KWAME NKRUMAH UNIVERSITY OF SICENCE AND TECHNOLOGY,

KUMASI

Exploring soil nutrient management and production performances to support building smallholder farms' resilience to climate change: case of South-Western Burkina Faso

by

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A Thesis submitted to the Department of Civil Engineering,

College of Engineering

in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Climate Change and Land Use

April, 2015

CERTIFICATION

I hereby declare that this submission is my own work towards the PhD and that, to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

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ABSTRACT

Sub-Saharan Africa remains the most affected region by food insecurity and poverty. Unsustainable soil nutrient management undermines crop production. Also, climate change impacts on farming by disrupting nutrient cycles which are key to farm production. Studies revealed large negative nutrient balances in many farming systems. Population's livelihood is at stake. There is a need to build resilient farming systems capable of improving soil nutrient closeness while ensuring efficient and profitable food production in climate change context. Farm resilience arises from internal decision making and from external decision making through policies and intervention measures.

The main objective of this research is to contribute to building African smallholder farms' resilience to climate change by analysing farms nutrient management use behaviour (decision making), soil nutrient balances and related production and economic performances, and identifying promising options for closing soil nutrient gaps. In a first step a multi-dimensional dataset was collected from 360 households-farms sampled in six villages of Ioba province in South-Western Burkina Faso. The Sustainable Livelihood Framework was used to analyse farms heterogeneity. Multiple linear and bi-logit regressions were run to analyse determinants of mineral fertilizer use intensity, separate adoption of mineral and organic fertilizer, and combined mineral-organic fertilizer adoption for different farm types. In a second step, the NUTMON framework was used to analyse farm nutrient management and economic performances. Five farm types for a total number of 15 farms were monitored for one year. Farms' agronomic and economic performances were evaluated. Whole farm and soil subsystem nutrient (N, P and K) balances of the farm types were calculated and their linkages with farm economic performances were investigated. The research finally discussed scenarios for closing soil nutrient gaps.

Findings revealed five socio-economic and ecological farm-types with different soil nutrient management strategies. Beside common determinants of fertilizer use and adoption, type-specific determinants and behaviour were unveiled. Farm and soil nutrient balance and economic performances analyses revealed two main cases: (1) farms with 'negative soil nutrient balance and low margin', and (2) farms with 'negative soil nutrient balance with better margin'. The first case faces the convergent problem of depleted soil resources, poor productivity and profitability. The second case, currently profitable, will become problematic as soon as the negative soil nutrient balance trend depicts nutrient stock depletion in near future. Balancing soil nutrient with only mineral fertilizers is likely unaffordable as the current fertilizer uses are not efficient with high rates of net soil nutrient loss. In this scenario the required amount of fertilizer to fill nutrient gaps will cost up to 72% of crop marginal revenue drawn per hectare. If crop residues are fully recycled, soil nutrient balance will be improved by 40-90%. The integration livestock-cropping was found to be the most promising option for sustainable smallholder farming. The research recommends that, rather than uniform interventions decision makers should distinguish between farming systems using relevant socio-ecological criteria in designing policies to promote sustainable soil nutrient management. Policy interventions and farm design should focus on the subsidiary linkages between livestock and crop production. Capacity building of smallholders' farms in agro meteorology is required to lay the basis for efficient adaptation and building resilience to climate change. From a methodological perspective, the research demonstrated the relationship between structural and functional typologies and the importance for considering both in regional farming system studies. The results also provide an empirical framework for scaling-out studies.

RÉSUMÉ

L'Afrique subsaharienne reste la région la plus affectée par l'insécurité alimentaire et la pauvreté. Les modes de gestion non durables de la fertilité des sols minent la production agricole. De plus, les changements climatiques altèrent le cycle des nutriments, essentiels à la production agricole. Des études ont révélés de grands déficits de la balance des nutriments dans plusieurs systèmes d'exploitation agricole, menaçant de fait les moyens de subsistances des populations. Il est nécessaire de mettre en place des systèmes d'exploitation agricole résilients capables d'améliorer la balance des nutriments du sol tout en assurant une production efficiente et rentable dans le contexte des changements climatiques. La résilience des exploitations agricoles se construit à partir des prises de décisions internes aux exploitations et des interventions externes à travers les mesures politiques.

L'objectif global de cette recherche est de contribuer à construire la résilience des exploitations agricoles face aux changements climatiques à travers une amélioration de la compréhension du comportement décisionnel des exploitations agricoles en termes de gestion des nutriments du sol, l'analyse de la balance des nutriments du sol et des performances agronomique et économique qui en résultent, et l'identification des meilleures options pour des exploitations agricoles durables. Dans une première étape, et utilisant le cadre conceptuel des moyens de subsistances durables, une base de données multidimensionnelle a été collectée chez 360 ménages agricoles de six villages de la province du Ioba dans le Sud-Ouest du Burkina Faso. Une typologie des exploitations a été construite. Le comportement décisionnel des exploitations a été étudié en analysant les déterminants de l'intensité d'utilisation et de l'adoption des engrais (minéraux, organiques, combinaison engrais minéraux et organiques). Dans une deuxième étape, le NUTMON a été utilisé pour analyser les performances économiques et la balance des nutriments du sol des exploitations agricoles. Cinq types d'exploitations (15 exploitations en tout) ont ainsi été suivis durant une année. La balance des nutriments (N, P et K) au niveau exploitation et celle du sous-système sol ont été calculées et leurs liens avec la performance économique des exploitations ont été analysés. La recherche a conclu en discutant les options durables pour combler les gaps de la balance des nutriments du sol.

Cinq groupes socioéconomiques et écologiques d'exploitations agricoles avec des stratégies différentes de gestion des nutriments du sol ont été identifiés. La recherche a révélé en plus des déterminants communs d'adoption et d'utilisation des nutriments du sol, des déterminants spécifiques aux différents types d'exploitations. L'analyse de la balance des nutriments a révélé deux principaux cas : (1) des exploitations avec 'une balance des nutriments du sol négative et un faible profit' et (2) des exploitations avec 'une balance des nutriments du sol négative mais un meilleur profit'. Le premier cas correspond à l'exploitation minière du sol accompagnée d'une faible productivité et rentabilité. Le deuxième cas, actuellement rentable, deviendra problématique une fois que le stock des nutriments du sol sera épuisé dans un future proche et ne sera plus à mesure d'assurer la production. Combler le gap en nutriments du sol avec les engrais minéraux uniquement apparait difficile à supporter financièrement par les producteurs vu l'ampleur des pertes des nutriments des sols. Ce scenario coûtera jusqu'à 72% du revenu marginal par hectare. Recycler entièrement les résidus de récolte améliore la balance des nutriments du sol de 40-90%. Cependant, sous ce scenario les producteurs seront confrontés à la compétition pour l'alimentation animale et l'utilisation domestique des résidus de récoltes. L'intégration élevage-production végétales se révèle être la solution pour des exploitations agricoles durables. En termes de recommandations, les décideurs doivent prioriser les interventions ciblées

distinguant les différents systèmes d'exploitations agricoles en vue de promouvoir la gestion durable de la fertilité des sols. Les politiques agricoles ainsi que de design des exploitations agricoles doivent également considérer l'intégration élevage-production végétales. Il faudra aussi renforcer la capacité des agriculteurs en agro météorologie pour une meilleure adaptation et la résilience au changement climatique. Au plan méthodologique, cette recherche démontre le lien entre typologies structurelle et fonctionnelle ainsi que la nécessité de les prendre en compte dans l'étude des systèmes d'exploitation agricole.

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DEDICATION

This thesis work is dedicated to:

- *My father who departed only few months after my admission to the PhD program. May he rest in peace.*
- *My mother, Kampoa Onadja for her precious support and blessings.*
- *My beloved spouse, Wend kuni Sabine Marie Flore Thiombiano/Doamba for her support, encouragements and for supporting my extended absences.*
- *My brothers Yentéma David Thiombinao and Hampougdi Thiombiano for their valuable support and investment in my studies*
- *My brother Olivier Thiombiano and my nieces Claudia Severina Banyala Thiombiano and Pouniyala Jessica Thiombiano. I expect you to use this thesis as an example and do better.*

To the memory of Fayçal Ouédraogo

To all farmers of Ioba Province, may the findings of this research contribute to better livelihoods.

ACKNOWLEDGMENT

I am grateful to German Federal Ministry of Education and Research (BMBF) which fully funded my PhD studies and this research through West African Science Service Center on Climate Change and Adapted Land use (WASCAL).

I would not have carried out this thesis without God's Grace and Blessings (Glory to Him), and without the valuable support of many persons.

I express my deep gratitude to my Main supervisor Dr Quang Bao Le. He accepted to supervise me on this thesis, a very exciting topic. Dr Le initiated me to many aspects of scientific research and introduced me to methodical and rigorous scientific work. He shared with me great ideas on land use, sustainable agriculture, farming systems design and farm resilience. My stay with him at the Natural and Social Science Interface (NSSI) at ETH-Zurich in Switzerland was a very rich experience. He has been available, patient in showing things and provided me with valuable comments for my thesis and my research carrier. I say thank you for the wonderful job he did. Beyond research, Dr Le was also very helpful in life abroad. Visiting Zurich was my very first time in Europe and it was not easy for me. Dr Le took me through European life. He allowed me to stay at his apartment when I was having accommodation issues upon my arrival in Zurich. He and his wife welcomed me and I had the opportunity to share wonderful moments like the Vietnamese dishes I enjoyed many weekends during my stay in Zurich. I really appreciate and will be forever grateful. God bless you and your wife.

I am grateful to my Co-supervisor Prof. Samuel Nii Odai. He accepted to supervise me on my request and provided me with valuable feedback on my work. It has been always a pleasure meeting him. As the Director of the GRP CCLU, he did a lot to "make life easy" for us at KNUST. I appreciated all his efforts during our PhD training. I remember when I call him on phone because I was having internet trouble for sending my application to WASCAL program. He received my call very nicely. This encouraged me to apply. God bless you, Prof.

I also express my gratitude to my Co-supervisor Dr Dénis Ouédraogo. His valuable comments and his constant encouragement are always greatly appreciated. He also helped me lifewise. I really appreciate and will be forever grateful. God bless you.

During my research I had the opportunity to work at a well-known institution, the Natural and Social Science Interface (NSSI) at ETH-Zurich in Switzerland. I am grateful to Dr Pius Krütli who accepted my visit at NSSI. I say thank you for the facilities, the access to international peer-reviewed journals for my research and all the valuable comments that greatly improved my work. I am also grateful to all the personnel, the researchers and students at NSSI who warmly welcomed me and made valuable comments on my work when I presented at a NSSI seminar. Special thanks to Maria Rey.

I met a wonderful family in Zurich and I would like to thank. They helped in my life abroad. Special thanks to Meier-Fröhlich Edeltrud and her family (Beat and Suzanne, Christine and Andy, and their respective families). They made me feel at home though I was very far from Africa. I will never forget what you did for me. God richly bless you.

My thanks also go to the Director of WASCAL Competence Center in Ouaga, Dr Barry Boubacar, who kindly provided a car and other supporting logistics for fieldwork at every time. Thank you for your commitment in helping students. I am grateful. I am also grateful to all the personnel (particularly Mrs. Aminata Barry/Sidibe and M. Igor Bado), researchers (Dr Sié Sylvestre Da, in particular), and drivers at WASCAL Competence Center for the permanent support and encouragements.

I am grateful to Dr Kwaku Amaning Adjei from KNUST, for reading my thesis and making precious comments.

I am grateful to M. Palamangui Onadja for his precious assistance during my fieldworkd. God richely bless you. I say thank you to M. Athanase Some, M. Nagnow Somda, M. Wenscelas Somda, M. Patrice Some, M. Désiré Somda, and M. Bertrand Somda for their help in the field.

I thank M. Moussa Sawadogo and M. Harouna Koné, from the Provincial Directorate of Agriculture in Dano, for their support and help in gathering secondary data.

I am grateful to my colleagues of GRP CCLU first batch for the friendly time we shared in Kumasi. Special thanks to M. Demba N.A. Trawally, M. Souleymane S. Traore, D. M. Maurice Ahouansou, Bernard. Batuuwie and Y. Lucette Akpa. Stay blessed.

1. INTRODUCTION

1.1. Background

Populations in Sub-Saharan Africa (SSA) largely rely on farming for their livelihood (Shiferaw *et al.*, 2014). Though farmers tend to diversify livelihood sources into non-farm activities (IFAD, 2010), farming is still the primary source of livelihoods. In countries like Burkina Faso, 80% of the population draw their living means from farming (SPCPSA, 2013). Farming in SSA is dominated by smallholder farming (Livingston *et al.*, 2011) characterised by low land holding, low mechanization and low investment in soil fertility. In this context and given the fast growing population (UN, 2013), SSA faces the challenge of ensuring food security and alleviating poverty.

SSA is poorer than other regions and poverty concerns much more rural populations relying essentially on farming (Livingston *et al.*, 2011). The region is also characterized by high food insecurity (FAO, 2010). It has the highest undernourishment prevalence estimated at 24.8% in 2011-2013 (FAO *et al.*, 2013). For decades food insecurity has affected many countries with not much improvement (FAO, 1993; FAO, 2006; FAO *et al.*, 2013). In Burkina Faso in particular, 37% of rural households were food insecure in 2013 (SPCPSA, 2013) and 25% of the population were undernourished in 2011-2013 (FAO *et al.*, 2013). As much as 43.9% of households in the country were poor in 2010 (INSD, 2010). Given the strong reliance of farming on rainfed agriculture, food insecurity and poverty are likely to worsen in coming years under climate change.

Indeed climate change is expected to negatively affect farming activities and aggravate crop production deficiencies, food insecurity, and thereby threaten livelihoods of populations (Jarvis *et al.*, 2010; Lobell and Burke, 2010; Jalloh *et al.*, 2013; Olsson *et al.*, 2014; Porter *et al.*, 2014). Studies (Blanc, 2012; Sultan *et al.*, 2013) estimated that yield of main staple crops in SSA (maize, millet and sorghum) will decrease by up to 25.5-27% under climate change during the 21st century.

1.2. Problem statement

Nutrient cycles link agricultural systems to their societies and surroundings(Vitousek *et al.*, 2009). There are four main issues related to nutrient cycles in agro-ecosystems: (i) nutrient balance, (ii) cycles' productivity and efficiency in warranting human demands, (iii) cycles' role in maintaining system resilience, and (iv) farmers' incentive to innovations in nutrient use and management.

In SSA, unsustainable soil nutrient management constitutes the root cause of food insecurity and poverty in smallholder farms. Low soil fertility undermines crop productivity as observed by Giller *et al.* (2006). Many studies reviewed by Cobo *et al.*(2010) highlighted ongoing nutrient mining in smallholder farms threatening farming sustainability. Henao and Baanante (1999) noted a high loss of more than 60 kg NPK per year from crop land soils in Burkina Faso. There exist proven technologies that may help in addressing soil nutrient depletion issue and improving crop productivity (Vlek *et al.*, 1997; Ingram *et al.*, 2008; Lal, 2009). However, adoption by farmers and nutrient use efficiency remain low. The low adoption is mainly due to poverty (Reardon and Vosti, 1995) and the failure of policy intervention (Anley *et al.*, 2007) to leverage farmer's incentive to adopt innovations in nutrient use and management. In addition, climate change impacts farming activities by modifying farm nutrient cycles and services. In effect, increased temperatures modify organic matter dynamics, while variability and high intensity of rainfall events lead to increased soil erosion (Brinkman, 1990). Against all of this, current SSA farming systems are highly vulnerable. As noted by Godfray *et al.*, (2010), Conway (2012) and Wheeler et *al.*,(2013) change in food production system is required.

In SSA in particular, this change should target building farms resilience based on nutrient cycles which are key to farming (crops and livestock). Farm resilience arises not only from farm internal structure and functioning but also from external intervention through policies. Therefore, helping to build farm resilience requires considering the farm in a holistic way, better understanding farm behaviour giving its social, economic and biophysical settings. It also requires redesigning policy intervention which sometime hampers food security (Grote, 2014) or lacks efficiency. Transformation of farming system has gained interest among researchers (Darnhofer *et al.*, 2012). This research aims at contributing to farming system design research and proposing options for transforming sub Saharan African smallholder farms into resilient farms in the face of climate change.

1.3. Objectives

The main objective of this research was to contribute building resilient farms to climate change through improved understanding of smallholder farms' behaviour in terms of soil nutrient management, linkages between nutrient balance and economic performances, as well as discussing promising scenarios for closing soil nutrient gaps. The specific objectives are to:

1. Identify socio-economic and ecological farm types in the study region, and analyse production performances and ecological efficiencies.
2. Analyse the role of climate change perception versus climate change awareness on sustainable soil nutrient management by smallholder farms.
3. Analyse the role of farm type-specific adoption behaviour in sustainable soil nutrient management by smallholder farms.
4. Analyse soil and farm nutrient balances and economic performances of smallholder farms

5. Discuss promising options for closing soil nutrient gaps in smallholder farms

1.4. Thesis outline

This thesis comprises 8 chapters in total. After the introductory chapter (this chapter), Chapter 2 presents a brief literature review.

Chapter 3 presents the general methodology used for carrying out the research. It contains an overview of the study region, a description of the screen survey and farm monitoring.

Chapter 4 explores socio ecological heterogeneity of smallholder farms in Ioba province. It aims at achieving objective 1. It established smallholder farms typology using screening surveys data. The chapter also analyses farm nutrient management and production performances as well as mineral nutrient use efficiencies across farm types.

Chapter 5 covers objective 2. By analysing successively the role of climate changes perception and awareness on sustainable soil nutrient management it highlights the important contribution of climate awareness in farmers' incentive to take action for better management of farm soil fertility in smallholder farms,.

Chapter 6 addresses objective 3. It analyses farm adoption behaviour for mineral fertilizer use and adoption as well as adoption of organic, and combined mineral-organic fertilizer.

Chapter 7 covers specific objectives 4 and 5. Nutrient (N, P and K) balances at farm level and for soil sub compartment are calculated. Soil nutrient balances performances and relationship to agronomic and economic performances of different smallholder farming systems are analysed. It ends by discussing scenario for closing observed soil nutrient gaps in smallholder farms.

Chapter 8 presents general conclusion comprising concluding remarks and recommendations.

2. LITERATURE REVIEW

2.1. Resilience of what to what?

Originated by Holling (1973), the resilience concept has no consensual definition (Gersonius *et al.*, 2012). Resilience of a Socio Ecological System (SES) can be given many definitions related to sustainability, to a property of dynamic models, or to a measurable quantity (Carpenter *et al.*, 2001). Based on the definitions of Gunderson and Holling (2001) and Pimm (1984), and in accordance with Carpenter *et al.*, (2001), a resilient SES is defined in the present research as a system that can undergo a given amount of change and still retain the same control on structure and function, be capable of self-organization, and build capacity to learn and adapt .

Studying the resilience of a SES requires specifying the system configuration and the type of disturbances one is interested in (Carpenter *et al.*, 2001). This research is interested in nutrient cycles' disturbances in agro ecosystems borne by climate change, and in smallholder farming systems in particular. Smallholder is mostly defined with regard to the farm land holdings. World Bank (2003) defines smallholder farm for developing countries as famers with holdings less than or equal to 2 ha. Chamberlin (2008) observed that some policy oriented papers have characterised smallholders farms as farms with limited land and capital, high exposure to risk, low input technologies, and low market orientation. In Burkina Faso, and for the present research, a smallholder farm fits more to the definition of Chamberlin (2008). It can be define as producers having farming as main source of income (Morton, 2007) and characterized by low capital input (e.g. financial investment) and subsistence agriculture (AGRA, 2014), high exposure to risk, low equipment, (e.g. no or low animal traction and no motorised equipment) and low soil nutrient input. A farm is defined in this work as a household for which members inhabit a communal compound, are using communal resources (e.g.

labour, financial, land resources) to produce and make a communal use of food and non-food products. Any use of the term household or farm, further in this study, should be understood as interchangeable terms.

2.2. Food insecurity and climate change impacts on Sub Saharan African farming

The rapid increase of the population in Sub-Saharan Africa poses the threat of the aggravation of food insecurity (AGRA, 2014). Population growth does not match with a consequent increase in food production (Jalloh *et al.*, 2013). Already, the region faces difficulties in meeting populations food demand (FAO, 2010). Undernourishment concerns 24.8% of Sub-Saharan Africa population (FAO *et al.*, 2013). In countries like Burkina, 37% of rural households were food insecure in 2013 (SPCPSA, 2013) and 25% of the country population was undernourished in 2011-2013 (FAO *et al.*, 2013). Sub-Saharan African countries heavily rely on smallholder farms for food production. These farms represent up to 80% of farms in Sub-Saharan Africa (AGRA, 2014). In some countries they contribute for as much as 90% of total food production (Wiggins, 2009). However, the low crop productivity, the lack of comprehensive and efficient policies as well as environmental constraints limits smallholder farms capacity to meet food needs of SSA region.

Environmental constraints consist mainly of soil degradation and growing climate change effects on farming activities. The fact that farming in Sub-Saharan Africa region depends for up to 98% on rainfed agriculture, render crops and livestock tributary of precarious situations under climate change (IPCC, 2014). For almost all Africa annual temperatures have risen by about 1^{o}C (Niang *et al.*, 2014) and temperature rise is expected to reach 2^{o}C by 2100 for Sub-Saharan Africa region (Grist, 2014). Basically, this means an increase of drought events, extreme temperatures and more erratic rainfall in some areas of the region. According to IPCC (2013), extreme precipitation events will likely become more intense and more frequent in Sub-Saharan Africa due to temperature rise. Jalloh *et al.*, (2013) stressed that rainfall decrease and temperature rise will certainly be a tremendous challenges for farming and related livelihood. Climate change will result in reduced yield of main staple crops (Blanc, 2012) in Sub-Saharan Africa.

2.3. Farming systems and soil nutrient issue: problems and needs for resilient farm management

Farming in Sub-Saharan Africa is dominated by smallholder farming systems. Most of smallholder farms practice mixed farming crop-livestock dominated by subsistence agriculture. They are characterized by low nutrient input, low mechanization and sometimes low educational level which constraints adoption of sustainable soil nutrient management practices. Farming systems in Sub-Saharan Africa faces four main problems: (i) population pressure causing expansion of cultivated land and reduction of farm land size (AGRA, 2013); (ii) very poor soil fertility management practices (Zingore, 2006) occasioning severe nutrient depletion in some cases, (iii) aggravation of soil degradation due to climate change, and (iv) nutrient cycles alteration resulting from climate changes effects.

Continuous cropping on the same piece of land, low nutrient input and soil erosion cause a declining of soil health. Indeed, the use of mineral and organic fertilizer is very low, particularly for staple crops (Sanchez and Swaminathan, 2005). Nutrient depletion is widespread (Bationo *et al.*, 1998; Cobo *et al.*, 2010). About 80% of arable land in SSA has serious soil fertility problems (AGRA, 2014). It is estimated that farmers lose 8 million tons of soil nutrients per year (Toenniessen *et al.*, 2008). Climate change impacts soil nutrient cycles through increased temperatures which accelerate the rate of soil organic matter decomposition, with negative effects on soil water-holding capacity and nutrient loss, more rapid organic matter decomposition will inevitably reduce the potential of innovations that seek to increase carbon sequestration in the soil. Also increases of rainfall amounts and intensity will lead to greater soil erosion and more intense leaching (AGRA, 2014).

In Ioba province in particular, high population density is causing increasing pressure on natural resources in general and on agricultural land in particular. DREP/Sud-Ouest(2000) reported a reduction of fallow duration from 4.5 to 2.5 years. Mineral fertilizers and compost uses are low (MAHRH, 2010; Gleisberg-Gerber, 2012).

Soil nutrient loss remains one of the biggest threat for sufficient food production in the world (Pimentel and Burgess, 2013). Given the level of poverty, the growing land pressure and expected impact of climate change in the region, this threat is most serious and more challenging for Sub-Saharan Africa. To be able to feed the estimated additional 1.6 billion people by 2050, the fundamental issue of soil depletion need to be successfully addressed (AGRA, 2014) at farm level. Existing production systems in Sub-Saharan Africa have been proven to be limited in maintaining productive and sustainable farm production. The situation is expected to worsen under climate change. There is a need to rethink farming system and build adaptive and resilient farms capable of maintaining a good enough nutrient cycling at farm level to ensure a sustainable and profitable farming.

2.4 Household-farm typology and related household behaviour

2.4.1. Sustainable livelihood framework

A livelihood is a means of gaining a living (Chambers and Conway, 1991). It comprises assets and capabilities mobilized for the living. The Sustainable Livelihood Framework (SLF) (Sconnes, 1998; DFID, 1999; de Sherbinin *et al.*, 2008) defines a sustainable livelihood as a livelihood that "can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base.'' Within this framework, household organizes its livelihood strategy by combining five types of capital that interact and vary over time: natural, social, physical, financial and human. The *natural capital* is the basis for farm crop and livestock production. It comprises land and forest resources, fisheries. These assets may lose value or their productivity (DFID, 1999) if they are not well managed. For instance sustainable land management is very important for maintaining soil productive function and its contribution to farmers' livelihood. *Social capital* which comprises household's social network and membership to organizations assets play an important role in valuing the natural capital. The *Physical capital* encompasses infrastructures and equipment used to support livelihood activities (e.g. road and transportation equipment). Physical capital requires *financial capital* (e.g. financial resources) to ensure maintenance and capacity building for an effective management. As for *Human capital*, it consists of skills, labour and capabilities necessary for valuing the others types of assets. The SLF is a holistic framework offering a better understanding of household-farm behaviour in relation to its environment.

2.4.2. Linkages between livelihood type and household behavior

Smallholder farms in Sub-Saharan Africa exhibit great diversity inherent to their livelihood characteristics (Zingore, 2006). Farmers draw their income from farming activities (crop and livestock), non-farm activities and transfers (e.g. remittance and pensions). Values of these income sources vary greatly at farm level (Ellis, 2005) and determine assets endowment. Farm livelihood structure (assets endowment) is closely related to its livelihood strategies (Ellis, 2000). In pursuing their living objectives households mobilize their biophysical and socio economical assets in livelihood strategies that guide their decision making and determine their behaviour. A farm might be well endowed in one livelihood asset but poor in another. The type of poverty can influence the farm's relation to its environment (Reardon & Vosti, 1995). For instance farm well-endowed in cattle have by far better access physical access to manure and may be more likely to use organic fertilizer than other. Also, among poor farms, receiving remittances can compel famer to purchase fertilizer in comparison to poor farms who received not or less remittance.

Giving level of assets endowment, farmers will have more or less options for building livelihood strategy (DFID, 1999). They will therefore be more or less incline to adopt and use soil nutrient. For instance, farm above poverty line can still choose to use its financial resources for consumption, savings or other type of investment rather than investing in soil fertility (Reardon and Vosti, 1995). Poor endowment in physical assets (e.g. road and communication facilities) reduces farm exposition to SNM technologies as well as access to markets for mineral fertilizer acquisition. Farm tools and equipment are useful for composting and transportation of fertilizer to plots. Besides being an important source of cash (Murungweni *et al.*, 2014) facilitating farm acquisition of mineral fertilizer, livestock provides draught power and manure. Also, availability in natural assets such as land may lead to extensive farming while land constraint may compel farmer to use more fertilizer (Tittonell *et al.*, 2005a). Social assets (e.g. networks) provide learning opportunities and improve farm access to fertilizer (e.g. credit system, remittances). Therefore, understanding smallholder farms behaviour in a broad way and for soil nutrient management and adaptation in particular requires exploring their livelihood heterogeneity.

3. GENERAL METHODOLOGY

3.1. Study region

3.1.1. Biophysical characteristics

The fieldwork took place in Ioba province located in South-Western region of Burkina Faso. The region represents 6% of the country's territory (INSD, 2009a). The region comprises of four provinces: Bougouriba, Poni, Noumbiel, and Ioba (10°42'-11°20'N and 02°36'-03°25'W) situated in the upper north and located within the Black Volta basin. Biophysical and socio-economical settings are summarized in Table 3.1.

Table 3.1. Biophysical and socio economical characteristics of the study region

Characteristics	Description	Sources
Climate	• South-Sudanian climatic zone • Annual rainfall: 900-965 mm	Dataset from Provincial directorate of agriculture of Ioba
Vegetation	• Savannah • Existence of a protected forest	MAHRH and GTZ (2004)
Soils	• Shallow • Main soil types: Plinthosol and Lixisol	MAHRH and GTZ (2004) DREP/Sud-Ouest and PNGT (2000) Schmengler (2011)
Hydrography	• Sub basin of the Black Volta river	BNDT (2002)
Demography	• 227,536 inhabitants in 2014 • 52% of females • Population density: 52 inhabitants/km^2	INSD (2009b; 2009a; 2013)
Socio-economic activities	Agriculture, animal husbandry, trade, traditional mining	DREP/Sud-Ouest (2000);INSD (2009a)
Supporting Institutions in soil fertility management	Directorate of Agriculture of Ioba; Dreyer Foundation; PABSO; PDA/GIZ; Sofitex; Varena Asso	Collected data

The Ioba province belongs to the South-Sudanian climatic zone. The rainfall is uni-modal and lasts for about 5-6 months starting from the end of April to October. The dry season starts from November to March-April and is characterized by harmatthan causing air borne diseases like meningitis. Wettest months are August and September while the hottest months are March and April. The Mouhoun River is the only permanent water body. Some dams exist offering the province opportunities for gardening and dry season irrigated cropping. Average rainfall varies between 900 mm and 960 mm (MAHRH and GTZ, 2004). The vegetation type is savannah. The only protected forest of the province is the Bontioli forest reserve which plays an important role in terms of biodiversity preservation and carbon sink. Outside this forest, deforestation is an alarming issue.

According to *Bureau national des sols* (Bunasol) inventory, dominants soils types encountered in the Ioba province are:

- Leached ferruginous tropical soils: they are dominant soils in Burkina Faso and represent 85% of the country lands (Pallo and Thiombiano, 1989). Two groups of this soil type are found in Ioba province:

i) Leached and hardened ferruginous tropical soils which are generally shallow and form the main soil type of the province. They cover nearly 52% of Ioba lands. Most of cultivated lands fall into this type.

ii) Leached ferruginous tropical soils with spots and concretions, encountered for only 2% of the lands in Ioba. These soils are poor in organic matter, macro nutrient (NPK) and have low Cationic Exchange Capacity (CEC) (Pallo and Thiombiano, 1989).

- Hydromorphic soils. Also characterized by low organic matter content and very low phosphorus content, they constitute the third main soil type in Burkina Faso and cover 13% of its lands (Kissou *et al.*, 2000) and around 37% of the Ioba province lands.
- Lithosols cover 3% of Burkina Faso territory (Kissou *et al.*, 2000) and represents 5% of lands in Ioba province.

- Brown eutrophic tropical soils: they form 6% of soils in Burkina and 4% of Ioba province lands. Brown eutrophic tropical soils are constrained in NPK (Kissou *et al.*, 2000).

3.1.2. Socio-economical characteristics

Ioba province comprises eight *communes*: Oronkua, Guéguéré, Koper, Ouessa, Niégo, Dissin, Zambo and Dano the sole urban *commune*. The town of Dano in Dano *commune* is the capital city of the province. Projections made by INSD (2009b) estimated the population to be 227,536 inhabitants in 2014. This population is dominated by females (52%) (INSD, 2013). The annual population growth between 1996 and 2006 was estimated at 1.8% and working population constitutes about 57% of the population. Population density is higher (59 inhabitants/km^2) than at the national level (52 inhabitants/km^2) (INSD, 2013). The province has the highest population density of the region. The main socio-economic activities are agricultural, animal husbandry, trade, handicraft, and mining activities. Agriculture is mainly for subsistence and is largely rain-fed. The main components of the regional agriculture are cereal, cotton and livestock (ruminants, pigs and poultry) productions.

3.2. Methods

Globally, the methodological approach consisted of two steps: a screen survey and an in-depth survey. The screen surveys aimed at appraising farming activities and farms' socio-ecological heterogeneity in the study region. Study cases were selected from identified typological farms and monitored for one year, March 2013-February 2014. Each of the two steps is described in details in the following sub-sections.

3.2.1. Screen surveys

3.2.1.1. Research sites selection and households sampling strategy

The research sites (Figure 3.1) were chosen based on the criteria of biophysical and socio-demographical indices that influences land use and soil nutrients use.

Selection of the research sites and sampling of households followed a step-wise procedure as illustrated by the flowchart in Figure 3.2. In the first step, based on land use map, land degradation information and demographic statistics, three *communes* were selected: Dano, Koper and Ouessa. In the second step, for each *commune*, two villages were randomly selected: Pontieba and Loffing (Dano *commune*), Babora and Dibogh (Koper *commune*), Kolinka and Bekotenga (Ouessa *commune*). An equal number of households (60) were drawn for each of the six villages within the research area using a simple random sampling technique. The list of households in each village was used for drawing the sample. A total number of 360 out of 1,232 households were sampled. This sample represented 29.22% of total households in the research area.

