Participatory Integrated Watershed Management in the north-western highlands of Rwanda

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Delighted

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Chapter 1

Introduction

Introduction

1.1 Agricultural production potentials and constraints in the north-western highlands of Rwanda

The north-western highlands of Rwanda are of great importance for agricultural production because of their fertile volcanic soils. The food production index for this area, between 1997 and 2009, steadily increased from 60 in 1997 to 121 in 2009 (NISR, 2010). This significant change was brought about mainly by: (1) bringing more land under cultivation, especially protected forests and (2) increasing the use of agricultural inputs such as fertilizers. Arable lands (% of agricultural lands) increased from 68% in 2000 to 81% in 2009 (NISR, 2010). This expansion was the result of reclaiming marginal lands such as steep hillsides and formerly protected natural forests. Some 77% of all agricultural lands in the north-western highlands of Rwanda have slopes between 13% and 55% (Verdoodt and Van Ranst, 2003). In some cases, even land with a slope of over 80% is put under cultivation (Clay and Lewis, 1990). The use of fertilisers increased rapidly with the most recent Crop Intensification Program (CIP) policy launched in Rwanda to boost agricultural productivity. From 2001 to 2011 the number of farmers using mineral fertilisers increased from 7% to 29%. Whereas the use of organic manure on the other hand increased only slightly, from 10% in 2000 to 13% of the farmers 2009 (NISR, 2010; NISR, 2012). To sustain the important contribution that the highlands make to Rwandan food security, some developing problems need to be addressed.

Despite the significant increase in agricultural production from this region we foresee problems in the near future as most of the arable lands are located on marginal, steep slopes and are continuously tilled with hoes leading to massive soil erosion and soil fertility depletion. Compared to potential yields of 5 t ha^{-1} for maize grain and 23 t ha^{-1} for potato, the actual yields are 1.5 t ha^{-1} and 14 t ha^{-1} for maize grain and potato, respectively (NISR, 2010). Two primary reasons for the gap between potential and actual yields can be identified: (1) high soil fertility depletion due to overexploitation and soil erosion, despite of the increase in the availability of fertilizer (Clay and Lewis, 1996) and (2) low adoption by farmers of promising agricultural technologies. Soil nutrients can be replenished better by applying adequate inorganic or organic fertilizer provided that farmers' technical skills and economical ability are enhanced. Also, there is a need to develop an approach that increases the adoption of existing agricultural technologies to cope with the high food demand of the population. If measures are not taken to address these issues, the agricultural potential of Rwanda's highlands will be compromised.

Technically these human-induced soil erosion and soil fertility depletion problems can be mitigated by soil & water conservation (SWC) measures (Stroosnijder, 2012). For the steep slopes of the north-western highlands, biological anti-erosion systems have been reported to be most efficient in reducing soil erosion (Roose and Ndayizigiye, 1997). Living hedges, where crops are grown on alleys in between the hedges (Drechsel et al., 1996), have been shown to be effective in minimizing soil erosion on steep slopes (Drechsel et al., 1996; Roose and Ndayizigiye, 1997). And integrated soil fertility management (IFSM) practices that include the use of fertilizer, organic inputs, and improved germplasm have been successfully tested at farmers' fields in the highlands of Rwanda (Kagabo et al., under preparation; Nabahungu et al., 2011). The challenge, and great need, is to bringing these tested and proven approaches into application to stop degradation and allow sustainable increases in crop production and hence improve farmers' livelihood.

1.2 Need for a new resource management approach: Problem definition and research questions

The above mentioned natural resource degradation is a critical problem in the north-western highlands of Rwanda leading to declining agricultural productivity and, as a consequence, decreasing food security and increasing rural poverty (REMA, 2010). Farm level interventions to improve natural resource management (NRM) have not yielded significant results because they overlook the fact that landscapes are interconnected and that the consequences of decisions about resource management and use extend beyond individual land users (German et al., 2012; Swallow et al., 2004). A more comprehensive approach is needed.

Development projects are biased towards soil and water management for agriculture despite a wide range of other NRM concerns among local actors. Similarly, agricultural research organizations often place undue emphasis on soil and water conservation without integrating livelihood concerns and other priority landscape level NRM challenges, e.g., competition for fodder where zero grazing is practiced in Rwanda (Kagabo et al., 2013) or crop destruction from free grazing in Ethiopia (German et al., 2012). As a result, watershed projects that relied heavily on government investments and were primarily structure-driven failed to address the equity issues of benefits, community participation, scaling-up approaches, monitoring and evaluation. Consequently these projects have fallen short of expectations, or left other important NRM issues unaddressed.

A higher level of intervention, like the watershed, has been proven to stimulate more coordinated efforts on the management of biophysical and social complexities (German et al., 2012; Mowo et al., 2010). Relevant boundaries for interventions are not necessarily the watershed, but units defined by non-biophysical parameters (administrative or cultural units) or at other scales such as a set of neighbouring farms or a particular landscape niche (German et al., 2007). Essential for the viability of the watershed approach is that ecological sustainability is linked with economical sustainability. The term ‘integrated’ represents this idea of coordinated linkage and leads to the concept of Integrated Watershed Management (IWM).

An essential component of IWM is “participation of relevant stakeholders”, implying that broad-based livelihood concerns guide the watershed management agenda (Wani et al., 2003). However, “participation of relevant stakeholders” as it is typically understood in IWM is too general for what is needed in the Rwandan highlands. For substantial progress to be made, the stakeholder participation needs to be active and effective. Enabling effective participation of stakeholders requires methodological innovations for ensuring effective representation in decision-making at watershed level by blending the “integration” and “participation” approaches. Hence the concept of Participatory Integrated Watershed Management (PIWM) is more suitable. In this context “integration” and “participation” are two approaches that feature in watershed-level work as a result of the synergies fostered between social, biophysical and policy innovations on the one hand, and efforts to systematically identify and integrate diverse interest groups in the innovation process on the other (German et al., 2012). Furthermore, PIWM helps to answer the question of “why would a farmer want to think beyond the farm level?”. PIWM has the potential to increase the collaboration and coordination of efforts among various partners who are all in search of appropriate technologies and alternatives for improved crop yields (German et al., 2012; Mutekanga, 2012).

Considering the above background, it is hypothesised that PIWM is a viable approach to promoting best SWC measures for more sustainable land use in the north-western highlands of Rwanda. To enable testing of this hypothesis, the following questions were addressed:

1. How sustainable is farming in the north-western highlands of Rwanda? (Chapter 2)
2. Can progressive (e.g. slow forming) terraces improve ecological sustainability? (Chapter 3)
3. Can Integrated Soil Fertility Management improve economic sustainability? (Chapter 4)
4. Can a PIWM approach stimulate farmers to manage their farms more sustainable? (Chapter 5)

1.3 Ecological and economic sustainability

The north-western highlands of Rwanda consist mainly of a rugged landscape with steep slopes. From a purely environmental perspective, these highlands should be converted to forest or grassland. However, there are few off-farm opportunities available for farmers if they vacate the steep lands. To face this reality, sustainable agricultural developement strategies need to be developed to use these marginal natural resources in such a way that they can still be used by future generations. Recent research evidence shows that the sustainability of these marginal lands is threatened by declining soil fertility leading to decreased food production (Kagabo et al., 2013; Nabahungu et al., 2011). Furthermore, most farmers living in these marginal lands are food insecure (Mugabo, 2010).

Despite the evidence of degradation of the environment, the role of the environment and sustainable agriculture development has been only narrowly defined in policy documents (Government-of-Rwanda, 2004). The link between the environment and agriculture development growth has not been adequately included in policy making processes. The policy documents usually only state that ecosystem services will ensure growth and poverty reduction if the well-being of the poorest groups is enhanced (Government-of-Rwanda, 2004). At the policy level, there are indications that still much need to be done in order to really integrate ecological, social and economic issues in agriculture development programs. The recognition of these issues among natural resource users and their integration into a holistic agricultural development program would be a good basis for striving for agricultural sustainability.

Smyth and Dumanski (1995) defined five indicators that can be used in assessing the sustainability of agriculture development programs including: (i) the level of productivity (productivity); (ii) the level of reduction of production risks (security); (iii) protect the quality/potential of natural resources (protection); (iv) economic viability (viability); and (v) social acceptance (acceptability). These indicators were further summarised by Castoldi and Bechini (2010) as being economic, environmental and social factors. Using a group of these indicators, or a single indicator such as nutrients, income, or energy, the sustainability of agricultural systems can be frequently evaluated (Castoldi and Bechini, 2010).

The sustainability of the current agricultural systems can be significantly enhanced by taking a holistic and dynamic approach that integrates technical and traditional practices for soil fertility management. This involves making the best use of inherent soil nutrient stocks, locally available soil amendments (e.g., crop residues, compost, manure), and mineral fertilizers to increase productivity while maintaining or enhancing the agricultural resource base. In addition, current agricultural development programs such as the Crop Intensification Program (CIP) should give consideration to Conservation Agriculture (CA). CA practices such as minimum or zero tillage has been reported to provide sustainability to intensification processes in hills and slopes in South America (Casão Junior et al., 2012). Available evidences suggest little or no adoption of CA by smallholder farms to date in most Sub-Saharan Africa (SSA) countries (Giller et al., 2009). Through a PIWM approach, CA practices such as minimum tillage and crop rotation can be easily promoted to farmers.

The viability of the PIWM approach can be improved if aspects of ecological and economic sustainability of natural resources are linked. Reducing the level of poverty and improving smallholder farmers' livelihoods depend on how agricultural production is organized and how the environment is harnessed for improved welfare without damaging it. A wide variety of technologies are available but improving the natural resource base without addressing issues of marketing and income generation, i.e., the resource to consumption logic, is a major reason for lack of their adoption. Adoption refers to the use and maintenance of technologies. NRM includes the use of improved germplasm and a minimum amount of inputs, thus requiring access to cash. Such cash can be made available if farm production is linked to potential local or urban markets and therefore re-invested in projects that protect NRs. Ecological, social and economic sustainability of agriculture systems can be achieved if the gap between income generation and investment in the natural resource base can be bridged.

1.4 Soil and water conservation (SWC) in the north-western highlands of Rwanda

The unique development challenge of the north-western highlands of Rwanda is how to quickly increase profitability and return on labour from smallholder, natural resource based, enterprises while at the same time increasing investment into the conservation of the steep and fragile terrains that are intensively cultivated (Kelly et al., 2001). Under these conditions, eradication of poverty through agriculture and other enterprises based on natural resources requires integrated measures which take multiple factors into account. Among these factors are understanding of the circumstances facing farmers, ecological potential, environmental needs, and economic opportunities and institutional context. These factors need to inform policies as well in order to create an enabling environment for tapping into the opportunities.

This intensive farming on steep slopes leads to crop productivity decline, as a result of soil loss and declining soil fertility (Clay and Lewis, 1996). Data from field plots and experimental stations (Byers, 1990; Lewis, 1988; Roose and Ndayizigiye, 1997) shows that soil losses range from 35 t ha^{-1} yr^{-1} to more than 100 t ha^{-1} yr^{-1}, depending on agricultural practices and slope steepness. However, recent field measurements of soil erosion found lower values (than reported before) that range from 12 t yr^{-1} to 42 t yr^{-1} on slopes ranging from 25% to greater than 60% (Kagabo et al., 2013). In many cases soil erosion rates are exaggerated because of inappropriate extrapolation from point measurements to field scale (Stroosnijder, 2012).

Human-induced soil erosion and soil fertility depletion can be mitigated by soil & water conservation (SWC) measures (Stroosnijder, 2012). However, a SWC measure on its own does not necessarily increase crop yields. Many SWC measures retain water and improve infiltration (Stroosnijder, 2009). Examples include mulching, organic inputs, terracing, hedgerow barriers (Drechsel et al., 1996). This extra water can only be used effectively if extra nutrients are added as well. It is rather that conservation methods capture more water and add new system components (e.g. trees, livestock) which increase the potential for improved productivity of crops (Stroosnijder, 2009; Vanlauwe et al., 2010).

Soil erosion is a local problem and often linked to poverty (Lomborg, 2001), hence realistic mitigation of land degradation is needed through public investments since poor farmers are seldom able to pay the full costs on their own (Stroosnijder, 2012). An alternative approach is the promotion of biological anti-erosion systems that are cost effective to smallholder farms (Kagabo et al., 2013; Tenge et al., 2007). Living hedges, where crops are grown on alleys in between the hedges (Drechsel et al., 1996), have been shown to be effective in minimizing soil erosion on steep slopes (Drechsel et al., 1996; Roose and Ndayizigiye, 1997). In the southern part of Rwanda, the annual soil loss under alley-cropping treatments ranged from 1 to 5 t ha^{-1} yr^{-1} in the fourth year of an experiment, while those under local farmers' practices were as high as 30 - 50 t ha^{-1} yr^{-1} with a maximum observed of 111 t ha^{-1} yr^{-1} (Konig, 1992). An even lower annual soil loss of < 3 t ha^{-1} yr^{-1} was recorded under anti-erosion ditches in combination with living hedges in the southern part of Rwanda (Konig, 1992; Lewis, 1988; Lewis and Nyamulinda, 1996; Roose and Ndayizigiye, 1997). Increased adoption of SWC measures as part of a more integrated solution can help to achieve the goals of reduced soil degradation, better NRM and increased crop productivity.

