitted to *Nutrient Cycling in Agroecosystems*.
- 3) **Sangare, S. K.**, Thioulouse, J., Bilgo, A., Prin, Y., Hien, V., Cissoko, M., Galliana, A., Duponnois, R., Soil microbial functions in response to arbuscular mycorrhizal 1 inoculation are not spatially distributed along radial gradients of plant influence. Submitted to *Functional Ecology*.
- 4) **Sangare, S. K.**, Lompo, J.D.P., Sedogo, M. P., Vanclooster, M., Biielders, C.L. Vertical leaching of mineral nutrient as affected by water and fertilizer management in urban vegetable production systems of West Africa. *To be submitted*.
- 5) **Sangare, S. K.**, Lompo, J.D.P., Compaore, E., Buerkert, A., Vanclooster, M., Sedogo, M. P., Biielders, C.L. Reduced fertilization as an option for improving nutrient use efficiency in a West African urban agricultural system. *To be submitted*.

Published in peer-reviewed journals

- 1) **Sangare, S. K.**, Compaore, E., Buerkert, A., Vanclooster, M., Sedogo, M. P., Biielders, C.L. Field-scale analysis of water and nutrient use efficiency for vegetable production in a West African urban agricultural system. *Nutrient Cycle in Agroecosysteme*, 92: 207–224.
- 2) Bilgo, A., **Sangare, S. K.**, Thioulouse, J., Prin, Y., Hien, V., Galiana, A., Baudoin, E., Hafidi, M., Bâ, A.M. and Duponnois, R., 2011. Response of native

- soil microbial functions to the controlled mycorrhization of an exotic tree legume, *Acacia holosericea* in a Sahelian ecosystem. *Mycorrhiza*, 22 : 175–187.
- 3) Dossa, L.H., Abdulkadir, A., Amadou, H., **Sangare, S.**, Schlecht, A., 2011. Exploring the diversity of urban and peri-urban agricultural systems in Sudano-Sahelian West Africa: An attempt towards a regional typology. *Landscape and Urban Planning* 102, 197– 206.
 - 4) Son, D., Compaore, E., Bonkougou, S., **Sangare, S.**, 2011. Effet du stress hydrique sur la croissance et la production du sésame (*Sesamum indicum*). *Journal of Applied Biosciences* 37: 2460 – 2467.
 - 5) **Sangare, S. K.**, Bilgo, A. And Hien, V., 2010. Effets de la mycorrhization contrôlée de *Acacia holosericea* A. Cunn ex G. Don sur les caractéristiques chimiques d'un lixisol et impact sur les rendements du maïs (*Zea mays* L.). *Science et Technique*. 31, n° 1- 2.
 - 6) Dabire, A. P., Hien, V., Kisa, M., Bilgo, A., **Sangare, S. K.**, Plenchette, C., Galiana, A., Prin, Y., Duponnois, R. 2007. Responses of soil microbial catabolic diversity to arbuscular mycorrhizal inoculation and soil disinfection. *Mycorrhiza* 17 (6): 537– 545.

Published as Abstracts

- 1) Sangare, S. K., Compaoré, E., Vanclooster, M., Sédogo, M. P., Biielders C. Vertical nutrient fluxes in soils of urban agriculture: Fiel-scale analysis of the study of nitrogen, phosphorus and potassium leaching in Bobo Dioulasso. Proceeding of the International Conference on Land and Water Degradation Processes and Management – “COMLAND 2009”. Magdeburg, Germany from 7th –12th September 2009. Book of abstract.
- 2) Sangaré, S.K., Compaoré, E., Vanclooster, Marnik, Sédogo, P.M., Biielders, Charles. 2010. Vertical nutrient fluxes in soils of urban agricultural systems: measuring and modeling the nitrogen, phosphorus and potassium leaching in Bobo Dioulasso (Burkina Faso). “Natural Resources Research in Africa”, Witzenhhausen, Germany (20–24 September 2010). Book of abstracts p. 19.
- 3) Sangaré, S.K., Compaoré, E., Sédogo, P.M., Biielders, Charles, Vanclooster, Marnik. 2009. Vertical nutrient fluxes in soils of urban agriculture: a study of N, P and K leaching in Bobo Dioulasso, Burkina Faso. Grantees Meeting

“Resources, their Dynamics, and Sustainability: Capacity–Development in Comparative and Integrated Approaches”. Dar Es Salam; Dar Es Salaam, Tanzania. Book of abstracts

- 4) **Sangaré, S. K.**, Vanclooster, M., Sédogo, M., Biielders, C. Vertical nutrient fluxes in urban agricultural soils: Measuring and modelling the N, P and K leaching in Bobo Dioulasso (Burkina Faso). In *Peri-urban horticulture in the century of cities International symposium / FAO*. Dakar, Republic of Senegal, 6-9 December 2010. *Book of abstracts*, page 66.

Dissertation (Engineers, DEA)

- 1) **Sangare S., 2007.** La mycorhization contrôlée d’une essence forestière exotique : conséquences sur la diversité fonctionnelle de la microflore endémique d'un Lixisol ferrique du Burkina Faso. Mémoire de DEA-GIRN. Université Polytechnique de Bobo-Dioulasso. 71p.
- 2) **Sangare S., 2002 :** Evaluation de la performance agro- écologique des techniques de lutte contre la désertification dans les provinces du Passoré et du Yatenga : Cas du zaï, de la demi-lune et du tapis herbacé. Mémoire de fin d’études IDR / INERA ; 84 p.