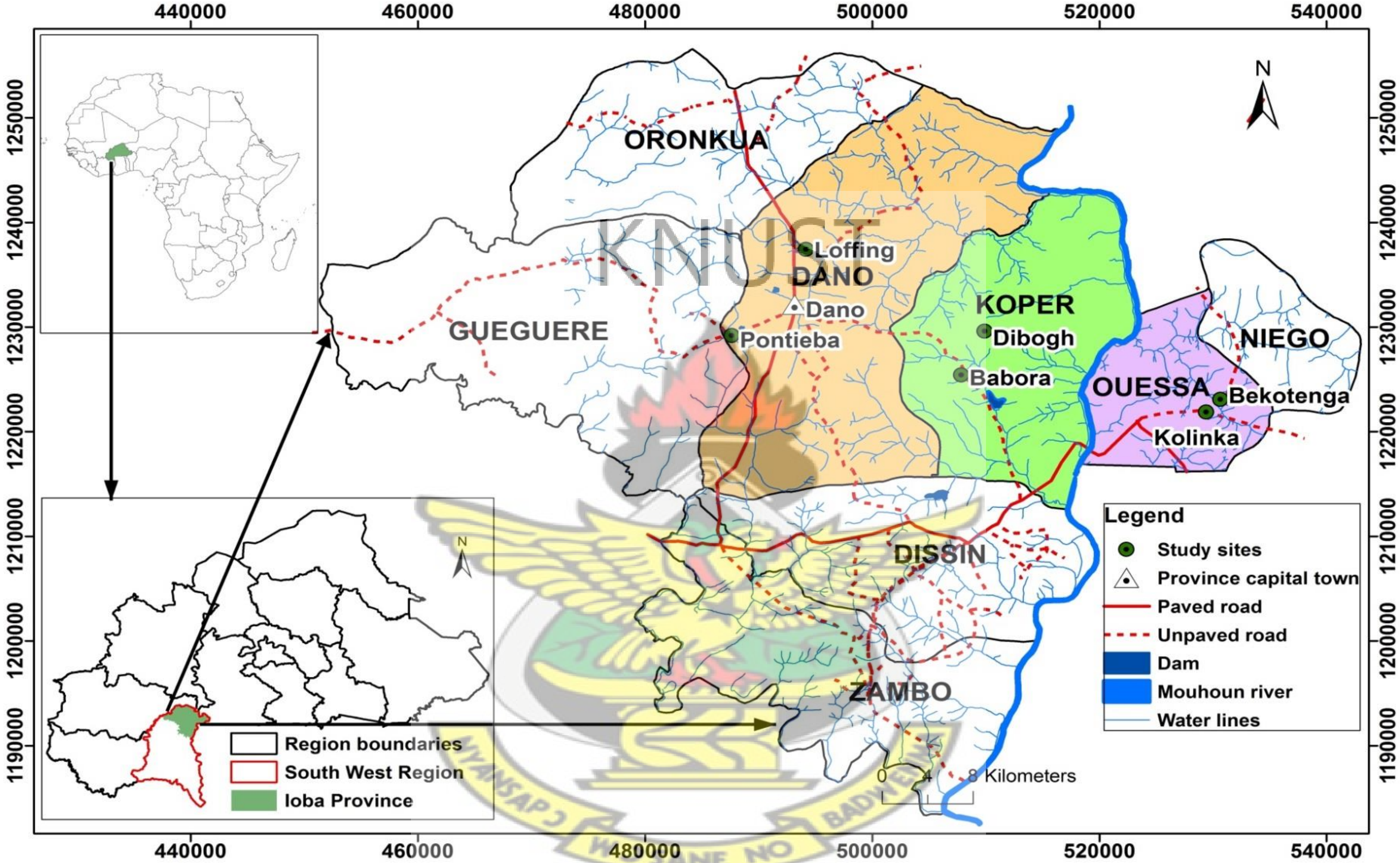


Figure 3.1. Study region.

Notes: *Text labels with capital and normal characters are for communes and villages, respectively. Pontiéba, Babora and Bekotenga are monitoring sites*

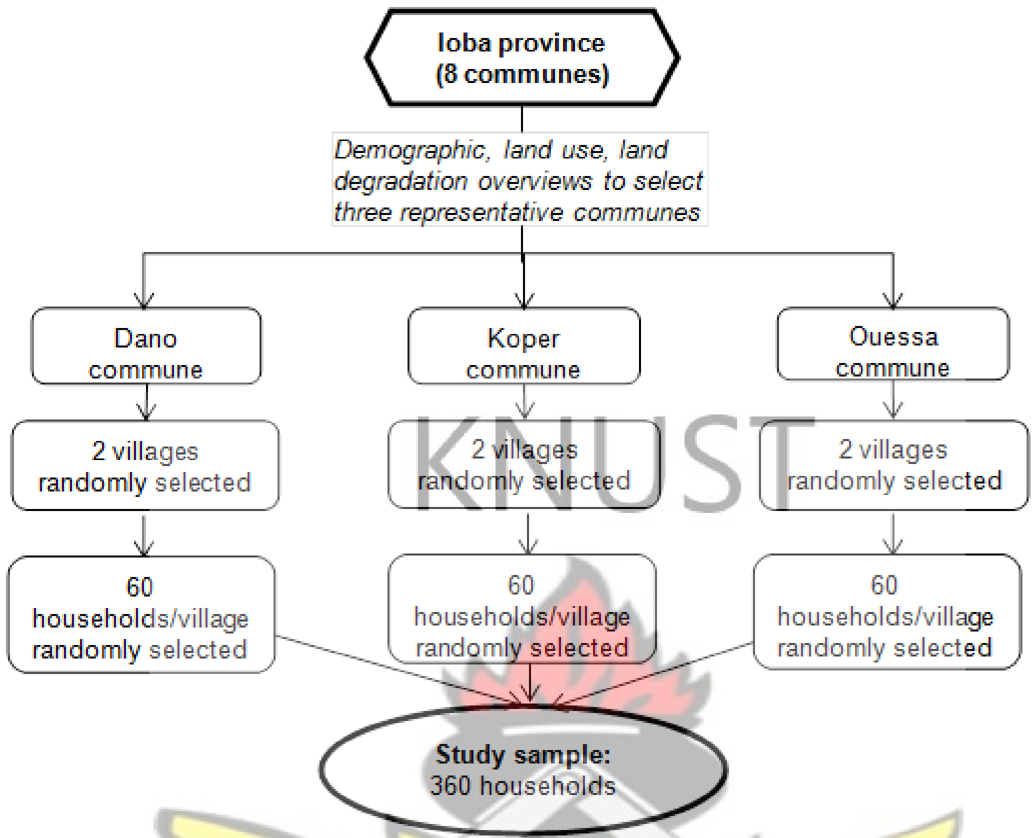


Figure 3.2. Sampling flowchart

3.2.1.2. Households-farms surveys and main content of surveys

To prepare households-farms surveys, informative meetings were held in each village with sampled households. These meetings aimed at informing farmers about the objectives of the research, the activities to be carried out and the expected contributions from the farmers. Local agricultural service agents (*Chef de zone*, *encadreur*) and local leaders (CVD or municipal councillor) were invited and provided assistance. The household-farm survey was performed around two to three months after harvests of the cropping season 2012/2013, in January and February. The questionnaire was primarily addressed to the head of the household-farm who is makes most of the decisions concerning the household livelihood. However, and where necessary, the head was helped by key members of the household (active members). In general an appointment was arranged ahead. When the head was away during the survey period the questionnaire was addressed to an active and well informed member of the household (e.g. wife and children).

Questionnaires were designed based on the Sustainable Livelihood Framework. The geographic coordinates of households were taken using GPS units. This allows geo-referencing the location of household houses on a map, and the calculation of households' proximity to roads and towns. The screen survey questionnaire comprised of nine sections that aimed at capturing and characterizing households' livelihood capital endowment and associated production strategies:

- Household characterization describing household socio-demography (e.g. demography, education and profession)
- Perception of climate change: this section captured how households perceived climate change and what were their strategies in the face of these changes.
- Land tenure section takes inventory of households' land holding and characterized the tenure system.
- Agricultural equipment inventoried the household agricultural equipment.
- Crop production estimated farm production for the previous campaign 2012/2013.
- Animal Production: it consisted in an inventory of livestock of the household.
- Non-farm activities section recorded non-farm activities and income drawn from it.
- Transfers are money households received as support from relatives.
- Food security: in this last section, the household appreciated its own food security.

3.2.2. In-depth surveys

3.2.2.1. Monitoring sites

Following the screening surveys, case study farm-types (five per village) were selected in three villages for farm monitoring: Pontieba, Babora, and Bekotenga in the communes of Dano, Koper and Ouessa respectively (See Figure 3.1). Pontieba, Babora and Bekotenga are located at around 5, 15 and 55 km away from the province main town Dano. Average annual rainfall of the last ten years (2004-2013) was 951.9 mm and 978.7 mm in Pontieba and Ouessa, respectively. These values were among the highest in the country. The year of the study (2013) recorded the lowest annual rainfall for the study sites while the previous year (2012) recorded the highest annual rainfall. The three village were among those identified as experiencing the worst land degradation in the province (MAHRH and GTZ, 2004). However, mineral fertilizers and compost use remain low (MAHRH, 2010; Gleisberg-Gerber, 2012) in the region despite many interventions to improve sustainable soil nutrient management.

3.2.2.2. Framework for farm nutrient balance analysis

The conceptual framework of this study was based on NUTMON framework (Smaling and Fresco, 1993; Smaling *et al.*, 1996; De Jager *et al.*, 1998b; Van den Bosch *et al.*, 1998b; Vlaming *et al.*, 2001) as a guideline for calculating soil nutrient balance in the farming systems. The farm boundaries were formed by the atmosphere, the physical boundaries of farm fields and 30 cm depth in the soil. This depth was considered as depth at which most of the crops in the study zone retrieve the majority of nutrients. The three main farm components considered in the framework included: primary production compartment (soil, crop, fertilizers and feed), secondary production compartment (animals, feed stock, dunghills) and homestead (family, food stock, garbage heap). Four flows entering the farm (IN1-IN4), six flows leaving the farm (OUT1-OUT6) and six farm and lower levels flows (FL1-FL6) were considered (Table 3.2). Sedimentation (IN5) was left out as irrigation water was not applied in monitored fields and most of the plots were situated at slope catena where sedimentation is negligible.

Three types of nutrient balance were computed: soil nutrient balance, farm partial and full nutrient balances. *Soil nutrient balance* (Equation 3.1) is defined as the difference between the sum of all flows entering the soil sub compartment and the sum of all flows leaving the soil sub compartment. The entering flows comprise applied mineral fertilizers (IN1) brought from outside the farm (e.g. NPK and urea), organic fertilizers (IN2b) consisting of compost, manure excretion on the plots from external grazing (IN2c), imported seeds from outside the farm (IN2e), atmospheric deposition (IN3), biological N-fixation (IN4), seeds from household stocks (FL2d), animal manure from dunghills or corrals redistributed to plots (FL5). The flows leaving the soil sub compartment consist of harvested crops products (OUT1a), exported crop residues from plot (OUT2a) either for household consumption (e.g. fuel, fencing) or for external use, nutrient leaching out of soil boundary (OUT3a), gaseous loss from soil (OUT4a), gaseous loss through crop residues burning (OUT4c), and soil erosion (OUT5).

$$Soil_{Nut\ Bal} = (IN1 + IN2b + IN2C + IN2e + IN3 + IN4a + IN4b + FL2d + FL5b) - (OUT1a + OUT2a + OUT3a + OUT4a + OUT4c + OUT5)$$

Equation 3.1

Table 3.2. Nutrients inputs, outputs and internal flows at the farm and lower levels.

Input (IN)	Output (OUT)	Farm and lower levels (Fl)
IN1 Mineral fertilizers	**OUT1 Farm products** (a) Crop products (b) Animals products	*FL1 External feeds* (a) Consumption of external feeds (b) Decay of external feeds
IN2 Organic inputs (a) Feeds (b) Organic fertilizers (c) External grazing (d) Purchased food (e) Seeds	**OUT2 Other organic** outputs (a) Crop residues (b) Manure	*FL2 Household waste and seeds* (a) Redistribution of household waste (b) Consumption of household waste (c) Decay of household waste (d) Seeds from stocks
IN3 Atmospheric deposition	**OUT3 Leaching** (a) Soil nutrients (b) Nutrients from dunghills	*FL3 Crop residues* (a) Redistribution of crop residues (b) Consumption of crop residues (c) Decay of crop residues
IN4 Biological N-fixation (a) Symbiotic fixation (b) Non-symbiotic fixation	**OUT4 Gaseous losses** (a) Soil nutrients (b) Nutrients from dunghills (c) Burning of crop residues	*FL4 Grazing of vegetation*
IN5 Sedimentation (a) Irrigation (b) Natural flooding	**OUT5 Erosion**	*FL5 Animal manure* (a) Excretion of manure by the animals (b) Redistribution of farm yard manure
	OUT6 Human excreta	*FL6 Farm products to homestead* (a) Crops products to food stock (b) Animal products to tfood stock (c) Consumption of food items

Source: *De Jager et al. (1998b).*

Whole farm partial nutrient balance ($FNut_{Part\ Bal}$): The whole farm partial nutrient balance (Equation 3.2) computes the balance between the sum of human and animal mediated inflows to the farm and the sum of human and animal mediated outflows. The inflows comprise imported mineral fertilizers (IN1) and imported organic inputs (IN2a-e). The outflows consist of exported crop products (OUT1a) and animal products (OUT1b), and other organic materials such as crop residues (OUT2a) and manure through grazing and excretion outside the farm (OUT2b).

$$FNut_{Part\ Bal} = (IN1 + IN2a + IN2b + IN2c + IN2d + IN2e) - (OUT1a + OUT1b + OUT2a + OUT2b) \qquad \textbf{Equation 3.2}$$

Whole farm full nutrient balance ($FNut_{Full\ Bal}$): The whole farm full nutrient balance computes balance of all inflows and outflows at farm level. It accounts for all farm level inflows and outflows in Table 3.2 apart from sedimentation (IN5) considered meaningless in this study (Equation 3.3). Included inflows are: imported mineral fertilizers (IN1), imported feeds (IN2a), imported organic fertilizers (IN2b), manure excretion from external grazing (IN2c), purchased food (IN2d), imported seeds (IN2e), atmospheric deposition (IN3), biological N-fixation (IN4). The outflows comprise harvested crops products (OUT1a), exported animal products (OUT1b), exported crop residues (OUT2a) for external use, manure excretion outside the farm (OUT2b), nutrient leaching out of soil boundary (OUT3a), nutrient leaching from dunghills (OUT3b), gaseous loss from soil (OUT4a), gaseous loss from dunghills (OUT4b), gaseous loss through crop residues burning (OUT4c), soil erosion (OUT5) and human excreta (OUT6).

$$FNut_{Full\ Bal} = (IN1 + IN2a + IN2b + IN2c + IN2d + IN2e + IN3 + IN4a + IN4b) - (OUT1a + OUT1b + OUT2a + OUT2b + OUT3a + OUT3b + OUT4a + OUT4b + OUT4c + OUT5 + OUT6) \qquad \textbf{Equation 3.3}$$

3.2.2.3. Farm monitoring

Two surveys were carried out: farm inventory surveys and input-output monitoring surveys (Table 3.3). The farm inventory surveys were carried out in the beginning of the dry season of year 2013 (January-February). The farm features were identified and described as well as farm livelihood activities. The main content of farm inventory surveys comprised of farm geographical data, inventory of farm fields, farm implements, farm livestock composition, household members and their socio economic characteristics (e.g. age, education and occupation), redistribution units (dunghills, garbage and compost pits), farm stocks, off-farm activities, and soil fertility management practices.

Farm monitoring surveys were performed during year 2013/2014, from March 2013 to February 2014. In each of the selected villages, and for each farm type, the closest farm to the group center (Euclidian distance in K-mean classification) was chosen as case study for the input-output monitoring. A total number of 15 farms (5 farm-types in each of the 3 villages) were monitored. The monitoring surveys content consisted mainly of identification and quantification of farm inflows and outflows as well as internal flows. Some flows were quantified asking the farmer (e.g. mineral fertilizers, organic fertilizers and seeds) and through direct measurements (e.g. harvested crop products and crop residues), and others using transfer functions (e.g. wet atmospheric deposition, N-fixation, leaching and erosion). Off-farm activities of household members were also estimated.

Table 3.3. Main data obtained from farm survey.

Data type	Description
Farm inventory	
General farm data	Geographical location, land tenure, access to permanent road, market, etc.
Household demography	Enumeration of household members, their age, sex, education and occupation
Primary production compartment	Plots number and sizes
Secondary production compartment	Types and number of animals
Farm sections	Identification and description of farm section units, soil physical-chemical analyses
Redistribution compartment	Livestock enclosures, compost pits, garbage heaps
Equipment	Number, age and acquisition cost of farm tools
Flows monitoring	
Primary production compartment	Plots and crops present at the monitoring period
Inflows to primary production compartment	Identification and quantification of agricultural inputs (e.g., seed, organic and mineral fertilizers, pesticides and labor)
Inflows to secondary production compartment	Identification and quantification of livestock inputs (e.g., feeds, veterinary services, labor)
Outflows from primary production compartment	Quantification of harvested products and crop residues, and identification of their destination
Outflows from secondary production compartment	Quantification of animal product (e.g., eggs and traction) and identification of their destination
Animals confinement	Confinement to kraals and outside the farm
Manure and household waste redistribution	Quantification of reused manure and household waste, and identification of their destination
Herd growth	Records of animal born, purchased, gift in or out, consumed and died.
Inputs and outputs from food stock	Records of food stock fluxes with outside the farm
Family labour	Records of working days of household members for cropping activities, livestock , general farm activities and off-farm activities
Off-farm activities income	Estimation of income drawn from off-farm activities

3.2.2.4 Material sampling and analyses methods

Sampling and analyses were done for soil, manure, compost, crop products and crop residues. Farm section units are defined as lands patches units in the farm considered to be homogenous in terms of topography and soil type. With a team of pedologists and with farmer help, farm section units were identified and soil profile pits were dug to characterize soils (e.g. soil type and rooting depth). On each plot, at least five subsamples of soil were sampled with auger, mixed on field and a composite sample taken. The number of subsamples per plot and their distribution were guided by plot size, topography and shape. Composite samples were air dried, ground and sieved with 2 mm sieve, and sent to laboratory for physico-chemical analyses. Manure and compost samples were also taken before application to the field and air dried for laboratory analyses. As for crop product and crop residues, given the difficulty for farmers to provide good estimation of harvested crop products weight, we used the yield-plot technique to quantify harvested crop products and exported crop residues. The yield-plot technique consists in laying a square frame, harvesting and weighing all crop products and crop residues within the frame. This operation is repeated several times according to the size of the plot and crop standing heterogeneity. The fresh weight is recorded. A fresh sample is taken, oven dried at 60 ^{o}C during 72 hours and weighed. The quantity of exported crop product or crop residues from a plot is estimated from: sample fresh and dry weights, the sum of fresh materials weight of yield-plots, yield-plot area and whole plot area.

Standard methods were used to analyse soil, organic fertilizer, crop products and crop residue. Soil organic carbon and total N were determined using the method of Walkley and Black (1934) and Kjeldahl method (Houba *et al.*, 1989) respectively. Bray 1 method (Bray and Kuretz, 1945) was used for determining soil available P. Total P and total K were determined using wet acid digestion and flame photometer analysis. Exchangeable K, Ca, Mg and CEC were determined from the ammonium acetate extract. Soil texture was determined by the Bouyoucos hydrometer method (Bouyoucos, 1962). For manure, compost, crop products and crop residues the dry matter content was determined by drying at 105 ^{O}C. Total N, total P and total K in these materials was determined by Kjeldahl, colorimetry and flame photometer methods.

Some of the flows difficult to quantify by field measurement or farmer declaration, were estimated using transfer functions: atmospheric deposition, N-fixation, leaching, gaseous loss (Stoorvogel and Smaling, 1990; Smaling *et al.*, 1993), soil erosion using Universal soil loss equation (USLE) (Wischmeier and Smith, 1978). Rain fall erosivity (R-USLE) was calculated using equation from Roose (1976) (Equation 3.4) and 10 years rainfall recordings (2004-2013) from Ioba provincial directorate of agriculture in Dano. K-USLE and C-USLE were retrieved from Schmengler (2011), Roose (1976), and Mati and Veihi (2001). Nutrient content of feeds and animal products, feeding requirements and manure excretion, N-fixation, nutrient loss through crop residues burning were retrieved from literature as indicated in Table 3.4.

$R = 0.5 \times P \pm 0.05$ **Equation 3.4**

R= Rainfall erosivity and P = average annual rainfall over at least 4 years

Table 3.4. Overview of nutrient content parameters and data sources

Parameter	Unit	Remarks	Source
Crops and crop products			
N, P and K content	kg/kg	Of crop products and crop residues	Laboratory analyses
		Of cotton	Ergle and Eaton (1956), Den Bosch (1998a), Wakelyn et al. (2006)
Unit price	FCFA	Of crop products and crop residues	Surveys
N-fixation of cowpea, ground and Bamabra nuts, soybean	%	Of total N uptake by plant	Guet (2003), Bado et al. (2006); Traore(2012); Kumaga et al.(1994); Salvagiotti et al. (2008)
Fraction garbage	%	Of harvested product	Computations from field data
Nutrient loss from crop residues burning	%	Of crop residues burned	Jain et al. (2014)
Livestock and livestock products			
Feed requirement	kg/head/day	Of dry matter	Ayantunde (1998); Schlecht (1995); Efdé (1996); Euroconsult (1989); Den Bosch (1998a)
Feed conversion fraction	%	N, P, K, bulk	Ayantunde (1998); Schlecht (1995); Den Bosch (1998a)
N, P and K content	kg/kg	Of meat	Den Bosch (1998a)
Unit price	FCFA	Of meat	Surveys
Return percentage	%	Fraction of total manure production deposited in farm	Den Bosch (1998a)
External input			
N, P and K content Maize brans	kg/kg		Kiendrébéogo et al.(2013)
Local beer cake (drèche)			Zoungrana(1995) ; Meffeja et al.(2003); Hainnaux and Gouzy(1980)
Soil and climate			
Total N content	kg/kg		Laboratory analyses of soil samples
Mineralization rate	g/kg/year		Den Bosch(1998a)
Total P content Total K content Exchangeable K Clay content	kg/kg kg/kg meq/100g %		Laboratory analyses of soil samples
Bulk density	kg/m^3		Field measurements
Precipitation	mm/year	Average annual precipitation	Provincial directorate of agriculture in Dano

4. SOCIO-ECOLOGICAL HETEROGENEITY EFFECT ON SOIL NUTRIENT MANAGEMENT

4.1. Introduction

Sub-Saharan Africa (SSA) is characterized by high food insecurity (FAO, 2010). It remains the region with the highest undernourishment prevalence estimated at 24.8% for the period 2011-2013 (FAO *et al.*, 2013). Though the region is threatened by negative effects of climatic changes (Blanc, 2012; Jalloh *et al.*, 2013) low soil fertility also undermines crop productivity (Giller *et al.*, 2006). Anthropogenic factors jeopardise soil fertility which is the basis of crop production. Soil nutrient balance studies reported many cases of nutrient mining in Sub-Saharan African smallholder cropping systems (Smaling *et al.*, 1993; Bationo *et al.*, 1998; Cobo *et al.*, 2010; Douxchamps *et al.*, 2012). The unsustainable management of soil resources, through reduction in crop productivity, exposes smallholders to rural poverty as they rely mainly on agricultural income. Together with population pressure (Vu *et al.*, 2014b), poverty fuels soil degradation. It can be a constrain to adopting sustainable soil management practices (Reardon and Vosti, 1995), thereby lowering agricultural productivity which in return contributes to aggravate food insecurity and rural poverty. Food insecurity denotes failure of households' livelihood to secure sufficient crop production (Devereux and Maxwell, 2001).

The persisting food insecurity reveals the failure of policies to efficiently promote sustainable soil nutrient management. Adoption of sustainable soil management practice remains low in SSA. Socio-ecological conditions of households constrain or promote sustainable farm management practices. These conditions often vary over smallholder population. Smallholders of different social-ecological settings can have different preferences in livelihood strategy which defines their perception and relation to their environment. Therefore, to better inform policy leveraging farmers' adoption of alternatives in sustainable soil nutrient management, there is the need to (i) identify the main social-ecological types of smallholder farms in a region, (ii) better understand how livelihood strategies in general and soil nutrient management practices in specific vary among farm types, as well as (iii) socio-ecological factors affecting nutrient use efficiency in relation to specific farm types. Previous studies have highlighted the paramount role households' livelihood play in farm soil nutrient management practices (Nkonya *et al.*, 2005; Jansen *et al.*, 2006; Anley *et al.*, 2007), soil nutrient stock (Iiyama *et al.*, 2008; Tittonell *et al.*, 2010), regional and within farm variability of soil fertility (Tittonell *et al.*, 2005a; Tittonell *et al.*, 2005b).

However, it is still hard to find studies that used a well-established and holistic livelihood framework to explore linkages between livelihood variation, farm soil nutrient management and crop production performances. Attempt made by Oumer *et al.*,(2013) rather used a subjective categorisation of households. Besides, most of the studies were conducted in Eastern Africa where biophysical, cultural and socio-economical settings are different from West Africa.

This study aimed at contributing to an improved understanding of the influential relationship between socio-ecological heterogeneity and smallholder farms soil nutrient management and efficiencies using case study of the Ioba province in South-Western Burkina Faso. It has the following specific objectives:

- To identify main household-farm types regarding biophysical and socio-economic characteristics of smallholder farms;

- To characterize type-specific food productivity, nutrient management and efficiency of the identified household-farm types;
- To identify type-specific factors that potentially influence nutrient use efficiency, thereby informing follow-up studies and agricultural policy.

4.2. Methods

4.2.1. Analytical framework

A livelihood is a means of gaining a living (Chambers and Conway, 1991). In pursuing their living objectives households mobilize their biophysical and socio economical assets in livelihood strategies that guide their decision making, for instance adoption of new technologies. To support building sustainable livelihood strategies, developmental policy interventions need to consider households in their different settings to better shape interventions. Increasing food needs and limited resources require maximizing crop production efficiency. This can be done by implementing sustainable soil nutrient management strategies that tackle nutrient depletion issue and ensure a sustainable and profitable crop production. Soil nutrient management practices for achieving food production take place within livelihood strategies built from available assets. Categorizing households-farms on the basis of their livelihood strategies gives a better contextualization of their choices and more chance for efficient policy intervention and farm design. Data was collected using a semi structured questionnaire guided by Sustainable Livelihood Framework. After classification, crop yield, nutrient use and economic performances of the different types were analysed to identify households-farms type specific effects as illustrated in Figure 4.1.

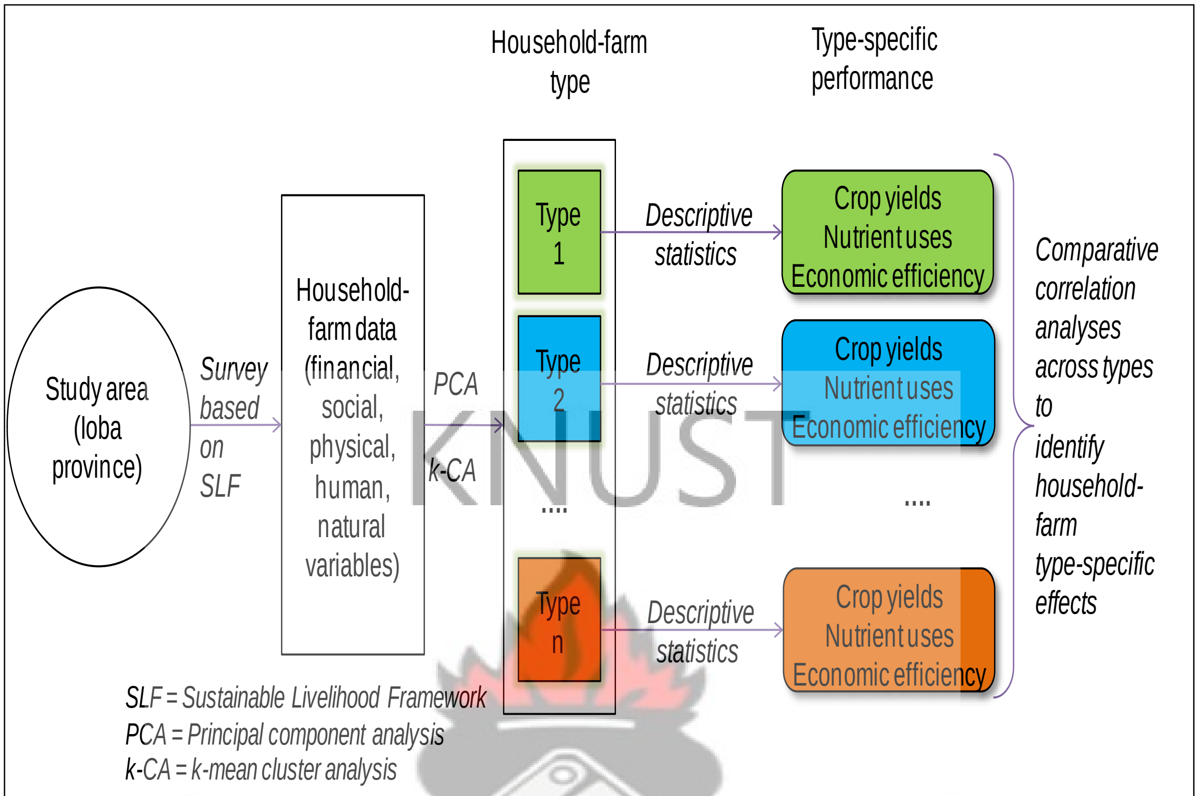


Figure 4.1. Analytical framework.

4.2.2. Methods for identifying household-farm types

A two steps method was used to identify farms with similar livelihood strategies. Firstly, Principal Component Analysis (PCA) was run in SPSS 16 (Statistical Package for Social Sciences). It reduced data complexity and grouped correlated initial variables into few and independent Principal Components (PC). PCs are linear combination of initial variables (Campbell *et al.*, 2001) and bear maximum initial information in a descending way. PCA was run with Varimax and Kaiser Normalisation methods. PCs with Eigen values ≥ 1 were retained and scores used for further analysis to avoid multi-collinearity (Le, 2005). Secondly, scores of retained PCs were used for K-mean Cluster Analysis (K-CA). For large samples like in this study, non-hierarchical clustering methods (e.g. K-CA) are more suited.

Results are easier to interpret. Also, the dataset was entirely quantitative and farm-types were compared based on their means in further analyses. K-CA was therefore convenient for an efficient discrimination of farms. The principle of K-CA is finding a clustering structure minimizing the Sum of Squared Error (SSE) of the total squared Euclidean distance of observations to their class centres (Jain *et al.*, 1999; Maimon and Rokach, 2010). The number of clusters was decided using the knee method. On a curve representing the sum of distances to clusters' centre against the number of clusters, optimal number of clusters is decided at the inflexion point. Candidate variables for PCA represented farms' livelihood assets and production orientation (Table 4.1). Generally, dynamic surveys allow a better understanding of households' strategies than screen surveys (Tittonell *et al.*, 2005a). It was hypothesized that households' production orientation do not vary much in short and medium terms and that income composition, land allocation to main crop types (e.g. cereal, cash crops and legumes) are good proxies of livelihood strategies and production orientation.

Table 4.1. Variables used for Principle Component Anaylsis (PCA)

Variable name	*Brief definition*	*Source*[a]
Human asset		
$H_{AGEMEMB}$	Average age of household members	C
H_{AGELAB}	Average age of household labour	C
$H_{HEADEDU}$	Number of education years of the household head	C
H_{SIZE}	Size of the household	D
H_{LABOUR}	Labour amount of the household (workers)	C
H_{DEPEND}	Dependency ratio of the household	C
Natural asset		
$H_{HOLDINGS}$	Total land area (ha) the farm possesses	C
H_{HOLDCP}	Farm land possession per capita (ha/capita)	C
$H_{\%\ OWNLAND}$	Share of owned lands within cultivated lands of the farm (%)	C
$H_{\%\ USERLAND}$	Share of user right lands within cultivated lands of the farm (%)	C
Physical asset		
$H_{TRANSPORT}$	Number of transport means of the household	C
H_{HOME}	Number of house equipment (Mattress, bed) of the household	C
$H_{TRACTION}$	Number of traction animals the farm possesses	D
Financial asset		
$H_{GROSSINC}$	Annual gross income of the farm (*CFA*)	C
$H_{GROSSINCCP}$	Annual gross income per capita (*CFA/Capita*)	C
H_{TLU}	Tropical Livestock Units of the farm	C
H_{TLUCP}	Tropical Livestock Units per capita (*TLU/Capita*)	C
H_{TLUHA}	Tropical Livestock Units per unit of cultivated land (*TLU/ha*)	C
Social asset		
$H_{\%\ TRANSFER}$	Share of transfer income (pension, gift) within gross income (%)	C
Production orientation		
$H_{\%\ CEREAL}$	Share of cereals within cultivated lands of the farm (%)	C
$H_{\%\ COTTON}$	Share of cotton within cultivated lands of the farm (%)	C
$H_{\%\ MFC}$	Share of marketable food crops within cultivated lands of the farm (%)	C
$H_{\%\ CROPINC}$	Share of crop income within gross income (%)	C
$H_{\%\ LIVSINC}$	Share of livestock income within gross income (%)	C
$H_{\%\ NFINC}$	Share of non-farm activities income within gross income (%)	C
Geographical variables		
$H_{DISTPAVED}$	Average distance of the household house to paved road (km)	R
$H_{DISTTOWN}$	Average distance of the household house to main town (km)	R

Note: *[a] D = Extracted directly from the questionnaire; C = Compound information calculated based on information coded in the questionnaire; R = Extracted from map reading.*

4.2.3. Analysis of farms performance

Performances of farms were assessed using crop yields, soil nutrient use dose and intensity (Equation 4.1 and Equation 4.2), and economic efficiency of mineral fertilizer use by households (Equation 4.3). Cereal yield (maize, rice, sorghum and millet) was expressed in maize-equivalent based on calorie content. For example, the corresponding amount of maize-equivalent of 1 kg of millet grains equal to the quantity of maize grains in kg containing the same amount of energy in kilo calories (Kcal). Cereal calories content and extraction ratio were taken from Direction de la nutrition (2005), and Thiombiano (2008), respectively. Yields of legumes and cotton crops were expressed in kilograms. Economical yield was estimated from survey data and local market prices were provided by DGPER (2013) and SONAGESS (2013). Nutrient content of mineral fertilizer, compost, and animal dung were extracted from CILSS (2012), Bunasol (1985), and Landais and Lhostes (1990), respectively. Yields were estimated at plot level and averaged at farm level. Economic efficiency of mineral fertilizer use was defined as marginal increase of crop yield due to incremental investment in mineral fertilizer acquisition.

$$\text{Dose}_{N-P-K} = \frac{\text{Amount of N-P-K applied}}{\text{Fertilized area}} \qquad \textbf{Equation 4.1}$$

$$\text{Int}_{N-P-K} = \frac{\text{Total amount of N-P-K applied on the farm}}{(\text{Fertilized area} + \text{unfertilized area})} \qquad \textbf{Equation 4.2}$$

$$\text{EEf}_{\text{NPK-Urea}} = \frac{\text{YieldValue}_{\text{NPK-Urea}} - \text{YieldValue}_{\text{No NPK-Urea}}}{\text{Cost}_{\text{NPK-Urea}}} \qquad \textbf{Equation 4.3}$$

With: Dose_{N-P-K} = Application dose of total nutrient N, P and K

Int_{N-P-K} = Use intensity of total nutrient N, P and K

$\text{EEf}_{\text{NPK-Urea}}$ = Economic efficiency of both NPK complex and Urea use

4.3. Results and Discussions

4.3.1. Livelihood-based household-farm types

4.3.1.1. Main factors discriminating household-farm types

The Principal Component Analysis (PCA) extracted 10 Principal components (PC) with total Eigen values equal to or greater than 1 (Table 4.2) and bearing 81.24% of the initial total variance. The rotated component matrix was used to determine loadings of each PC. PCs were named after the variable with the greater loading and the most correlated to the principal component (Table 4.3). The factors discriminating the most household-farms in the study region with more than 10% of initial variance each (PC1, PC2 and PC3) are highly correlated with Financial (H_{TLUCP}), human (H_{LABOUR}) and production orientation ($H_{\% COTTON}$) variables. The PC1 representing 18.92% of total initial variance is highly correlated with H_{TLUCP} (loading b = 0.91) and is named Livestock PC. PC2 (11.37% of total initial variance) was much more correlated with H_{LABOUR} (loading b = 0.91) and was named Labour PC. The PC3, more correlated with $H_{\% COTTON}$ (loading b= - 0.94) and bearing 10.90% of total initial variance is named Cotton PC. Education PC (PC9) and Dependency PC (PC10) carry the lowest initial information, therefore discriminating less the households. The other discriminating factors are Labour age PC (PC4), Non-farm activities PC (PC5), Land security PC (PC5), Land holdings PC (PC6) and Marketable food crops PC (PC7).