1.5 Integrated Soil Fertility Management (ISFM)

With increases in population of 2.9% per annum (NISR, 2010), food demand is rising and will continue to rise as a result. By 2017, for instance, the national maize grain demand for food is expected to total 555,000 t^{-1} yr^{-1}, 50% more than in 2010 (GoR, 2011). Grain supply is the product of crop area and crop yields (production per hectare). To meet this demand will require an increase in both crop area and crop yield, or an even larger increase in one of the two factors. In Rwanda cropland expansion is not a viable option since most of arable lands are already under cultivation (NISR, 2012).

In the densely populated north-western highlands of Rwanda, there is large variability in soil fertility and also differences in nutrient management between and within farms (Kagabo et al., 2013; Roose and Barthès, 2001). These differences are linked to the resource endowment of farmers which defines their capacity for investment (Clay et al., 1998; Giller et al., 2011; Nabahungu, 2012; Zingore et al., 2007). This implies that single solutions for improving farm productivity do not exist (Giller et al., 2011). Hence, in order to sustainably meet the national food demand without the expansion of croplands, more appropriate technologies and practices, e.g. ISFM, that positively impact environmental quality and ecosystem services while also improving crop yields need to be promoted. ISFM is defined by Vanlauwe et al., (2010) as "a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity".

ISFM practices can enhance the use of inherent soil nutrient stocks, mineral fertilizers and locally available organic inputs. Research conducted in several sub-Saharan countries demonstrated that implementation of ISFM principles on smallholder farms can substantially improve soil fertility and crop yield, and maximize the agronomic efficiency (AE) of applied nutrient inputs (e.g. Bationo et al., 2007; Lunze et al., 2012; Nabahungu et al., 2011; Vanlauwe et al., 2010). Adapting fertilizer recommendations to conform to specific combinations of crops and soil conditions is important for sustaining yields in landscapes with highly variable soil fertility gradients (Tittonell et al., 2007). Besides contributing to the increase in crop yields the mineral fertilizers also contribute to the improvement of the availability and quality of soil organic matter and, therefore, eventually their own efficiency (Vanlauwe et al., 2010). Organic resources are not substitutes for mineral fertilizers, they are however valuable soil conditioners and improve mineral fertilizer use efficiency (Vanlauwe et al., 2010; Vanlauwe et al., 2011). ISFM is as much principle as prescription which provides flexibility that is important for implementation by farmers of different economic means.

With the recent growing recognition by policy makers that enhanced farm productivity is a major strategy for breaking the vicious cycle underlying rural poverty (Vanlauwe et al., 2011), there is hope that more investment will be oriented toward rural farm management. This would lead to increased use of suitable technologies including ISFM components that are accessible to and affordable for resource-poor farmers. The most recent Crop Intensification Program (CIP) policy launched in Rwanda to boost agricultural productivity acknowledges that sustainable agricultural intensification requires the use of external nutrient sources, in particular improved germplasm and inorganic fertilizers in addition to more readily available farmyard manure (FYM). However, because of the low quality of available manure in Sub Saharan Africa (SSA) (Nyamangara et al., 2009), Vanlauwe et al. (2011) propose that organic resources such as FYM of poor quality should be mixed with mineral fertilizer to obtain optimal yields. This combination is seen as a sound management principle since neither of the two inputs is usually available in sufficient quantities or at affordable prices, and both inputs are needed in the long-term suitability of farms (Vanlauwe et al., 2011). The scientific evidence suggests that there is a need to follow a judicious and balanced policy of ISFM which simultaneously strongly promotes the use of inorganic fertilizer and also enhances the use of FYM for sustainable crop intensification in Rwanda.

1.6 Participatory integrated watershed management (PIWM)

The participatory integrated watershed management (PIWM) approach is defined as a process whereby users define problems and priorities, set criteria for sustainable management, evaluate possible solutions, implement programs, and monitor and evaluate impacts at the watershed scale (German et al., 2012). An essential component of this approach is its focus on active participation of relevant stakeholders. This has resulted in a variety of participatory methods. These include Participatory Rural Appraisal (PRA), Participatory Learning and Action (PLA) and Participation and Learning Methods (PALM). Although these approaches are differently termed, they share a general interest in addressing local scale processes through the use of participatory techniques (King, 2002). PIWM has the potential to blend these participatory approaches, and is driven mainly by the idea of working as a consortium of institutions, rather than taking a single institution approach (Mowo et al., 2010). PIWM, as a participatory tool to capture the knowledge of natural resource users, has gained huge support from scholars (Bekele et al., 2008; German et al., 2012; German and Taye, 2008; Joshi et al., 2004; Kerr, 2002; Kerr et al., 2007; Mowo et al., 2010; Pattanayak, 2004) and is well suited to the conditions in the north-western highlands of Rwanda.

While the standard approach to delineation of watersheds is strictly based on hydrological boundaries (Heathcote, 2009), in the east African highlands watershed boundary delineation for the purpose of improved NRM is based on the spatial characteristics of specific challenges to be addressed and the social dynamics therein (German et al., 2012). SWC measures are usually required across whole landscapes above the level of a watershed (German et al., 2012). This is because, while some watershed problems conform to hydrological boundaries, many others do not (German et al., 2012). Problems related to the declining quality and quantity of water and destruction of property from excess run-off, as well as the land-use practices contributing to this resource degradation, have clear hydrological boundaries (German et al., 2012). Yet many other landscape-level natural resource management problems do not. Soil fertility status of farms which can vary from field to field or farm to farm is a primary example (Tittonell et al., 2007). People are organized with administrative boundaries but natural resources which are interrelated to people do not recognize administrative boundaries (German et al., 2012). This explains why a watershed is nowadays considered as a landscape-level unit, an ideal natural environmental unit for implement of development programs. Water, soil and vegetation can be conveniently and efficiently managed in this unit. A watershed can therefore be defined (German et al., 2012) as the bio-hydro-geological unit consisting of land, water, vegetation, animals, ecology, climate, and people, and its socio-economic environment. As such the watershed is a system in which each of its components needs to be characterized, as well as the reciprocal relations between them, to ensure a complete comprehension of the system.

In many parts of Africa (e.g. Ethiopia, Kenya, Rwanda), governments, NGO’s and other development agencies have focused on coercion or incentives to promote the adoption of SWC, mostly bench or stone terraces (e.g. Amsalu Taye, 2006; Bizoza, 2011). This top-down approach has hindered rapid adoption of promising SWC measures (Bekele et al., 2008; Bizoza, 2011). To understand what farmers do and why is a prerequisite for successful adoption of SWC measures, and it requires a participatory approach (Stroosnijder, 2012). A participatory approach builds more trust among communities involved in SWC development programs. The participation induces decision sharing and has the potential to increase farmers' ownership of the existing and future SWC measures as well as ensuring their future sustainability (Bizoza and de Graaff, 2012). Higher yields as a result of SWC measures and farmers’ capacity to invest have been identified as additional key stimuli for increasing ownership and adoption of SWC measures (Bizoza, 2012). SWC measures initiated for instance in India through watershed projects have been reported to increase community participation (Bekele et al., 2008) and significantly contribute to agricultural productivity and natural resource conservation (Mula, 2008). Based on experiences elsewhere, a move from coercion to participatory decision making and implementation is the way forward.

Although PIWM is at its early stage, e.g., in Rwanda, Kenya and Ethiopia, it has already been proven to stimulate coordinated efforts on the management of biophysical and social complexities (German et al., 2012; Mowo et al., 2010). The essential components of PIWM have been adapted in Rwanda by the "Agasozi ndatwa" program. The "Agasozi ndatwa" program is defined as an effective way or a competitive approach to mobilizing a community to jointly implement the development plans - and uses a watershed as a planning unit while integrating social, economic, ecological and policy concerns. The concept of "Agasozi ndatwa" is based on the theory that each administrative entity should have a development model that includes all the features that make human livelihood meaningful, including soil conservation and best agricultural practices (REMA, 2010). "Agasozi ndatwa" creates synergies within development programs such as: (1) crop intensification programs (CIP), (2) zero grazing programs, (3) soil conservation programs and (4) 'one farm, one cow' programs (Kagabo et al., under review). This package of programs implemented simultaneously within "Agasozi ndatwa" enables full participation of diverse interest groups and stakeholders, as well as integrated decision-making that acknowledges system linkages (among water, soils, crops, trees, and livestock) and multiple spin-offs from any given intervention (German et al., 2007; Rhoades, 1998). In this context "participation" and "integration" are two concepts that help to ground the conceptual evolution and methodological innovation of "Agasozi ndatwa". "Agasozi ndatwa" addresses the question of "why would a farmer want to think beyond the farm level?". In this regards, "participatory" implies that the relevant boundaries for interventions are not necessarily the "watershed", but units defined by non-biophysical parameters (administrative or cultural units) or at other scales (for example, a set of neighbouring farms or a particular landscape niche) (German et al., 2007).

While some of the principles of PIWM have been adapted into "Agasozi ndatwa", a new development is the attempt by the government of Rwanda to channel policy programs toward farmers through pre-established innovation platforms (IPs). IPs provide a platform for working out how the "demand for integration", as an organizing principle for multi-stakeholder institutions and multiple disciplines, translates itself into a context for multi-stakeholder learning practice (Tenywa et al., 2011). The integrated approach emphasizes the integration of disciplines with technical, social and institutional dimensions (German et al., 2007; Rhoades, 1998) and objectives such as conservation and income generation (German et al., 2007; Joshi et al., 2004; Kerr, 2001; Kerr, 2002; Rhoades, 1998). While it is increasingly clear that the success of watershed management programs rests on the integration of conservation and livelihood goals, and technical and institutional interventions (German et al., 2012; German and Taye, 2008), few developing countries have effectively implemented such integration in practice (German et al., 2007). It is therefore essential that PIWM, locally adapted as "Agasozi ndatwa", integrates an understanding of the principles operating within natural and social systems to assure effective synergies of policies simultaneously implemented in a watershed. And the goals of PIWM for the north-western highlands of Rwanda should be increased collaboration and coordination of efforts among various partners who are striving together in search of appropriate technologies and alternatives for improved crop yields.

1.7 Description of the study area

This study was conducted in two contrasting agro-ecological zones of the north-western highlands of Rwanda, namely Gataraga and Rwerere (Figure 1.1). Gataraga is located in the Musanze district (01° 32' S, 29° 31' E), at the border of the Western and Northern Provinces and is part of the volcanic agro-ecological zone lying about 2400 m above sea level. Rwerere is located in the Burera District (01° 32' S, 29° 52' E) of the Northern Province. It is located in the highlands of the Buberuka agro-ecological zone of Rwanda at around 1650 m above sea level. Both Rwerere and Gataraga have a bimodal distribution of rainfall which allows crop cultivation during two subsequent cropping seasons. The average annual rainfall is 1584 mm in Gataraga and 1219 mm in Rwerere. Both sites are highly populated but present differences in soil erosion risk and in soil fertility potential (Byers, 1991). Due to a high population density and the limited land availability, land parcels are small with the average size of the holding (for one household) being just 0.5 ha (Mukuralinda et al., 2009). Furthermore, this 0.5 ha holding does not consist of one single parcel but of several parcels, sometimes distributed at some distance from the homestead.

The soil at the Gataraga site is developed on fertile volcanic ashes (Byers, 1992) and, hence, has a high potential for crop productivity. Gataraga has two distinct landscapes, a landscape comprised of mountains under the protected forest of the volcanoes national park, and another landscape sloping down to intensively cultivated lava plains. These lava plains are highly permeable and comprise fertile soils. The soils at the Rwerere site have moderate soil fertility (Kagabo et al., 2013) and are highly vulnerable to erosion (Yamoah et al., 1990). The soils in Rwerere are predominantly Ferralsols, interspersed with lithic Entisols on quartrite ridges (Yamoah, 1985). Rwerere is located in a steep and mountainous area and cultivation is often practiced on steep slopes (> 60%).