Table 4.2. Total variance explained by main Principal.

	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
PC	Total	% of Var.[b]	Cum.[a] %	Total	% of Var.[b]	Cum.[a] %	Total	% of Var.[b]	Cum.[a] %
1	5.11	18.92	18.92	5.11	18.92	18.92	4.07	15.07	15.07
2	3.07	11.37	30.30	3.07	11.37	30.30	3.00	11.12	26.20
3	2.94	10.90	41.19	2.94	10.90	41.19	2.87	10.61	36.81
4	2.13	7.87	49.07	2.13	7.87	49.07	2.12	7.84	44.65
5	2.10	7.76	56.83	2.10	7.76	56.83	2.02	7.48	52.13
6	1.64	6.07	62.89	1.64	6.07	62.89	1.97	7.30	59.43
7	1.50	5.55	68.44	1.50	5.55	68.44	1.83	6.77	66.20
8	1.35	5.02	73.46	1.35	5.02	73.46	1.55	5.72	71.92
9	1.08	3.98	77.44	1.08	3.98	77.44	1.32	4.87	76.80
10	1.03	3.80	81.24	1.03	3.80	81.24	1.20	4.45	81.24

***Note**:* [a] *Cumul.= Cumulative.*
[b] *Var.=Variance*
Principal Components with Eigenvalues less than 1 are not shown.

Table 4.3. Rotated Component Matrix (i.e., loadings) using Varimax rotation method and Kaiser Normalization of first ten PCs

	Principal components (PC)									
Variables	1-Liv. PC (18.92)	2-Lab. PC (11.37)	3-Cot. PC (10.90)	4-Lab.age PC (7.87)	5-N.F PC (7.76)	6-L.S. PC (6.07)	7-Land PC (5.55)	8-M.F PC (5.02)	9-Ed. PC (3.98)	10-Dep. PC (3.80)
$H_{AGEMEMB}$	0.09	-0.15	0.02	0.89	0.07	0.02	0.03	0.06	-0.05	-0.24
H_{AGELAB}	0.06	-0.20	0.00	**0.90**	0.06	0.06	0.05	0.04	-0.06	0.06
$H_{HEADEDU}$	0.04	-0.13	-0.03	-0.05	-0.07	-0.01	0.02	0.00	**0.80**	-0.08
H_{SIZE}	0.04	0.90	-0.04	-0.21	0.02	0.06	0.00	0.05	-0.08	0.17
H_{LABOUR}	0.04	**0.91**	-0.05	-0.18	0.03	0.08	0.00	0.06	-0.06	-0.23
H_{DEPEND}	-0.01	-0.06	0.04	-0.12	-0.04	-0.01	-0.03	-0.03	0.00	**0.96**
$H_{HOLDINGS}$	0.17	0.39	0.02	-0.04	0.06	-0.01	0.84	0.00	0.06	0.07
H_{HOLDCP}	0.01	-0.25	0.05	0.20	0.08	-0.03	**0.85**	-0.01	0.14	-0.11
$H_{\% CEREAL}$	-0.13	-0.11	0.67	0.04	-0.01	-0.01	-0.05	0.67	0.01	0.01
$H_{\% COTTON}$	0.15	0.04	**-0.94**	-0.05	0.00	0.01	0.00	-0.02	-0.02	0.01
$H_{\% MFC}$	-0.02	0.08	0.25	0.00	-0.01	-0.01	0.08	**-0.89**	0.02	-0.02
$H_{\% OWNLAND}$	0.01	-0.03	-0.04	0.00	-0.03	**-0.98**	0.02	0.02	0.03	0.02
$H_{\% USERLAND}$	0.00	0.04	0.03	0.00	0.05	0.98	0.00	-0.03	-0.03	0.01
$H_{TRANSPORT}$	0.22	0.72	0.00	0.05	0.06	-0.05	0.04	-0.11	0.22	-0.04
H_{HOME}	0.23	0.31	0.07	0.12	0.06	-0.04	0.16	-0.05	0.64	0.14
$H_{GROSSINC}$	0.85	0.34	-0.12	-0.03	-0.15	-0.01	0.12	0.02	0.04	0.00
$H_{GROSSINCCP}$	0.91	-0.04	-0.16	0.08	-0.15	0.00	0.08	0.02	0.08	-0.09
$H_{\% CROPINC}$	-0.08	0.05	-0.91	-0.03	0.06	-0.03	0.05	0.02	-0.08	0.04
$H_{\% LIVSINC}$	0.22	0.04	0.27	0.01	0.88	0.08	0.05	0.03	-0.02	-0.06
$H_{\% NFINC}$	-0.08	-0.07	0.31	-0.18	**-0.89**	-0.02	-0.08	0.02	0.01	0.00
$H_{\% TRANSFER}$	-0.20	0.07	0.06	0.55	0.03	-0.10	0.07	-0.16	0.34	0.01
H_{TLU}	0.86	0.26	0.02	-0.05	0.23	0.00	0.10	0.00	0.03	0.06
H_{TLUHA}	0.68	0.00	0.02	0.02	0.36	-0.02	-0.37	0.08	0.05	0.00
H_{TLUCP}	**0.91**	-0.07	0.02	0.02	0.28	0.02	0.04	0.04	0.07	-0.02
$H_{DISTPAVED}$	0.20	0.23	0.13	-0.02	0.03	-0.07	0.13	0.41	-0.08	-0.08
$H_{DISTTOWN}$	-0.09	0.12	0.63	-0.04	0.09	0.09	0.27	-0.26	-0.14	0.20
$H_{TRACTION}$	0.41	0.39	0.01	-0.12	0.31	0.06	0.29	0.06	-0.14	0.18

Note*: **Liv**= Livestock, **Lab**= Labour, **Cot**= Cotton, **N.F** =Non-Farm activities, **L.S**= Land Security, **M.F**= Marketable Food crops, **Ed**= Education, **Dep**= Dependency. Numbers in parenthesis are percentages of total variance of original variables explained by the principal components. Bold and underlined are the high loadings, indicating most important original variables representing the principal components and used for clusters description.*

4.3.1.2. Socio ecological household-farm types in Ioba province

Five optimal classes were found and their livelihood structure is shown in Figure 4.2.

Farm-type I: Better-off, cotton-and livestock-based farms (31% of study sample): Its livelihood is based on livestock and cotton. Revenue from cotton and livestock contributed 54% and 21% of annual gross income, respectively. Annual income was estimated to be 110,217 FCFA/capita and off-farm activities had the lowest contribution to annual gross income (only 19%). Farm-type I was best endowed in land resources (1.0 ha/capita). Cotton usually requires having enough lands; the bigger the cropped area, the higher the profitability of cotton production (PAFASP and CAPES, 2011).

Farm-type II: Better-off, non-farm activities preference farms (30% of study sample): this farm-type is different from the other farm types by the high contribution of off-farm activities income (e.g., milling station, shops tenancy, motorbike and bicycle repairing, remittance) to annual gross income (77%). The annual income was estimated to be 107,343 FCFA/capita/year.

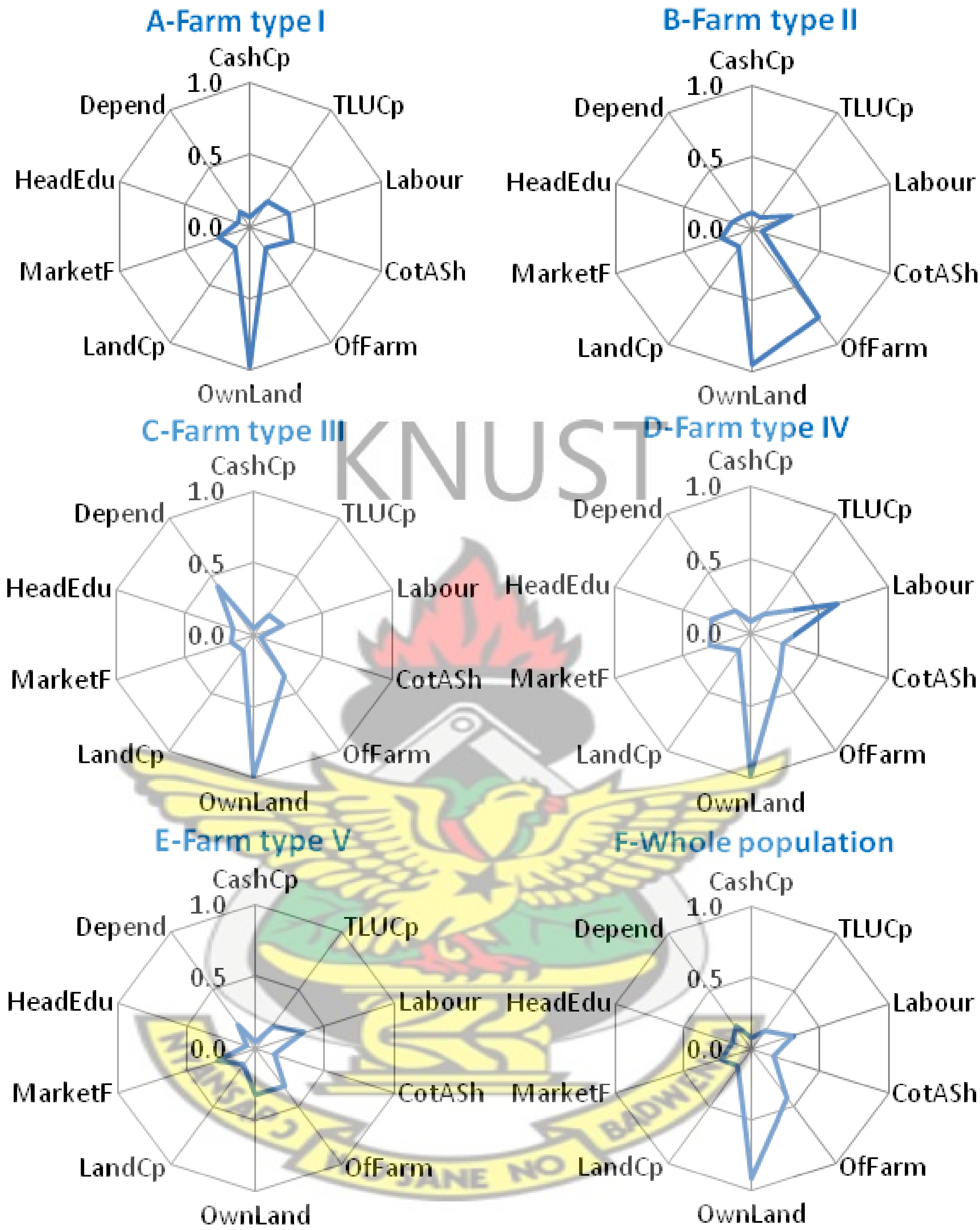
Farm-type III: Pro-poor, labour-poor-and landless farms (21% of study sample). This farm type was the most constrained in land and labour. It had only 4 workers on average and possessed 0.7 ha/capita. The dependency ratio was the highest (0.84). The low land access limited cotton cropping (3% of farmed land) which is the main cash crop of the region. Farm-type III drew the lowest annual income; i.e. 78,236 FCFA/capita. Its livelihood was based on subsistence cereals and livestock: 86% of farmed land was allocated to subsistence cereals and livestock formed half of annual gross income.

Farm-type IV: Medium income, labour-rich, marketable food crop oriented and educated farms (9% of study sample). This farm-type was the most endowed in labour (11 workers) and had the most educated heads (4 years of classic education). It had the most diversified livelihood: main livelihood activities individually contributed less than

50% of annual gross income, contrary to the other farm-types. Livestock, non-farm activities and cotton contributed 44%, 34% and 16% of annual gross income respectively.

Farm-type V: Poor, insecure-land tenure, livestock based farms (9% of study sample). This farm-type drew an annual income of 86,413 FCA/capita. Farms are characterized by insecure land tenure. They had only user-rights for most of lands they farmed. Up to 68% of farmed land was borrowed. The land holding was evaluated to be 0.78 ha/capita. Their livelihood is based on livestock (59% of annual income), which in the region exploits mainly common lands for pastures and does not require having necessarily own lands.

In the study region livestock appeared to be an important component of all farm types' livelihood. As already observed by Zaibet *et al.*, (2010), livestock plays an important role in West African smallholders' livelihood. It constitutes, in general, a form of capitalization of financial resources. It can be sold out and the money used in case of food shortage or for purchasing mineral fertilizer. Beyond the financial aspect, livestock can be a valuable source of soil nutrient in livestock-agriculture integration scheme. Results also showed that land constrained farms (low access and unsecured land tenure) prioritized subsistence cereals production (more than 80% of farmed land). Their main agricultural cash income is drawn from rice grown on common land developed by state or projects. For these farms, interventions improving land access may improve their livelihood.



CashCp: Annual cash income per capita
TLUCp: Tropical Livestock Units per capita
Labour: Number of household's workers
CotASh: Share of cotton area
OfFarm: Share of non-farm activities income
OwnLand: Share of own land
LandCp: Land holding per capita
MarketF: Share of marketable food crops area
HeadEdu: Highest schooling year of household head
Depend: Dependency ratio

Figure 4.2. Key variable indicators of livelihood dimensions of the five household-farm types.

Though the annual gross income was significantly different across household types, the annual gross income per capita which gives a better information (Le, 2005) does not show any significant difference among household-farm types. Poverty is widespread in the study region. Around 47% of households live below the poverty line (INSD, 2010). This may explain the lack of significant difference among surveyed farms for annual gross income. The cash income per capita however revealed significant heterogeneity among household-farm types (Appendix 1). Available cash plays important role in farm livelihoods since it is the first resort of farmers for purchasing goods and services. Available cash will be critical for purchasing mineral fertilizer when farmers do not have access to a credit system. The non-farm activities oriented farms (farm type II) had highest cash income per capita (88,794 FCFA/person/year) while poor farms (farm types III and V) had the lowest cash income.

4.3.2. Crop production performances of the different farm types

Figure 4.3 shows yields of the main crops grown by farm types. No significant difference was found among farm types for yield of legumes (soya, cowpea and Bambara groundnuts) (Figure 4.3C) and tubers (Sweet potatoes and yams) (Figure 4.3E). However, significant differences were found among farm types for cereals (e.g. rice, millet, sorghum and maize), groundnuts and cotton. Farm-type I had highest yield than farm-type II for cereals (668 kg maize equivalent/ha against 538 kg maize equivalent/ha). Farm-type I also performed significantly better than farm-type V for groundnuts (567 kg/ha against 320 kg/ha). As for cotton, farm-type I and IV showed no significant difference (890 kg/ha and 972 kg/ha, respectively) but were both significantly different from farm-type II (632 kg/ha). The farm-types I and IV comprise biggest cotton producers drawing up to 26% and 16% of their annual income from cotton. Farm-type II allocates only 5% of farmed land to cotton which provide only 3% of annual income.

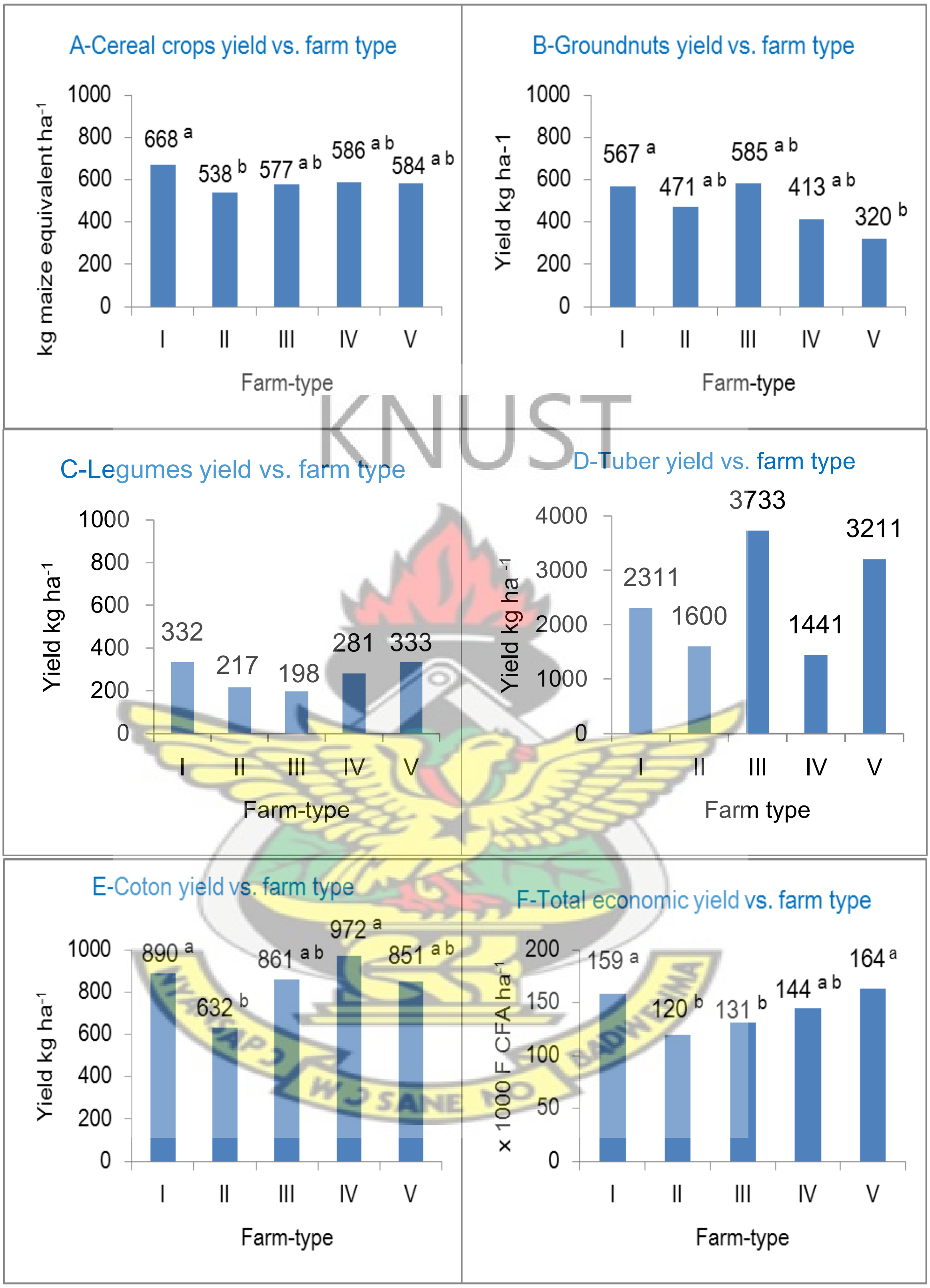


Figure 4.3. Crop yields of the five household-farm types.

Notes: *Number on the top of the yield columns are the average yield. For each chart, the group mean values with same letter are not significantly different from each other at 95% (p < 0.05).*

When considering the monetary income per unit of land (economic yield) farm-types I and V had highest economic yield (159,000 FCFA/ha and 164,000 FCFA/ha, respectively), but they were not significantly different from each other. They were both significantly different from farm-type II (120,000 FCFA/ha) and farm-type III (131,000 FCFA/ha). The economic yield depends both on productivity and economic value of crops grown by these farms. Therefore, farm-types I and IV which grow more of cash crops presented better economic yields. Farm-type II and III not only have low crop yield but also grow less cash crops. This explains the observed difference in their respective economic yields.

4.3.3. Farm-types soil nutrient management strategies

The main soil nutrients resources in the study region are mineral fertilizers, animal dung (mainly goat, sheep and poultry) and compost. Compost is mostly made from household waste, animal dung and crop residues. Recycling of crop residues was very low for all farm-types and no significant difference was found among farm types (Table 4.4).

Table 4.4. Soil nutrient management practices

Farm-type	n	Recycling crop residues (%)	Using stone bunds (%)	Fallow land possession (% of farms)			Farm land using mineral fertiliser (%)
				0 ha/pers.	>0<=1 ha/pers.	>1<3 ha/pers.	
I	104	26.67	16.60 [a]	51.50	42.70	5.80	24.90
II	102	23.53	11.10 [b]	44.00	52.00	4.00	12.10
III	71	19.72	10.40 [b]	54.30	45.70	0.00	18.90
IV	28	24.14	23.00 [c]	41.40	55.20	3.40	20.50
V	29	21.43	20.40 [ac]	42.30	57.70	0.00	15.20

Notes*: For each indicator, farm-types with same subscript letter are not significantly different from each other at 95% ($p < 0.05$).*

On average only 24% of farmers recycled part of their crop residue at the study sites whilst Ebanyat et al. (2010) found that up to 78% of farmers were recycling crop residue in Uganda. Farmers of Ioba province are missing valuable nutrient resources for replenishing soil fertility. Low rate of crop residues recycling can be explained by the competition (Ebanyat *et al.*, 2010) with other uses like livestock feeding or fencing. Famers operate trade-offs for the use of crop residues. However, it can also be the result of labour constraint or insufficient knowledge and lack of system thinking. Most farmers are illiterate or have very low education level. This raises the issue of policy intervention efficiency given the high number of programs and NGO intervening to promote sustainable soil nutrient management in the region. Farmers also used stone bunds to reduce water erosion and preserve soil fertility. The farm-type IV had the highest proportion of plots where this technology (24%) was implemented. Farm-type III had the lowest proportion (10.40%). Stone bunds contributed to improve soil fertility through increase of soil macro fauna, soil carbon and soil nitrogen (Zougmoré *et al.*, 2004c; Doamba *et al.*, 2011). However, most farmers in the study region implement stone bunds inconsistently, reducing its efficiency. Fallowing, used in the past for soil fertility restoration is declining mainly due to population pressure. Most farms have less than 1ha of fallow lands per capita. This suggests that agriculture in the region is bound to evolve toward intensification of mineral fertilizer use or toward innovative and affordable soil nutrient management strategies valuing locally available resources.

All farm types seem to have applied nutrient with similar dose per nutrient resource (Figure 4.4). No significant difference was found among farm types. The application doses were low compared to the recommended doses. This might result in unbalanced soil nutrients. The observed application doses seem to be the result of nutrient resources availability; and farmers are therefore trying to make an extensive use of the available nutrient.

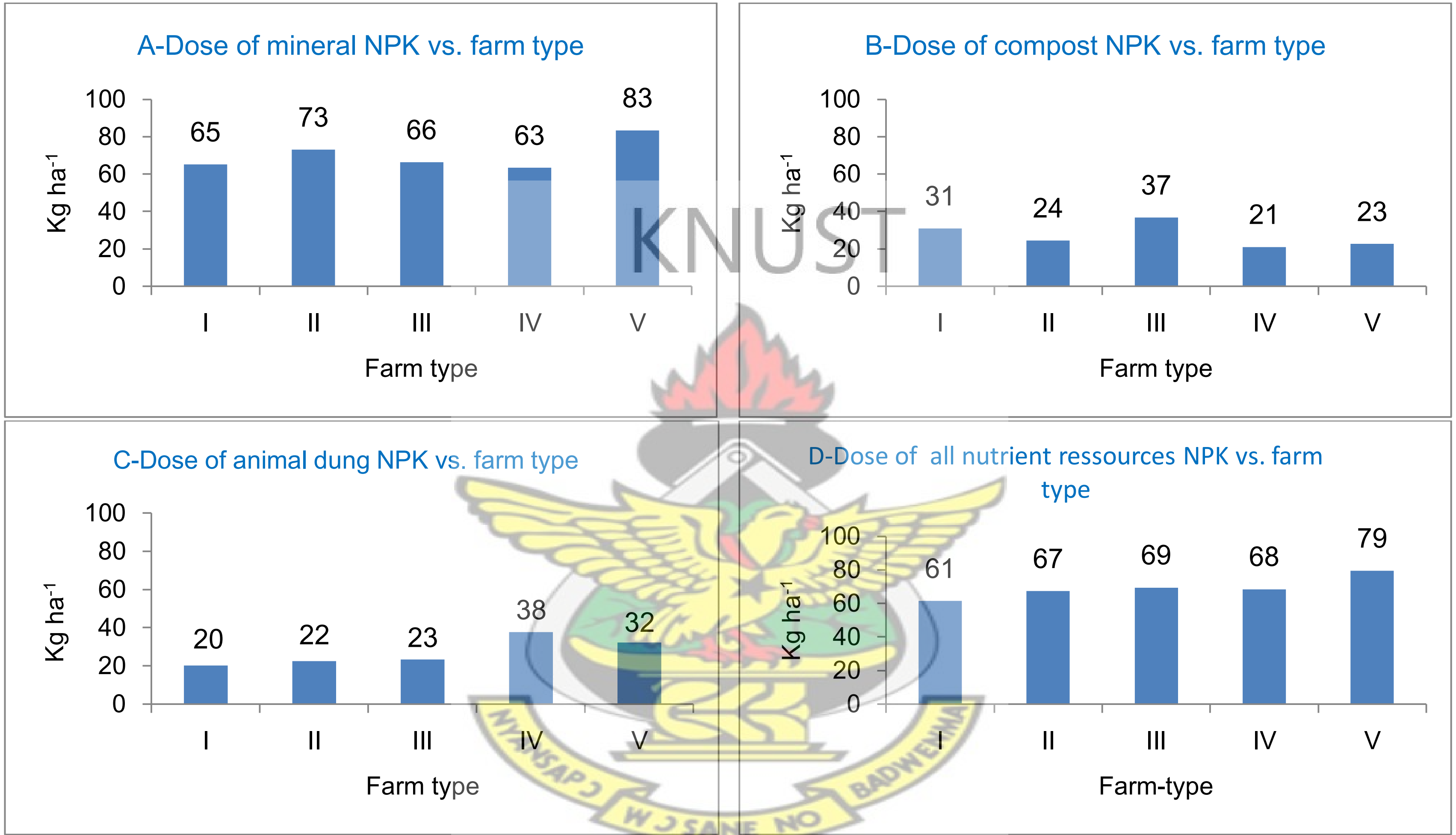


Figure 4.4. Nutrient application dose per nutrient ressource for five household-farm types.

Notes*: Numbers on top of columns are average nutrient application dose. Values with same letter are not significantly different from each other at 95% (p < 0.05).*

For nutrient use intensity, no significant difference was found among farm-types for animal dung and compost nutrient use intensity (Figure 4.5). The observed values were very low. It can be due to a low performance in collecting animal dung for farm types like farm-type IV and V which possess the biggest number of small ruminants per household: 13 and 8, respectively. There is also the fact that compost and manure are in general applied to non-distant homestead fields (Tittonell *et al.*, 2005b). So, even when available, it may not be applied to bush fields. Composting of crop residues is constrained by the remoteness of fields and by water availability to water the compost during composting. This issue can however be solved by keeping crop residues within on-field compost pits or as heaps for two or more years as already practiced by few farmers (see Plate 4.1).

Plate 4.1. Cotton straw heap of one year old in a farmer field

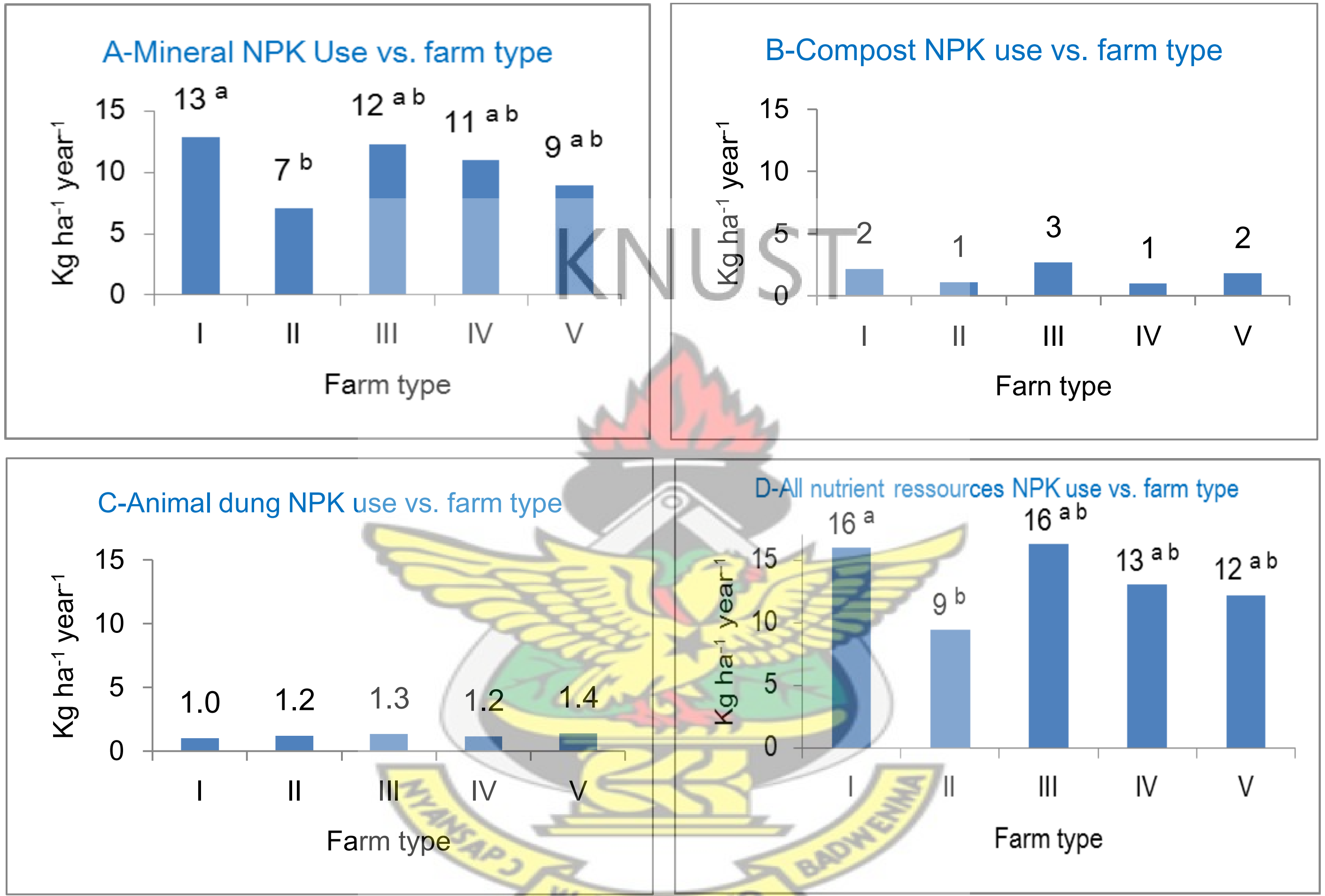


Figure 4.5. Nutrient use intensity per nutrient ressource for five household-farm types

***Notes**: Numbers on the top columns are average nutrient use intensity. values with same letter are not significantly different from each other at 95% ($p < 0.05$).*

Significant difference was found between farms-types for mineral NPK and Total NPK. Only Farm-type I and Farm-type II were significantly different. Farm-type II had lowest mineral NPK use intensity. Possibly because of non-farm activities preference (Haileslassie *et al.*, 2006), farm type II covers only 12.1% of farmed lands. It has the highest cash income per capita and this could have allowed purchasing more fertilizer than other groups. This suggests that the capacity to cover a relative largely amount of lands in mineral fertilizer depends not only on the financial resources available but also on farm livelihood orientation. The farm-type III and V, which had lowest income were not significantly different from more endowed farm-types. Despite their low income, they had as much mineral nutrient use intensity as higher income farm-types. This follows the Boserup's path of agricultural intensification through increase of investment in fertilizer rather than through intensification of labour. The latter was considered to be less sustainable (Reardon and Vosti, 1995). As observed by Malmberg and Tegenu (2007), agriculture intensification usually intervenes land constrained and high dependency ratio context. The other possible explanation of the situation is that the governmental fertilizer subsidy programme implemented since 2008 favours the acquisition of fertilizer by less endowed farm and improves their nutrient use intensity.

When comparing crop yields (Maize equivalent and physical production) performances of the different farm types to their nutrient management profile, a relationship was found between the two. Farm-type I, which had the highest nutrient use intensity, also had the best values for cereal, cotton and economic yields. Also farm-type II with lowest nutrient use intensity had lowest yields. These results demonstrate the functional relationship between crop production and nutrient management performances. Therefore, improving food productivity necessarily requires improving nutrient management strategies of farm types through adoption of sustainable soil nutrient practices.

4.3.4. Economic efficiency of mineral fertilizer use by the five farm types

The Farm types showed strong heterogeneity for combined use of NPK and Urea economic efficiency (Figure 4.6). In effect farm type I is significantly different from farm types II, III and V. It had a positive economic efficiency (3.49). By investing 1,000 FCFA in mineral fertilizer, farm-type I increased its monetary yield by 3,490 FCFA, more than three folds the invested amount of money. Farm type II and III also had positive economic efficiency. However they were not economically efficient: the marginal monetary yield was less than the invested amount of money for fertilizer acquisition. For 1,000 FCFA invested in mineral fertilizer, the marginal monetary yield is 100 FCFA (10%) and 300 FCFA (30%) for farm types II and III respectively.

The farm type V had a negative economic efficiency, suggesting that farms are unable to draw economic surpluses from additional investment in mineral fertilizer. This low performance can be explained by inefficient use of mineral fertilizer causing important losses. Given the above results it can be concluded that farm livelihood (endowment in good land, financial endowment, crop production orientation) influences its economic efficiency of fertilizer use.

The analysis of Pearson correlation coefficient table (Table 4.5) allows identifying and understanding possible factors that may influence farmers' economic efficiency. Farm livelihood variables, which were significantly correlated to farms' economic efficiency varied across farm types.

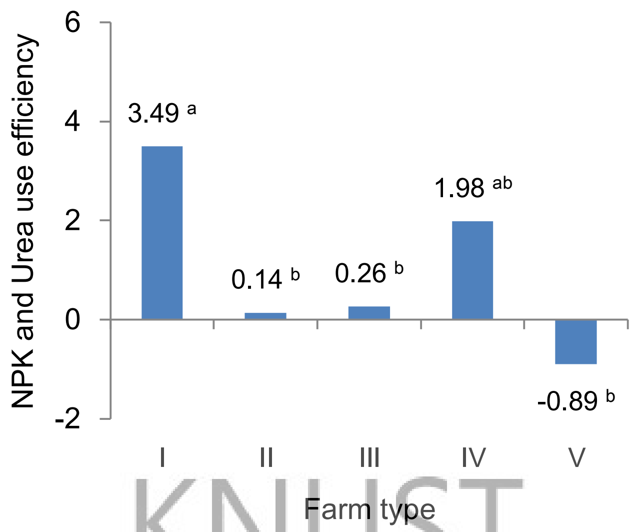


Figure 4.6. Economic efficiency of mineral fertilizer uses of five household-farm types

Note: *Numbers on top of yield columns are average economic efficiencies. Values with same letter are not significantly different from each other at 95% ($p < 0.05$).*

Table 4.5. Coefficients of correlation (*R*) measuring the effects of livelihood factors on farms' nutrient use efficiency

Variables differentiating farm types	Whole sample (*n* = 149)	Household-farm type-specific *R*				
		Farm-type I (*n*= 54)	Farm-type II (*n* = 34)	Farm-type III (*n* = 32)	Farm-type IV (*n* = 18)	Farm-type V (*n* =11)
H_{TLUCP}	-0.01	-0.26*	-0.05	0.49**	-0.07	0.25
$H_{\%COTTON}$	0.01	-0.23*	0.01	-0.03	-0.2	0.44
$H_{\%NFINC}$	-0.10	0.15	0.35**	-0.36**	-0.11	-0.25
$H_{\%MFC}$	0.07	0.29**	-0.16	-0.20	0.35	-0.54*
$H_{HEADEDU}$	0.12	-0.09	0.36**	0.28	0.54**	0.14
H_{DEPEND}	-0.16*	-0.07	-0.10	-0.19	-0.25	-0.38
$F_{AGEMEMB}$	0.08	0.10	-0.17	0.12	0.41*	0.53
F_{SIZE}	-0.04	-0.12	0.18	0.01	-0.41*	0.22
$F_{HOLDINGS}$	-0.10	-0.23*	0.09	0.04	-0.35	-0.27
$F_{GROSSINC}$	-0.01	-0.18	0.09	0.38**	-0.36	0.34
$F_{\%LIVSINC}$	0.02	-0.05	-0.33*	0.27	-0.01	-0.13
$F_{\%TRANSFER}$	0.05	-0.02	-0.09	-0.21	0.47*	0.20
$H_{DISTPAVED}$	-0.17*	-0.14	-0.18	0.06	-0.37	0.09
$H_{DISTTOWN}$	-0.24**	-0.23	-0.04	-0.17	-0.40	-0.88**

***Note**: * and ** indicate statistical significance (2-tail) at 90% and 95%, respectively.*

For whole sample, the dependency ratio (R= -0.16) and the remoteness variables (R= -0.17 for distance to paved road and R = -24 for distance to main town) reduced farm economic efficiency. Household head education (R=0.36), Gross income (R=0.38), Tropical livestock units (R=0.54), Age of households members (R=0.41) and Transfer (R=0.47) were the main type specific variables that promoted economic efficiency. Type specific correlated variables with negative effect were Farm size (R= -0.41), Distance to main town (R= -0.88) and Marketable food crops area (R= -0.54). These results revealed that economic efficiency of farms is influenced by access to modern infrastructures, education and financial resources. In effect, remoteness limits access to extension services, to fertilizers at affordable prices and to learning opportunities on sustainable soil management. Education was proven to be a critical factor in land management. Low education limits farm soil nutrient management skills and, therefore, affect its economic efficiency. The negative impact of dependency ratio can be explained by the fact that a high dependency ratio causes inconsistent application of mineral fertilizer due to low crop income.

4.4. Conclusion

The use of the Sustainable Livelihood Framework has allowed for a clear identification of household-types in the study region. Five typical farms were found: two better-off farm-types amongst which a cotton and livestock-based farm type (Farm-type I), and a non-farm preference farm type (Farm-type II); a labour-rich and marketable food crop-oriented farm type (Farm-type IV); a poor, insecure-land tenure, livestock based farm-type (Farm-type V); and a pro-poor, labour-poor-and landless farm-type (Farm-type III). The soil fertility management practices in use by these five farm-types were correlated with their livelihood profile. Wealth, livelihood strategy, land access, labour availability and existing policies were factors found to be influencing farms nutrient management practices. The land constrained and land unsecured farms intensify mineral nutrient use while better-off farms make high investment in mineral fertilizer if crop production is the main activity in their livelihood strategy. Crop yields performances of farms as well as their economic efficiency are linked to nutrient management practices and livelihood.

On methodological level, SLF has proven to be a suitable framework for properly identifying farm types in a region. It allows better understanding of the relationship between socio-ecological heterogeneity of smallholder farms and on their nutrient management. This can be used for reflecting on promising pathways for sustainable land management. The study demonstrated the need for categorizing household-farms when analysing nutrient management and crop production performances. The results showed that influential factors of household-farm economic efficiency are not uniform across household-farm types. Common and type specific factors exist and ignoring it may give misleading results in farm studies.

5. THE ROLE OF CLIMATE CHANGE AWARENESS IN SUSTAINABLE SOIL NUTRIENT MANAGEMENT

5.1. Introduction

Climate change negatively impacts farming activities and aggravates crop production deficiencies, food insecurity, and threatens livelihoods (Jarvis *et al.*, 2010; Lobell and Burke, 2010; Olsson *et al.*, 2014; Porter *et al.*, 2014). Recent studies (Blanc, 2012; Sultan *et al.*, 2013) estimated that yield of main staple crops in Sub-Saharan Africa (maize, millet and sorghum) will decrease by up to 25.5 - 27% due climate change during the 21st century. Adapting to climate change and building farm resilience is paramount to improving food security and livelihood of smallholder farms.

To improve and sustain food production, smallholders farms need to change current agricultural practices, which are mostly inadequate in the context of climate change (IFPRI, 2007). As highlighted by previous studies (Place *et al.*, 2003; Bationo *et al.*, 2006; Anley *et al.*, 2007; Chianu *et al.*, 2012a; Chianu *et al.*, 2012b), adoption of sustainable soil nutrient management practices is still limited in Sub-Saharan African countries. Beside financial constraints and to some extent, insufficient technical know-how, the lack of understanding of ongoing climate variability and its implications contributes to the poor soil fertility management performances in Sub-Saharan African smallholder farms.

There is a need to increase knowledge on farmers' awareness to climate change for guiding decision making on smallholder farms adaptation and resilience to climate change. The extent of climate change impact largely depends on the farmers' awareness (Fosu-Mensah *et al.*, 2012). Awareness is a key determinant of adaptation to climate change (IFPRI, 2007; Ishaya and Abaje, 2008). For being proactive and taking efficient adaptation actions smallholder farms need to understand climate change, its causes and implications. Marshall *et al.*, (2013) associated climate awareness to enhanced adaptive capacities.

Most of the past studies (Gbetibouo, 2009; Fosu-Mensah *et al.*, 2012; Nzeadibe *et al.*, 2012) did not clearly distinguish climate change perception from climate change awareness. Also it is hard to find studies on awareness of different farming systems to climate change. It has been proven (Zingore *et al.*, 2007; Oumer *et al.*, 2013) that farms heterogeneity plays an important role in explaining farm behaviours. Moreover it is difficult to find studies analysing climate change awareness in relation to soil nutrient management practices.

Therefore, the main objective of this study is to analyse climate change perception and awareness of different socio ecological farm types and their implications on sustainable nutrient management. The specific objectives are: (i) to assess climate change perception and awareness of smallholder farms; (ii) to analyse climate change awareness of different farm types; and (iii) to analyse the effect of climate change awareness on soil nutrient management.

5.2. Methodology

5.2.1. Conceptual framework

Temperatures rise, and rainfall decrease and variability in a location are some of the most obvious evidences of climate change in the tropics. Farmers can realize, feel and observe these changes without classic scientific measurements. The study defines this as perception of climate change. In perceiving the evidences, farmers can give trend (appreciation) over a period (e.g. increase or decrease of the evidence amplitude). When farmers have only perception they take no or less action to adapt (Figure 5.1). Beside the perception, farmers can understand the perceived evidences, their causes and their implications for their activities. This allows them to take more and take more and strong actions, build strategies in order to cope, adapt to or mitigate these evidences. The understanding of the causes of the evidences as well as their implication for livelihood activities is defined as awareness. Awareness is raised by education, learning (e.g. from extension services and other developmental stakeholders), and through information (e.g. exposure to media). Due to their differences in assets endowments (education, financial resources, equipment, exposure to outside world), farmers of different socio ecological settings are expected to have different levels of climate change awareness. Previous studies used interchangeably climate change perception and awareness (Mertz *et al.*, 2008; Gbetibouo, 2009; Fosu-Mensah *et al.*, 2012; Nzeadibe *et al.*, 2012).

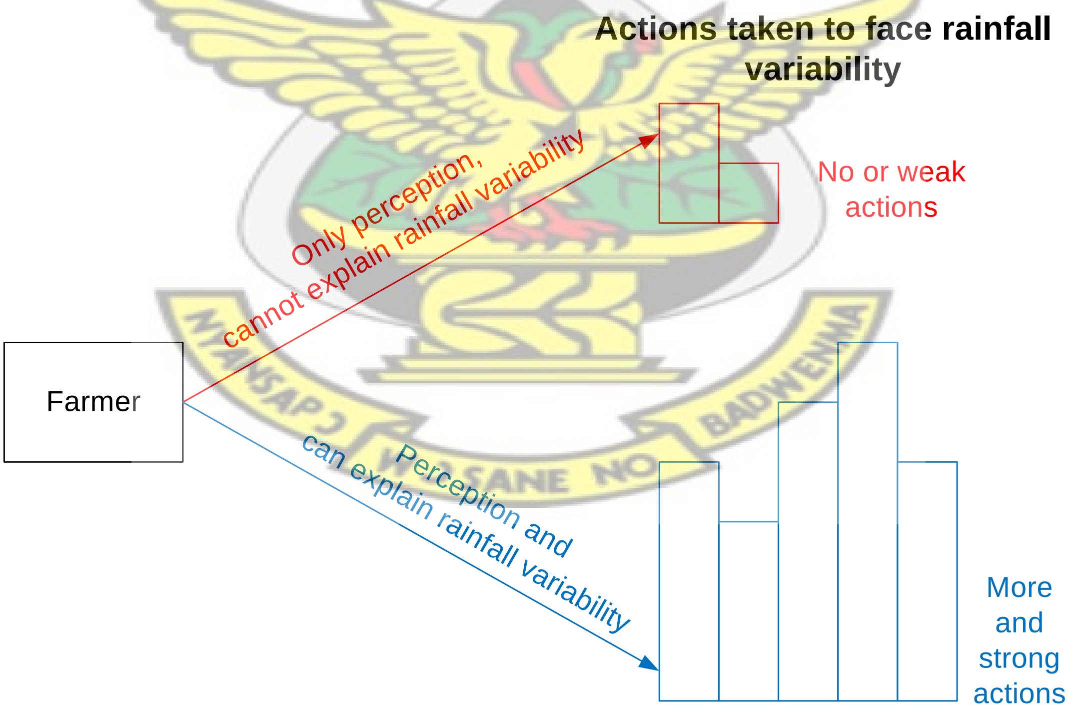


Figure 5.1. Conceptual framework of climate change perception versus awarenss

5.2.2. Methods

5.2.2.1. Assessing climate change perception and awareness of farms

From field observations, the climate parameter farmers usually monitor closely is rainfall because of its most patent effect on plants and feedback effects on temperatures. Therefore, rainfall was used to assess climate change perception of farmers. The longer the period of study, the better it is for observing variations due to climate change. Studies used a time span of ten years (Komba and Muchapondwa, 2012). However, using a long time span for studying climate change perception may alter the accuracy of farmers' responses. To compromise between the need for having a long enough period and the need of accuracy in farmers' responses, a time span of five years was used. Farmers were asked to appreciate the trend of rainfall for the last five years (2009-2013). Farmers' perception of rainfall trend was confronted to the trend of measured rainfall data. The awareness was assessed by asking farmers to give the causes and implications of rainfall variability on their farming activities. Descriptive analyses of responses were performed in SPSS version 20 (Statistical Package for Social Sciences) and z-test used to test the difference of responses between farm types.

5.2.2.2. Analysing effects of climate change perception and climate change awareness on sustainable soil nutrient management

Rainfall data was analyzed for trend detection in XLSTAT 2014 using Mann-Kendall trend test. The results were compared to the perception of farmers for the last five years. For analysing the effect of climate change perception and of climate change awareness on sustainable soil nutrient management, we run descriptive analyses using crosstabs and chi-square test to evaluate the difference in the responses of the different farm types.

5.3. Results and discussions

5.3.1. Climate change perception in Ioba province

As much as 99% of farmers perceived variability in rainfall during the last five years. In addition, 72.4% of farms noted a late onset of the cropping season. This shows that farmers largely perceive ongoing climate change as previously found by Ouedraogo *et. al.*, (2010). The perceived trend of rainfall varied across farm types (Figure 5.2). The chi-square test revealed that farm-type IV was significantly different from farm-types II and III. Farm-type I was significantly different from farm-type II in terms of climate change perception. Farmers largely perceived a decreasing rainfall for all farm types. Only farm-type IV was dominated by farmers who perceived a fluctuating rainfall (51.7%). Most farms of the farm-types II and III (67.0 and 64.8 % respectively) perceived a decreasing rainfall.

The perceived trend in the rainfall of farmers was compared to the trend of measured rainfall data. The Mann-Kendall trend analysis (Table 5.1) showed no trend in the rainfall data for the last five years. This means a fluctuation of rainfall for the period. Only perception in farm-type IV matched trend of the measured rainfall. Less than 50% of the farmers in the others farm-types perceived a trend matching the trend observed in the measured rainfall data. It shows that different farm types can perceive rainfall trend in different ways that may affect their adaptive response. Farm-type IV being the most educated, the results support the fact that education plays a primordial role for an accurate perception of rainfall variability by smallholder farms. The results also highlight the difficulty for farmers to keep accurate track of rainfall over years. The issue can be solved by building farmers' capacities in agro meteorology through extension services and media. It could contribute to a better management of farming activities and efficient response to climate change. It requires widening rain gauge use and close collaboration of extension services with farmers.

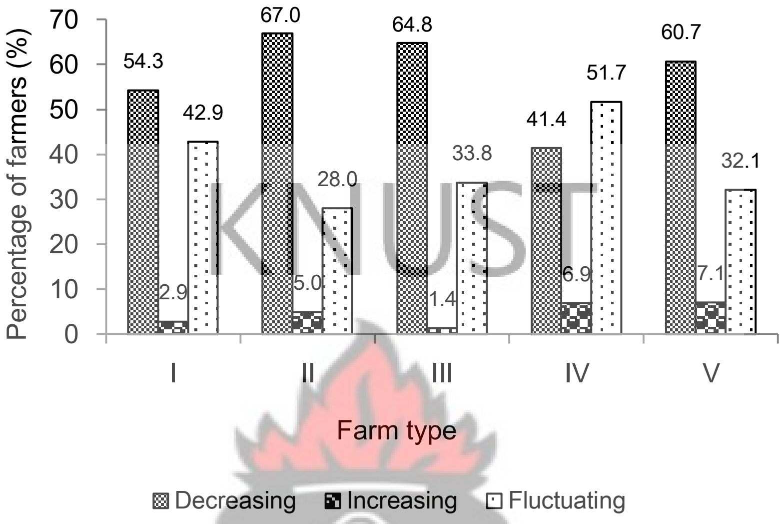


Figure 5.2. Farmers' Climate change perception

Table 5.1 Mann-Kendall trend test

Kendall's tau	0.156
S	7.000
Var(S)	0.000
p-value (Two-tailed)	0.601
alpha	0.05

5.3.2. Smallholder farms heterogeneity and climate change awareness

It was found that about 50% of the farms could not explain observed rainfall variation (Figure 5.3). Around 26% of the farmers explained it by their religious beliefs (e.g. God's punishment and non-observance of traditional rituals). Only a few of them referred to climate change (4.1%) or anthropogenic causes like deforestation (19.2%) or bush fires (0.9%). The distribution of responses across farm-types revealed significant heterogeneity. Farmers whose responses were climate change or deforestation were considered as having climate change awareness. As such, farm-type IV was again the farm type with highest proportion of farmers having climate change awareness (36.7%). It was significantly different from farm-types II and V. Farm-type IV had lowest proportion of farmers who explained rainfall variation by believes (16.7%). It can be explained by their education level. Farm-type IV had most educated household heads (4 years on average). Farm-type IV was not significantly different from farm-type I which had low educational level but comprised the biggest cotton producers benefiting from close technical assistance of cotton companies. Undoubtedly, this gives them opportunity to learn about climate change, related causes and challenges. It shows the importance of the farm social network. Education, learning and extension services are therefore important means for farmers to build knowledge on climate change. These services should be strengthened and extended for improving and raising climate change awareness of farmers.

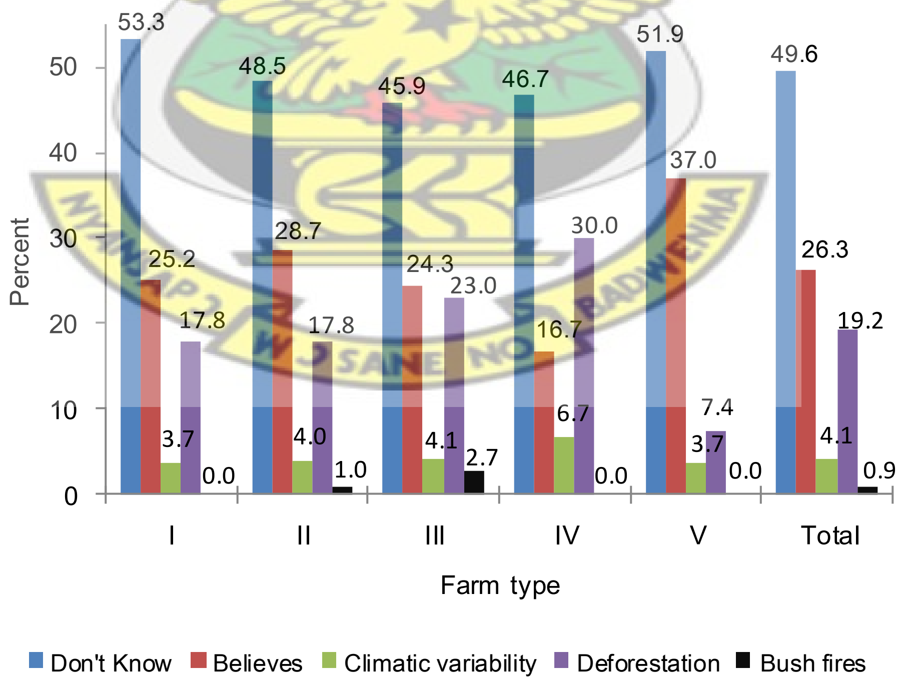


Figure 5.3. Causes of perceived rainfall variation by farmers

5.3.3. Adaptive measure against rainfall variability

In response to rainfall variation, farmers may undertake actions to ensure farm productions (e.g. crops and livestock). Action is taken according to perceived trend, understanding of ongoing changes, farm assets endowment and capabilities. Farmers having climate change awareness are expected to take more actions. Multi-response analysis was used with the aim of identifying measures undertaken by farmers in response to the perceived rainfall variation and according to their climate change awareness. The main adaptive measures that were identified are presented in Figure 5.4. As expected, a large proportion of farmers having climate change awareness (83.3%) took measures to counter the negative effects of rainfall variation on their farming activities.

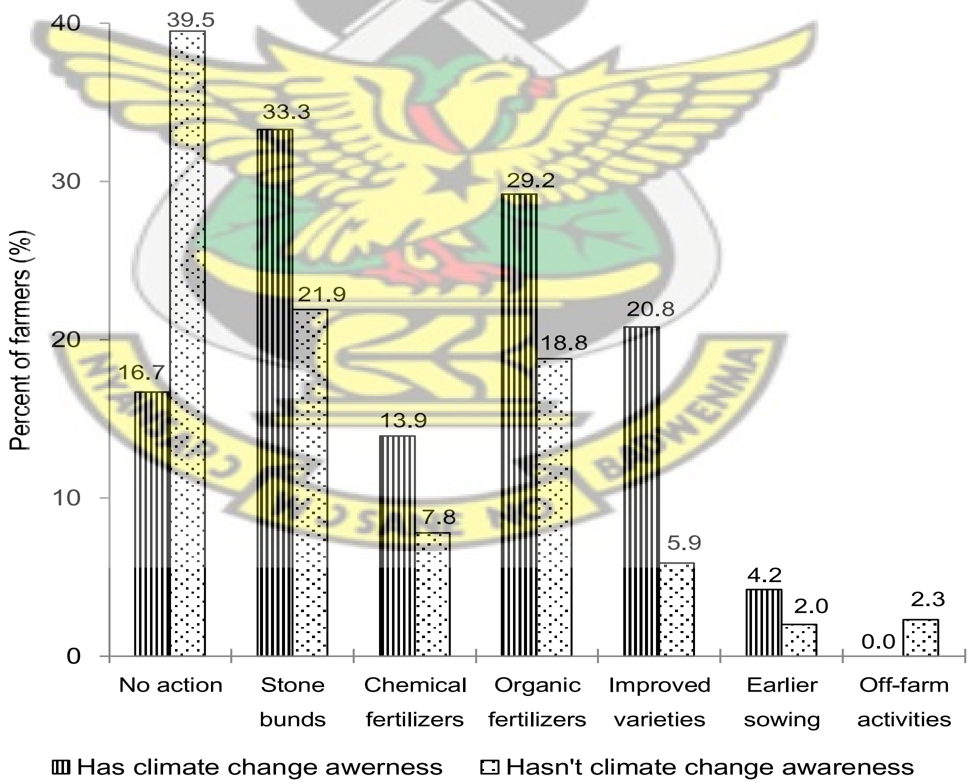


Figure 5.4. Adaptive measures against rainfall variation

The main implemented measures were:

- Stone bunds reducing water erosion (33.3% of farmers having awareness against 21.9% of farmers with no awareness). The use of stone bunds is labour intensive and is sometimes constrained by labour availability;
- The use of chemical fertilizers (13.9 % against 7.9%).
- The use of organic fertilizer (29.2% against 18.8%). Like the use of stone bunds, organic fertilizer adoption is constrained by labour (see chapter 3).
- Improved varieties (20.8% against 5.9%): these are short cycle and drought resistant varieties promoted by extension services.
- Few farmers stated early sowing as a measure against rainfall variation.
- Only farmers not aware of climate change (2.3%) diversified their activities into off-farm activities.

Not all the farmers having climate change awareness took measures to address rainfall variability. Up to 16.7% took no actions. This can be explained by the fact that farmers are constrained by resource endowment. Indeed, mineral fertilizer use is still limited in the region despite subsidies to support fertilizer consumption. Soil conservation and replenishment measures like stone bunds and organic fertilizer are constrained by farmers' labour availability and financial resources (See chapter 4 and 6). So, awareness alone appears not to be enough for farmers to take coping or adaptive measures. Their response to climate change may be constrained by their assets and capabilities.

The lack of awareness limited the adoption of measures against rainfall variability. In effect, around 40% of farmers who were not aware of climate change took no action to face the rainfall variability. This shows the importance of awareness in the adaptation to climate changes. Therefore, climate perception only is not enough in climate change studies or policy interventions. Climate change awareness should also be investigated to better understand farmers' behaviour and their readiness to adopt coping and adaptation measures. The results showed that despite lack of climate change awareness, around 60% of farmers who had no awareness adopted some measures against rainfall variability. However, this does not necessarily mean that without awareness farmers will still adopt efficient measures based only on their perception of climate change. Other factors can compel them to adopt. As noted by Barbier *et al.*, (2008) farmers may adopt soil fertility management measures because of growing land scarcity and new market opportunities rather than the perceived climate change. The study region is facing important land pressure.

5.4. Conclusion

The study showed that farmers (99%) perceive very well rainfall variation and late onset of cropping seasons. However not all farmers knew and understood the causes of these variations. They don't have climate change awareness which is crucial for farmers to undertake and invest into efficient adaptive practices. These results highlight the importance of distinguishing perception from awareness in climate change adaptation studies. Though the two items are interrelated they are differently correlated to sustainable soil nutrient management by smallholder farms. Also, climate change perception and awareness varied across farm types. The most educated farm-types had a better perception of rainfall trend and their perception matched better with the trend of measured rainfall data. Education and access to extension services play a paramount role in raising climate change awareness of farmers. Findings highlight the key role of farm heterogeneity in climate change awareness. Farming system design need to account for climate change awareness and the influence of farm heterogeneity on smallholder awareness. To raise farmers' awareness to climate change, policy intervention should be to reinforce extension services collaboration with farmers for their capacity building in agro meteorology and use of historical rainfall data to better tailor and plan farming activities. As noted by AGRA (2014), opportunities to adapt agricultural systems to a variable and changing climate depend on access to climatic information, and can be constrained if the right information is not available at the right spatial and temporal scale.

6. RESPONSIVE HETEROGEINTY IN SUSTAINABLE SOIL NUTRIENT MANAGEMENT: THE CASE OF SMALLHOLDER FARMS IN IOBA PROVINCE

6.1. Introduction

Hunger and undernourishment are still rife in Sub-Saharan Africa. For decades food insecurity has affected many countries with not much improvement (FAO, 1993; FAO, 2006; FAO *et al.*, 2013) despite numerous interventions. In Burkina Faso in particular, 37% of rural households were food insecure in 2013 (SPCPSA, 2013) and 25% of the country's population was undernourished in 2011-2013 (FAO *et al.*, 2013). Food insecurity is prone to failure of households to ensure sustainable food production (Devereux and Maxwell, 2001; Devereux, 2009). Most cropping systems in Sub-Saharan African (SSA) are characterized by alarming soil nutrient depletion (Stoorvogel and Smaling, 1990; Lal, 1995; Bationo *et al.*, 1998; Anonymous, 2006; Cobo *et al.*, 2010). Resulting soil degradation affects food security through low crop yields and reduced household income (Stocking, 2003; Lal, 2009; Pimentel and Burgess, 2013; Grote, 2014).

Combatting food insecurity requires tackling soil nutrient mining issues while improving food productivity and profitability. Adoption of proven soil fertility management practices (e.g. mineral and organic fertilizers) has the potential of improving crop productivity (Vlek *et al.*, 1997; Ingram *et al.*, 2008; Lal, 2009). Indeed, mineral fertilizers are shortest way for replenishing soil in macronutrient and avoiding widespread nutrient mining. Organic fertilizers improve soil fertility (Gaur and Singh, 1993) and are crucial for farmers who are unable to purchase mineral fertilizers (Palm *et al.*, 2001). It improves soil physical properties through strengthening of organic matter

(Palm *et al.*, 1996; Vanlauwe and Giller, 2006; Ding *et al.*, 2012; Körschens *et al.*, 2012). Beyond macronutrients it can contain micronutrients (Cu, B, Zn, Mn, Mo) which greatly increase soil productivity (Parr and Colacicco, 1987). Combined organic-mineral fertilizers reduces nitrogen losses observed in sole mineral fertilizer use (Neeteson, 1993). It generate better yields than sole use of mineral fertilizers (Mucheru-Muna *et al.*, 2007; Ding *et al.*, 2012; Kearney *et al.*, 2012; Kismányoky and Tóth, 2012).

However, adoption of Sustainable Nutrient Management (SNM) practices remains very low in SSA (Place *et al.*, 2003; Bationo *et al.*, 2006; Anley *et al.*, 2007; Chianu *et al.*, 2012a; Chianu *et al.*, 2012b). Inefficient agricultural policies (Anley *et al.*, 2007) contribute to the low adoption of SNM. Indeed, interventions promoting SNM adoption often implement uniform policies while farmers' population is characterized by inherent social and ecological diversity. It is necessary to better understand factors affecting farmers' adoption and based on that to inform policy leveraging farmers' incentive to adopt.

Most studies (Adesina, 1996; Makokha *et al.*, 2001; Chianu and Tsujii, 2005; Waithaka *et al.*, 2007; Kassie *et al.*, 2013; Lambrecht *et al.*, 2014) analyzed the effects of a range of different factors on nutrient adoption/use but with a uniform affecting pattern. However, given an affecting factor, its significance, affecting direction and magnitude can be different over different types of farm/farmers. This responsive heterogeneity needs to be understood.

The main objective of the study is to analyze responsive heterogeinity of smallholder farms in the use and adoption of mineral and organic fertilizers. The specific objectives are to:

- analyze the common determinants of mineral and organic fertilizers uses/adoption for different farms types
- analyze farm type-specific determinants of mineral and organic fertilizer uses/adoption

6.2. Methods

6.2.1. Conceptual framework

The conceptual framework of this study (Figure 6.1) is based on Sustainable Livelihood framework (Sconnes, 1998; DFID, 1999; de Sherbinin *et al.*, 2008). Adoption/use of sustainable land management practices by the farmer/farm is a function of available resources (Jones, 2002). The readiness of farmer to apply soil nutrients is not only affected by perception of soil fertility. It is also determined by farm assets (e.g. natural, physical, financial, social and human assets). In pursuing its livelihood objectives (e.g. food security and well-being), farmer mobilizes and allocates its assets within a livelihood strategy. This strategy needs to be accounted for when analyzing soil fertility management. Livelihood-based farm typology gives therefore more insight into soil fertility management (Tittonell *et al.*, 2005b; Bidogeza *et al.*, 2009; Tittonell *et al.*, 2010; Oumer *et al.*, 2013). Besides common determinants, there are farm-type specific factors that influence the response of farms to soil degradation and, therefore, affect the adoption/use of soil nutrient. This specific responsiveness is inherent to level of assets endowment and to farm livelihood strategy profile. It may change overtime with the change in farm livelihood strategy and assets endowment.

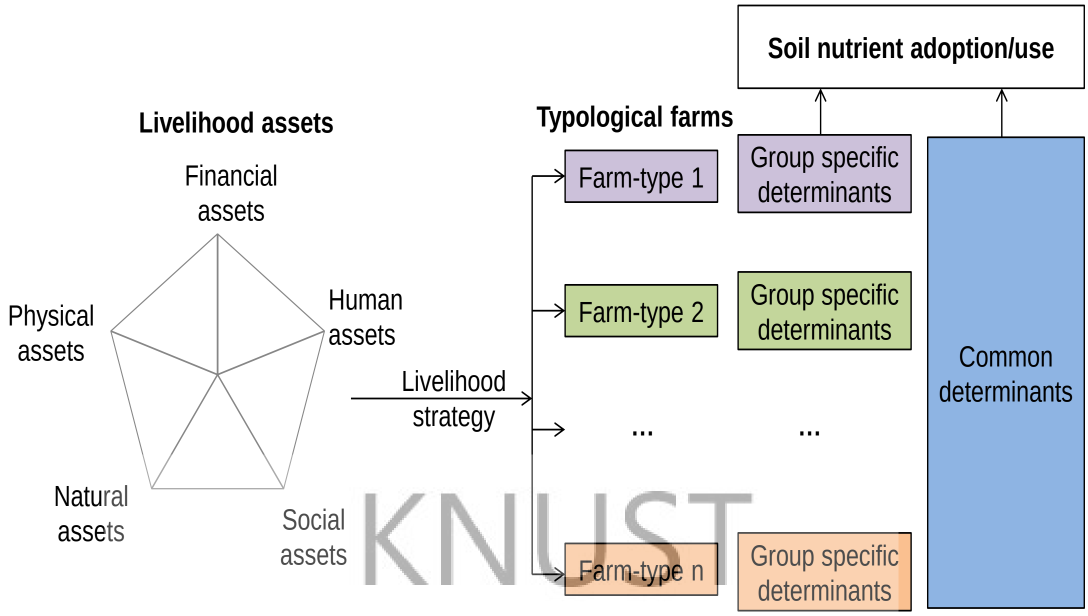


Figure 6.1. Conceptual framework of responsive heterogenity

6.2.2. Dependent variables

Because of limited acess, farmers may apply very small (insignificant) amount of nutrient. Applied amount of nutrient was considered significant when it was more than 10% of the recommended application rate. Only famers observing this threshold were considered as users of mineral and organic fertilizers. Dependant variables and corresponding inferential statistical methods used are summarized in Table 6.1.

- Use/adoption of mineral fertilizers (NPK + Urea): NPK(14-23-14) and Urea (46N) are the commonly used mineral fertilizer in the study region. Given previously defined threshold and recommended rates of application for mineral fertilizer (CILSS, 2012), fertilizer users apply more than 9.7 kg N-P-K ha/year. The dependent variable mineral fertilizer use intensity (Y_{MinUse}) expressed the amount of mineral nutrient annually applied per unit of land (kg N-P-K ha/year). It was computed dividing the amount of nutrient applied by the total cultivated area with and without mineral fertilizer. The variable Adoption of mineral fertilizer use (Y_{MinApt}) refelected the farm choice to apply or not mineral nutrient. Y_{MinApt} = 1 if farm adopts mineral fertilizer and 0, otherwise.