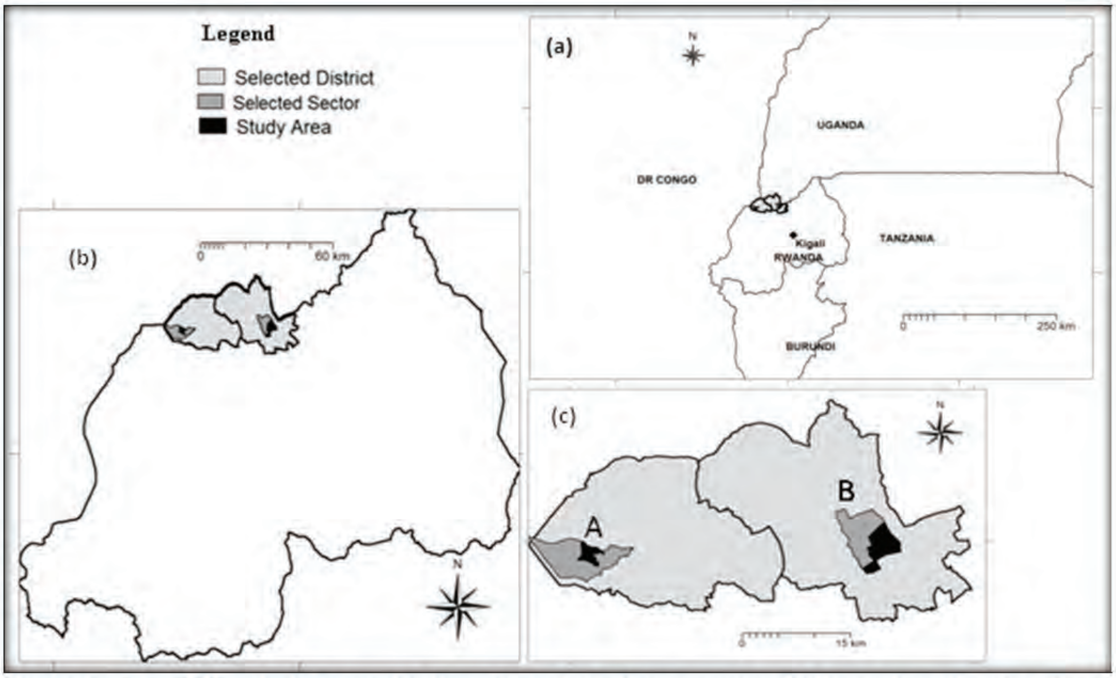

Figure 1.1 Localization of the study areas. (a) Rwanda in East African region, (b) Rwanda with selected districts, (c) selected sectors with A the Gataraga site and B the Rwerere study area.

1.8 Methodology overview and thesis outline

This thesis is the result of conducting assessments on the extent of current resource use and management practices using PIWM as a viable approach to promote best SWC measures for more sustainable land use. The impact of watershed development activities such as bench terraces, contour bunds and grass strips was assessed using net present value (NPV), internal rate of return (IRR), the economic surplus method and data collected from field experiments and diverse farm surveys. Three spatial scales comprising field, farm and watershed were identified, and Chapters 2 through 5 report results obtained at these three scales. All chapters are interrelated as recommendations from each preceding chapter served as the basis for the research conducted and reported in the next chapter. Chapters 2 to 5 have been developed as separate papers.

Following this introduction, Chapter 2 addresses the ecological and economic sustainability of Rwandan smallholder farmers using nutrient flow balance and economic indicators obtained at field and farm levels. Chapter 3 explores the efficiency of progressive (e.g. slow forming) terraces from farmers' fields across the watershed through quantifying soil loss and assessment of the impact of soil erosion on the soil fertility gradient, and the effect this has on crop yield. In Chapter 4, 'appropriate' technologies and alternatives for natural resources management were proposed to farmers including a package of technologies such as the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions. Chapter 5 discusses the impact of watershed development activities on agricultural production, socio-economics and environmental components in the region. Finally, Chapter 6 provides a synthesis of the research findings from the previous chapters and concludes with research and policy suggestions.

Chapter 2

Ecological and economic sustainability of smallholder farms in the densely populated Highlands of Rwanda

This paper will be submitted as:
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Abstract

The sustainability of smallholder farming systems in Rwanda is threatened by declining soil fertility leading to decreased food production. Improving the level of nutrient recycling of farm activities by using the outputs of one activity as input for another activity may increase the sustainability of food production on smallholder farms. In two contrasting agro-ecological zones nutrient balances, the level of nitrogen recycling between farm activities and farm income, were used to evaluate the ecological and economic sustainability of 49 smallholder farms in the highlands of Rwanda. The “Monitoring for quality improvement” (MonQI) toolbox was used to assess nutrient balances and economic performance at individual activity and farm wide levels. Three indicators (Finn Cycling Index (FCI), Dependency on external inputs (D) and Path Length (PL)) were considered to determine the level of integration and nitrogen recycling between farm activities. Nutrient balances and flows differed for the two agro-ecological zones due to differences in crop management and the importance of livestock. Positive nutrient balances were found for relatively fertile volcanic soils, but on steep slopes and acidic soils, N, P and K stocks were declining at rates of 8.6, 1.4 and 17.5 kg ha^{-1} $year^{-1}$, respectively. For farms with steep slopes and acidic soils, the cost of replenishment of mined nutrients was 20% of gross margin compared to only 0.2% of the gross margin of smallholder farms in the relatively high agricultural potential site. Nitrogen recycling between farm activities was low, varying between 1.8 and 6%, which may decrease the adaptability and reliability of the current farming systems in the highlands of Rwanda. Little of the farm produce reached the market and the contribution of crop produce to the net farm income was about 90% implying that the economic diversity of smallholder farms was very low with the exception of smallholder farms keeping large tropical livestock units (TLU). These findings reveal challenges and opportunities within the current farming systems for policy makers and other agriculture agencies in developing sustainable agricultural production and practices in the highlands of Rwanda.

Keywords: Smallholder farms, sustainability, nitrogen recycling, nutrient balance, Rwanda

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2.1 Introduction

Rwandan highlands are densely populated with 250 to 700 people per km^2 (Drechsel and Reck, 1997; Roose and Barthès, 2001) and most families are engaged in subsistence farm activities on steep slopes of 15% to > 60% (Roose and Ndayizigiye, 1997). In general the farm size in Rwanda is less than one hectare and the farm has to provide food for 5 to 10 family members (Kagabo and Nsabimana, 2010; Mugabo et al., 2007). Population density and the size of the land holdings have reached exceptional levels in the northern highlands forcing the farmers to over-exploit the available natural resource base (May, 1995).

Land degradation in Rwanda has been reported to be a consequence of intensive farming on steep slopes which leads to high erosion rates and, along with it, declining soil fertility (Clay and Lewis, (1996). As a result, farmers use a substantial amount of capital for farm inputs to enhance soil fertility and combat erosion (Byiringiro and Reardon, 1996; Clay et al., 1998; Roose and Barthès, 2001). In Rwanda, nearly 70% of smallholder farms use organic matter inputs and practice soil conservation with grass strips, anti-erosion ditches, hedgerows, and radical terraces (Clay et al., 1998). Available inputs, especially composted manure or farmyard manure (FYM), are preferentially spread on parcels of land around homesteads (Roose and Barthès, 2001) leading to variation in soil fertility within and across farms. Crops tolerant to low soil fertility such as sweet potatoes are planted on parcels that are far away from homesteads (Roose and Barthès, 2001). Furthermore, in the tropics biophysical conditions vary within short distances due to relief, parent rock material and altitude (Nizeyimana and Bicki, 1992). The compounding farming practices that prevail in the highlands of Rwanda increase these natural differences even more (Steiner, 1998). This implies that variability of soil fertility within and across small householder farms poses a major challenge in defining site specific options to improve crop productivity.

A certain level of controversy exists regarding the seriousness of soil fertility decline of small household farms in Rwanda. Stoorvogel et al. (1993) estimated depletion rates for Rwandan farms 60 kg N, 11 kg P_2O_5 and 61 kg K_2O $ha^{-1}year^{-1}$. However, Lewis (1988) reported that soil fertility decline is low in Rwanda compared to other countries having similar environmental conditions because of the layout of Rwandan agricultural fields. Especially the widespread cultivation of banana and the prevailing agricultural practice of intercropping provide good groundcover throughout the rainy season and as such a good protection against erosion by water. Byiringiro and Reardon (1996) reported that smaller farms are not more eroded than larger farms. Clay et al. (1998) reported that in Rwanda, crops on small householder farms have on average fairly high crop cover though variation across farms is high. Similar results were reported in the Mbeere District of Eastern Kenya where low levels of nutrient decline in small farms were observed, i.e., averages of just 1.7 kg P and 5.4 kg K ha^{-1} half $year^{-1}$ (Onduru and Du Preez, 2007).

Nutrient balances are frequently used to provide information on nutrient use efficiency and environmental impacts at farm system level (De Jager et al., 1998a). Although nutrient balances give insights into the nutrient utilization in the systems (De Jager et al., 1998a), they do not evaluate the role of internal nutrient cycling directly (Rufino et al., 2009a). For example, while several studies (Clay et al., 1998; Drechsel et al., 1996; Lewis, 1992; Roose, 1996; Roose and Ndayizigiye, 1997) reported that most Rwandan small householder farms use organic manure as an input, these studies fail to detail the level of nitrogen recycling between farm compartments or activities therefore limiting their use in making best practices recommendations.

Ecological sustainability of farming systems is often associated with the integration between farm household activities, i.e. by the use of output of one activity as input in another activity (Dalsgaard and Oficial, 1997). This process reduces adverse effects to the environment (avoiding danger and risks to humanity) and decreases the dependency on external (non-renewable and renewable) resources through recycling (Rufino et al., 2009a; Rufino et al., 2009b; van Beek et al., 2009). Hence, this study investigates the ecological sustainability of current practices of smallholder farms using nutrient balances and flows, and the nitrogen recycling level to characterize integration of farming activities. In addition, analysis of gross margin and net farm income provide deeper insights into the economic sustainability. The findings will allow decision makers to plan and implement integrated nutrient management policies and strategies at field and farm levels to improve crop productivity.

2.2 Materials and methods

2.2.1 The study area

The study was conducted in two contrasting agro-ecological zones of the Northern highlands of Rwanda, namely; Gataraga and Rwerere (Figure 2.1). Gataraga is located in the Musanze district (01° 32' S, 29° 31' E), Northern Province and is part of the volcanic agro-ecological zone lying about 2400 m above sea level. Rwerere is located in the Burera District (01° 32' S, 29° 52' E), Northern Province and is located in the highlands of the Buberuka agro-ecological zone of Rwanda at around 1650 m above sea level. Both sites are highly populated but differ in soil erosion risk and soil fertility. Due to the high population density and low land availability, land parcels are small averaging just 0.5 ha per holding or household (Mukuralinda et al., 2011) . Furthermore, this 0.5 ha holding does not consist of one single parcel but of several parcels, some of which can be quite far away from the homestead.

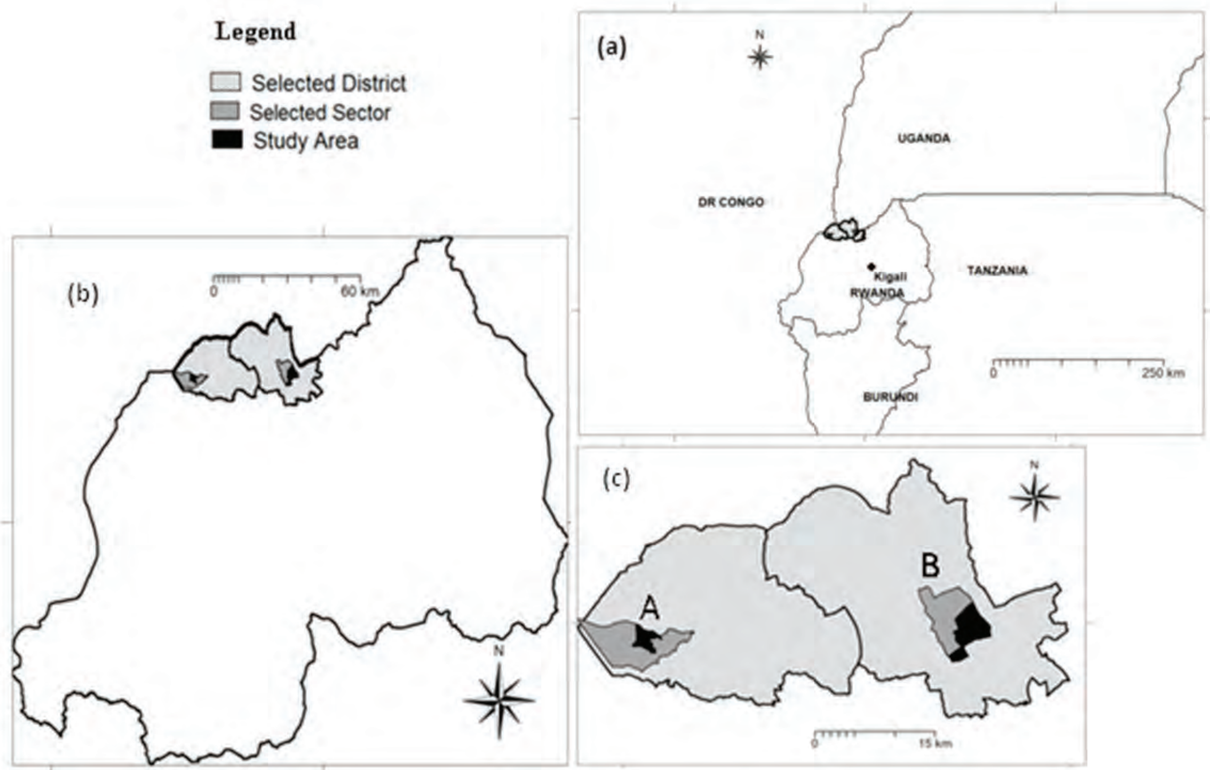

Figure 2.1. Localization of the study areas. (a) Rwanda in East African region, (b) Rwanda with selected districts, (c) selected sectors with A the Gataraga site and B the Rwerere study area.