- Adoption of organic fertilizers (Y_{OrgApt}): the variable refelected the farm choice to apply organic fertilizer (compost and animal dung) or not. Y_{OrgApt} =1 if farm adopts organic fertilizer and 0 ifotherwise. According to the recommended application rates from Ioba provincial directorate of agriculture and CILSS(2012), and given threshold defined above (significant amount of fertilizer) organic fertilizer users apply more than 4.1 kg N-P-K ha/year and 2.7 kg N-P-K ha/year from compost and animal dung, respectively.

- Adoption of both mineral and organic fertilizers (Y_{MinOrg}). This variable expressed combined use of mineral and organic fertilizers (Mineral-organic fertilzers). Y_{MinOrg} = 1 if the farm applies both mineral and organic fertilizers and 0 if otherwise.

Table 6.1. Dependent variables and corresponding inferential statistical methods

Dependent variable	Brief definition	Inferential statistical method
Y_{MinUse}	Annual amount of mineral fertilizer used for the plot (kg N-P-K /ha/year)	Multiple linear regression
Y_{MinApt}	Adoption of mineral fertilizer: 1 = farmer adopt mineral fertilizer use for the plot (> 9.7 kg N-P-K /ha/year); 0= otherwise	Binary logistic regression
Y_{OrgApt}	Adoption of organic fertilizer: 1= farmer adopt either animal dung or compost for the plot (> 2.7 kg N-P-K /ha/year and > 4.1 kg N-P-K /ha/year in the cases of animal dung and compost, respectievly); 0 = otherwise	Binary logistic regression
Y_{MinOrg}	Adoption of both mineral and organic fertilizer: 1 = farmer adopt both mineral and organic fertilizer for the plot (> 9.7 kg N-P-K , > 2.7 kg N-P-K /ha/year and > 4.1 kg N-P-K /ha/year for mineral fertilizer, animal dung and compost, respectievly); 0 = otherwise	Binary logistic regression

6.2.3. Inferential statistical methods

Multiple linear regression (MLR) was used for explaining mineral fertilizer use intensity (Y_{MinUse}). MLR is a common inferential statistical method for continuous variables.

$$\mathbf{Y_{MinUse} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n}$$

Where X_i are explanatory variables, βi (i = 1, 2, 3, . . ., n) their weights and α the intercept.

Binary logit regressions were used for adoption analysis. Binary logit regression is common method used for adoption analysis.

$$\mathbf{p(y = 1)} = \frac{\mathbf{e^{(\alpha+\beta_1 X_1+\beta_2 X_2+\cdots+\beta_n X_n)}}}{\mathbf{1+e^{(\alpha+\beta_1 X_1+\beta_2 X_2+\cdots+\beta_n X_n)}}}$$

With y = Y_{MinApt} ; Y_{OrgApt} *or* Y_{MinOrg}, and p(y= 1) the probability of y = 1.

In the study region, maize is the main food crop for which famers usually apply nutrient. The number of fertilized plots of other food crops in the study sample was not high enough for conducting regression analyses. Inferential analyses were then performed only for maize plots. Three farm types out of the five farm types identified in the study region had high enough number of fertilized maize plots for regression analyses. Effects of hypothesized determinants (X_i) were estimated for plots of whole population (n = 292 plots), and of the three main farm types (i.e., *Better-off, cotton-and livestock-based farms* (n= 107), *Better-off, non-farm activities preference farms* (n = 104), and *Pro-poor, labourless-and landless farms* (n= 81).

6.2.4. Explanatory variables

Candidate explanatory variables and their hypothesized effects are presented in

Table 6.2. They were gathered from literature based on the Sustainable Livelihood Framework.

6.2.4.1. Variables of financial assets

Poverty is often a factor fuelling land degradation (Scherr, 2000; Vu *et al.*, 2014b) and constraining the use of soil nutrients by smallholder farmers. The variable cash income per capita per year (H_{CashCp}) and the variable remittance income per capita per year ($H_{RemitCp}$) increase farm income and are expected to augment the chance for farmers to adopt mineral nutrient and increase its use intensity. Amekawa (2013) highlighted that remittance can be a valuable source of income for farmers. It was hypothesized that these variables are common factors affecting nutrient adoption and use.

6.2.4.2. Variables of natural assets

Cropped land allocation within the farm contributes to determine soil management practice. Some crops (e.g. maize and rice) are more demanding in nutrient while others (legumes) are less and even contribute to enrich the soil through biological N fixation, and therefore reducing nutrient mining effect (Enyong *et al.*, 1999). Increases in size of maize and rice plots may reduce the adoption and use of soil nutrient because of the limited access. By planting more legumes, the farmer has the opportunity to save soil nutrient for other crops. Also, by cultivating intervention-targeted crops, farmers have more chance to adopt and use nutrient due to facilitated access to fertilizers (e.g. credit system for conventional cotton). Therefore, area of legumes per capita (H_{LegCp}) and area of conventional cotton per capita (H_{CCotCp}) are expected to augment the chance of nutrient adoption and increase their use. However, area of maize and rice per capita ($H_{MzeRceCp}$) will tend to reduce adoption and use of nutrient. Through monetary income generation, area of dry season irrigated land per capita ($H_{IrrigCp}$) is expected to augment the chance of mineral nutrient adoption and its use intensity. Livestock is an important source of nutrients through manure production (Place *et al.*, 2003; Kassie *et al.*, 2013). The variable number of small ruminants (goats and sheep) per capita (H_{SRumCp}) is hypothesized to have positive effect on organic fertilizer adoption and negative effect on adoption and use of mineral fertilizer. The expected common determinants are $H_{MzeRceCp}$, H_{CCotCp}, H_{LegCp} and expected farm type specific determinant are $H_{IrrigCp}$ and H_{SRumCp}.

6.2.4.3. Variables of physical assets

Animal power ($H_{AniPowCp}$) plays an important role (Kassie *et al.*, 2013) in smallholder farms which usually are not or very lowly mechanized. It allows saving time during ploughing. It also helps transporting to distant plots the organic fertilizer which is usually applied to homestead plots (Kassie *et al.*, 2013). $H_{AniPowCp}$ is expected to increase the chance of a farmer adopting and using more intensively soil nutrient. Farms with low access to permanent road may also have low access to big markets. This may constrain farmers' capabilities to purchase fertilizers or farming equipment. Therefore, average distance of household to nearest paved road ($H_{DistRoad}$) is expected to reduce farm chance of adopting and using mineral nutrient. The resulting low access to fertilizer can compel the farmer to turn into adoption of organic fertilizer or not. So, expected effect of $H_{DistRoad}$ on mineral nutrient adoption and use is negative but unclear for adoption of organic nutrient.

6.2.4.4. Variables of human assets

Human assets are very important for the successful use of the other assets in sustainable nutrient management (SNM). Household size (H_{Size}) is a source of labour necessary for applying available soil nutrient. Age of household head (H_{HAge}) may reflect accumulated experience of the farm and compel it to adopt and use sustainable nutrient management practices (Mkhabela and Materechera, 2003; Ketema and Bauer, 2011). Both variables may also have a negative effect (Freeman and Omiti, 2003; Chianu and Tsujii, 2005). In effect, the load of large household size may limit available cash for purchasing mineral fertilizer. Ageing labour may reduce available labour for composting or recycling crop residue for instance and they may not like taking risk. The above mentioned two variables hypothesized effects on nutrient adoption and use are unclear. These two variables however, are expected to act as common factors affecting soil nutrient use

Educated famers may better understand the importance and benefit of sustainable nutrient management. Training, through learning and exposure to SNM practices (e.g. Field schools and demonstrations plots) may render farmers more receptive to new technologies and SNM practices in particular. Therefore, number of education years of the household head (H_{HEdu}) (Freeman and Omiti, 2003) and number of time household members attended a training session in the last five years ($H_{Training}$) (Nkamleu, 2007) are expected to increase adoption and use intensity of soil nutrient. It is hypothesized that H_{HEdu} and $H_{Training}$ will be group specific determinants: H_{HEdu} is expected to be significant for best educated heads farm types while $H_{Training}$ is expected to be significant for farm types with less educated heads.

Table 6.2. Brief description and hypothesized explanatory variables for nutrients adoption and use

Variable	Definition	Hypothesized effect on		
		Y_{MinUse} or Y_{MinApt}	Y_{OrgApt}	Y_{MinOrg}
Financial attributes				
H_{CashCp}	Cash income per capita per year (FCFA/capita/year)	+	-	+/-
$H_{RemitCp}$	Remittance income per capita per year (FCFA/capita/year)	+	-	+/-
Natural attributes				
$H_{MzeRceCp}$	Area of maize and rice per capita (ha/capita)	-	-	+/-
H_{LegCp}	Area of legumes per capita (ha/capita)	+	+	+/-
$H_{CCotCp*}$	Area of conventional cotton per capita (ha/capita)	+	+	+/-
$H_{IrrigCp}$	Area of dry season (irrigated) land per capita (ha/capita)	+	-	+/-
H_{SRumCp}	Number of small ruminants (goats and sheep) per capita	-	+	+/-
Human attributes				
H_{Size}	Size of the household	+/-	+/-	+/-
H_{HAge}	Age of household head	+/-	+/-	+/-
H_{HEdu}	Number of education years of the household head	+/-	+/-	+/-
$H_{Training}$	Number of times household members attended a training session the last five years	+/-	+	+/-
Physical attribute				
$H_{AniPowCp}$	Animal power (number of oxen and donkeys) per capita	+	+	+/-
$H_{DistRoad}$	Average distance (Km) of the household house to the nearest paved road	-	+/-	+/-

6.2.5. Evaluation of performance of models

Existence of multi-collinearity was checked using Variance Inflation Factor (VIF) and contingency coefficient. There will be risk of multi-collinearity if VIF is greater than 5 and contingency factor is less than 0.2 (DeFries *et al.*, 2010). The performance MLR model was evaluated using F-statistics for overall performance and adjusted R-square for goodness-of-fit. A model can be considered as having good performance for R-square values between 0.5 and 0.3 (Greene, 2012). For binary logistic regressions, the Chi-square test was used to evaluate models' overall performance. Goodness of fit was evaluated using percent of good prediction and area under the Receiver Operating Characteristic (ROC) curve (Hosmer and Lemeshow, 2000). For values of area under ROC of 0.60-0.70, the models' performance is appreciated to be poor. For values of area under ROC between 0.70 and 0.80, the performance of the model is considered to be acceptable. It will be good if the area under ROC is between 0.8 and 0.90. When values are between 0.90 and 1, the perofrmamce of the model is excellent.

6.3 Results

6.3.1. Soil nutrient use and adoption models performance

No multicollinearity was found between explanatory variables (Table 6.3). The MLR was significant at 1% (Table 6.4). Prediction power of models was strong: R^2=0.44, R^2 = 0.36 and R^2 = 0.41 for farm-types I, II and III respectively. But it was less strong for whole population: R^2 = 0.24. For bi-logit models, Hosmer and Lemeshow test at 5% showed a good fit of models to the data for mineral fertilizer adoption for whole population, farm-types II and III ($p>0.05$) but not for farm type I ($p<0.05$). Values of area under ROC (Table 6.5) showed good performance of models for whole population, farm types I and II (0.81, 0.88 and 0.86, respectively) and excellent for farm-type III (0.91). Models for organic fertilizer adoption also had good overall performance ($p>0.05$ for Hosmer and Lemeshow test) and area under ROC varied from 0.68 to 72.6 (Table 6.6). Results of Hosmer and Lemeshow test (Table 6.7) showed good performance for models of combined mineral-organic nutrient adoption: $p>0.05$.

Prediction power was good (77-85%) and Area under ROC varied from 0.77 to 0.85 (Table 6.7)

Table 6.3. Multi-collinearity statistics of multiple regression analyses for factors affecting mineral fertilizer use.

Explanatory variable	Whole population		Farm type I		Farm type II		Farm type III	
	Tol.*	VIF	Tol.*	VIF	Tol.*	VIF	Tol.*	VIF
H_{CashCp}	0.62	1.61	0.37	2.71	0.35	2.85	0.47	2.14
$H_{RemitCp}$	0.96	1.04	0.73	1.36	0.84	1.19	0.77	1.30
$H_{MzeRceCp}$	0.67	1.48	0.66	1.52	0.51	1.96	0.44	2.28
H_{LegCp}	0.69	1.45	0.39	2.56	0.57	1.75	0.51	1.96
H_{CCotCp}	0.61	1.65	0.36	2.76	0.38	2.62	0.46	2.16
$H_{IrrigCp}$	0.90	1.11	0.65	1.54	0.66	1.51	0.59	1.69
H_{SRumCp}	0.79	1.26	0.59	1.69	0.68	1.47	0.49	2.04
H_{Size}	0.79	1.27	0.58	1.72	0.64	1.56	0.68	1.47
H_{HAge}	0.88	1.13	0.82	1.22	0.73	1.36	0.65	1.54
H_{HEdu}	0.82	1.22	0.60	1.68	0.77	1.30	0.58	1.73
$H_{Training}$	0.90	1.11	0.63	1.58	0.78	1.28	0.91	1.11
$H_{AniPowCp}$	0.71	1.42	0.71	1.40	0.64	1.56	0.51	1.96
$H_{DistRoad}$	0.77	1.29	0.75	1.33	0.69	1.46	0.71	1.41

Note*:There will be a collinearity if the tolerance value < 0.2 and VIF > 5; *Tol.= Tolerance*

Explanatory varibales did not affect fertilizer use and adoption in the same way (e.g. direction and amplitude) for whole population and for different farm types. Two different types of affecting factors were found:

(i) Common factors affect fertilizer use and adoption by whole population and by different farm types. A common factor exhibits same direction for whole population and accross affected farm types

(ii) Farm type specific factor affects a particular farm type and does not appear as affecting factor for whole population. This type of factor was named type specific factor of first order. A factor may also affect a particular farm type in a direction opposite to its affecting direction for whole population and other affected farm types. Or, it may affect a particular farm type and only whole population in same direction but with lower amplitude for whole population. This suggests that the presence of non-affected farm types in whole population reduces coefficient amplitude. This affecting factor was type specific factor of second order.

6.3.2. Determinants of mineral fertilizer use and adoption

6.3.2.1. Common affecting factors

As expected, $H_{AniPowCp}$ had a positive effect (Table 6.3). The number of draught animals increases mineral fertilizer use for whole population, farm-types I and II. $H_{DistRoad}$, had a positive effect on mineral fertilizer use. It was statistically significant for whole population, farm-types I and III. Remotness augmented mineral fertilizer use. Age of household members (H_{Age}) reduced the use of mineral fertilizer. Aged household members may mobilize less financial resources for purchasing fertilizer. Also, old farmers may not fully understand importance of sustainable soil nutrient management, contrary to young farmers who are usually better educated and more open to new technologies. H_{Age} was significant for whole population only.

Common affecting factors for mineral fertilizer adoption were cash income per capita per year (H_{CashCp}), household size (H_{Size}) and average distance of household to nearest paved road ($H_{DistRoad}$). They all had positive effect on fertilizer adoption (Table 6.5). H_{CashCp} was statistically significant at 5% for whole population, farm-types I and II. H_{Size} and $H_{DistRoad}$ were siginficant for whole population but not for individual farm types, at 5% and 1% respectively. Cash income per capita per year, household size and average distance of household to nearest paved road increased mineral fertilizer adoption.

Table 6.4. Multiple linear regression analyses for factors affecting mineral fertilizer use (kg of N-P-K ha^{-1} $year^{-1}$).

Explanatory variable	Estimated β coefficients			
	Whole population (N =292)	Farm type I (n= 107)	Farm type II (n = 104)	Farm type III (n = 81)
Intercept	24.85	16.71	21.76	28.24
H_{CashCp}	1.13E-04**	1.02E-04	1.63E-04*	5.36E-05
$H_{RemitCp}$	2.00E-03*	0.01***	-2.02E-04	-1.00E-03
$H_{MzeRceCp}$	-57.00**	6.60	-86.19	-78.43*
H_{LegCp}	20.16	-23.80	-72.46	43.66
H_{CcotCp}	4.20	-10.91	-41.54	31.71
$H_{IrrigCp}$	611.97***	918.68***	494.15	409.15
H_{SrumCp}	3.27	2.89	24.09**	1.04
H_{Size}	1.14	1.42	0.73	1.50
H_{Hage}	-0.42**	-0.42	-0.17	-0.43
H_{Hedu}	1.19	2.73	1.41	-0.65
$H_{Training}$	10.53*	-11.15	14.55	40.45*
$H_{AniPowCp}$	41.24**	49.09*	250.75***	36.27
$H_{DistRoad}$	1.70***	1.35*	0.21	2.25**
F-test	df=13 F=4.84 P=0.000	df=13 F=3.57 P=0.000	df=13 F=2.55 P=0.007	df=13 F=2.61 P=0.008
R^2	0.24	0.44	0.36	0.41
Adjusted R^2	0.19	0.32	0.22	0.25

***Note**: symbols *, **, and *** indicate statistical significance at 10% (p< 0.1), 5% (p< 0.05), and 1% (p< 0.01), respectively; Std. = Standardized*

6.3.3.2. Farm-type specific affecting factors

Most of the significant variables for MLR were farm-type specific affecting factors (Table 6.4). Variables of financial assets (e.g. H_{CashCp} and $H_{RemitCp}$) had positive effect on mineral fertilizer use for whole population and only one of the three farm types. They were type specific affecting factors of second order. $H_{IrrigCp}$ (Natural asset), $H_{Training}$ (Human asset) and $H_{MzeRceCp}$ were also type specific affecting factors of second order. $H_{IrrigCp}$, and $H_{Training}$ had positive effect while $H_{MzeRceCp}$ had negative effect on mineral fertilizer use intensity as expected. Amplitude of variables‘ coefficients was larger for farm types than for whole population. Only one farm-type specific affecting factor of first order was found: H_{SrumCp}. It appeared statistically significant only for farm-type III and increased mineral fertilizer use intensity. It was not significant for whole population.

The bi-logit regression revealed more farm-type specific affecting factors of first order (Figure 6.5). $H_{RemitCp}$ and $H_{Training}$ were siginificant only for farm-type I and farm-type II repectively. They increase the chance for the farmer to adopt mineral fertilizer. $H_{MzeRceCp}$ was significant for farm-types I and II but with opposite affecting direction and amplitude. It increases adoption of mineral fertilizer for farm-type I while reducing it for farm-type II. $H_{IrrigCp}$, H_{SrumCp} and $H_{AniPowCp}$ were all farm-type specific affecting factors of second order. In effect, in addition to whole population, they increased the chance of adopting mineral fertilizer for only farm-type I and farm-type II respectively. Their coefficients were larger for farm-types than for whole population.

Table 6.5. Binary logistic regressions for factors affecting farmer adoption of mineral fertilizer

Explanatory Variable		Estimated β coefficients			
		Whole population	Farm type I	Farm type II	Farm type III
Intercept		-2.38	-4.91	-1.73	-2.33
H_{CashCp}		1.52E-05***	3.48E-05**	2.76E-05**	4.78E-05
$H_{RemitCp}$		-2.89E-05	9.87E-04**	-1.03E-04	-8.87E-05
$H_{MzeRceCp}$		-1.08	6.35**	-11.98***	-1.22
H_{LegCp}		0.34	-4.12	-2.35	-2.19
H_{CcotCp}		2.03	0.08	2.27	1.70
$H_{IrrigCp}$		33.99**	72.96**	20.1	15.51
H_{SrumCp}		0.57**	0.73	1.95**	-0.47
H_{Size}		0.15**	0.3	-0.1	0.25
H_{Hage}		-0.01	-0.03	0.04	-0.03
H_{Hedu}		0.09	0.01	-0.07	0.16
$H_{Training}$		0.10	-1.16	1.27*	18.99
$H_{AniPowCp}$		2.48*	3.06	16.52*	5.78
$H_{DistRoad}$		0.09***	0.11	-0.05	0.14
Hosmer and Lemeshow test	χ^2	13.15	18.07	4.74	4.40
	df	8	8	8	8
	p	0.107	0.021	0.786	0.819
% correct prediction		73.20	82.20	76.70	79.40
Area under ROC		0.81	0.88	0.86	0.91

***Note**: symbols *, **, and *** indicate statistical significance at 10% (p< 0.1), 5% (p< 0.05), and 1% (p< 0.01), respectively.*

6.3.3. Determinants of organic fertilizer adoption

6.3.3.1. Common affecting factors

Two common affecting factors associated with organic nutrient adoption in whole population were identified (Table 6.6). Remittance income per capita per year ($H_{RemitCp}$) was positively associated to organic nutrient adoption, and Area of maize and rice per capita ($H_{MzeRceCp}$) was negatively associated to organic nutrient adoption. $H_{RemitCp}$ had the opposite of expected direction and $H_{MzeRceCp}$ had the expected direction. These common variables were not significant for individual farm types.

Table 6.6. Binary logistic regressions for factors affecting farmer adoption of organic fertilizer

Explanatory Variable		Estimated β coefficients			
		Whole population	Farm type I	Farm type II	Farm type III
Intercept		-1.63	-0.49	-2.71	-2.11
H_{CashCp}		3.12E-06	3.37E-06	4.83E-06	-1.36E-06
$H_{RemitCp}$		1.30E-04*	5.47E-05	1.89E-04	2.41E-04
$H_{MzeRceCp}$		-2.86**	-3.65	-0.66	-4.69
H_{LegCp}		1.65	3.70	-7.36	3.24
H_{CcotCp}		-1.91	-3.26	1.56	-0.58
$H_{IrrigCp}$		7.63	19.04	-1.10	-47.33
H_{SrumCp}		0.21	0.46*	0.26	0.77
H_{Size}		0.10	0.14	0.18	0.11
H_{Hage}		-2.00E-03	-0.04	0.01	0.02
H_{Hedu}		0.08	0.16	0.03	0.01
$H_{Training}$		0.13	-0.65	0.78	-0.61
$H_{AniPowCp}$		1.12	0.43	8.99*	1.74
$H_{DistRoad}$		0.04	0.09*	-0.01	0.01
Hosmer and Lemeshow test	χ^2	6.18	4.42	4.49	4.5
	df	8	8	8	8
	p	0.627	0.817	0.811	0.809
% correct prediction		68.4	72.6	72.6	66.7
Area under ROC		0.68	0.75	0.73	0.75

Note*: symbols *, **, and *** indicate statistical significance at 10% (p< 0.1), 5% (p< 0.05), and 1% (p< 0.01), respectively.*

6.3.3.2.Farm-type specific affecting factors

Number of small ruminants per capita (H_{SrumCp}) and average distance of the household house to the nearest paved road ($H_{DistRoad}$) were positively associated with organic nutrient adoption for Farm type I. Within this farm type, the chance for farmers to adopt organic nutrient increase with endowment in small ruminants (goat and sheep) and distance from paved road. In farm-type II, however, adoption of organic nutrient was positively associated with animal power per capita ($H_{AniPowCp}$). The higher the number of draught animal the farm possses, the higher the chance of adopting organic nutrient. $H_{AniPowCp}$ and H_{SrumCp} had expected effect.

6.3.4. Determinants of adoption of combined mineral-organic fertilizers

6.3.4.1.Common affecting factors

Adoption of combined mineral-organic fertilizer was influenced by three common affecting factors (6.7). Two of these factors were significant for whole population and had no significant effect on individual farm-types: H_{CashCp} increases adoption of combined mineral-organic fertilizer and H_{MzeRce} reduces this adoption in whole population. $H_{DistRoad}$ was statistically significant for farm-types I, II and whole population. Average distance of household to nearest paved road ($H_{DistRoad}$) increases the chance of adopting combined mineral-organic fertilizer use.

Table 6.7. Binary logistic regressions for factors affecting farmer adoption of combined mineral-organic fertilizer

Explanatory Variable		Estimated β coefficients: Whole population	Farm type I	Farm type II	Farm type III
Intercept		-2.94	-2.37	-2.79	-4.69
H_{CashCp}		6.48E-06*	7.13E-06	6.93E-06	1.22E-05
$H_{RemitCp}$		7.61E-05	1.45E-04	3.90E-05	8.48E-05
$H_{MzeRceCp}$		-2.9*	-0.4	-4.05	-3.27
H_{LegCp}		1.08	-0.51	-1.72	-1.33
H_{CcotCp}		-0.62	-2.06	1.49	-5.19
$H_{IrrigCp}$		27.25**	45.25*	22.37	12.86
H_{SrumCp}		0.27	0.48*	0.5	-0.05
H_{Size}		0.12*	0.22	-2.21E-03	0.29*
H_{Hage}		-0.01	-0.06	0.01	-0.02
H_{Hedu}		0.09	0.21	-0.05	0.32*
$H_{Training}$		0.46	-0.99	1.28**	-0.26
$H_{AniPowCp}$		1.64*	0.87	7.69	2.81*
$H_{DistRoad}$		0.11***	0.14**	0.08	0.14*
Hosmer and Lemeshow test	χ^2	3.31	11.68	12.49	4.11
	df	8	8	8	8
	p	0.914	0.166	0.131	0.85
% correct prediction		77.0	75.3	85.0	79.4
Area under ROC		0.77	0.81	0.78	0.85

Note: symbols *, **, and *** indicate statistical significance at 10% ($p< 0.1$), 5% ($p< 0.05$), and 1% ($p< 0.01$), respectively.

6.3.4.2. Farm-type specific affecting factors

Farm-type specific affecting factors of first order included H_{SrumCp}, H_{HEdu}, and $H_{Training}$. They were all likely to increase the chance for farmers to adopt combined mineral-organic fertilizer use. H_{SrumCp} was significant for farm-type I. As for H_{HEdu} and $H_{Training}$, they had a significant effect for farm-type III and farm-type II, respectively. Farm-type specific affecting factors of second order involved $H_{IrrigCp}$, H_{Size}, and $H_{AniPowCp}$. Increase in area of dry season irrigated land per capita ($H_{IrrigCp}$) significantly increases adoption of combined mineral-organic fertilizer use for farm-type I and for whole population. The effect on adoption had lowest amplitude for whole population compared to farm-type I. The chance of adopting combined mineral-organic fertilizer use augmented with household size (H_{Size}) for farm-type III and for whole population. The amplitude of the effect was highest for farm-type III. As for $H_{AniPowCp}$, it affects positively the adoption of combined mineral-organic fertilizer use by farm-type III and by Whole population. The amplitude of the effect was lowest for whole population.

6.3.5. Discussions

6.3.5.1. Contextualization of main findings to other research

Identifying and understanding factors affecting adoption and use of fertilizer in a region is crucial for improving sustainable soil nutrient management in that particular region. In using a set of thirteen socio-economic and ecological independent variables it was found results consitent with findings of past studies. Farm financial assets play a significant role in soil nutrient management as noted by Nkamleu (2007), Sanni and Doppler (2007), Marenya and Barrett (2007), Amekawa (2013), and Martey *et al.*,(2014). Indeed, it was found that farm income components cash income (H_{CashCp}) and remittance received per capita ($H_{RemitCp}$) augment the use intensity (Table 6.4) and adoption of mineral (Table 6.5) and organic nutrient by farms (Table 6.6). In a study conducted in another region of Burkina Faso, Somda *et al* (2002) observed that farm income significantly augment adoption of organic fertilizer. However, and like in this study, they pointed out that animal power (H_{AniPow}) and training ($H_{Training}$) have no significant effect on organic fertilizer adoption (Table 6.6). This suggests that income generation constitutes the main entry for interventions aiming at improving organic fertilizer adoption.

The present study also revealed that dry season irrigation land per capita ($H_{IrrigCp}$) had a significant effect on mineral fertilizer use (Table 6.4) and adoption (Table 6.5), and on combined mineral-organic fertilizer adoption (Table 6.7). In rural areas where off-farm activity opportunities are often limited, dry season irrigation is a valuable source of income that could be invested in purchasing mineral fertilizer. This shows that adoption and use of mineral fertilizer can be increased by policy interventions promoting dry season irrigation as noted by Yilma and Berger (2006). Not surprisingly, Training ($H_{Training}$) increases mineral fertilizer use and adoption (Table 6.4; Table 6.5). This is consistent with findings of Martey et al. (2014) who highlighted that proximity with extension services improves adoption of mineral fertilizer. Distance from paved road ($H_{DistRoad}$) increased the use and adoption of mineral and organic fertilizers (Table 6.4, Table 6.5; Table 6.6 and Table 6.7). As showed by Vu et al. (2014b), distance to road increases land degradation extent and thereby compels farmers to use more fertilizer. This effect of $H_{DistRoad}$ can also be seen as a sign of the declining importance of distribution constraints on fertilizer use through increased fertilizer retail outlets availability in rural areas (Freeman and Omiti, 2003). The positive effect of animal power ($H_{AniPowerCp}$) on mineral nutrient use intensity (Table 6.4), as well as its positive influence with small ruminant number (H_{SRumCp}) on mineral fertilizer adoption (Kassie *et al.*, 2013) demonstrate the beneficial interrelationship between livestock and cropping activities (Kristjanson *et al.*, 2005; Marenya and Barrett, 2007). The integration of livestock-agriculture needs, therefore, to be boosted for a better soil nutrient management.

Studies use to consider a uniform affecting pattern when analysing adoption and use of fertilizers. The present study on the contrary considered that due to differences in socio-economic and ecological characteristics, farmers/farms are not affected in the same way by determinants of fertilizer use and adoption. Beside common affecting factors, type specific factors were found that affected only specific farm types, with different amplitude or with different directions. In other words parameters of independent variables (β) varied across socio ecological farm types. It demonstrated importance of considering farm types rather than whole population only when analyzing soil nutrient management. Considering the whole population only can be misleading and cause the failure or inefficient policies and intervention measures.

6.3.5.2. New methodological features of the present study

Although the benefits of combined use of mineral and organic fertilizers have been recognized (e.g., reduction of N losses (Neeteson, 1993); organic matter (Palm *et al.*, 1996; Vanlauwe and Giller, 2006; Ding *et al.*, 2012; Körschens *et al.*, 2012); nutrient cycling in the system (Mkhabela and Materechera, 2003), long term soil fertility improvement (Mkhabela and Materechera, 2003), increase in soil productivity (Parr and Colacicco, 1987); generate better yields than sole use of mineral fertilizers (Mucheru-Muna *et al.*, 2007; Ding *et al.*, 2012; Kearney *et al.*, 2012; Kismányoky and Tóth, 2012)), it is hard to find published work analyzing factors affecting the adoption of these combinational uses.

Also, in this study responsive/behavior/preference parameters (betas) are analyzed in specific to different farm/household types rather than uniform/constant to the whole population. This way of analysis allowed the capture of responsive heterogeneity. The study demonstrated the relationship between structural and functional typologies and the importance in considering both of them in regional farming system studies. In addition, the results can provide an empirical framework for scaling-out studies. Responsive heterogeneity has been considered in land use choice analyses (e.g., Le (2005)), but in only a few of mineral adoption analysis (Vu *et al.*, 2014a). However, *Vu et al.*, (2014a) worked in Vietnam where the background of fertilizer uses and the socio-ecological conditions are very different from Burkina Faso.

6.3.5.3.Limitations of the study

Despite interesting results the study presents some limitations. First, the study used only MLR and bi-logit. It is important to also use also a multinomial logit to explore the responsive heterogeneity, to analyze marginal effects of variables. Secondly, the responsive heterogeneity could also be examined using non-parametric methods like Participatory Rural Appraisal tools (PRA), decision tree analysis, which can allow capture effect of factors having less variation in sampled data (e.g. climate, prices).

6.4. Conclusion

Soil degradation is an increasing issue contributing to food insecurity in Sub-Sahara African countries despite numerous policy interventions to improve the situation. The present study used an empirically defined rural livelihood-based typology to analyze fertilizer use/adoption behavior of different smallholder farming systems. The determinants of adoption and use of mineral, organic, and combined mineral-organic nutrient were analyzed. The results showed that these determinants do not affect use and adoption of fertilizer in a uniform way. Besides common determinants in all farm types, the results revealed type-specific determinants and behavior of fertilizer use and adoption. The study showed that effective policy interventions promoting adoption of sustainable soil nutrient management (SNM) practices need to be appropriate per farming system type. Rather than uniform interventions, decision makers should distinguish between farming system types using relevant socio-ecological criteria in designing policies to promote sustainable soil nutrient management. Interventions schemes need to be revised to have a better impact and to be more efficient.

7. SMALLHOLDER FARMS' NUTRIENT BALANCES AND ECONOMIC PERFORMANCE

7.1. Introduction

Quite a number of studies have drawn attention on imbalance soil nutrient in many sub-Saharan Africa countries as a result of inadequate soil nutrient management practices and nutrient mining (Smaling *et al.*, 1993; Stoorvogel *et al.*, 1993; Harris, 1998; Bekunda and Manzi, 2003; Esilaba *et al.*, 2005; Haileslassie *et al.*, 2005; Haileslassie *et al.*, 2007). These studies revealed relatively strong negative soil nutrient balances in many cases. In Burkina Faso in particular, Bationo *et al.*, (1998) aggregating values of different cropping systems from Stoorvogel and Smaling(1990) found -14 N kg/ha/year, -2 P kg/ha/year and -10 K kg/ha/year for the year 1983-1984. Still in Burkina Faso, Henao and Baanante (1999) reported nutrient balances of -27.6 N kg/ha/year, -9.8 P kg/ha and -24.2 K kg/ha in 1993-1995, unveiling a worsening of soil health in the country. Given these deficiencies and for countries permanently stricken by food insecurity, improved nutrient management is one of the keys to improving food production and security in Sub-Saharan Africa (Vitousek *et al.*, 1997; Vlek *et al.*, 1997; Mueller *et al.*, 2012).