The contrasts in agro-ecological characteristics include differences in soil, landform and cultivation practices. The soil at the Gataraga site is developed on fertile volcanic ash (Byers, 1992) and, hence, has high potential for crop productivity. Gataraga has two distinct landscapes, one comprised of mountains under protected forest in the Volcanoes National Park, and the other being cultivated land below the park which slopes down to the even more intensively cultivated lava plains. These lava plains are highly permeable and comprise fertile soils. The soils at the Rwerere site are moderately fertile and highly vulnerable for erosion (Yamoah et al., 1990). Rwerere is located in a steep and mountainous area and cultivation is often practiced on the steep slopes (> 60%). General biophysical characteristics of the sites are given in Table 2.1. The rainfall regime in both sites is bimodal in distribution, with relatively short rains from September/October to January, and long rains from February to June/July.

Table 2.1. General characteristics of the studied sites.

Characteristic	Gataraga	Rwerere
Altitude (m)	2350	1960
Annual temperature (^{o}C)	17	19
Annual precipitation (mm)	1564	1346
Soil pH (water)	5.8	4.8
Total N (%)	0.55	0.38
% organic carbon	5.4	3.5
ECEC (cmol kg^{-1})	16.5	8.9
Base saturation (%)	76	59
Clay (%)	25	43
Dominant lithology	Volcanic material	Quartzite and schist complex

2.2.2 *Sampling*

The data used in this study were collected through an inventory and monitoring questionnaire which is part of the MonQI tool (De Jager et al., 1998b; Van den Bosch et al., 1998a; Van den Bosch et al., 1998b). MonQI is an extension of NUTMON and is a multi-scale and multi-disciplinary tool for monitoring management and performance of small scale agricultural enterprises.

In each study zone a three stage random sampling procedure was used to select households: (i) from each zone one administrative sector was selected, (ii) from the selected sector, one cell (an administrative unit composed of at least three villages) was selected, and (iii) from the selected cell, one village was selected. The villages have between 80 and 150 households. In both Gataraga and Rwerere 31 households were randomly selected but only 18 households in Rwerere could participate in the study since other farmers had moved to a newly established village and were no longer interested to participate in the study.

2.2.3 *Farm nutrient balances and flows*

A total of 49 smallholder farms were involved in the study. The cropping calendar follows the bimodal rainfall distribution pattern. Interviews were held at the end of two consecutive cropping seasons to capture information on nutrient flows into and out of the farms and the distribution of nutrients within the farms. Flows into the farm (inflows) are in the form of inorganic fertilizers (IN 1), organic inputs (IN 2), atmospheric deposition (IN 3), nitrogen fixation (IN 4) and sedimentation (IN 5). Flows out of the farm (outflows) are harvested products (OUT 1), exported crop residues (OUT 2), leaching losses (OUT 3), gaseous losses (OUT 4), and erosion (OUT 5). Table 2.2 provides an overview of the in- and output fluxes that were used for the quantification of the nutrient balances.

Table 2.2. Parameters used in the quantification of nutrient balances (after De Jager et al., 1998).

Inputs	Outputs
IN1: mineral fertilizer	OUT1: harvested products
IN2: organic inputs	OUT2: residues removed
IN3: atmospheric deposition	OUT3: leaching losses
IN4: nitrogen fixation	OUT4: gaseous losses
IN5: sedimentation	OUT5: erosion

Quantities of product flows were recorded using farmers' units and then converted into standard metric units. To quantify the soil nutrient stocks, soil samples were taken from the 0 to 30 cm soil layer using a stratification method. Laboratory analysis of total N, P and K, organic carbon, base saturation, particle size distribution and bulk density was conducted using methods recommended for tropical soils (Anderson and Ingram, 1994). Secondary data included rooting depth (m), N mineralisation rate (% per year), bulk density (kg m^{-3}), erodibility (K factor in USLE equation), a nutrient enrichment factor and dry matter and N, P, K content in crop products.

Rainfall was collected from a weather station in the watershed. All data were processed using MonQI computer software. The validity and consistency of data were checked through debugging options in the software. Processed data were then exported and statistical calculations were performed using PASW Statistics 17.0 (SPSS Inc., Chicago, IL, USA).

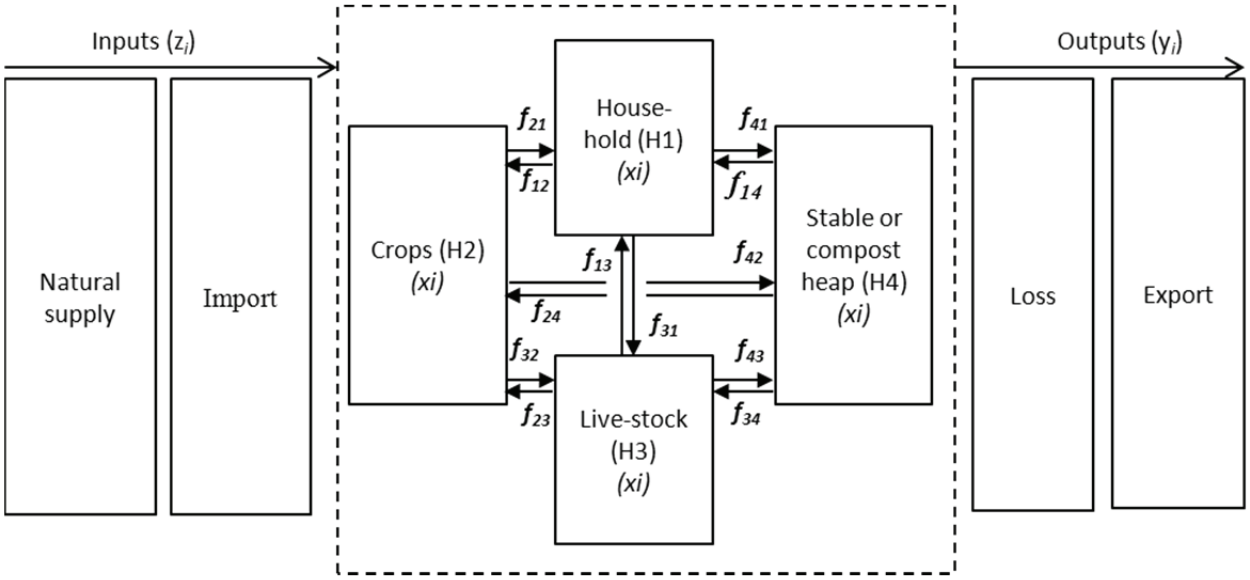

Figure 2.2 .Schematic N flow diagram with four compartments H1, H2, H3 and H4 and their storage (xi), internal flows (f_{ij}) and exchanges from (z_i) and to the external environment (y_i) for smallholder farms. Adapted from Rufino et al. (2009) and Tabata et al. (2009). The dashed rectangular box defines the farm system boundary.

2.2.4 Nitrogen recycling between farm activities

We selected a simple methodological approach called Network Analysis (NA) to quantify the integration of smallholder farm compartments/activities, a method described in detail by Rufino et al. (2009a; 2009b). Since nitrogen is the most limiting production factor in low input agriculture, flows of nitrogen were used in the analysis. Figure 2.2 shows a flow diagram of N in the production system. The system consists of four aggregated compartments (crops, livestock, stable/compost heap and household). N flowing between these compartments was defined as internal flow and symbolized by (f_{ij}) where $_i$ represents inflows and $_j$ represents outflows of N imported into and exported from a compartment. N flowing from an external source to farm compartments was symbolized by (z_i) and outflows from the whole system were symbolized by (y_i). The direction of N flow is expressed by arrows in Figure 2.2.

Based on the N flows diagram model, a set of three indicators was used to assess the degree of integration of farm household activities. The selected indicators are: (1) The Finn Cycling Index (FCI), (2) Dependency on external inputs (D) and (3) Path length (PL). The Finn Cycling Index (FCI) is computed according to equation 2.1.

$$FCI = TSTc/TST \qquad [2.1]$$

Where:
TSTc is the total of cycling efficiencies and
TST is the total system through flow (T_i), i.e. the sum of all the T_i in the system.

Through flow (T_i) is defined as the flow of N from one compartment into another compartment plus the inflow from external and the N stored (xi) in the compartment, see equation 2.2.

$$T_i = \sum_{j=1}^{n} f_{ij} + zi - (xi) \qquad [2.2]$$

Total of cycling efficiencies (TSTc) is computed according to equation 2.3.

$$TSTc = \sum_{i=1}^{n} RE_i T_i \qquad [2.3]$$

Where:
RE is defined as the recycling efficiency of N estimated as the fraction of Ti that returns to the compartment, see equation 2.4.

$$RE_i = (N_{ii}^{**} - 1)/N_{ii}^{**} \quad [2.4]$$

Where:
N_{ii}^{**} is the diagonal of the matrix of flows generated by a unit of flow.

The indicator of dependency on external inputs (D) is computed according to equation 2.5.

$$D = IN/TST \quad [2.5]$$

Where:
IN are imports estimated as the amounts of N that are imported from the external environment into the system, and
TST is the sum of all the T_i in the system.

Path length (PL) is a measure of nutrient cycling intensity within a farm system. PL indicates the average number of compartments that a unit of inflow passes through and was computed according to equation 2.6.

$$PL = TST/TIN \quad [2.6]$$

Where:
The total inflow (TIN) into the system was defined as the sum of N flows from external inputs (z) into all n compartments (H1-H4) plus the amounts of N stored (*xi*) in all compartments, see equation 2.7.

$$TIN = \sum_{i=1}^{n} zi - \sum_{i=1}^{n} (xi) \quad [2.7]$$

2.2.5 Economic indicators and determinants of nutrient balances

For the analysis and tracking of farm financial performance and profitability, a number of economic indicators, summarized in Table 2.7, were used. Lumped economic indicators such as Variable Costs (VCs), Gross Income (GI), and their difference (Gross Margin, GM), were used to establish the relationship between crops and nutrient balances. Indicators such as market share were used as a measure for the level of subsistence and participation in the market. The gross margin (GM) was calculated as the difference between the value of production (VP) and total direct costs (TC) (variable costs + fixed specific costs). The sum of variable costs includes the costs of pesticides, fertilizers, seeds and labour. The information for this analysis was provided by farmers during the MonQI survey.

Economic performance indicators of household farms were determined using nutrient deficit market value (NDMV) which is the value of nutrients mined per hectare if such nutrients were to be replenished by applying purchased fertilizer (der Pol, 1993). Depleted nutrients were considered to have a monetary value equal to the market value of an equivalent amount of fertilizers (De Jager et al., 1998a). The share of a farmer’s income “generated” from soil nutrient mining was determined using the economic nutrient depletion ratio (ENDR) defined as follows: ENDR = (*NDMV/GM) x* 100, where GM is the gross margin from agricultural activities per household. ENDR is the value of mined nutrient for entire farm as a % of household income (De Jager et al., 1998a; der Pol, 1993; Drechsel et al., 2004; Nkonya et al., 2005). An analysis of the determinants of nutrient balances was also conducted using major factors that affect land management at farm and field levels. These included off farm income (NFI), GM, farm size, livestock herd measured in tropical livestock units (TLU), education level, age of HHH, slope (%), soil conservation measures and organic and inorganic inputs.

2.3 Results

2.3.1 Nutrient flows and balances

Results of nutrient flows and balances are presented in Table 2.3. On the input side, organic material (IN2) dominated with 93, 90 and 94% of the total farm inflows for N, P and K, respectively, for Gataraga and 82, 85 and 87% for Rwerere. Chemical fertilizers (IN1) represented only 1% to 6% of the total farm N inputs. In Gataraga, the average partial nitrogen balance is positive (Table 2.3) indicating that farmers apparently import more nutrients through inputs than are exported through sale of products, but factors such as erosion cause the total balance of N to still be negative. The averages for both partial and full nutrient balance were negative for Rwerere (Table 2.3) as a result of intensive farming on the steep slopes which leads to high incidence of erosion and soil loss.

Regarding output effects, in Gataraga, N loss was primarily caused by the removal of harvested products (OUT1) whereas in Rwerere the major loss pathway for N was erosion (OUT5) which accounted for 45% of total N outflows. In both Rwerere and Gataraga, P and K losses were mainly caused by the removal of crop residues (OUT2).

Full nutrient balances differed significantly between farms and across locations for N and K ($P < 0.001$) as well as for P ($P < 0.05$). The N, P and K depletion rates varied greatly among farms and locations. The depletion rate of N varied between 2.17 kg N ha^{-1} year^{-1} in Gataraga and 8.56 kg N ha^{-1} year^{-1} in Rwerere.

2.3.2 N flows between farm compartments

Table 2.4 shows a matrix of N flows between farm compartments in the two study locations. Major N fluxes were found between compost heaps and crops as well as between households and compost heaps, a portion of which is used for animal bedding and feed. Harvested products were to a large extent used at household level for consumption while household waste was used as organic fertilizer.

In Rwerere high flows of N (2054 kg of N) were recorded between compost heaps and cattle compartments. Similarly, the translocation of N (588 kg of N) was high between external inflows and the compost heap compartment. This is because livestock are mostly kept in stables and fed with either crop residues, domestic wastes or wild shrubs/grasses collected in nearby swamps. In Gataraga, less translocation of N occurs between cattle and compost heaps because most of the manure produced by the cattle is either sold to other farmers or transferred directly to other farm compartments. The largest inflow of N from compost heaps to crops was observed on beans (104 kg of N) in Gataraga and peas in Rwerere (38 kg of N). In Rwerere, maize had the least N inflow from compost heaps (0.9 kg of N). Maize was mainly grown as a field crop on steep slopes of the Rwerere hillside. Only 7.5 kg of N from compost heaps were transferred to potato in Rwerere while much more N (42 kg of N) was applied to potato in Gataraga. While Rwerere had more N internal and external flows especially from organic materials on most crops compared to Gataraga, most of crop nutrient balances (N, P and K) were negative due to high erosion (Table 2.5). Contrary to the anticipated expectations, higher yields of maize (3 t ha^{-1}) and wheat (2.9 t ha^{-1}) were recorded in Rwerere, where nutrient flows and balances were negative, than in Gataraga where maize yield was 1.4 t ha^{-1}, wheat yield was 2.1 t ha^{-1} and where nutrient balances and flows were mostly positive (Table 2.5).

Table 2.3. Average flows and balances of major nutrients (kg ha^{-1} $year^{-1}$) of smallholder farms in Gataraga and Rwerere, Rwanda (standard deviation in parenthesis).

Inflows	Gataraga			Rwerere		
	N	P	K	N	P	K
IN1	0.32	0.15	0.25	0.09	0.005	0.01
	(1.43)	(0.64)	(1.19)	(0.97)	(0.04)	(0.08)
IN2	16.64	2.13	9.84	5.6	0.63	2.74
	(34.03)	(5.97)	(20.68)	(12.4)	(1.50)	(6.14)
IN3	0.54	0.09	0.35	0.63	0.103	0.41
	(0.70)	0.12)	(0.46)	(0.69)	(0.114)	(0.46)
IN4	0.43	0.00	0 .00	0.51	0.00	0.00
	(0.57)			(0.56)		
Outflows						
OUT1	-4.59	0.00	0.00	-7.07	0.00	0.00
	(19.42)			(16.60)		
OUT2	-0.19	-1.47	-3.59	-0.49	-2.13	-15.97
	(0.87)	8.78)	(11.64)	(1.44)	(10.25)	(38.90)
OUT3	-2.22	0.00	0.00	-0.37	0.00	-0.97
	(5.04)		(2.15)	(0.77)		(0.95)
OUT4	-1.21	0.00	0.00	-0.54	0.00	0.00
	(2.33)			(0.78)		
OUT5	-11.88	-0.08	-5.47	-6.96	-0.03	-3.85
	(19.01)	0.12)	(9.05)	(13.36)	(0.06)	(7.38)
Partial Balance	12.17	0.81	6.49	-1.83	-1.49	-13.23
	(28.44)	(7.70)	(22.73)	(19.38)	(9.60)	(37.16)
Full Balance	-2.17**	0.82*	0.09**	-8.56**	-1.42*	-17.6**
	(10.41)	(2.74)	(6.82)	(14.68)	(4.33)	(17.49)

*IN1 Mineral Fertilizers, IN2 Organic inputs, IN3 Atmospheric deposition, IN4 Biological nitrogen fixation, OUT1 Harvested products, OUT2 Crop residues and Manure, OUT3 Leaching, OUT4 Gaseous losses, OUT5 Erosion. Partial Balance=(IN1+IN2)-(OUT1+OUT2). Full balance=∑IN-∑OUT, * P<0.05, **P<0.01*

Table 2.5. Average yield (t ha^{-1}), nutrient balances (kg ha^{-1}) for selected crops in smallholder farms in Gataraga and Rwerere, Rwanda (standard deviation in parenthesis).

Crop	Gataraga				Rwerere				National Average
	Yield (t ha^{-1})	N	P	K	Yield (t ha^{-1})	N	P	K	Yield (t ha^{-1})
Potato	17.2	5	3	4	14.0	-6	0	-9	8
	(4.9)	(37)	(3)	(23)	(3.8)	(29)	(2)	(19)	
Maize	1.4	5	3	10	3.0	-36	-6	-14	1.2
	(0.9)	(22)	(5)	(31)	(0.8)	(30)	(5)	(13)	
Beans	1.5	8	2	-2	1.1	-14	0	-59	0.9
	(0.4)	(34)	(4)	(24)	(0.5)	(22)	(2)	(47)	
Wheat	2.1	-23	1	0	2.9	-82	-1	-1	1.7
	(1.8)	(28)	(2)	(12)	(0.7)	(47)	(2)	(6)	

Table 2.4. Analysis of averaged N (kg of N per compartment per year) flows for household farms in Gataraga and Rwerere, Rwanda.

Gataraga

	j (from) →	1	2	3	4	5	6	7	8	9	10	0
i (to)	Compartment	Beans	carrots	Cattle	Chicken	Compost heaps	Maize	Potato	Sheep	Household	Wheat	Inflows
1	Beans	0.0	0.0	0.0	0.0	104.0	0.0	0.0	0.0	0.6	0.0	7.5
2	Carrots	0.0	0.0	0.0	0.0	36.2	0.0	0.0	0.0	11.0	0.0	0.0
3	Cattle	0.3	0.0	0.0	0.0	0.0	0.4	0.6	0.0	0.0	3.5	0.4
4	Chicken	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	Compost heaps	0.3	0.0	0.0	0.0	0.0	0.6	0.4	0.0	226.5	0.1	4.1
6	Maize	0.0	0.0	0.0	0.0	55.3	0.0	0.0	0.0	0.1	0.0	6.8
7	Potato	0.0	0.0	0.0	0.0	42.0	0.0	0.0	0.0	0.2	0.0	3.6
8	Sheep	0.3	12.9	0.0	0.0	0.0	0.2	0.5	0.0	0.0	0.0	0.0
9	Household	4.3	13.7	0.3	0.0	0.0	1.4	2.4	0.0	0.0	45.7	1.9
10	Wheat	0.0	0.0	0.0	0.0	75.0	0.0	0.0	0.0	2.5	0.0	29.9

Rwerere

	j (from) →	1	2	3	4	5	6	7	8	9	10	0
i (to)	Compartment	Bean	Cattle	Compost heaps	Maize	Peas	Potato	Sheep	House-hold	Sweet potato	Wheat	Inflows
1	Bean	0.0	0.0	10.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.6
2	Cattle	0.5	0.0	0.0	4.0	2.4	0.5	0.0	0.0	0.0	0.0	0.4
3	Compost heaps	0.1	2053.8	0.0	5.3	0.2	0.1	0.0	0.0	0.0	0.0	588.3
4	Maize	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
5	Peas	0.0	0.0	37.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	Potato	0.0	0.0	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
7	Sheep	0.1	0.0	0.0	0.0	0.1	0.4	0.0	0.0	2.7	0.0	0.0
8	Household	9.3	3.4	23.8	22.5	26.2	2.5	0.0	0.0	2.0	43.3	0.4
9	Sweet potato	0.0	0.0	18.2	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0
10	Wheat	0.0	0.0	23.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.2

N flows from one compartment (column j) to another (row i = 1, …10) expressed in kg of N per compartment per year. Inflows (column j = 0) and outflows (row i = 1, …10) are the total amounts of N imported to and exported from a compartment.

2.3.3 Degree of integration of farm compartments

Table 2.6 shows values for N flows as well as calculated values for the indicators presented in section 2.4. Total cycling efficiencies (TSTc) and the Finn Cycling Index (FCI) were large in Rwerere (TSTc nearly 214 kg N farm $^{-1}$ year^{-1}, FCI = 6%) and relatively small for Gataraga (TSTc less than 13 kg N farm $^{-1}$ year^{-1}, FCI = 1.8%). This is due to the strong variation in the management of manure, stable or compost heaps and livestock, between Rwerere and Gataraga.

The dependency, D = IN/TSP, on external N inputs was close to zero in both Rwerere (0.076) and Gataraga (0.17) indicating that the management of smallholder farms depended little on external inputs. The amount of P and K translocated between crops and animals (data not presented here) accounted for 98% of the total P flows and for 77% of the total K flows. Finally, the path length, PL, (Table 2.6) which shows the intensity of nutrients re-cycling between farm compartments before leaving farm boundaries was high (PL = 6 for Rwerere and PL = 13 for Gataraga).

2.3.4 Economic indicators at farm and activity levels

Four crops (wheat, potato, maize and beans) were monitored on the farms with the aim of considering the management effects on nutrient flows and economic indicators. Variables costs were high, with extreme variability among farms (Figure 2.3c). Seeds represented the main proportion of all variable costs (data not presented here), 77% for Gataraga and 87% for Rwerere. Variable costs attributable to mineral fertilizers was very low in Rwerere (1% of the total variable costs) whereas in Gataraga it reached up to 13% of the total variables costs. Generally, the total cost of farm inputs (seeds, fertilizers, manures, and pesticides) outweighed the costs of labour. For instance, in Gataraga, the total labour costs to grow potato averaged US$ 135 ha^{-1}, which is about 30% of the costs of inputs at US$ 360 ha^{-1}.

Higher gross margin was found for crops with the highest variable costs of production, mostly potatoes (Figure 2.3a), indicating that increasing the use of inputs has the potential to increase economic sustainability. Nevertheless, the major economic indicators (Table 2.7) show that the studied smallholder farm systems operated on a subsistence scale since most of the farm production is utilized immediately in the household as food (low % of produce sold). While Table 2.7 indicates that the mean net farm income for both sites is positive, it was found that net cash flow for about 58% and 27% of investigated farms was negative in Rwerere and Gataraga, respectively. We also see that off farm income contributed to household earnings by nearly 58% for Gataraga and 42% for Rwerere. This suggests that farm production was not sufficient for the household food needs and that farmers resorted to other means to bridge income and food gaps.

Table 2.6. N flows and integration indicators of farms activities in Gataraga and Rwerere, Rwanda.

N flows	Gatagara	Rwerere
IN (kg N farm $^{-1}$ year^{-1})	54.1	595.7
TIN (kg N farm $^{-1}$ year^{-1})	57.6	599.2
TST (kg N farm $^{-1}$ year^{-1})	710.4	3569.2

Integration indicators	Gatagara	Rwerere
TSTc (kg N farm $^{-1}$ year^{-1})	12.5	213.6
FCI (%)	1.8	6
D or the ratio of IN/TST	0.076	0.17
T (kg N farm $^{-1}$ year^{-1})	1026.1	3995.7
PL	13.1	6.0