A few of previous studies have distinguished farm nutrient balance for different farms based on farming systems (Haileslassie *et al.*, 2006) or farm wealth (Zingore *et al.*, 2007). However many nutrient balance studies did not do so (Stoorvogel and Smaling, 1990; Van der Pol, 1992; van der Pol and Traore, 1993; Harris, 1998; Zougmoré *et al.*, 2004b; Haileslassie *et al.*, 2005). To improve the understanding of potential soil degradation and for sustainable farm design options, nutrient balance studies distinguishing different farm types still need to be carried out in Sub-Saharan Africa and, particularly, in West Africa.

In addition, soil component's nutrient balance is crucial but not often addressed in many farm nutrient balance studies (Cobo *et al.*, 2010). Land degradation is the most serious threat to food production (Bationo *et al.*, 2006) and more investigation on farm soil nutrient balance is required to improve soils productive capacity.

Moreover, given many farm nutrient balance studies done in Sub-Saharan Africa, relationship between soil and farm nutrient balances (environmental performance) and farming profitability (economic performance) is still poorly investigated.

The goal of this study is therefore to analyze soil and farm nutrient balances in the context of climate change and their correlation to farm activities profitability. It pursued four specific objectives:

- To analyse whole farm nutrient balance of five different socio-ecological farm types previously identified in Ioba province;
- To analyse soil subcomponent nutrient balance of different farm types;
- To study relationship between soil nutrient balance and farming profitability
- To discuss scenarios for filling observed soil nutrient gaps

7.2. Methods

7.2.1. Metrics for evaluating farm economic performance

In order to evaluate economic performance, a set of indicators were computed using the monitoring data. The net farm income for all activities and farm earnings per capita were computed as in Equation 7.1 and Equation 7.2. Farm' crop gross margins were computed per household capita, per unit of cultivated land and per unit of invested labour-day in cropping activities (Equation 7.3 – Equation 7.5). The return to farm investment was evaluated through return to land, return to capital and return to invested family labour-days (Equation 7.6 - Equation 7.8).

Net farm income = Total crop gross margin + Total livestock gross margin + Total redistribution units gross margins + Trade bonus – Fix cost **Equation 7.1**

$$\text{Farm earnings} = \frac{\text{Net farm income + Off-farm income}}{\text{Household size}}$$ **Equation 7.2**

$$\text{Crop gross margin per area} = \frac{\text{Total crop gross margin}}{\text{Total cultivated area}}$$ **Equation 7.3**

$$\text{Crop gross margin per capita} = \frac{\text{Total crop gross margin}}{\text{Household size}}$$ **Equation 7.4**

$$\text{Crop gross margin per labour day} = \frac{\text{Total crop gross margin + cost hired labour}}{\text{Family labour + Communal labour +Hired labour}}$$ **Equation 7.5**

$$\text{Return to land} = \frac{\text{Net farm income - ValFarmLabCrop - Partial capital cost}}{\text{Area owned land}}$$ **Equation 7.6**

$$\text{Return to capita} = \frac{\text{Net farm income - ValFarmLabAll - Land cost}}{\text{Partial Capital Value}} * 100$$ **Equation 7.7**

$$\text{Return to labour} = \frac{\text{Net farm income - Partial capital cost - Land cost}}{\text{Family labour}}$$ **Equation 7.8**

With Trade Bonus = Correction for income based on differences of average prices and received/paid prices; ValFamLabCrop = Value of family labour for cropping and ValFarmLabAll = Value of all family labour used for farming

7.2.2. Relational nutrient balance - economic performance analysis

The relational soil nutrient balance-economic performance was investigated to provide better understanding of soil nutrient balance and the way the farm is performing economically. These diagrams also aimed at evaluating trade-offs or synergies between farm environmental performance (soil nutrient balance) and economic outcome. To this end two dimensional diagrams of farm economic performance indices versus soil nutrient balance were plotted for the five farm types.

7.3. Results

7.3.1. Whole farm nutrient balance

The whole farm partial nutrient balance and the whole farm full nutrient balance were calculated for every monitored farm. The balances were averaged per farm type. The partial nutrient balances (Figure 7.1(b)) were positive for all farm types and for all nutrients except potassium for farm type I. The negative partial potassium balance of farm-type I (-4.47 kg/ha/year) is related to a poor management of potassium resources. Though positive for farm-types II, III and V, the partial potassium balance remains low for these farm types. Only farm-type IV had an acceptable partial potassium balance. It can be seen as a better potassium resource manager while farm-types II, III and V are bad managers and farm-type I the worst. Better off-farms (farm-types I and II) and middle class farm type (farm-type IV) had close values for partial phosphorus balance and partial nitrogen balance. The less endowed farm-types (III and V) had the lowest values. Considering the set of the three nutrients, farm-type III has lowest partial nutrient balance performance. Farm type II appeared to be a better manager of N and P. Farm type IV a middle class manager for all nutrients.

The whole farm full nutrient balance results showed heterogeneity among farm types. The potassium full balance is negative for farm type I, II and IV (Figure 7.1 (a)). It is positive but close to zero for the less endowed farm types with 0.71 P kg/ha/year and 0.76 P kg/ha/year for farm-type III and farm-type V respectively. Compared to the partial nutrient balance a dramatic drop of nitrogen was observed for farm types I, II and IV. This could be due to important loss through erosion or burning which are important source of nutrient depletion. Low variation of full phosphorus balance was observed between better-off farm types (I, II and IV). Full phosphorus balance was globally higher with better off farm than with less endowed farm types.

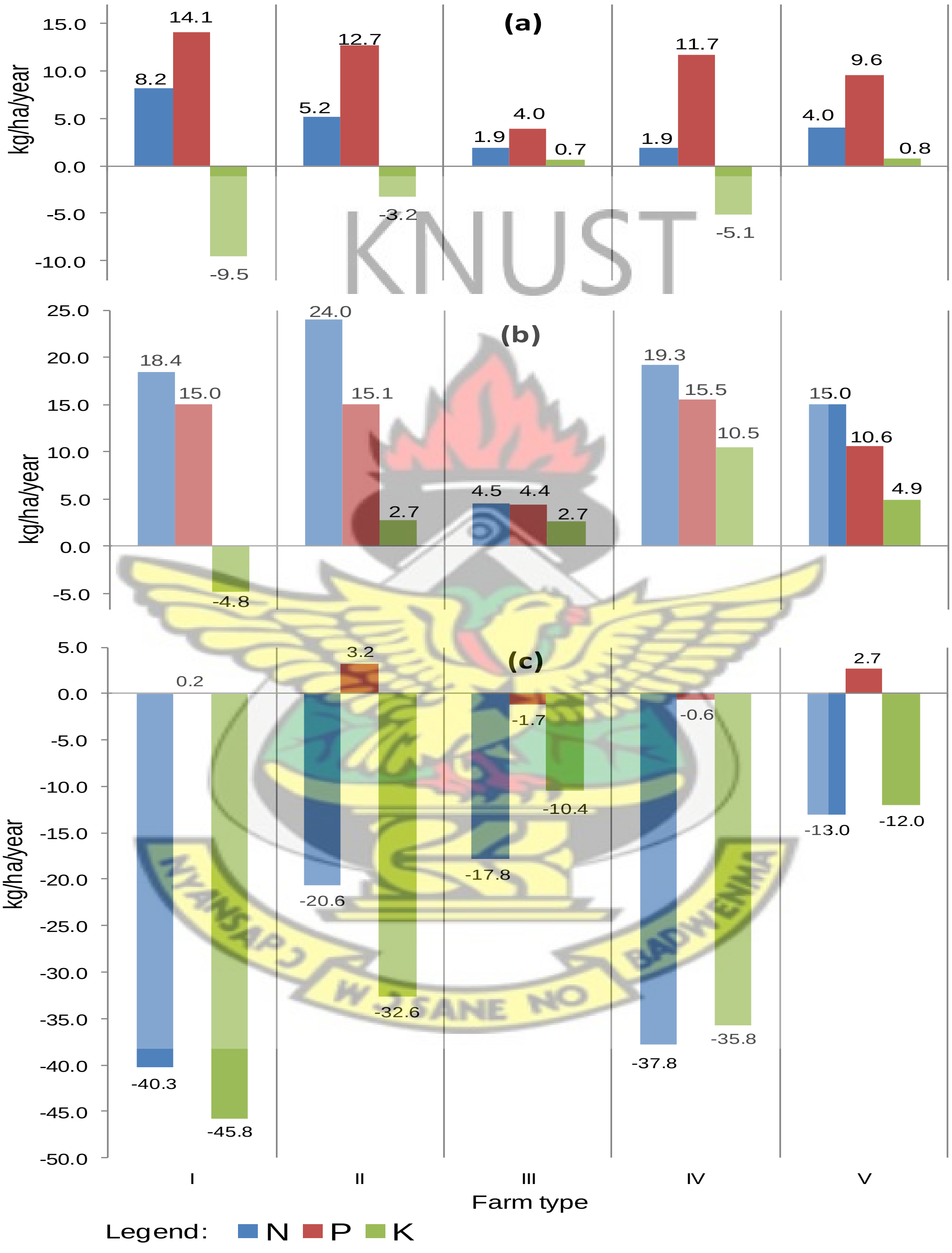


Figure 7.1. Nutrient balances of five study farm types: (a) whole farm balance, (b) partial balance, and (c) soil component's balance.

7.3.2. Soil nutrient stock and soil nutrient balance

The calculation of total soil nutrient stock at 30 cm depth (Figure 7.2) showed close total N stock values for farm-type I (6010 N kg/ha), farm-type IV (5970 N kg/ha) and farm-type V (5600 N kg/ha). Farm types III and II had the lowest total N and total K stocks with farm-type III having almost twice (3670 N kg/ha and 6540 K kg/ha) the stocks of farm-type II (1700 N kg/ha and 2610 K kg/ha). Farm-type V had the highest total K stock (11470 K kg/ha) followed by farm-type IV (8210 K kg/ha) and farm-type I (7480 K kg/ha). Soil total potassium stock was low for all the farm types with not much variability apart from farm-type II, which had less than half of P stock of the other farm types. Low P stock reflects the phosphorus deficiency of tropical soils in general (Lompo, 2007) and of Burkina Faso soils in particular (Sédogo, 1993; Ouattara, 2007; Coulibaly, 2012). Farm-type II had the lowest nutrient stock for the three nutrients (e.g. N, P, and K). Soil fertility management contributes for a great part in determining soil nutrient stock. The farm-type II was identified (see chapter 4) as applying the least amount of nutrients (organic and inorganic) among the five farm types. When relating to soil nutrient stock (Table 7.1.), only farm-type II losses more than 1% of nutrient stock per year.

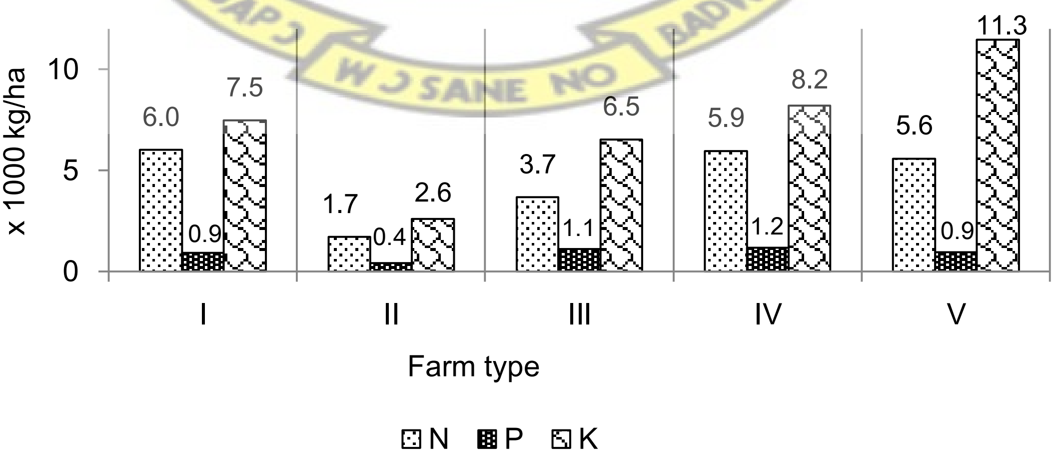


Figure 7.2 Nutrient stock of topsoil (0 - 30 cm depth)

The soil nutrient balance showed large negative balance across farm types (Fig.7.1(c)). Soil phosphorus balance is negative for farm types III and IV (-1.16 P kg/ha/year and -0.61 P kg/ha/year, respectively) almost zero for farm-type I (0.17 P kg/ha/year). It is slightly above zero for farm types II (3.15 P kg/ha/year) and V (2.65 P kg/ha/year). For N and K, the soil balances are strongly negative for farm-type I and farm-type IV, fairly for farm-type II and less for farm-type III and farm-type V. This suggests that less endowed farm-types have better soil N and K balances than better-off and middle class farm-type.

Table 7.1. Corresponding percent of yearly soil nutrient loss in soil nutrient stock

Farm type	Percent of soil nutrient stock		
	Nitrogen	Phosphorus	Potassium
I	0.67	0.00	0.61
II	1.21	00.00	1.25
III	0.49	0.10	0.16
IV	0.63	0.05	0.44
V	0.23	00.00	0.10

7.3.3. Soil balance versus economic performances of farm types

Farm-types economics performances were computed (Table 7.2), and relationships with soil nutrient balance explored using diagrams. In Figure 7.3(a)-(c) farm cropping margin per area was plotted against soil nutrient balance. It showed two cases for N and K. *Case A: negative soil nutrient balance and low margin*. Farm-types II, III and V were found in this case. *Case B corresponds to negative soil nutrient balance but better margin*: farm-types IV and I were in this case with margins of 234069 FCFA/ha/year and 203705 FCFA/ha/year respectively. As for P, four cases were observed. Farm-type III was again in Case A like for N and K. Farm IV also was again in Case B like for N and K. Farm-types II and V were in *Case C: positive soil nutrient balance but low performance.* As for farm-type I, it was in *Case D: positive soil nutrient balance and* *better performance*. Crop margin per labour-day was computed to evaluate remuneration of the total invested labour days for cropping (family, communal and hired labour). For this indicator (Figure 7.3(d)-(f)) and for N and K, farm-type III was found with farm-types I and IV in the Case B. Farm-types V and II remained in Case A. For phosphorus, Case B comprised farm types III and IV while farm type I was in Case C and farm-types V and II in Case D. In Figure 7.3 (g)-(i) crop margins per capita were plotted against soil nutrient balance, and compared to Burkina Faso national poverty. All farm-types had crop margin per capita below poverty line. In reference to the poverty line all farm-types were situated in Case A for N and K. Two cases were observed for P: farm-types III and IV were in Case A and farm-types I, II and V were in case C.

Table 7.2. Farm economic performance indicators

Farm type	Net farm income (10^3 FCFA/ year)	Farm Earnings (10^3 FCFA /pers /year)	Crop gross Margin Per capita (10^3 FCFA /pers./ year)	Crops gross margin per area (10^3 FCFA /ha/year)	Crops gross margin per labour day (10^3 FCFA /day)	Return to land (10^3 FCFA /ha/year)	Return to capital (%)	Return to labour (10^3 FCFA / day)
I	814.6	161.7	99.3	203.7	3.80	132.9	82	2.65
II	364.0	81.4	35.1	139.4	1.74	84.7	13	0.63
III	506.8	98.9	88.6	140.7	3.25	94.2	176	2.38
IV	469.0	103.1	55.7	234.1	2.91	77.6	53	1.37
V	674.1	296.3	63.3	109.2	2.17	62.0	95	1.63

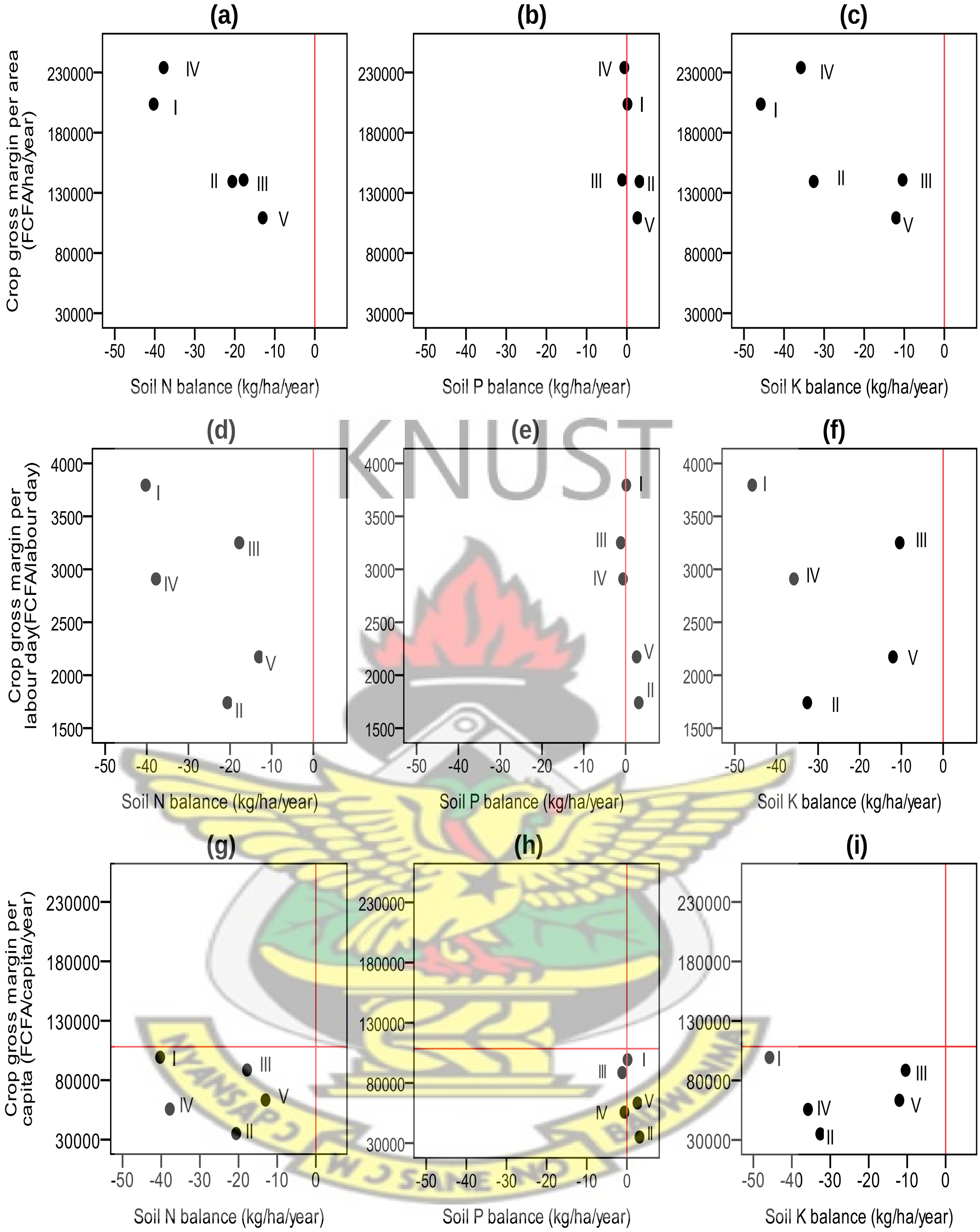


Figure 7.3. Distribution of study farm types over cropping margin and soil nutrient balance.

Notes: Horizontal red lines indicate the official poverty line in Burkina Faso on the basis of 108454 FCFA/capita/year (INSD, 2010), i.e., 217 USD/capita/year. Vertical red lines indicate zero net nutrient loss.

Examination of the return to farm investment showed that the outstanding farm types were farm-type I for return to land (Figure 7.4(a)-(c)), farm-types I and III for return to labour (Figure 7.4(d)-(f)), and farm-type III for return to capital with more than 100% (Figure 7.4(g)-(i)). This placed in Case B, farm-type I for return to land, farm-type III for return to capital and both farm-type I and farm type III for return to labour, for nutrients N and K. Still for N and K, the following farm-types were found in Case A: farm-types II-V for return to land, farm-type II, IV and V for return to labour and farm-types I, II, IV and V for return to capital. As for P, Case A involved farm-types III and IV for return to land, only farm-type IV for return to labour and return to capital. Case C involved farm-types II and V for the three indices of return to investment. Farm-type I was in Case D for return to land and return to labour, but for return to capital it was farm-type III.

Farm-types I and V showed best performances for farm earnings per capita (Figure 7.5). This indicator accounted for all farm (cropping and livestock) and off-farm earning. Only farm-types I and V earned a net income above poverty line. They were found in Case A for N and K. For P, they were in Case D. The three other farm types were in Case A for N and K, but farm-types III and IV were found in Case B and farm-type II in Case C.

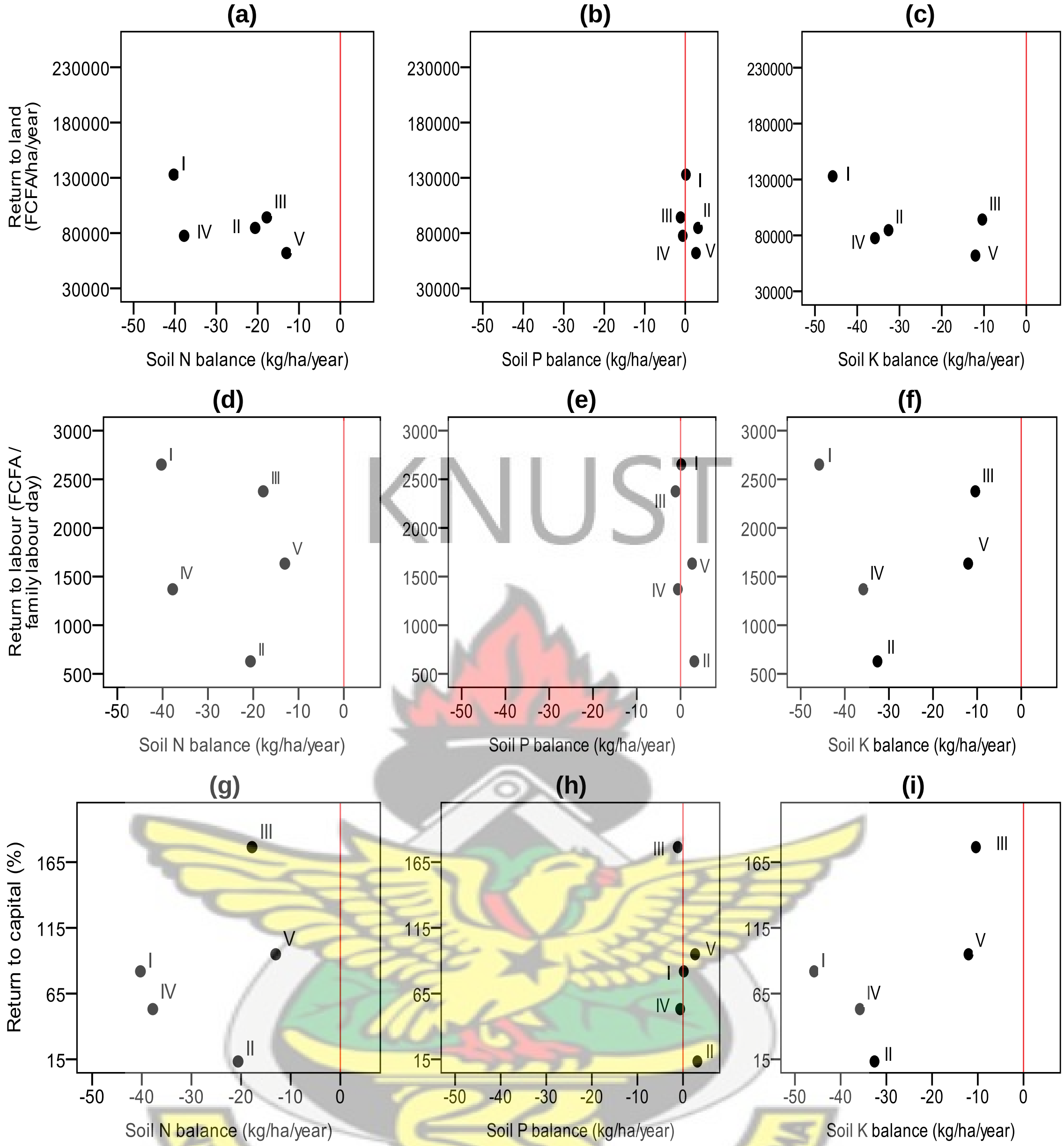


Figure 7.4. Distribution of study farm types over return to investment and soil nutrient balance.

***Note**: Vertical red lines indicate zero net nutrient loss.*

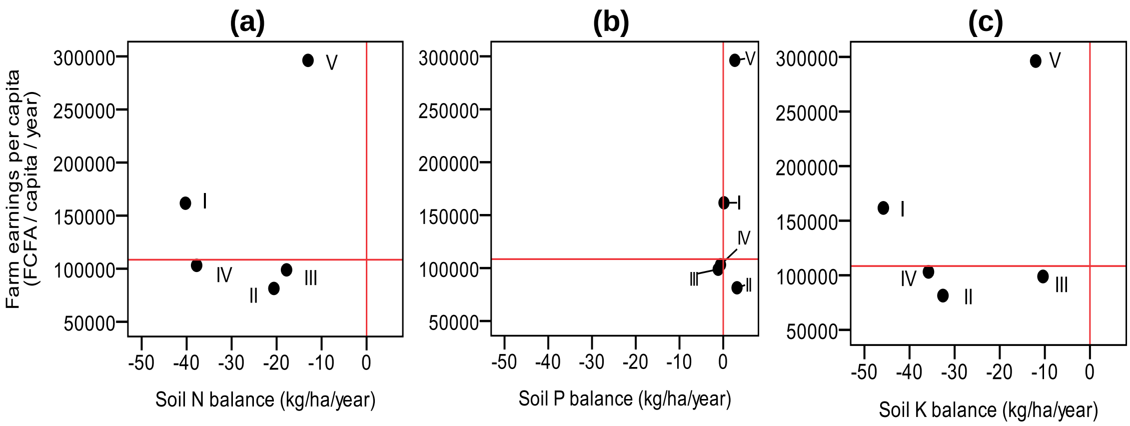


Figure 7.5. Distribution of study farm types over farm annual earnings and soil nutrient balance.

Notes*: Horizontal red lines indicate the official poverty line in Burkina Faso on the basis of 108454 FCFA/capita/year (INSD, 2010), i.e., 217 USD/capita/year. Vertical red lines indicate zero net nutrient loss.*

7.3.4. Soil nutrient management scenarios in Ioba province

Business as usual (BAU): This scenario represents the actual soil nutrient management pattern in Ioba province. This actual soil management is characterized by heterogeneous soil nutrient balance performances across socio ecological farm types. Soil nutrient balances are globally large with wealthy farm types being the farms depleting the most soil nutrients. Main sources of nutrient supply are mineral fertilizers and compost according to farm types. The strongest causes of soil nutrient depletion are harvested crops, crop residues removal through livestock grazing, on-field burning and domestic use (e.g. fuel, fencing). If farmers continue with BAU, the farming systems of the region already afflicted by current management practices will be critical in a short future.

Intensification of mineral fertilizer use (IMF): Strong nutrient depletion observed in BAU need to be addressed by taking strong actions to restore soil fertility. The IMF scenario considers that farmers are choosing to intensify the use of mineral fertilizer to quickly balance soil budget. This scenario requires less or more important investment for acquiring mineral fertilizer according to the nutrient balance performance.

Recycling crop residues (RCR): Given the actual rate of exploitation of non-renewable nutrients like potassium and phosphorus, recycling crop residues is required for facing the increasing demand of crop products (Vlek *et al.*, 1997). In BAU, crop residues removal is, with crop harvest, the main sources of nutrient depletion. It is grazed, burnt on field or used as fuel or fencing. The reuse of the residues can play an important role in soil nutrient replenishment. It is however subject to trade-offs since it is used for feeding livestock which is an important component of the farming system. Beyond fertility dimension, recycling crop residues rather than burning it is a good way of reducing emission of greenhouse gases which is an important strategy for mitigating greenhouse effect (Lal, 2005).

Integration livestock-agriculture (ILA): ILA is an integrated scenario recognising the importance of livestock in smallholder farming system. It then focuses on farm management options placing livestock in the front of soil nutrient replenishment. It is stressing on livestock and cropping activities complementarities and synergies for balancing soil nutrient and building sustainable farming system.

7.4. Discussions

7.4.1. Farm heterogeneity affecting farm nutrient balance performance

Whole farm level partial nutrient balance relates to management (Haileslassie *et al.*, 2006) as it accounts for flows mainly driven by management options decided by the farmer. The fact that farm-type I had negative partial balance (Figure 7.1.a) can be explained by exportation of raw cotton and crop residues burned or exported. Farm-type V produced less cotton and therefore exported less cotton compared to farm-type I.

Market crop-based farms tend to have negative farm level partial balance for some nutrient like potassium. Whole farm partial balance for N and P were better for better endowed farm types reflecting their ability to resort to the use of mineral or organic fertilizer compared to financially constrained and labour-less farm types. Better educated farm-type was able to maintain fairly high balance for the set of the three nutrients. This suggests the importance of education in having a better performing soil nutrient management system. Also subsistence agriculture plays a role in limiting exportation of some nutrients as it is the case of farm-type II for N. Farm type II, off-farm activities based practice cropping mainly for subsistence purpose (see chapter 4) with less crop selling. The farm full nutrient balance also showed disparities across farm-type. Flows like leaching, gaseous loss, erosion and human excreta led to a lower or more negative full nutrient balance. Poor farms tend to have lower farm full nutrient performances. However, as observed by De Jager *et al.*,(1998a) in Kenya, strongly market oriented farm-types had more negative potassium

7.4.2. Implication of soil nutrient balance for farming sustainability

Observed heterogeneity in soil nutrient stock was supposed to be due to inherent soil fertility, terrain characteristics, soil nutrient management practices and land use. Like for whole farm partial and full nutrient balances, disparities were also observed between farm-types for soil nutrient balance. Though no large nutrients losses were found for farm types, phosphorus is a concern for crop production in the region due to soil being inherently poor in phosphorus. Compared to previous studies in Burkina Faso (Stoorvogel and Smaling, 1990; Bationo *et al.*, 1998; Henao and Baanante, 1999), the study results revealed increasing soil nutrient loss for nitrogen and phosphorus. This suggests aggravation of soil nutrient balance in the country throughout the years. Better endowed and on-farm based farms were subjected to large nutrient loss as observed for farm-type I and IV. Relating nutrient losses to soil nutrient stock showed that farm-type II lost more than 1% of soil total N and total K stock.

Apart from farm-type V, all the other farm-types had a loss of more than or close to 0.5% total N and total K stock. According to Hilhorst *et al.*, (2000) a farming system quickly becomes unsustainable when nutrient loss accounts for more than 1% of the active pool. Unavailable nutrient pool to plant reaches 80-90% of soil total nutrient stock (Hilhorst *et al.*, 2000). It can, therefore, be assumed for this study that observed nutrient loss per year (negative balances) accounted for more than 1% of available nutrient stock. This means most of the studied farm-types may be unsustainable in the medium and long term.

7.4.3. Linkages between soil nutrient balance and farming profitability

Analysis of farm crop margin per area in relation to soil nutrient balance showed that farm-type I and farm-type IV had the best crop margin performances. These farm types were also farms with largest soil nutrient depletion (N and K). They correspond to best-off, on farm-based farm-type, and middle class, on-farm based farm-type. Van der Pol (1992) attributed the high income of many farms in northern Mali to soil nutrient mining. Our study showed that the actual cropping profitability of some farms comes from soil nutrient mining. These farms are placed in *Case B* corresponding to *negative soil nutrient balance but with better margin*. In this case immediate economic profit is rendered possible thanks to the relatively important nutrient stock. However, as soil nutrient stock will become depleted in the long term, farms will lose their profitability and the case will become problematic. Case B is an example of unsustainable farming system in the long term. Less endowed farm types and off-farm based farm-type had lower crop margin per area and found themselves in case A (Figure 7.3.a-c), which is a situation of negative nutrient balance and low profit. Case A corresponds to a situation where farmers find themselves in poverty trap with very limited financial access to mineral fertilizer even in the presence of fertilizer subsidies.

The performances of farm types varied according to the considered economic indicator. Farm-type III (labour constrained), farm-type I and farm-type IV (better endowed in labour, and with better margin per area) had the best crop margin per labour (Figure 7.3.d-f). This means that labour constraint pushes farms to use the available labour more efficiently. When considering the crop margin per capita, none of the farm type was able to draw from cropping activities only a margin higher than poverty line. However, for the farm earnings (including margins from cropping, livestock and off-farm activities), only farm-type I and V were situated above the poverty line (Figure 7.5.a-c). For farm-types II, III and IV, these results revealed insufficient integration of livestock-crops that should offer benefits for both activities.

Analysis of the return to investment showed that better-off farm type (farm type I) valued better land resource while the pro-poor farm type (farm-type III) valued better the capital (Figure 7.4.g-i). This can be explained by the fact that pro-poor farm type was less equipped, and most of the cropping was done manually. Since land was not hired, the main production capital in the study region was farming equipment. The performance of pro-poor farm-type III, which had the highest return to labour with better-off farm type I (Figure 7.4.d-f) showed the ability of labour and financially constrained farms to efficiently use the available labour.

It is worth noting that the year of the study had the lowest rainfall of the last ten year. On one hand this has certainly been a factor that greatly influenced crop productivity. On other hand, in the absence of a long term study, a study in this particular year of rainfall also helped to appreciate capability of farms to withstand climatic shocks. Therefore farm-types with better economic performances can be seen as farms capable of better resisting to rainfall drop. Then farm-types I and V appear to be resisting the better.