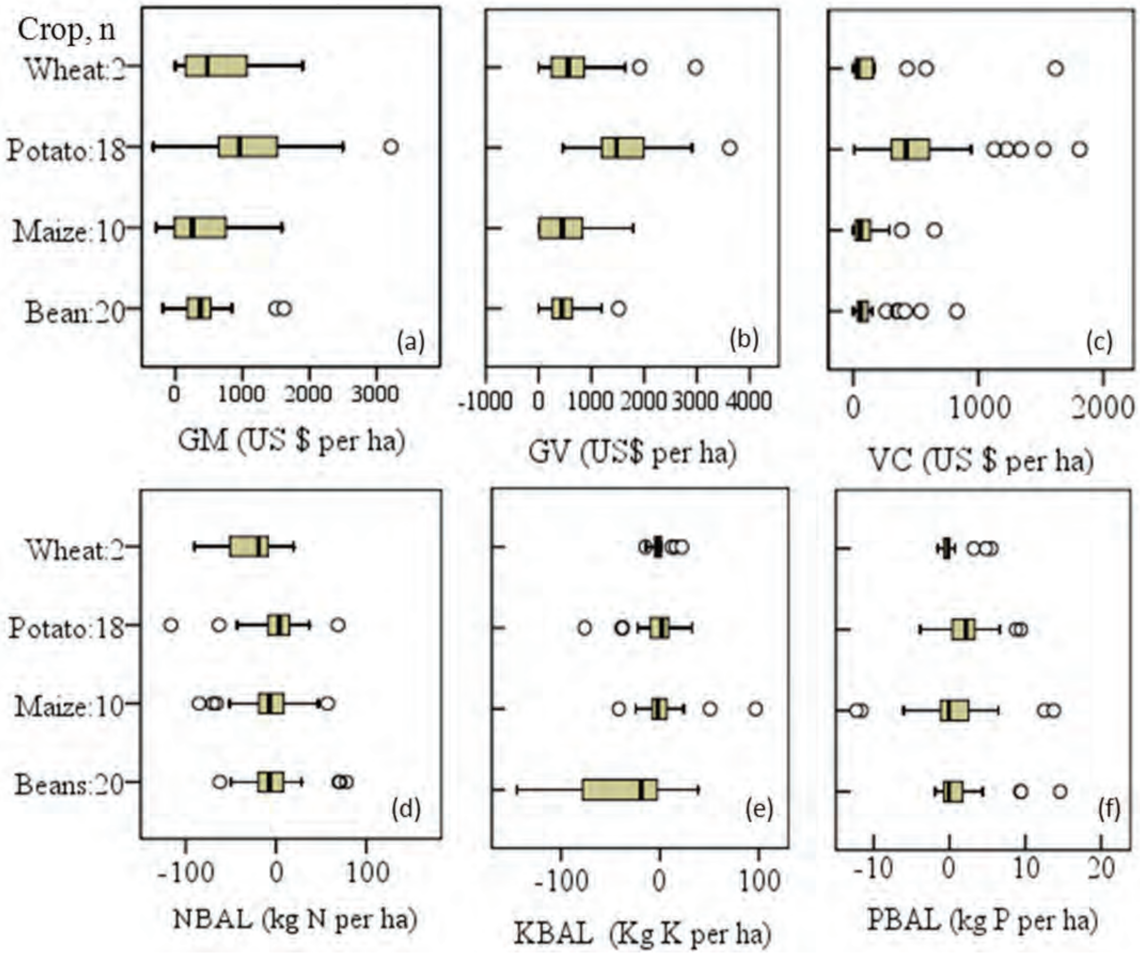

Figure 2.3. Box plots of agro-ecological and economic indicators calculated for 4 crops in the northern highlands of Rwanda: (a) gross margin (GM); (b) gross value (GV); (c) variable costs (VC); (d) nitrogen full balance (NBAL); (e) potassium full balance (KBAL); (f) Phosphorus full balance (PBAL). The boxes indicate the 1st and 3rd quartiles of the distribution, the bold line is the median, the bars are the maximum and minimum, and the points represent the outliers.

Table 2.7. Farm economic indicators for Gataraga and Rwerere (Rwanda) over a half-year period.

Economic Indicators	Mean value of economic indicators	
	Gataraga	Rwerere
Net farm income (US $)	191	146
Off-farm income (US $)	110	46
Off-farm income (% of net farm income)	58	32
Farm earnings (US $)	301	192
Farm earnings (US $ person^{-1})	50	38
Farm net cash flow (US $)	172	50
Farm net cash flow (% of farms with negative values)	27	58
Market share (% of produce sold)	15	5
Family labour on land activities (adults day^{-1})	20	27
Hired labour on land activities (adults day^{-1})	2	4
Agricultural wage labourer (adults day^{-1})	2	5
Return to family labour (US $ adult^{-1} day^{-})	1.2	0.8
Opportunity cost of labour (US $ adult^{-1} day)	0.9	0.7

Net farm income (NFI = Gross margin at Agriculture Enterprise level – Fixed cost); Family earnings = net farm income + off-farm income

2.3.5 Determinants of nutrient flows and economic evaluation of nutrients depletion

In Table 2.8, regressions between a large number of farm characteristics with major nutrient balances or flows show that tropical livestock unit (TLU) has a significant influence on nutrient flows. This suggests that farmers with more livestock are likely to apply on-farm produced animal manure to their plots and hence manage their farms more sustainably. In both Rwerere and Gataraga livestock is under strict zero grazing regulations indicating that most of the FYM produced and collected in the animal enclosure is available for use as crop fertilizers. Soil conservation practices, gross margin and the slope were also important, especially for P and K balances and flows (Table 2.8).

Table 2.8. Standardized regression coefficients for determinants of smallholder farm nutrient balances.

Variables	Full Balance (kg ha^{-1})			Partial Balance (kg ha^{-1})		
	N	P	K	N	P	K
Intercept	2.178 ns	6.143*	15.843 ns	14.62 ns	6.171*	21.414 ns
Organic Inputs (kg ha^{-1})	-0.001 ns	0 ns	-0.001 ns	-0.002*	0 ns	-0.001 ns
Mineral Inputs(kg ha^{-1})	0.027 ns	-0.002 ns	0.022 ns	0.013 ns	-0.002 ns	0.013 ns
Off Farm income (US$)	0.012 ns	0.004 ns	0.007 ns	0.017 ns	0.004 ns	0.008 ns
GM (US$)	0.02 ns	0.017*	0.043 ns	0.033 ns	0.017*	0.046 ns
NFI (US$)	-0.002 ns	-0.003 ns	-0.002 ns	-0.002 ns	-0.003 ns	-0.002 ns
TLU	2.403*	0.409*	3.547*	3.128**	0.413*	3.712*
Farm size (ha)	-0.001 ns	0 ns	-0.001 ns	-0.001 ns	0 ns	-0.001 ns
Age HHH	0.028 ns	-0.015 ns	0.01 ns	-0.075 ns	-0.015 ns	-0.047 ns
Year of Education	0.781 ns	0.289 ns	1.167 ns	0.763 ns	0.289 ns	1.107 ns
Slope (%)	-0.499 ns	-0.4***	-1.272**	-0.026 ns	-0.398***	-1.033*
Soil conservation (m ha^{-1})	-0.001 ns	0 ns	-0.001*	-0.002*	0 ns	-0.002*
Observations (n)	49	49	49	49	49	49
Probability>F	0.664	0.037	0.022	0.145	0.04	0.068
R-squared	0.179	0.205	0.235	0.112	0.201	0.167

Asterisks denote associated coefficient is significant at: P<0.05 (*); P<0.01 (**) and P<0.001 (***); ns: non-significant, , HHH denotes Household Head, TLU Tropical Livestock Unit (one unit=270 kg of animal live weight), GM Gross margin, NFI Net farm Income.

Table 2.9. Effects of socio-economic variables on investments in soil conservation and inputs for smallholder farms in Gataraga and Rwerere, Rwanda.

Variables	Conservation technologies	Organic inputs	Chemical inputs
Intercept	4177811 ns	399872 ns	46543 ns
Off Farm income	11905 ns	-3421 ns	-0.082 ns
NFI	-1920 ns	-3125*	0.031 ns
GM	25418***	13102**	0.053ns
TLU	1140016 ns	457300 ns	1787 ns
Farm size	-0.101 ns	-0.029 ns	0.001 ns
Age HHH	-50800 ns	1738 ns	-0.366 ns
Year of Education	191887 ns	161223 ns	-1694 ns
Slope	-106005 ns	-51405 ns	-1207 ns
Observations (n)	49	49	49
Probability>F	0.000	0.029	0.291
R-squared	0.66	0.32	0.19

Asterisks denote associated coefficient is significant at: P<0.05 (*); P<0.01 (**) and P<0.001 (***); ns: non-significant, HHH Household Head, TLU Tropical Livestock Unit (one unit=270 kg of animal live weight), GM Gross margin, NFI Net farm Income

Table 2.10. Economic evaluation of nutrient depletion expressed as the share of gross margin that is derived from mining soil nutrients at farm level of Rwerere and Gataraga in highlands of Rwanda.

Sites	Rwerere		Gataraga	
	Kg ha^{-1}	US\$ ha^{-1}	Kg ha^{-1}	US\$ ha^{-1}
N	-12.7	-11.8	-1.8	-1.6
P	-2.0	-1.6	0.9	0.7
K	-20.4	-15.3	0.3	0.2
Total market value of deficit		-28.8		-0.7
Gross margin on agricultural activities		146.0		191.0
Nutrient depletion on gross margin		19.7%		0.2%
Sustainable fraction of gross margin		80.3%		99.8%
% of farmers with positive NPK balance	21%		58%	

To provide more insight into the economic sustainability of farms, we determined the correlation between smallholder farms where soil conservation technologies, organic matter, and mineral fertilizers were used and various biophysical and economic factors as presented in Table 2.9. Unexpectedly, there was a negative association between net farm income and the intensity of use of organic matter. This negative association suggests that farmers with high net farm income are likely to use less FYM since they can afford to buy inorganic fertilizers. This is consistent with Nkonya et al. (2005) who showed that farmers with high net farm income use more inorganic fertilizer in land management practices, which in turn lead to higher yields. A positive correlation between gross margin and soil conservation practices and the level of organic inputs was also noted.

Furthermore, computation of the economic value of the nutrient balances using market prices for fertilizers, showed the value of the average nutrient deficit per hectare to be around 29 US\$ ha^{-1} in Rwerere and just 0.7 US\$ ha^{-1} in Gataraga (Table 2.10). In Rwerere, the soil nutrient depletion represented as much as 20% of the average of gross margin of farmers while in Gataraga it represented only 0.2% (Table 2.10). This implies that a site with higher soil depletion rates requires more investments from the farmers' gross margin to replenish the depleted soil nutrients while in areas with better soils (less erosion) the depletion rate is low and farmers can use their financial resources to enhance soil fertility levels through fertilization and hence boost crop productivity.

2.4 Discussion

Nutrient inputs varied with the agricultural potential of the sites, resulting in the relatively fertile volcanic soils of Gataraga receiving higher inputs. This can be explained by a combination of different factors but mostly by the intensive land use, in particular for potato production. Our findings are consistent with results obtained in the volcanic soils of Birunga by Mugabo (2010). He pointed out that the intensity of mineral fertilizer use by smallholder farmers on the steep slopes of Rwerere and on the volcanic soils of Gataraga is totally different. Gataraga with its relatively fertile volcanic soils has the largest proportion of households using mineral fertilizers (91%) and most farmers grow potatoes which is considered to be a cash crop (Mugabo, 2010). As previously mentioned, Rwerere has soils that are relatively acidic with very low productivity and high risk to erosion (Yamoah et al., 1990). Recent results, e.g. (Mugabo, 2010), showed that Rwerere has the highest proportion of households using organic fertilizers (95%) and the lowest number of households using mineral fertilizers (36%). Rwerere with its acidic soils needs more investments, e.g. manure and lime to correct the soil acidity and since smallholder farmers with low farm income cannot afford it, farmers could only resort to the readily available organic manure.

On all farms and locations, estimates of N losses via erosion were generally high. Similar results were reported in Kenya and Ethiopia (Haileslassie et al., 2005; Onduru and Du Preez, 2007) where erosion was the main pathway of N outflow. Our findings of negative partial nutrient balances on steep slopes of Rwerere are comparable to those of Nabahungu et al. (in press), who observed that in the maize and bean farming systems in eastern and southern Rwanda, partial balance of N was about -12 kg ha^{-1}. A positive partial nutrient balance was observed on the relatively fertile volcanic soils of Gataraga. Similar results were reported by Nabahungu et al. (in press) in rich soils of wetlands in the eastern and southern regions of Rwanda where partial balance of N was around 28 kg ha^{-1}. The causes of higher levels of nutrient depletion rates on steep slopes of Rwerere were related to the input of nutrients and other natural causes such as soil erosion. This indicates that more efforts in controlling soil erosion should be accompanied by the use of "integrated soil fertility management options" defined as a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions (Vanlauwe et al., 2011).

According to the scale developed by Stoorvogel et al. (1993), depletion rates of soil nutrients of this study are classified as moderate to very high. However, the depletion rate of N reported in our study is much lower than the value of 60 kg N $year^{-1}$ reported by Stoorvogel et al. (1993). These contrasting results may be attributed to approaches used in the estimation of nutrients depletion. Our study used data obtained at farm level while Stoorvogel et al. (1993) used a supra national scale approach in the estimation of nutrient depletion for Rwanda. The negative nutrient balances we observed in Rwerere do not necessarily mean that crop production declines, as soils may still have sufficient stocks of nutrients to keep productivity (Haileslassie et al., 2005).

Internal flows of N are strongly related to Tropical Livestock Units (TLU); farms with more livestock units achieved higher N internal flows (Figure 2.4). Similar results were reported in small household farms in Mbeere and Kiambi, Kenya (van Beek et al., 2009). Most N was drawn from compost heaps and surpassed the amount of N from external inflows (Table 2.4) which represented only 8 and 19% of the TST for Gataraga and Rwerere respectively. Contrary to our findings, results from similar socio- economic environments in the highlands of Ethiopia showed that inflows depended largely (66 to 70% of TST) on imported N (Rufino et al., 2009b). Large differences between TST and T are observed when the system is in equilibrium, i.e. when N imports equal N exports (Rufino et al., 2009b). Small differences between TST and T mean that the stock of the various compartments contributes to N exports, balancing out the system activity (Ulanowicz, 2004). In both Rwerere and Gataraga large differences between TST and T were observed implying that most N was recycled between farm compartments and this means that one compartment could be a source or a destination of resources to or from other farm compartments.