The study showed the great influence of soil nutrient balance on farm economic performance. An improvement of soil nutrient balance, through better nutrient management, will help improve farm situation. Therefore, farms in case A *"negative soil nutrient balance and low margin",* though some of these farm-types may be labour constrained, need to (i) better integrate livestock and agriculture to benefit from advantages of this integration; (ii) use affordable erosion control measures like grass strip or cover crops; (iii) recycle crop residue by piling up crop residues and keeping the heap over one or two years when labour availability is limited for classic composting operation. Farms in case B *"negative soil nutrient balance but with better margin"* need: (i) to consistently implement technologies reducing soil erosion as none of the monitored farms did so; (ii) to reduce nutrient gaps by recycling crop residues (composting) to avoid nutrient losses through exportation and burning. As noted by Vlek *et al*. (1997), recycling locally available resources is required to close soil nutrient gaps in Sub Saharan Africa where access to mineral fertilizer is very limited. Also (iii) the combine use of mineral-organic fertilizers is needed as compost improves soil organic matter and physical properties, improving thereby soil resistance to erosion. Many researches showed that the combined use of mineral-organic fertilizers has more benefit than mineral fertilizer alone (Neeteson, 1993; Mucheru-Muna *et al.*, 2007; Ding *et al.*, 2012; Kearney *et al.*, 2012; Kismányoky and Tóth, 2012). Case *C "positive soil nutrient balance but low performance",* that could be early stage of organic farming or inadequate marketing is observed for farm-types V and II for phosphorus only. Since the main source of soil P inflow was inorganic for both farm-types, Case C can be seen as a case of inadequate marketing. Usually after harvest in October-November, many farms use to sell their crops at a moment of high offer on the market but with low prices. Prices are higher late in the year or during food shortage periods. These farms will profit from a better organization crops market. Still for phosphorus, the position of farm-type I in *Case D "positive soil nutrient balance and better performance*" is debatable since its soil phosphorus balance is nearly zero. Further studies on farm-type I are needed to better apprehend its situation.

7.4.4. Implications of the use of IMF for balancing soil nutrients

The Table 7.3 shows the required investment for balancing soil nutrient under the scenario IMF. Globally, farms will have to make big investment in acquiring fertilizer. The required amount of NPK complex corresponds to 7 bags of 50 kg /ha for the highest demand (Farm type I) and 2 bags of 50 kg/ha for the lowest demand (Farm type V). In total absence of fertilizer subsidy, it implies the use of at least 36 % of the farm crop gross margin per hectare. The investment to fill soil nutrient gap can claim up to around 72% in the case of farm-type II. Even under the ongoing fertilizer subsidy programme (around 32% of market price), the cost for replenishing soil nutrient at equilibrium is still high: 24.72-48.41% of crop gross margin. Therefore, bringing soil nutrient balance from BAU to zero soil nutrient loss through IMF scenario is costly for farmers already suffering from poverty. Off-activities revenues may be of help to farmers. However this supposes farmers are able to draw high enough income from off-farm activities and have not severe nutrient gaps. Estimations showed that only farm-type V will invest less than 10% (e.g 7.45%) of its annual earnings for filling soil nutrient gaps in the absence of subsidy. The percentage drops at 5% when considering the actual subsidy programme. Farm-type V will be the only farm-type able to maintain itself above the poverty line after investing the necessary financial resources for balancing soil nutrient. Farm-type I which was above the poverty line with farm-type V will drop under poverty line by making the necessary investment to fill nutrient gaps. The other farm type will get their poverty status worsen due to such investment. These results, beyond the alarming nature of soil nutrient depletion, indicate how deep farms live in a poverty trap nutrient mining-poverty. Smallholder farming system is heading toward a problematic situation from which it will be extremely difficult to recover.

Table 7.3 Required fertilizer investment for balancing soil nutrient in IMF Scenario

Farm type	Per unit of cultivated land (ha)			At farm level		
	Amount of NPK complex* (50 kg bag)	Equivalent share in crop margin (%)		Amount of NPK complex* (50 kg bag)	Equivalent share in crop margin (%)	
		With no subsidy	With 32.5% subsidy		With no subsidy	With 32.5% subsidy
I	7.00	68.73	46.39	24.00	43.15	29.12
II	5.00	71.72	48.41	11.00	35.16	23.73
III	3.00	42.64	28.78	10.00	37.96	25.62
IV	5.50	46.99	31.72	13.00	30.28	20.44
V	2.00	36.62	24.72	11.00	7.45	5.03

Note: ** NPK complex: 14N-23P-14K*

7.4.5. Implication of RCR scenario for improving soil nutrient balance

Given the huge investment required for filling soil nutrient gaps, farmers can value on-farm organic resources. In most smallholder farms crop residues are not given enough importance due to lack of understanding of the role these residues can play in restoring and maintaining soil fertility. The present scenario RCR evaluates the effect of fully recycling crop residues on farm soil nutrient gaps severity. Figure 7.6 shows what the soil nutrient balance performances of the different farm types will be if they entirely recycle crop residues. The scenario supposes no competition with livestock or domestic uses like fuel or fencing.

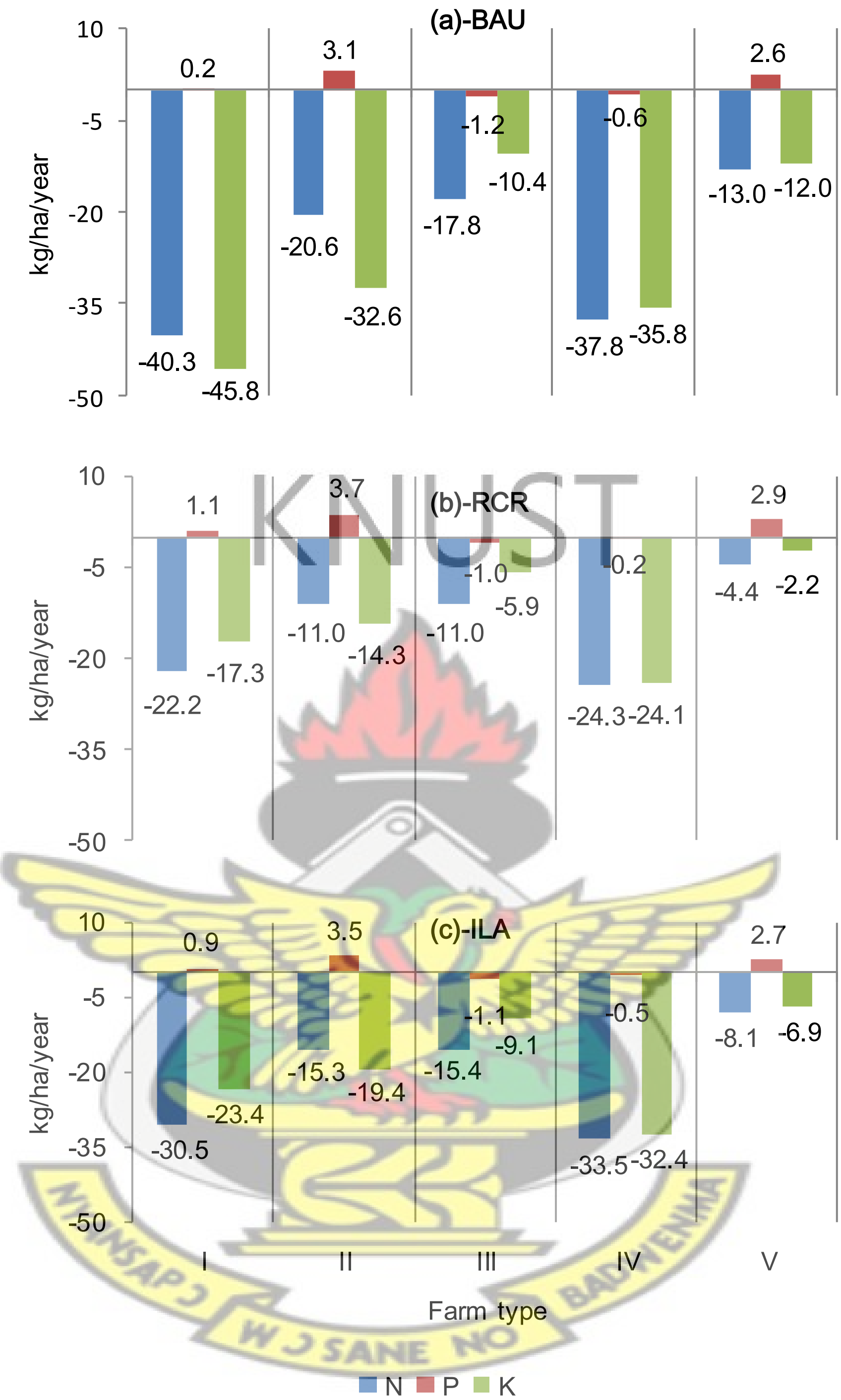


Figure 7.6. Soil nutrient balance performance for different scenarios

None of the farm types was able to fill soil nutrient gaps. Soil nutrient balances were less severe than in BAU scenario. Farmers will still rely on soil stock for almost all nutrients. Recycling crop residues however can play a valuable role in farm soil nutrient management. Soil nitrogen balance could be improved by 40-90% while potassium balance could be improved by 47 to 95%. This improvement will be more important for less endowed farms (farm-type V and III). This can be explained by soil nutrient stock and the type of cultivated crops.

7.4.6. Implication of ILA scenario for improving soil nutrient balance

Livestock plays a crucial role in smallholder farming by serving as investment of margins from cropping activities or of revenue drawn from farm activities. It is also a source of nutrient true dejection from outside grazing. However, there is poor integration of livestock-crop. Therefore farms are losing opportunity to boost their farm soil fertility and improve livestock productivity. This scenario ILA illustrates a management option implicating livestock. Part of crop residue is used for livestock feeding. The rest is either used for other purposes on farm or exported outside the farm for other needs. As shown in Figure 7.6, farms presented lower soil nutrient performances compared to RCR scenario. However soil nutrient balances are less large than in the case of BAU. Some imperceptible aspect in this scenario is its effect on livestock productivity which will undoubtedly improve. Soil nutrient performance in this scenario can be improved by implementing soil erosion control measures like stone bunds and grass strips. These measures have been proven to be efficient in preserving and restoring soil fertility (Zougmoré *et al.*, 2004a; Doamba *et al.*, 2011).

7.4.7. Limitation of the study

The main limitation of the study was the period of study. The use of one year does not allow understanding of dynamic processes. Monitoring over many years would allow better capturing the dynamic of soil nutrient balance for the different farm types over time and have a better estimation of the share soil nutrient stock being depleted annually. This would also help evaluate nutrient balance and economic performance under different rainfall level, for example for a particular year of abundant rains.

7.5. Conclusion

Soil fertility is a big concern in the smallholder farming system, and moreover under the threat of climate change. This study investigated soil nutrient balances of different farm types, their linkage with farm economic performances, and thereby discussed scenarios for replenishing soil nutrient in smallholder farms. Soil nutrient (N, P and K) balances were computed at farm level and soil sub-compartment for typical smallholder farms. Result showed that soil nutrient balances in Ioba province are alarming. Farms lose up to 40.3 N kg/ha/year, -1.7 P kg/ha/year and 45.8 K kg/ha/year. The study also found that farm heterogeneity influences greatly nutrient balances as well as agronomic and economic performance. The *Better-off, cotton-and livestock-based farm type* (fam-type I) and *Medium income, labour-rich, marketable food crop oriented and educated farms* (farm-type IV) drew the best margins per unit of cropped land. By analysing the relationship between soil nutrient balance and farm economic performances, the study identified two main cases in the study region: (1) farms with 'negative soil nutrient balance and low margin', and (2) farms with 'negative soil nutrient balance and better margin.' The first case faces the convergent problems of depleted soil resource, poor productivity and profitability. The second case is currently profitable but will become problematic as soon as the negative soil nutrient balance trend depicts nutrient stock depletion in near future. Balancing soil nutrient with only mineral fertilizers is likely unaffordable as the current fertilizer uses are not efficient with high rates of net soil nutrient loss. In this scenario, the necessary amount of fertilizer will cost up to 72% of crop marginal revenue drawn per hectare. If crop residues are fully recycled, soil nutrient balance will be improved by 40-90%. Policy interventions and farm design should focus on the subsidiary linkages between livestock and crop production.

8. CONCLUSION AND RECOMMENDATIONS

Climate change poses a big challenge to livelihoods of Sub Saharan African populations who rely largely on rainfed farming. In the 2014 IPCC report, Olsson *et al*.,(2014) highlighted that climate change will jeopardize sustainable development. Climate change in disrupting farm nutrient cycles will deepen soil nutrient depletion issue, which is already alarming in many smallholder farming systems. Unless adaptive and resilient farming systems are designed, food security and poverty in Sub Saharan Africa will worsen. Below *et al.*, (2010) stressed that adaptation is highly context sensitive. Beyond the environmental context it requires considering the livelihood assets endowment and strategies of farms (e.g. Land, financial resources, skills and technologies) in a holistic way. Therefore to support building resilient farming systems, there is the need to better understand smallholder farms behaviour giving their livelihood profile for guiding farm design and policy decision making. To contribute to building smallholder farm resilience, this thesis explored the role of farm heterogeneity in explaining smallholder farm soil nutrient use and adoption behaviour, as well as soil nutrient balance and related agronomic and economic performances, and discussed options for replenishing soil nutrient in smallholder farms

8.1. Summary of key findings

The thesis demonstrated the paramount importance of farm heterogeneity in Sustainable Soil Nutrient Management. Using the Sustainable Livelihood Framework, the thesis identified the main socio-economic and ecological farm types in the Ioba province. Five different farm types were identified. *Farm-type I (Better-off, cotton-and livestock-based farms):* its livelihood is based on livestock and cotton cropping. The *Farm-type II (Better-off, non-farm activities preference farms)* was characterized by the high contribution of off-farm activities income to annual income (77%). The *Farm-type III (Pro-poor, labour-poor-and landless farms)* was the more constrained in land and labour. Their livelihood was based on subsistence farming. *Farm-type IV (Medium income, labour-rich, marketable food crop oriented and educated farms)* was the most endowed in labour (11 workers) and had the most educated heads (4 years of classic education in average). It had the most diversified livelihoods. Finally, the *Farm-type V (Poor, insecure-land tenure, livestock based farms)* was characterized by insecure land tenure. Result showed that farms' economic efficiency varied among farming systems.

It was also shown that famers are likely to take good adaptive measures when they have climate change awareness. Climate change perception alone was found not to be enough to compel farmers to take adaptive measures.

The study also contributed to the knowledge of factors affecting sustainable soil nutrient management. Fertilizer use and adoption behavior of smallholder farms was not affected in the same pattern for same determinants across farm types and whole population. The farm adoption behavior was influenced by common determinants as well as by type specific determinants.

The thesis analyzed farm nutrient balances as well. Nutrient (e.g. N, P and K) balances were computed at farm level and soil sub compartment level. The findings corroborated previous nutrient balance studies in Africa which drew attention on alarming soil nutrient depletion. Large negative soil nutrient balances were found for all farming systems in Ioba province. This confirms the declining soil fertility in the region. Two main cases were identified in the region: (1) farms with 'negative soil nutrient balance and low margin', and (2) farms with 'negative soil nutrient balance with better margin'. The first case faces the convergent problems of depleted soil resource, poor productivity and profitability. The second case is currently profitable but will become problematic as soon as the negative soil nutrient balance trend depicts nutrient stock depletion in near future. Scenario analysis showed that balancing soil nutrient with only mineral fertilizers is likely unaffordable as the current fertilizer uses are not efficient with high rates of net soil nutrient loss. In this scenario the necessary amount of fertilizer will cost up to 72% of crop marginal revenue drawn per hectare. If crop residues are fully recycled, soil nutrient balance will be improved by 40-90%. The scenario livestock-agriculture integration can help improve soil nutrient balance while ensuring a better productivity and profitability sound trade-offs are made.

8.2. Added value of the research

From a methodological perspective, the thesis showed that Sustainable Livelihood Framework is a suited framework for properly identifying typological farm types in a region. The identified typology can serve as a guide for studies and policy intervention in the region and in similar regions. The thesis demonstrated the role of responsive heterogeneity in sustainable soil nutrient management. It also demonstrated the relationship between structural and functional typologies and the importance of considering both in regional farming system studies. Also, the results provide an empirical framework for scaling-out studies. Furthermore, the nutrient balance analysis presented in this thesis is new in the region. To our knowledge, no such studies were available for the study region and very few of these studies are available for the rest of Burkina Faso. The results provide precious information to developmental stakeholders in Burkina Faso as well as to decision makers. It can serve as working material to extension services. It also provided a basis for further studies in the region. In the overall the thesis has contributed to a better understanding of smallholder farm behaviour which is crucial for supporting build farms' resilience to climate change.

8.3. Recommendations

8.2.1. Recommendations for farm design and for improving policies

The results of this thesis pave the way for new ways of intervention in the agricultural sector in terms of sustainable land management.The findings showed the need for targeting specific livelihood farm-types for understanding their behaviour and better design policy interventions. It recommends the use of the proposed framework to identify typological farm types in order to formulate and implement well-targeted and efficient policies in sustainable soil nutrient management. The identified typology should serve as a guiding study for policy intervention in Ioba province. The results indicate that farmers' economic efficiency can be improved by acting on specific livelihood components rather than a global intervention. Training and learning from extension services should be improved for farm types II and IV. Supporting policies for livestock sector, income generation activities can help farm type III (pro poor) improve its nutrient use efficiency. As for farm type V, the remoteness from main town seems to be one of the main factors influencing their economic efficiency. More of training and of demonstration fields could improve their knowledge on best nutrient management practices.

The thesis showed that for building efficient adaptation strategies to climate change, perception alone is not enough. Policies should distinguish and account for awareness, and for farms/households heterogeneity as their response to climate change may be constrained by their assets and capabilities. The lack of awareness limits adoption of sustainable soil nutrient management in particular and adaptation measures in general. To raise farmers' awareness to climate change, extension services should be strengthened and decentralised for building farmers capacity in agro meteorology. Rainfall data collected by extension services should be exploited and used to educate farmers on climate change. This information helps farmers to more effectively protect their families and farms against the long-term consequences of adverse extreme climatic events (AGRA 2014).

8.2.2. Recommendations for farming system studies and for further research

The findings of this study should serve as a guide for future studies in Burkina Faso and in SSA. The study should be reproduced in different socio-ecological and economic context. The study used one year data for the analyses. Given that land management is a dynamic process, there is the need to explore the responsive heterogeneity with time series data. More biophysical data (e.g. rainfall) could then be included in the analysis. Given the influence of social settings in human-environment relation, further research should take a second step by including perception data in the classification of farmers. Sustainable Livelihood Framework should account for the quality of lands.

This research has provided insight into the role of farm heterogeneity in sustainable soil nutrient management. It has characterised farm decision making for soil nutrient management, as well as the relationship between environmental and economic performances of smallholder farms. A further step should consist in building an actor-oriented feedback loop system model to guide the decision-making of African smallholder farms' transformation to resilience in response to climate and other socio-economic changes.

Bibliography

ADESINA, A. (1996) Factors affecting the adoption of fertilizers by rice farmers in Côte d'Ivoire. *Nutrient Cycling in Agroecosystems,* 46**,** 29-39.

AGRA (2013) Africa agricultural status report: Focus on staple crops. Nairobi, Kenya, Alliance for a Green Revolution in Africa (AGRA).

AGRA (2014) Africa Agriculture Status Report 2014: Climate Change and Smallholder Agriculture in Sub-Saharan Africa. Nairobi, Kenya, AGRA.

AMEKAWA, Y. (2013) Understanding the local reality of the adoption of sustainable practices and farmer livelihoods: the case of pummelo farming in Chaiyaphum, Northeast Thailand. *Food Security,* 5**,** 793-805.

ANLEY, Y., BOGALE, A. & HAILE-GABRIEL, A. (2007) Adoption decision and use intensity of soil and water conservation measures by smallholder subsistence farmers in Dedo District, Western Ethiopia. *Land Degradation & Development,* 18**,** 289-302.

ANONYMOUS (2006) African soil exhaustion. *Science,* 312.

AYANTUNDE, A. A. (1998) *Influence of grazing regimes on cattle nutrition and performance and vegetation dynamics in Sahelian rangelands,* Wageningen, The Netherlands, Wageningen Agricultural University, PhD Thesis, p.

BADO, B. V., BATIONO, A. & CESCAS, M. P. (2006) Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa) *Biology and Fertility of Soils,* 43**,** 171-176.

BARBIER, B., YACOUBA, H., KARAMBIRI, H., ZOROMÉ, M. & SOMÉ, B. (2008) Human Vulnerability to Climate Variability in the Sahel: Farmers' Adaptation Strategies in Northern Burkina Faso. *Environmental Management,* 43**,** 790-803.

BATIONO, A., HARTEMINK, A., LUNGU, O., NAIMI, M., OKOTH, P., SMALING, E. & THIOMBIANO, L. (2006) African Soils: Their Productivity and Profitability of Fertilizer Use. IN BATIONO, A., A., H., O., L., M., N., OKOTH, P., SMALING, E. & THIOMBIANO, L. (Eds.) *African Ferilizer Summit.* 9-13 June 2006, Abuja, Nigeria.

BATIONO, A., LOMPO, F. & KOALA, S. (1998) Research on nutrient flows and balances in west Africa: state-of-the-art. *Agriculture, Ecosystems and Environment* 71**,** 19-35.

BEKUNDA, M. & MANZI, G. (2003) Use of the partial nutrient budget as an indicator of nutrient depletion in the highlands of southwestern Uganda. *Nutrient Cycling in Agroecosystems,* 67**,** 187-195.

BIDOGEZA, J. C., BERENTSEN, P. B. M., GRAAFF, J. & OUDE LANSINK, A. G. J. M. (2009) A typology of farm households for the Umutara Province in Rwanda. *Food Security,* 1**,** 321-335.

BLANC, E. (2012) The Impact of Climate Change on Crop Yields in Sub-Saharan Africa *American Journal of Climate Change,* 1**,** 1-13

BNDT (2002) Base nationale des terres du Burkina Faso. Ouagadougou, Burkina Faso.

BOUYOUCOS, G. J. (1962) Hydrometer method improved for making particle size analysis of soil. *Agronomy Journal,* 54**,** 464-465.

BRAY, R. H. & KURETZ, L. T. (1945) Determination of total, organic, and available forms of phosphorus in soils. *Soil Science,* 59**,** 39-46.

BRINKMAN, R. (1990) Resilience against climate change? Soil minerals, transformations and surface properties, Eh, pH 51-60.

BUNASOL (1985) *État de connaissance de la fertilité des sols du Burkina Faso*, Ministère de l'Agriculture et de l'Élevage

CAMPBELL, B., SAYER, J. A., FROST, P., VERMEULEN, S., PÉREZ, M. R., CUNNINGHAM, A. & PRABHU, R. (2001) Assessing the Performance of Natural Resource Systems. *Conservation Ecology* 5**,** 22.

CARPENTER, S., WALKER, B., ANDERIES, J. M. & ABEL, N. (2001) From Metaphor to Measurement: Resilience of What to What? *Ecosystems,* 4**,** 765–781.

CHAMBERLIN, J. (2008) ***It's a Small World After All Defining Smallholder Agriculture in Ghana***. IFPRI, Discussion Paper 823 28 p.

CHAMBERS, R. & CONWAY, G. (1991) Sustainable rural livelihoods: Practical concepts for the 21 st century. Institute for Development Studies.

CHIANU, J. N., CHIANU, J. N. & MAIRURA, F. (2012a) Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. *Agronomy for Sustainable Development,* 32**,** 545-566.

CHIANU, J. N., CHIANU, J. N. & MAIRURA, F. (2012b) Organic Fertilizers in Sub-Saharan Farming Systems. IN LICHTFOUSE, E. (Ed.) *Organic Fertilisation, Soil Quality and Human Health.* Springer Netherlands,31-65.

CHIANU, J. N. & TSUJII, H. (2005) Determinants of farmers' decision to adopt or not adopt inorganic fertilizer in the savannas of northern Nigeria. *Nutrient Cycling in Agroecosystems,* 70**,** 293-301.

CILSS (2012) *Bonnes pratiques agro-sylvo-pastorales d'amélioration durable de la fertilité des sols au Burkina Faso* Ouagadougou, Burkina Faso, 194 p.

COBO, J. G., DERCON, G. & CADISCH, G. (2010) Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. *Agriculture, Ecosystems & Environment,* 136**,** 1-15.

CONWAY, G. (2012) *One billion hungry: can we feed the world?,* Ithaca and London, Cornell University Press

COULIBALY, K. (2012) *Analyse des facteurs de variabilité des performances agronomiques et économiques des cultures et de l'évolution de la fertilité des sols dans les systèmes culturaux intégrant les légumineuses en milieu soudanien du Burkina Faso: approche expérimentale chez et par les paysans,* Bobo-Dioulasso, Burkina Faso, Université Polytechnique de Bobo-Dioulasso, Doctorat unique, 149 p.

DARNHOFER, I., GIBBON, D. & DEDIEU, B. (2012) Farming Systems Research: an approach to inquiry. IN DARNHOFER, I., GIBBON, D. & DEDIEU, B. (Eds.) *Farming Systems Research into the 21st Century: The New Dynamic.* Springer Netherlands,3-31.

DE JAGER, A., KARIUKU, I., MATIRI, F. M., ODENDO, M. & WANYAMA, J. M. (1998a) Monitoring nutrient flows and economic performance in African farming systems (NUTMON): IV. Linking nutrient balances and economic performance in three districts in Kenya. *Agriculture, Ecosystems & Environment,* 71**,** 81-92.

DE JAGER, A., NANDWA, S. M. & OKOTH, P. F. (1998b) Monitoring nutrient flows and economic performance in African farming systems (NUTMON) I. Concepts and methodologies. *Agriculture, Ecosystems and Environment,* 71**,** 37- 48.

DE SHERBININ, A., VANWEY, L. K., MCSWEENEY, K., AGGARWAL, R., BARBIERI, A., HENRY, S., HUNTER, L. M., TWINE, W. & WALKER, R. (2008) Rural household demographics, livelihoods and the environment. *Global Environmental Change,* 18**,** 38-53.

DEFRIES, R. S., RUDEL, T., URIARTE, M. & HANSEN, M. (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience,* 3**,** 178-181.

DEVEREUX, S. (2009) Why does famine persist in Africa? *Food Security,* 1**,** 25-35.

DEVEREUX, S. & MAXWELL, S. (2001) *Food security in Sub-Saharan Africa* London, United Kingdom, ITDG,350.

DFID (1999) Sustainable livelihoods guidance sheets.

DGPER (2013) Enquêtes Permanentes Agricoles (EPA) 2013. IN DGPER (Ed.). Ouagadougou, Burkina Faso, DGPER.

DING, X., HAN, X., LIANG, Y., QIAO, Y., LI, L. & LI, N. (2012) Changes in soil organic carbon pools after 10 years of continuous manuring combined with chemical fertilizer in a Mollisol in China. *Soil and Tillage Research,* 122**,** 36-41.

DIRECTION DE LA NUTRITION (2005) *Equivalent calories des produits alimentaires,*

DOAMBA, S. M. F., NACRO, H. B., SANON, A. & SEDOGO, M. (2011) Effet des cordons pierreux sur l'activité biologique d'un sol ferrugineux tropical lessivé (Province du Kouritenga au Burkina Faso). *International Journal of Biological and Chemical Sciences,* 5**,** 304-313.

DOUXCHAMPS, S., AYANTUNDE, A. & BARRON, J. (2012) *Evolution of agricultural water management in rainfed crop-livestock systems of the Volta Basin.* 58 p.

DREP/SUD-OUEST & PNGT (2000) *Monographie de la Province du Ioba.* Gaoua, Burkina Faso, Direction Regionale de l'Economie et de la Planification du Sud-Ouest, 82 p.

EBANYAT, P., RIDDER, N., JAGER, A., DELVE, R. J., BEKUNDA, M. A. & GILLER, K. E. (2010) Drivers of land use change and household determinants of sustainability in smallholder farming systems of Eastern Uganda. *Population and Environment,* 31**,** 474-506.

EFDÉ, S. L. (1996) *Quantified and integrated crop and livestock production analysis at the farm level,* Wageningen, The Netherlands, Wageningen Agricultural University, PhD Thesis p.

ELLIS, F. (2000) The Determinants of Rural Livelihood Diversification in Developing Countries. *Journal of Agricultural Economics* 51**,** 289-302.

ELLIS, F. (2005) Small-Farms, Livelihood Diversification and Rural-Urban Transitions: Strategic Issues in Sub-Saharan Africa. Paper prepared for the Research Workshop on. *The Future of Small Farms.* 26-29 June 2005, Withersdane Conference Centre, Wye, Kent, UK

ENYONG, L. A., DEBRAH, S. K. & BATIONO, A. (1999) Farmers' perceptions and attitudes towards introduced soil-fertility enhancing technologies in western Africa. *Nutrient Cycling in Agroecosystems,* 53**,** 177-187.

ERGLE, D. R. & EATON, F. M. (1956) Aspects of phosphorus metabolism in the cotton plant. *Plant Physiology***,** 106-113.

ESILABA, A. O., NYENDE, P., NALUKENGE, G., BYALEBEKA, J. B., DELVE, R. J. & SSALI, H. (2005) Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda. *Agriculture, Ecosystems & Environment,* 109**,** 192-201.

EUROCONSULT (1989) *Agricultural compendium for rural development in the tropics and subtropics,* Amsterdam, The Netherlands, Elsevier Science Publishers

FAO (1993) *Integrated plant nutrition systems.* Rome, Italy, FAO, FAO Fertilizer and plant nutrition bulletin 424 p.

FAO (2006) *Food security and agricultural development in Sub-Saharan Africa: Building a case for more public support.* Rome, Italy, FAO, Working paper 90 p.

FAO (2010) *The State of Food Insecurity in the World.* Rome, Italy:, Food and Agriculture Organization, p.

FAO, IFAD & WFP (2013) *The State of Food Insecurity in the World 2013. The multiple dimensions of food security.* Rome, Italy, Food and Agriculture Organization of the United Nations, 52 p.

FOSU-MENSAH, B. Y., VLEK, P. L. G. & MACCARTHY, D. S. (2012) Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. *Environment, Development and Sustainability,* 14**,** 495-505.

FREEMAN, H. A. & OMITI, J. M. (2003) Fertilizer use in semi-arid areas of Kenya: analysis of smallholder farmers' adoption behavior under liberalized markets. *Nutrient Cycling in Agroecosystems,* 66**,** 23-31.

GAUR, C. & SINGH, G. (1993) Organic and biological plant nutrient sources: potential, methods for reducing the bulk and improving the availability of nutrients. IN R, D. & ROY, R. N. (Eds.) *Integrated Plant Nutrition.* Rome, Italy, FAO,85-112.

GBETIBOUO, G. A. (2009) *Understanding Farmers' Perceptions and Adaptations to Climate Change and Variability.The Case of the Limpopo Basin, South Africa* International Food Policy Research Institute (IFPRI), IFPRI Discussion Paper 00849 849, 36 p.

GERSONIUS, B., ASHLEY, R. & ZEVENBERGEN, C. (2012) The identity approach for assessing socio-technical resilience to climate change: example of flood risk management for the Island of Dordrecht. *Natural Hazards and Earth System Science,* 12**,** 2139-2146.

GILLER, K. E., ROWE, E. C., DE RIDDER, N. & VAN KEULEN, H. (2006) Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agricultural Systems,* 88**,** 8-27.

GLEISBERG-GERBER, K. (2012) Livelihoods and land management in the Ioba Province in south-western Burkina Faso.

GODFRAY, H. C. J., BEDDINGTON, J. R., CRUTE, I. R., HADDAD, L., LAWRENCE, D., MUIR, J. F., PRETTY, J., ROBINSON, S., THOMAS, S. M. & TOULMIN, C. (2010) Food security: the challenge of feeding 9 Billion people. *Science,* 327**,** 812-818.

GREENE, W. H. (2012) *Econometric Analysis,* Prentice Hall, Boston, USA

GRIST, N. (2014) Transformative adaptation in Africa's agriculture. Contribution Note for Africa Progress Panel meeting. *Expert Consultation: an African Agenda for Green, Low Carbon Development.* Geneva, October 30th 2014.

GROTE, U. (2014) Can we improve global food security? A socio-economic and political perspective. *Food Security,* 6**,** 187-200.

GUET, G. (2003) Mémento d'agriculture biologique: guide pratique à usage professionnel.

GUNDERSON, L. & HOLLING, C. S. (Eds.) (2001) *Panarchy: understanding transformations in human and natural systems,* Washington (DC), Island Pressp.

HAILESLASSIE, A., PRIESS, J., VELDKAMP, E., TEKETAY, D. & LESSCHEN, J. P. (2005) Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agriculture, Ecosystems & Environment,* 108**,** 1-16.

HAILESLASSIE, A., PRIESS, J. A., VELDKAMP, E. & LESSCHEN, J. P. (2006) Smallholders' Soil Fertility Management in the Central Highlands of Ethiopia: Implications for Nutrient Stocks, Balances and Sustainability of Agroecosystems. *Nutrient Cycling in Agroecosystems,* 75**,** 135-146.

HAILESLASSIE, A., PRIESS, J. A., VELDKAMP, E. & LESSCHEN, J. P. (2007) Nutrient flows and balances at the field and farm scale: Exploring effects of land-use strategies and access to resources. *Agricultural Systems,* 94**,** 459-470.

HAINNAUX, G. & GOUZY, M. (1980) *Analyse chimique des composts HUMUCI diagnostic agronomique.* ORSTOM, p.

HARRIS, F. M. A. (1998) Farm-level assessment of the nutrient balance in northern Nigeria. *Agriculture, Ecosystems and Environment,* 71**,** 201-214.

HENAO, J. & BAANANTE, C. (1999) *Estimating Rates of Nutrient Depletion in Soils of Agricutural Lands of Africa.* Alabama, USA, International Fertilizer Development Center, Technical Bulletin No 48 76 p.

HILHORST, T., MUCHENA, F., DEFOER, T., HASSINK, J., SMALING, E. & TOULMIN, C. (2000) Managing soil fertility in Africa: diverse settings and changing practice. IN HILHORST, T. & MUCHENA, F. M. (Eds.) *Nutrients on the move-Soil fertility dynamics in African farming systems.* London, UK, International Institute for Environment and Development,1-27.

HOLLING, C. S. (1973) Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics,* 4**,** 1-23.

HOUBA, V. J. G., VAN DER LEE, J. J., NOVOZAMSKY, I. & WALINGA, I. (1989) *Soil and plant analysis,* Wageningen, Netherland, Wageningen Agricultural University,4-10.

IFAD (2010) *Rural Poverty Report 2011-New realities, new challenges: new opportunities for tomorrow's generation.* Rome, Italy, IFAD, p.

IFPRI (2007) *Micro-Level Analysis of Farmers' Adaptation to Climate Change in Southern Africa.* Washington DC, USA, IFPRI, Discussion Paper 00714 30 p.