The estimated PL as a measure of the cycling intensity within a farm system (Rufino et al., 2009a) was very high in this study (6 and 13) when compared to the PL under similar socio-economic conditions in Ethiopia (between 1.4 and 1.7) as reported by Rufino et al. (2009a). The high PL reported in this study is likely the result of high nutrient transactions within the system due to the presence of livestock under zero grazing conditions. Results from the Mbeere District in Kenya showed that small farms with larger number of livestock under zero grazing achieved high nitrogen re-use (van Beek et al., 2009).

Compared to other crops, potato had the highest GM highlighting the appreciable performance of potato (Figure 2.3a-c). The management strategy for potato production is to aim at a high productivity that is accompanied by considerable investments which are reflected by high variable cost (VC). From an economic perspective, other farm produce contributed less to the market share since most of it was used for household consumption (75% for Gataraga and 95% for Rwerere) indicating that farming activities are conducted first and foremost to secure food needs for the family. Similarly, the contribution of crop produce to the net farm income was estimated to be about 90% implying that the economic diversity of smallholder farms was low. Similar results were reported in the Mbeere District, Kenya where the share of crops of smallholder farms in net farm income was about 88% (Onduru and Du Preez, 2007). Smallholder farming systems are complex and strongly tied to tradition. A real change in the cropping system and associated practices is considered to be what is needed for the sustainable development of the currently unbalanced and overexploited smallholder farms.

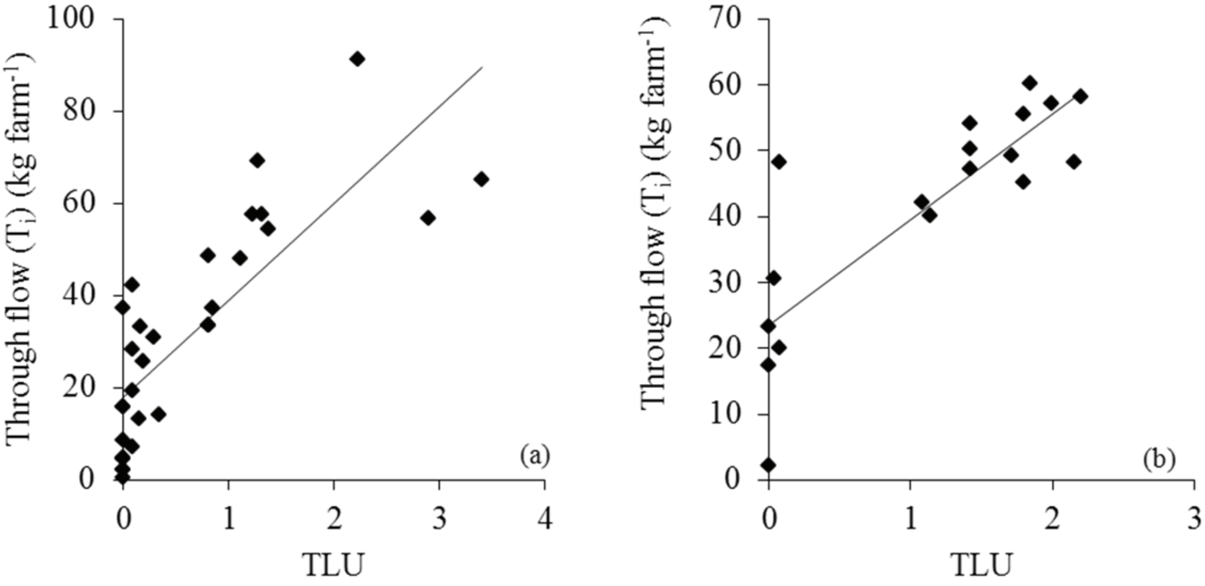

Figure 2.4. Relation between number of tropical livestock units (TLU) and through flow (T_i) defined as the flow of N between smallholder farms' compartments. Line shows linear relationship ($R^2 = 0.64$, $P < 0.0001$) for Gataraga (a) and ($R^2 = 0.69$, $P<0.0001$) for Rwerere (b), Rwanda.

The productivity of crops (Table 2.5) is almost double that of the national average. However, due to small landholding per household (0.5 ha) (Mukuralinda et al., 2011), the contribution of crop production to household income remains low (only 58% for Gataraga and 42% for Rwerere) and could not satisfy households' food demand. As a result farmers are forced to look for alternative livelihood strategies to bridge income and food gaps. This indicates that the main limiting factor for low contribution of crop production to livelihood is landholding. This raises the question of whether smallholder farms in the highlands of Rwanda can be sustainable even with improved technological practices.

Our findings show that agricultural potential (of a site), type of crops, gross margin, size of livestock herd (expressed as TLU) and slope all influence the magnitude and the degree to which nutrient fluxes may be imbalanced. Sustainable fractions of gross margin computed with the economic value of nutrient deficits are around 80% indicating that around 20% of the gross margin is based upon nutrient mining in Rwerere. However, in the intensively used volcanic soils of Gataraga, farmers are operating at almost a zero nutrient balance. Comparable results were reported by De Jager et al. (1998a) in Kenya where the Farm Income Sustainability Quotient (FISQ) varied with agricultural potential of districts, in which the Embu District recorded the highest FISQ (0.80). In Rwerere, if inorganic fertilizer were used to restore the mined nutrients, it would cost an equivalent of 20% of the gross margin. Similar results were reported by Nkonya et al. (2005) in Uganda on maize farming systems where the share of farm income derived from mining soil nutrients was about one fifth of farm income.

2.5 Conclusions

The diversity of the flows of N to, from and within the smallholder farms differed more across sites than between farms due to the strong variation in the management of FYM, stable or compost heaps and livestock. Higher internal flows of N were obtained in farms with large livestock units (TLU) which in turn influenced the N inflows (e.g. organic fertilizer) and N recycling between farm activities. Using nutrient balances of N, P and K as indicators of sustainability of agricultural production, the number of smallholder farms with positive N, P, K balances or who were able to operate with zero nutrient mining varied with sites. A higher number of farmers (58%) with positive nutrient balances or zero nutrient mining was found in the site with relatively high agricultural potential (Gataraga) compared to only 21% of smallholder farms located on acidic steep slope soils (Rwerere). The management systems of smallholder farms on steep slopes resulted in higher nutrient depletion and 20% of smallholder gross margin being used to replenish mined nutrients compared to only 0.2% of the gross margin of smallholder farms in the relatively high agricultural potential site.

While the findings of this study indicate that farmers are operating at almost a zero nutrient balance, the economic sustainability remains insufficient for several reasons. First, little of the farm produce reaches the market since most of it is used for household consumption (75% to 95%) indicating that farming activities are mainly concerned with securing food needs for the family. Secondly, the contribution of crop produce to the net farm income is about 90% implying that the economic diversity of smallholder farms is very low with the exception of smallholder farms keeping large tropical livestock units (TLU). These findings reveal challenges and opportunities within the current farming systems for policy makers and other agriculture agencies in developing sustainable agricultural production and practices in the highlands of Rwanda. Increasing the sustainability of smallholder farmers in the highlands of Rwanda will require changes on many fronts. In addition to controlling soil erosion, changes in cropping systems and practices are likely needed and should be studied. In particular the use of “integrated soil fertility management options”, which includes the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions should be investigated and encouraged.

Chapter 3

Soil erosion, soil fertility and crop yield on slow forming terraces in the highlands of Buberuka, Rwanda

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Soil erosion, soil fertility and crop yield on slow-forming terraces in the highlands of Buberuka, Rwanda

Abstract

Crop productivity in Rwanda is declining as a result of intensive farming on steep slopes, which leads to soil loss and declining soil fertility particularly in the northern highlands. Slow-forming terraces have been widely adopted in the northern highlands of Rwanda to control soil erosion however not much been done to evaluate their efficiency. We hypothesized that slow-forming terraces reduce soil loss and soil fertility gradients compared with non-conserved land. A field experiment compared the soil erosion rates and fertility gradients of 20+ year old terraces where sole grass strips (*Pennisetum purpureum*) or grass strips combined with infiltration ditches were used with those of land where no soil conservation technologies were applied. The experiment was conducted on three landscape positions (Upperslope, Hillslope and Footslope) along a representative toposequence using farmers' fields where potato and maize were grown in two consecutive cropping seasons. The lowest annual soil loss (18 t ha^{-1}) was recorded with grass strips combined with infiltration ditches, a 57% reduction in soil loss when compared with plots receiving no soil conservation practices. The slow-forming terraces showed a marked "within" spatial difference in both soil quality and crop yield. The soil in the lower part of the terraces showed as much as 57% more organic carbon content and 31% more available phosphorous than the soil in the upper part. Less than 10% of potato and maize yield was recorded on the uppermost third of the terraces on all three landscape positions. The marked soil fertility gradients indicate that the sustainability of slow-forming terraces is threatened, unless a site-specific fertilizer strategy is developed. For the sustainability of these terraces, the current practice of "harvesting" the fertile soil from the lower edge of the grass strip and using it as fertilizer for the nutrient deficient upper parts of terraces needs to be stopped.

Keywords: Terrace, sustainability, erosion, grass strips, fertility gradient, Rwanda

3.1 Introduction

Crop productivity in Rwanda is declining as a result of intensive farming on steep slopes, which leads to soil loss and declining soil fertility (Clay and Lewis, 1996). Productivity decline resulting from excessive soil loss occurs everywhere (Roose and Ndayizigiye, 1997) but is particularly acute in the highlands of Rwanda (Clay et al., 1998; Clay and Lewis, 1996; Lewis and Nyamulinda, 1996; Nizeyimana and Bicki, 1992; Roose and Ndayizigiye, 1997; Steiner, 1998). Data from field plots and experimental stations (Byers, 1990; Lewis, 1988; Roose and Ndayizigiye, 1997) shows that soil losses range from 35 t ha^{-1} yr^{-1} to more than 100 t ha^{-1} yr^{-1}, depending on agricultural practices and slope steepness.

Most soil erosion control measures implemented on cultivated fields are physical structures (Bizoza and de Graaff, 2011). However, some physical structures such as anti-erosion ditches were reported to be inefficient, as they require 200 - 350 labour days^{-1} ha^{-1} yr^{-1} for their construction and 20 -50 labour days^{-1} ha^{-1} yr^{-1} for their maintenance (Roose and Ndayizigiye, 1997). For the mountainous steep slopes of Rwanda, biological anti-erosion systems were reported to be more efficient in reducing soil erosion (Roose and Ndayizigiye, 1997). Living hedges, where crops are grown on alleys in between the hedges (Drechsel et al., 1996), have been effective in minimizing soil erosion on steep slopes (Drechsel et al., 1996; Roose and Ndayizigiye, 1997). In a study conducted in southern Rwanda, the annual soil loss under alley-cropping treatments ranged from 1 to 5 t ha^{-1} yr^{-1} in the fourth year of the experiment, while those under local farmers' practices were as high as 30 - 50 t ha^{-1} yr^{-1} with a maximum observed of 111 t ha^{-1} yr^{-1} (Konig, 1992). An even lower annual soil loss of < 3 t ha^{-1} yr^{-1} was recorded under anti-erosion ditches in combination with living hedges (Konig, 1992; Lewis, 1988; Lewis and Nyamulinda, 1996; Roose and Ndayizigiye, 1997).

On steep lands, between two consecutive living hedges, terraces form naturally at a slow rate. Such terraces often have a high soil fertility gradient (Niang et al., 1998) due to the combined effect of water erosion and tillage practices. These processes result in the movement of fertile topsoil from the upper part of the alley to the lower part (Lewis and Nyamulinda, 1996). Niang et al. (1998) reported that yields of wheat and beans significantly varied between the upper part and the lower part of the alley of a slow-forming terrace in the highlands of Buberuka.

Considerable interest exists among various government institutions and NGOs in promoting the use of living hedges on steep lands, to act as: barriers for soil erosion control; an alternative source of fodder; and a means of producing green manure. In the Buberuka highlands, at least 83% of farmers either build terraces on at least some of their fields, or plant living hedge strips (81%) on the lower ends of fields to stop erosion (Ndiaye and Sofranko, 1994).

In an attempt to promote sustainable food production, the Rwandan government has funded a national program for soil conservation with a participatory watershed approach known as *"Agasozi indatwa"*. As an integral part of the government performance contract known as "*Imihigo"*, a field research site was set up in 2010 in the Rwerere watershed in the Buberuka highlands. Objectives of this study were: (i) to evaluate the effectiveness of grass strips with and without infiltration ditches on slow-forming terraces through quantifying soil loss, and (ii) to assess the impact of soil erosion on the soil fertility gradient and its effect on crop yield.