IIYAMA, M., KARIUKI, P., KRISTJANSON, P., KAITIBIE, S. & MAITIMA, J. (2008) Livelihood diversification strategies, incomes and soil management strategies: a case study from Kerio valley, Kenya. *Journal of International Development,* 20**,** 380-397

INGRAM, J. S. I., GREGORY, P. J. & IZAC, A. M. (2008) The role of agronomic research in climate change and food security policy. *Agriculture, Ecosystems & Environment,* 126**,** 4-12.

INSD (2009a) *Monographie de la région du Sud-Ouest.* Ougadougou, Burkina Faso, INSD, 152 p.

INSD (2009b) *Projections démographiques de 2007 à 2020 par région et province.* Ouagadougou, Burkina Faso, Institut national de la statistique et de la démographie (INSD), 73 p.

INSD (2010) *Analyse de quelques résultats des données de la phase principale de l'enquête intégrale sur les conditions de vie des ménages, EICVM 2009* Ouagadougou, Institut National de la Statistique et de la Démographie, 13 p.

INSD (2013) *Annuaire statistique 2011.* 464 p.

IPCC (2013) Summary for Policymakers. IN STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (Eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA., Cambridge University Press

IPCC (2014) Summary for Policymakers. *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA., Cambridge University Press,

ISHAYA, S. & ABAJE, I. B. (2008) Indigenous people's perception on climate change and adaptation strategies in Jema'a local government area of Kaduna State, Nigeria. *Journal of Geography and Regional Planning,* 1**,** 138-143.

JAIN, A. K., MURTY, M. N. & FLYN, P. J. (1999) Data Clustering: A Review. *ACM Computing Surveys,* 31**,** 264-323.

JAIN, N., BHATIA, A. & PATHAK, H. (2014) Emission of Air Pollutants from Crop Residue Burning in India. *Aerosol and Air Quality Research,* 14**,** 422-430.

JALLOH, A., NELSON, G. C., THOMAS, T. S., ZOUGMORÉ, R. & ROY-MACAULEY, H. (2013) *West African Agriculture and Climate Change. A Comprehensive Analysis,* Washington, DC, International Food Policy Research Institute

JANSEN, H. G. P., RODRIGUEZ, A., DAMON, A., PENDER, J., CHENIER, J., SCHIPPER, R. & CALINSKI, T. (2006) Determinants of income-earning strategies and adoption of conservation practices in hillside communities in rural Honduras. *Agricultural Systems,* 88**,** 92-110.

JARVIS, A., RAMIREZ, J., ANDERSON, B., LEIBING, C. & AGGARWAL, P. (2010) Scenarios of Climate Change Within the Context of Agriculture. IN REYNOLDS, M. P. (Ed.) *Climate Change and Crop Production.* Oxfordshire, UK and Cambridge, USA, CAB International,9-37.

JONES, S. (2002) A Framework for Understanding On-farm Environmental Degradation and Constraints to the Adoption of Soil Conservation Measures: Case Studies from Highland Tanzania and Thailand. *World Development,* 30**,** 1607-1620.

KASSIE, M., JALETA, M., SHIFERAW, B., MMBANDO, F. & MEKURIA, M. (2013) Adoption of interrelated sustainable agricultural practices in smallholder systems: Evidence from rural Tanzania. *Technological Forecasting and Social Change,* 80**,** 525-540.

KEARNEY, S., FONTE, S. J., SALOMON, A., SIX, J. & SCOW, K. M. (2012) Forty percent revenue increase by combining organic and mineral nutrient amendments in Ugandan smallholder market vegetable production. *Agronomy for Sustainable Development,* 32**,** 831-839.

KETEMA, M. & BAUER, S. (2011) Determinants of Manure and Fertilizer Applications in Eastern Highlands of Ethiopia. *Quarterly Journal of International Agriculture,* 50**,** 237-252.

KIENDRÉBÉOGO, T., MOPATÉ LOGOTÈNE, Y., IDO, G. & KABORÉ-ZOUNGRANA, C.-Y. (2013) Procédés de production d'aliments non conventionnels pour porcs à base de déchets de mangues et détermination de leurs valeurs alimentaires au Burkina Faso. *Journal of Applied Biosciences,* 67**,** 5261-5270.

KIÉNOU, B. & A., S.-C. (2005) *Prise en compte de données nutritionnelles dans le cadre de l'Enquête Permanente Agricole : étude comparative de la couverture des besoins alimentaires des ménages agricoles et l'état nutritionnel des enfants de 6 à 59 mois.* Ouagadougou, Burkina Faso, Direction des Préventions et de l'Alerte Précoce (DPAP), 35 p.

KISMÁNYOKY, T. & TÓTH, Z. (2012) Effect of mineral and organic fertilization on soil organic carbon content as well as on grain production of cereals in the

IOSDV (ILTE) long-term field experiment, Keszthely, Hungary. *Archives of Agronomy and Soil Science*, 59**,** 1121-1131.

KISSOU, R., THIOMBIANO, L., NÉBIÉ, A. K., SEMDE, A. & YAGO, K. J. (2000) La Base mondiale de données sur les sols: avantages et faiblesses pour la connaissance et l'utilisation des milieux édaphiques au Burkina Faso. *Quatorzième Réunion du Sous-Comité ouest et centre africain de corrélation des sols pour*
la mise en valeur des terres. 9 au 13 octobre 2000, Abomey, République du Bénin, FAO, Rome.

KOMBA, C. & MUCHAPONDWA, E. (2012) *Adaptation to Climate Change by Smallholder Farmers inTanzania.* Economic Research Southern Africa (ERSA), ERSA working paper 299 32 p.

KÖRSCHENS, M., ALBERT, E., ARMBRUSTER, M., BARKUSKY, D., BAUMECKER, M., BEHLE-SCHALK, L., BISCHOFF, R., ČERGAN, Z., ELLMER, F., HERBST, F., HOFFMANN, S., HOFMANN, B., KISMANYOKY, T., KUBAT, J., KUNZOVA, E., LOPEZ-FANDO, C., MERBACH, I., MERBACH, W., PARDOR, M. T., ROGASIK, J., RÜHLMANN, J., SPIEGEL, H., SCHULZ, E., TAJNSEK, A., TOTH, Z., WEGENER, H. & ZORN, W. (2012) Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. *Archives of Agronomy and Soil Science,* 59**,** 1017-1040.

KRISTJANSON, P., OKIKE, I., TARAWALI, S., SINGH, B. B. & MANYONG, V. M. (2005) Farmers' perceptions of benefits and factors affecting the adoption of improved dual-purpose cowpea in the dry savannas of Nigeria. *Agricultural Economics,* 32**,** 195-210.

KUMAGA, F., DANSO, S. K. A. & ZAPATA, F. (1994) Time-course of nitrogen fixation in two bambara groundnut (Vigna subterranea L. Verdc.) cultivars. *Biology and Fertility of Soils,* 18**,** 231-236.

LAL, R. (1995) Erosion-crop productivity relationships for soils of Africa. *Soil Science Society of America Journal,* 59**,** 661-667.

LAL, R. (2005) World crop residues production and implications of its use as a biofuel. *Environment International,* 31**,** 575-584.

LAL, R. (2009) Soil degradation as a reason for inadequate human nutrition. *Food Security,* 1**,** 45-57.

LAMBRECHT, I., VANLAUWE, B., MERCKX, R. & MAERTENS, M. (2014) Understanding the Process of Agricultural Technology Adoption: Mineral Fertilizer in Eastern DR Congo. *World Development*, 59**,** 132-146.

LANDAIS, E. & LHOSTES, P. (1990) L'association agriculture-élevage en Afrique intertropicale : un mythe techniciste confronté aux réalités du terrain. *Cahiers des Sciences Humaines,* 26**,** 217-235.

LE, Q. B. (2005) Multi-agent system for simulation of land-use and land cover change: A theoretical framework and its first implementation for an upland watershed in the Central Coast of Vietnam IN L.G.VLEK, P., DENICH, M., MARTIUS, C., RODGERS, C. & GIESEN, N. V. D. (Eds.). Bonn.

LIVINGSTON, G., SCHONBERGER, S. & DELANEY, S. (2011) Sub-Saharan Africa: The state of smallholders in agriculture. IN DEVELOPMENT, I. F. F. A. (Ed.) *IFAD Conference on New Directions for Smallholder Agriculture.* Rome, Italy, International Fund for Agricultural Development

LOBELL, D. & BURKE, M. (2010) Economic Impacts of Climate Change on Agriculture to 2030 IN REYNOLDS, M. P. (Ed.) *Climate Change and Crop Production.* Oxfordshire, UK and Cambridge, USA, CAB International,38-49.

LOMPO, F. (2007) *Effets induits des modes de gestion de la fertilité sur les états du phosphore et la solubilisation des phosphates naturels dans deux sols acides du Burkina Faso,* Abidjan, Côte d'Ivoire, Université de Cocody, Doctorat, p.

MAHRH (2010) Suivi de la campagne agricole 2010-2011. Ouagadougou, Burkina Faso, Premier minister.

MAHRH & GTZ (2004) *Mission d'appui à l'identification des interventions du Programme de Developement de l'Agriculture de la coopération germano-burkinabè dans la région administrative du Sud-Ouest.* Ouagadougougou, 35 p.

MAIMON, O. & ROKACH, L. (2010) *Data Mining and Knowledge Discovery Handbook,*

MAKOKHA, S., KIMANI, S., MWANGI, W., VERKUIJL, H. & MUSEMBI, F. (2001) *Determinants of Fertilizer and Manure Use for Maize Production in Kiambu District, Kenya.* Nairobi, Kenya, KARI, 25 p.

MALMBERG, B. & TEGENU, T. (2007) Population pressure and dynamics of household livelihoods in an Ethiopian Village: an elaboration of the Boserup-Chayanovian framework. *Population and Environment,* 29**,** 39-67.

MARENYA, P. P. & BARRETT, C. B. (2007) Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya. *Food Policy,* 32**,** 515-536.

MARSHALL, N. A., PARK, S., HOWDEN, S. M., DOWD, A. B. & JAKKU, E. S. (2013) Climate change awareness is associated with enhanced adaptive capacity. *Agricultural Systems,* 117**,** 30-34.

MARTEY, E., WIREDU, A. N., ETWIRE, P. M., FOSU, M., BUAH, S. S. J., BIDZAKIN, J., AHIABOR, B. D. K. & KUSI, F. (2014) Fertilizer Adoption and Use Intensity Among Smallholder Farmers in Northern Ghana: A Case Study of the AGRA Soil Health Project. *Sustainable Agriculture Research,* 3**,** 36.

MATI, B. M. & VEIHE, A. (2001) Application of the USLE in a savannah environment: Comparative experience from East and West Africa. *Singapore Journal of Tropical Geography,* 22**,** 138-155

MEFFEJA, F., DONGMO, T., FOTSO, J.-M., FOTSA, J.-C., TCHAKOUNTÉ, J. & NKENG, N. (2003) Effets du taux d'incorporation de la drêche ensilée des brasseries dans les rations alimentaires sur les performances des porcs en engraissement. *Cahiers Agricultures,* 12**,** 87-91.

MERTZ, O., MBOW, C., REENBERG, A. & DIOUF, A. (2008) Farmers' Perceptions of Climate Change and Agricultural Adaptation Strategies in Rural Sahel. *Environmental Management,* 43**,** 804-816.

MKHABELA, T. S. & MATERECHERA, S. A. (2003) Factors influencing the utilization of cattle and chicken manure for soil fertility management by emergent farmers in the moist Midlands of KwaZulu-Natal Province, South Africa. *Nutrient Cycling in Agroecosystems,* 65**,** 151-162.

MORTON, J. F. (2007) The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences,* 104**,** 19680-19685.

MUCHERU-MUNA, M., MUGENDI, D., KUNG'U, J., MUGWE, J. & BATIONO, A. (2007) Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agroforestry Systems,* 69**,** 189-197.

MUELLER, N. D., GERBER, J. S., JOHNSTON, M., RAY, D. K., RAMANKUTTY, N. & FOLEY, J. A. (2012) Closing yield gaps through nutrient and water management. *Nature,* 490**,** 254-257.

MURUNGWENI, C., VAN WIJK, M. T., GILLER, K. E., ANDERSSON, J. A. & SMALING, E. M. A. (2014) Adaptive livelihood strategies employed by farmers to close the food gap in semi-arid south eastern Zimbabwe. *Food Security,* 6**,** 313-326.

NEETESON, J. J. (1993) Combined use of inorganic and organic plant nutrients in a West European arable farming system. IN DUDAL, R. & ROY, R. N. (Eds.) *Integrated plant nutrition.* Rome, Italy, FAO,391-396.

NIANG, I., RUPPEL, O. C., ABDRABO, M. A., ESSEL, A., LENNARD, C., PADGHAM, J. & URQUHART, P. (2014) Africa. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press

NKAMLEU, G. B. (2007) Modeling farmers' decisions on integrated soil nutrient management in sub-Saharan Africa: A multinomial Logit analysis in Cameroon. IN BATIONO, A. (Ed.) *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities.*891-903.

NKONYA, E., KAIZZI, C. & PENDER, J. (2005) Determinants of nutrient balances in a maize farming system in eastern Uganda. *Agricultural Systems,* 85**,** 155-182.

NZEADIBE, T., EGBULE, C., CHUKWUONE, N., AGWU, A. & AGU, V. (2012) Indigenous innovations for climate change adaptation in the Niger Delta region of Nigeria. *Environment, Development and Sustainability,* 14**,** 901-914.

OLSSON, L., OPONDO, M., TSCHAKERT, P., AGRAWAL, A., ERIKSEN, S. H., MA, S., PERCH, L. N. & ZAKIELDEEN, S. A. (2014) *Livelihoods and poverty.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 793-832 p.

OUATTARA, K. (2007) *Improved Soil and Water Conservatory Managements for Cotton-Maize Rotation System in the Western Cotton Area of Burkina Faso* Umeå, Sweden, Swedish University of Agricultural Sciences p.

OUÉDRAOGO, M., DEMBÉLÉ, Y. & SOMÉ, L. (2010) Perceptions et stratégies d'adaptation aux changements des preécipitations : cas des paysans du Burkina Faso. *Sécheresse,* 21**,** 87-96.

OUMER, A. M., HJORTSØ, C. N. & NEERGAARD, A. (2013) Understanding the relationship between livelihood strategy and soil management: empirical insights from the central highlands of Ethiopia. *Food Security,* 5**,** 143-156.

PALLO, F. J. P. & THIOMBIANO, L. (1989) Les sols ferrugineux tropicaux lessivés à concrétions du Burkina Faso : Caractéristiques et contraintes pour l'utilisation agricole. *Soltrop,* 89**,** 307-327.

PALM, C. A., GACHENGO, C. N., DELVE, R. J., CADISCH, G. & GILLER, K. E. (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems & Environment,* 83**,** 27-42.

PALM, C. A., MYERS, R. J. K. & NANDWA, S. M. (1996) Prospects for integrated soil fertility management using organic and inorganic inputs: evidence from smallholder African agricultural systems. IN BURESH, R. J., SANCHEZ, P. A. & CALHOUN, F. (Eds.) *88th Annual Meetings of the American Society of Agronomy and the Soil Science Society of America.* Indianapolis, Indiana,, Soil Science Society of America American Society of Agronomy.

PARR, J. F. & COLACICCO, D. (1987) Organic Materials as Alternative Nutrient Sources IN HELSEL, Z. R. (Ed.) *Energy in plant nutrition and pest control.* Amsterdam, The Netherlands, Elsevier Science Publishers B.V.

PIMENTEL, D. & BURGESS, M. (2013) Soil Erosion Threatens Food Production. *Agriculture,* 3**,** 443-463.

PIMM, S. L. (1984) The complexity and stability of ecosystems. *Nature,* 307**,** 321-326.

PLACE, F., BARRETT, C. B., FREEMAN, H. A., RAMISCH, J. J. & VANLAUWE, B. (2003) Prospects for integrated soil fertility management using organic and inorganic inputs: evidence from smallholder African agricultural systems. *Food Policy,* 28**,** 365-378.

PONS JR, W. A. & GUTHRIE, J. D. (1946) Determination of Inorganic Phosphorus in Plant Materials. *Industrial & Engineering Chemistry Analytical Edition,* 18**,** 184-186.

PORTER, J. R., XIE, L., CHALLINOR, A. J., COCHRANE, K., HOWDEN, S. M., IQBAL, M. M., LOBELL, D. B. & TRAVASSO, M. I. (2014) *Food security and food production systems.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 485-533 p.

REARDON, T. & VOSTI, S. A. (1995) Links Between Rural Poverty and the Environment in Developing Countries: Asset Categories and Investment Poverty *World Development,* 23**,** 1495-1506.

ROOSE, E. J. (1976) *Use of the universal soil loss equation to predict erosion in West Africa Soil Erosion: Prediction and control. Soil Conservation Society of America, Ankeny, Iowa* Ankeny, Iowa, Soil Conservation Society of America, p.

SALVAGIOTTI, F., CASSMAN, K. G., SPECHT, J. E., WALTERS, D. T., WEISS, A. & DOBERMANN, A. (2008) Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. *Field Crops Research,* 108**,** 1-13.

SANCHEZ, P. A. & SWAMINATHAN, M. S. (2005) Hunger in Africa: the link between unhealthy people and unhealthy soils. *The Lancet,* 365**,** 442-444.

SANNI, A. & DOPPLER, W. (2007) Socio-economic determinants of household fertilizer use intensity for maize based production systems in the northern Guinea Savannah of Nigeria. *Journal of Applied Sciences,* 7**,** 1774-1779.

SCHERR, S. J. (2000) A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. *Food Policy,* 25**,** 479-498.

SCHLECHT, E. (1995) *The influence of different levels of supplementation on feed intake and nutrient retention of zebu cattle in Sahelian agro-pastoral systems,* Hohenheim, Germany, University of Hohenheim, PhD Thesis, p.

SCHMENGLER, A. C. (2011) Modeling soil erosion and reservoir sedimentation at hillslope and catchment scale in semi-arid Burkina Faso

SCONNES, I. (1998) *Sustainable rural livelihoods. A framework for analysis.* IDS Working Paper 72, 22 p.

SÉDOGO, P. M. (1993) *Évolution des sols ferrugineux lessives sous culture: incidence des modes de gestion sur la fertilité,* Abidjan, Côte d'ivoire, Université nationale de Côte d'ivoire, Doctorat, p.

SHIFERAW, B., TESFAYE, K., KASSIE, M., ABATE, T., PRASANNA, B. M. & MENKIR, A. (2014) Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and Climate Extremes,* 3**,** 67-79.

SMALING, E. M. A. & FRESCO, L. O. (1993) A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). *Geoderma,* 60**,** 235-256

SMALING, E. M. A., FRESCO, L. O. & DE JAGER, A. (1996) Classifying, monitoring and improving soil nutrient stacks and flows in African agriculture. *Ambio,* 25**,** 492-496.

SMALING, E. M. A., STOORVOGEL, J. J. & WINDMEIJER, P. N. (1993) Calculating soil nutrient balances in Africa at different scales II. District scale *Fertilizer Research,* 35**,** 237-250.

SOMDA, J., NIANOGO, A. J., NASSA, S. & SANOU, S. (2002) Soil fertility management and socio-economic factors in crop-livestock systems in Burkina Faso: a case study of composting technology. *Ecological Economics,* 43**,** 175-183.

SONAGESS (2013) Système d'Information sur les Marchés (SIM) 2013. IN SONAGESS (Ed.). Ouagadougou.

SPCPSA (2013) *Politique nationale de sécurité alimentaire et nutritionnelle.* Ouagadougou, Burkina Faso, SPCPSA, 58 p.

STOCKING, M. A. (2003) Tropical Soils and Food Security: The Next 50 Years. *Science,* 302**,** 1356-1359.

STOORVOGEL, J. & SMALING, E. (1990) *Assessment of soil nutrient depletion in Sub-Saharan Africa, 1983-2000.* Wageningen Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), 48, p.

STOORVOGEL, J. J., SMALING, E. M. A. & JANSSEN, B. H. (1993) Calculating soil nutrient balances in Africa at different scales. I. Supra-national scale *Fertility Research,* 35**,** 227-235.

SULTAN, B., ROUDIER, P., QUIRION, P., ALHASSANE, A., MULLER, B., DINGKUHN, M., CIAIS, P., GUIMBERTEAU, M., TRAORE, S. & BARON, C. (2013) Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters,* 8**,** 9.

THIOMBIANO, B. (2008) *Analyse de la contribution des cultures de saison sèche à la lutte contre la pauvreté au Burkina,* Bobo-Dioulasso, Université polytechnique de Bobo-Dioulasso (UPB), Ingéniorat, 55 p.

TITTONELL, P., MURIUKI, A., SHEPHERD, K. D., MUGENDI, D., KAIZZI, K. C., OKEYO, J., VERCHOT, L., COE, R. & VANLAUWE, B. (2010) The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa-A typology of smallholder farms. *Agricultural Systems,* 103**,** 83-97.

TITTONELL, P., VANLAUWE, B., LEFFELAAR, P. A., ROWE, E. C. & GILLER, K. E. (2005a) Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. *Agriculture, Ecosystems & Environment,* 110**,** 149-165.

TITTONELL, P., VANLAUWE, B., LEFFELAAR, P. A., SHEPHERD, K. D. & GILLER, K. E. (2005b) Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agriculture, Ecosystems & Environment,* 110**,** 166-184.

TOENNIESSEN, G., ADESINA, A. & DEVRIES, J. (2008) Building an Alliance for a Green Revolution in Africa. *Annals of the New York Academy of Sciences,* 1136**,** 233-242.

TRAORE, O. Y. A. (2012) *Etude de la fixation symbiotique de l'azote atmosphérique par le niébé (Vigna unguiculata L. Walp) avec la méthode de l'abondance naturelle en 15 N sous diverses pratiques culturales dans le Centre-Ouest du Burkina Faso,* Bobo-Dioulasso, Université polytechnique de Bobo-Dioulasso, Mémoire de DEA, p.

UN (2013) *World population prospects: The 2012 revision, highlights and advance tables.* New York, United Nations, Department of Economic and Social Affairs, Population Division, Working Paper No. ESA/P/WP.228 p.

VAN DEN BOSCH, H., GITARI, J. N., OGARO, V. N., MAOBE, S. & VLAMING, J. (1998a) Monitoring nutrient flows and economic performance in African farming systems (NUTMON). III. Monitoring nutrient flows and balances in three districts in Kenya. *Agriculture, Ecosystems and Environment,* 71**,** 63-80.

VAN DEN BOSCH, H., JAGER, A. D. & VLAMING, J. (1998b) Monitoring nutrient flows and economic performance in African farming systems (NUTMON) II. Tool development. *Agriculture, Ecosystems and Environment*, 71**,** 49-62.

VAN DER POL, F. (1992) *Soil mining. An unseen contributor to farm income in southern Mali.* Amsterdam, Netherlands, Royal Tropical Institute (KIT), Bulletin 325 p.

VAN DER POL, F. & TRAORE, B. (1993) Soil nutrient depletion by agricultural production in Southern Mali. *Fertilizer Research,* 36**,** 79-90.

VANLAUWE, B. & GILLER, K. (2006) Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystems & Environment,* 116**,** 34-46.

VITOUSEK, P. M., ABER, J. D., HOWARTH, R. W., LIKENS, G. E., MATSON, P. A., SCHINDLER, D. W., SCHLESINGER, W. H. & TILMAN, D. G. (1997) Human alteration of the global nitrogen cycle: Sources and consequences. *Ecological Applications,* 7**,** 737-750.

VITOUSEK, P. M., NAYLOR, R., CREWS, T., DAVID, M. B., DRINKWATER, L. E., HOLLAND, E., JOHNES, P. J., KATZENBERGER, J., MARTINELLI, L. A., MATSON, P. A., NZIGUHEBA, G., OJIMA, D., PALM, C. A., ROBERTSON, G. P., SANCHEZ, P. A., TOWNSEND, A. R. & ZHANG, F. S. (2009) Nutrient Imbalances in Agricultural Development. *Science,* 324**,** 1519-1520.

VLAMING, J., VAN DEN BOSCH, H., VAN WIJK, M. S., DE JAGER, A., BANNINK, A. & VAN KEULEN, H. (2001) *Monitoring nutrient flows and economic performance in tropical farming systems (NUTMON) - Part 1: Manual for the NUTMON-Toolbox,* Wageningen, The Netherlands, Alterra

VLEK, P. L. G., KÜHNE, R. F. & DENICH, M. (1997) Nutrient resources for crop production in the tropics. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences,* 352**,** 975-985.

VU, LE, Q. B. & FROSSARD, E. (2014a) Socio economic determinant of fertilizer use in Vietnam. *Sumitted.*

VU, Q. M., LE, Q. B., FROSSARD, E. & VLEK, P. L. G. (2014b) Socio-economic and biophysical determinants of land degradation in Vietnam: An integrated causal analysis at the national level. *Land Use Policy,* 36**,** 605-617.

WAITHAKA, M., THORNTON, P., SHEPHERD, K. & NDIWA, N. (2007) Factors affecting the use of fertilizers and manure by smallholders: the case of Vihiga, western Kenya. *Nutrient Cycling in Agroecosystems,* 78**,** 211-224.

WAKELYN, P. J., BERTONIERE, N. R., FRENCH, A. D., THIBODEAUX, D. P., TRIPLETT, B. A., ROUSSELLE, M.-A., WILTON R. GOYNES, J., EDWARDS, J. V., HUNTER, L., MCALISTER, D. D. & GAMBLE, G. R. (2006) *Cotton Fiber Chemistry and Technology,* CRC Press

WALKLEY, A. & BLACK, I. A. (1934) An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science,* 37**,** 29-38.

WHEELER, T. & VON BRAUN, J. (2013) Climate change impacts on global food security. *Science,* 341**,** 508-513.

WIGGINS, S. (2009) Can the smallholder model deliver poverty reduction and food security for a rapidly growing population in africa? *FAO Expert Meeting on How to feed the World in 2050.* 24-26 June 2009, Rome, Italy.

WISCHMEIER, W. H. & SMITH, D. D. (1978) Predicting rainfall erosion losses-A guide to conservation planning. *Agriculture Handbook No 537.* Washington D.C., USA, U.S. Department of Agriculture.

WORLD BANK (2003) *Reaching the rural poor: A renewed strategy for rural development.* Washington, DC, USA, World Bank, 174 p.

YILMA, T. & BERGER, T. (2006) Complementarity between Irrigation and Fertilizer Technologies-A justification for increased Irrigation Investment in the Less-Favored Areas of SSA *International Association of Agricultural Economists Conference.* Gold Coast, Australia, August 12-18, 2006

ZAIBET, L., TRAORE, S., AYANTUNDE, A., MARSHALL, K., JOHNSON, N. & SIEGMUND-SCHULTZE, M. (2010) Livelihood strategies in endemic livestock production systems in sub-humid zone of West Africa: trends, trade-offs and implications. *Environment, Development and Sustainability,* 13**,** 87-105.

ZINGORE, S. (2006) *Exploring diversity within smallholder farming systems in Zimbabwe: Nutrient use efficiencies and resource management strategies for crop production.,* Wageningen, The Netherlands., Wageningen University, PhD thesis, 258 p.

ZINGORE, S., MURWIRA, H. K., DELVE, R. J. & GILLER, K. E. (2007) Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems & Environment,* 119**,** 112-126.

ZOUGMORÉ, R., MANDO, A. & STROOSNIJDER, L. (2004a) Effect of soil and water conservation and nutrient management on the soil–plant water balance in semi-arid Burkina Faso. *Agricultural Water Management,* 65**,** 103-120.

ZOUGMORÉ, R., MANDO, A., STROOSNIJDER, L. & GUILLOBEZ, S. (2004b) Nitrogen flows and balances as affected by water and nutrient management in a sorghum cropping system of semiarid Burkina Faso. *Field Crops Research,* 90**,** 235-244.

ZOUGMORÉ, R., OUATTARA, K., MANDO, A. & OUATTARA, B. (2004c) Rôle des nutriments dans le succès des techniques de conservation des eaux et des sols (cordons pierreux, bandes enherbées, zaï et demi-lunes) au Burkina Faso. *Science et changements planétaires/Sécheresse,* 15**,** 41-48.

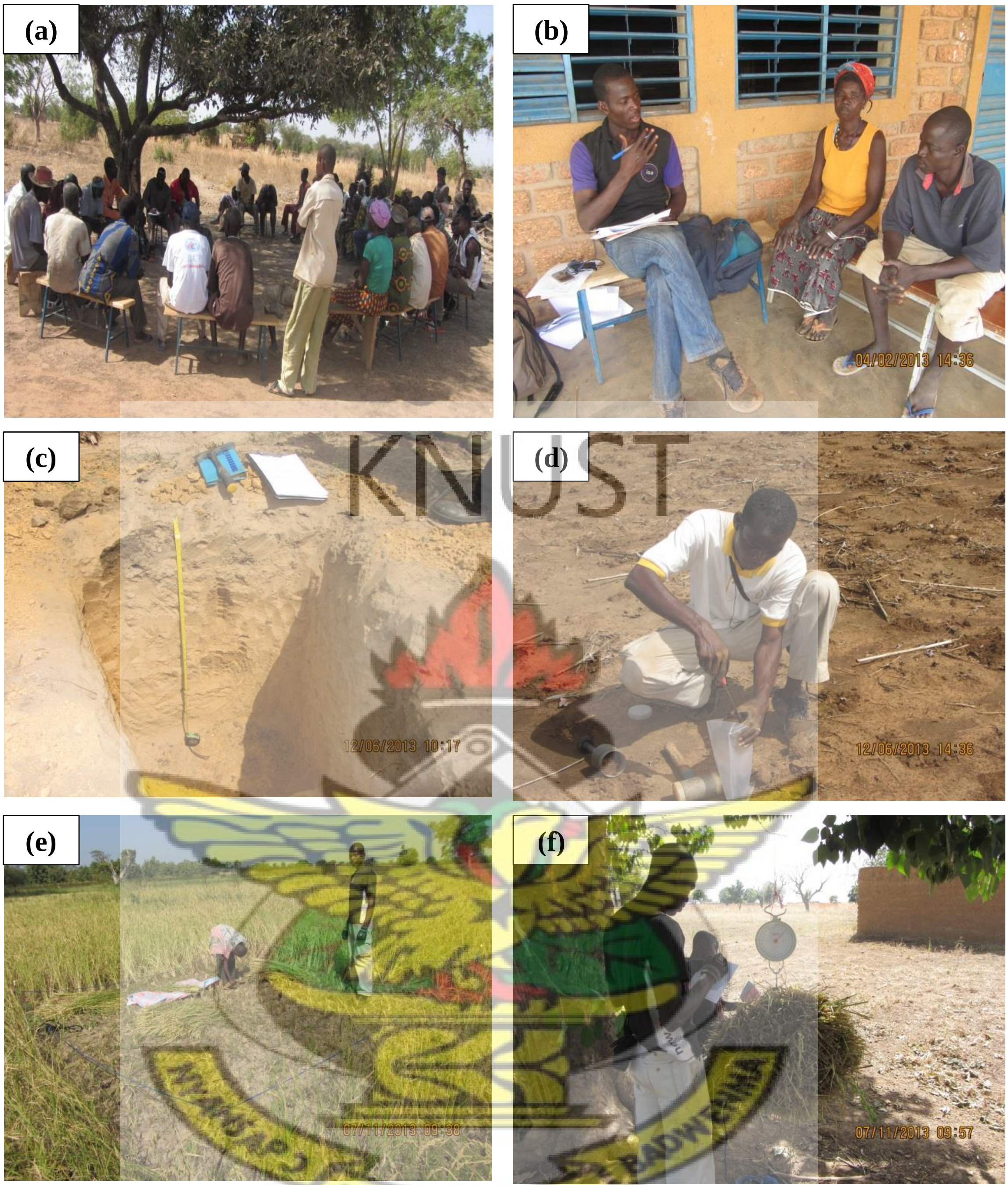
ZOUNGRANA- KABORÉ, C. (1995) *Composition chimique et valeur nutritive des herbacées et ligneux des pâturages naturels soudaniens et des sous-produits du Burkina Faso*, Ouagadougou, Burkina Faso, Université de Ouagadougou, Doctorat d'état, 224 p.

Appendices

Appendix 1 Descriptive statistics of main characteristics of five farm types.

Key variables	Household type				
	Type I (*Better-off, cotton- and livestock-based farms*)	Type II (*Better-off, non-farm activities oriented farms*)	Type III (*Pro-poor, labor-less and landless farms*)	Type IV (*Medium income, labor-rich, marketable food crop oriented and educated farms*)	Type V (*Poor, insecure-land tenure and livestock-based farms*)
Cash income per capita (FCFA/capita/year)	53,753[a]	**88,794**[b]	**31,502**[c]	59,453[ab]	**31,893**[c]
Tropical Livestock Units per capita	0.3[a]	0.1[b]	0.2[a]	0.2[ab]	0.3[ab]
Household's workers	6[a]	6[a]	**4**[b]	**11**[c]	7[a]
Share of cotton area (%)	**21**[a]	5[b]	3[b]	15[ac]	9[bc]
Share of non-farm activities income (%)	**19**[a]	**77**[b]	36[c]	34[c]	33[ac]
Share of owned land (%)	98[a]	96[a]	99[a]	97[a]	**32**[b]
Land holding per capita (ha/capita)	1.0[a]	0.8[ab]	**0.7**[b]	0.8[ab]	0.8[ab]
Share of marketable food crops area (%)	15[a]	14[ab]	**10**[b]	18[a]	17[a]
Highest schooling year of household head	**1**[a]	2[ab]	2[ab]	**4**[b]	**1**[a]
Dependency ratio	0.25[ac]	**0.22**[a]	**0.84**[b]	0.38[c]	0.40[ac]

Notes: For each variable, the group's mean values with same letter are not significantly different from each other at 95% ($p < 0.05$).



(a)-An informative meeting with farmers in the village of Loffing

(b)- A screen survey interview with a household in the village of Pontiéba

(c)- A soil profile in a farmer field in the village of Bekotenga

(d)- Soil sampling in a farmer field in the village of Kolinka

(e)- Yield-plot harvest in a rice field in the village of Pontiéba

(f)-Weighing crop and biomass harvested form a yield-plot in a rice field