3.2 Methods

3.2.1 Description of the study area

Experiments were conducted at Rwerere in the agro-ecological zone of Buberuka, Northern Province, Rwanda, with a latitude of 01° 32' S and longitude of 29° 52' E, at around 1960 m above sea level (Figure 3.1). The area has a bimodal distribution of rainfall, which allows crop cultivation during two consecutive cropping seasons (Figure 3.2). The average annual rainfall is 1219 mm, with a mean annual temperature over a 30-year period of 15.7°C, a mean maximum of 20°C, and a mean minimum of 11.6°C. Soils in Rwerere are predominantly Oxisols, interspersed with lithic Entisols on quartrite ridges (Yamoah, 1985). These soils generally have a moderate soil fertility status, as described in Kagabo et al. (Submitted), and are highly vulnerable to erosion (Yamoah et al., 1990).

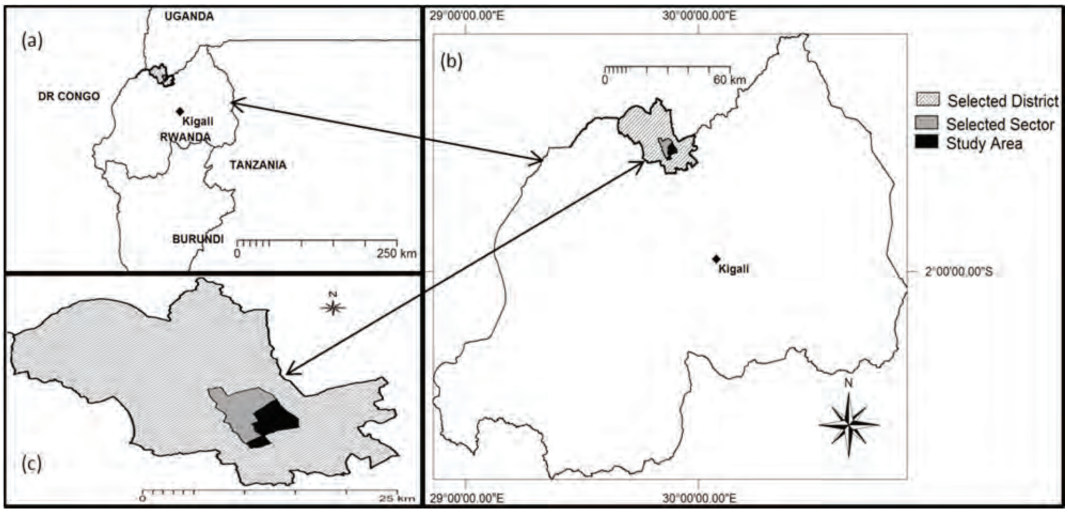

Figure 3.1. (a) Location of Rwanda in East Africa, (b) Rwanda with selected district, and (c) study area.

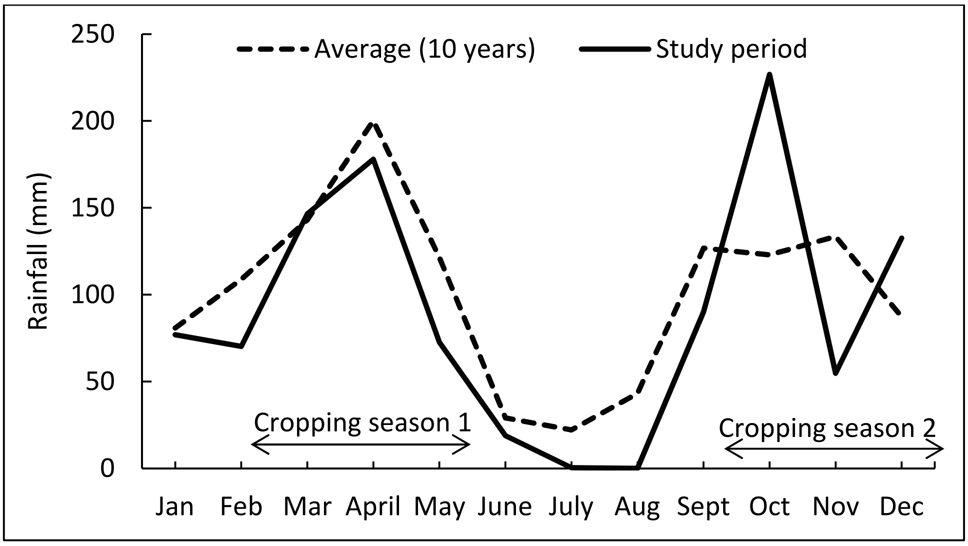

Figure 3.2. Ten year average (2000-2010) of monthly rainfall showing the bimodal pattern and cropping seasons of Rwerere, Rwanda.

3.2.2 Description of land positions with terraces

A toposequence representative of the slopes and terraced fields was selected as the study site (Figure 3.3). Three landscape positions with terraces were selected along this toposequence: the Upperslope (more marginal and less fertile terraces) with a slope between 10 and 30%; the Footslope (more productive lands) with a similar variation in slope percent); and the Hillslope with a slope between 30 and 70% that was generally a narrow bench and subject to high erosion risks (Figure 3.3). On each landscape position, slow-forming terraces that were initiated about 20 years ago with grass strips of napier grass (*Pennisetum purpureum*), with or without infiltration ditches, were chosen. The height and width of the banks between the grass strips and the next terrace varied between 30 to 70 cm and 20 to 30 cm respectively. Only terraces with 50 cm of bank height and 25 cm wide grass strips were selected for this study. Two months prior to the establishment of experiments, grass strips were trimmed in order to allow them to regenerate uniformly.

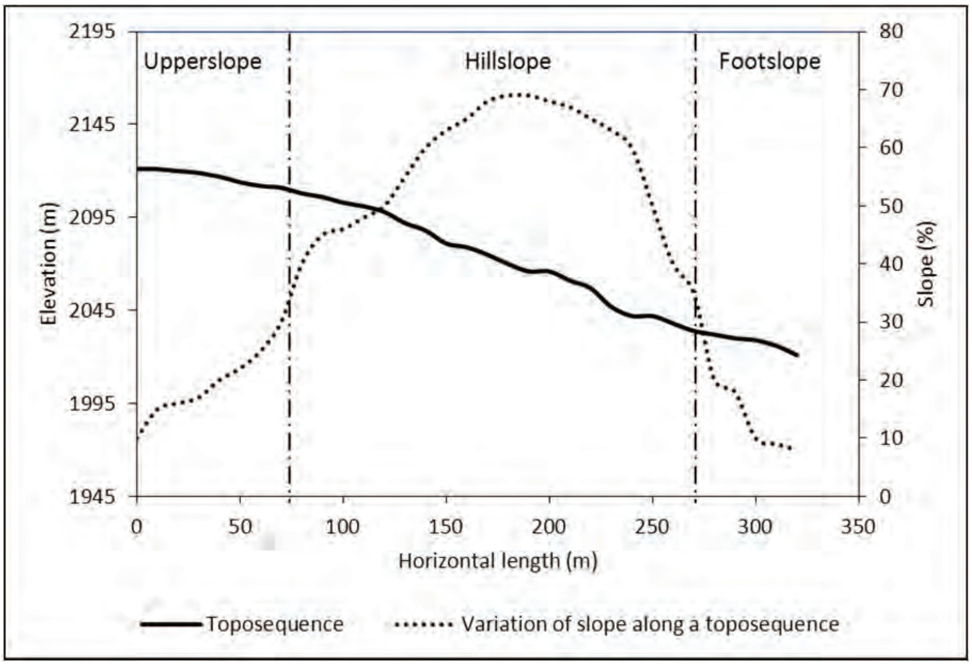

Figure 3.3. Representative toposequence with the variation of slope and location of three landscape positions for field experiments.

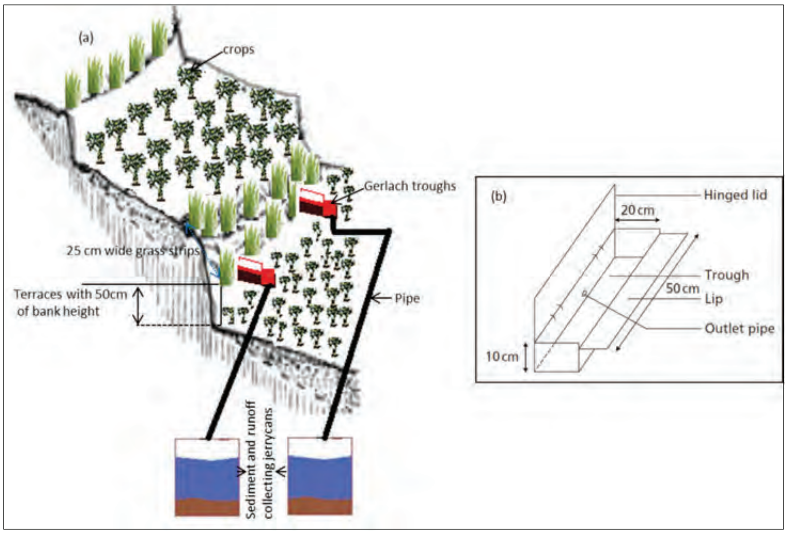

Figure 3.4. Layout of Gerlach trough in the field (a), Gerlach trough view (b), adapted from Morgan, (2005).

3.2.3 Experimental design and plot establishment

In two consecutive cropping seasons, farmers' terraces with maize and potato were used to evaluate the effectiveness of grass strips with and without infiltration ditches in minimizing soil erosion. Three treatments comprising grass strips alone, grass strips with infiltration ditches and a control (fields without soil conservation practice) were laid out on 48 m^2 plots in a randomized complete block design and replicated 9, 14 and 16 times on the Upperslope, Hillslope and Footslope respectively (total 117 plots). The number of replicates varied because of the limited number of fields available for experiments, particularly on the Upperslope position. Maize was grown from September 2009 to February 2010, and potatoes were planted as a rotation crop from March 2010 to June 2010.

3.2.4 Soil erosion assessment

Locally constructed Gerlach troughs – a device consisting of a simple metal gutter to capture the surface run-off from the upper unbounded area – were used in the assessment of soil erosion (Figure 3.4a and 3.4b). The trough was made of metal sheet, closed at the sides and with a removable lid on the top to prevent direct entry of rain. An outlet pipe runs from the base of the gutter to a collection jerry can (Figure 3.4a). The total amount of surface run-off was measured and the water and sediment mixture stored after each erosive rainfall. The soil that settled at the bottom of the storage containers was dried and weighed, giving the sediment content per volume surface run-off (Morgan, 2005). In the field, two gutters were placed side-by-side across the slope (Figure 3.4a). The catchment area was estimated considering the width of the gutter (0.5 m) times the length of the slope above the Gerlach trough (Figure 3.4a). The assumption is that any loss of water and sediment from this area during its passage down slope is balanced by inputs from adjacent areas (Morgan, 2005). The area above the Gerlach trough was divided into grid intervals of 0.5 m using tape measure and strings. The number of grids within the contributing area was counted and used to estimate the area (Tenge et al., 2007).

3.2.5 Soil sampling and analysis

Five soil samples, 0-15 cm depth, were collected at equidistance along a predefined transect on each plot, beginning 1 m from the lower and upper parts of each terrace. A total of 585 soil samples were taken. Nine soil properties – i.e. pH(H_2O), pH(KCl), organic carbon, total nitrogen, available phosphorus, potassium, and textural content (sand, clay, silt) –were analysed in the soil laboratory of the High Learning Institute of Agriculture and Animal Husbandry of Rwanda, using standard methods recommended for tropical soils (Anderson and Ingram, 1994).

3.2.6 Measurement of crop yield response

The 48 m^2 plots were subdivided into three parts: the sediment deposition zone localized at the bottom of the terrace, the central zone in the middle part of the terrace, and the upper part of the terrace which is considered the most vulnerable to erosion. On each subplot, the crop yield of a 2 m^2 was measured at harvest.

3.2.7 Statistical analysis

Data analysis of variance (ANOVA) was conducted using the mixed procedure (REML) in Genstat version 13.2 to determine the effects of the different treatments. Landscape position, crops grown, and soil conservation technologies were considered as fixed effects, while farmers' fields in each landscape position were considered as random variables. In all figures in this paper, error bars represent standard errors of the differences (SED) of means at a significance level of 0.05.

Since the width of alleys between two grass strips varied from 6 to 12 m, the parameter relative distance (Dr), adapted after Dercon et al. (2003) and Vancampenhout et al. (2006), was used to standardize the position of a soil sample in the experiment plot, see equation 3.1.

$$D_r = L_i / L \qquad [3.1]$$

Where:

D_r is the relative distance (dimensionless),

L_i the slope position at sampling site i with the upper part of the terrace as reference (m), and

L the total slope width (top to bottom) of the slow-forming terrace (m).

For instance, D_r values of 0 and 1 indicate the lower and upper parts of the terraces respectively. Since all samples are taken at equidistance, the relative distances on each plot are: 0.00 (lower sample), 0.25, 0.50, 0.75 and 1.00 (upper sample).

Data analysis revealed significant variation (p=0.05) in measured soil fertility indicators (e.g. Carbon, Nitrogen and Phosphorus) between plots. This is an indication that there is a major influence of fields, or location and management, on soil fertility. To correct for this plot effect, the residuals of ANOVA were used for available phosphorous, total nitrogen and organic carbon.

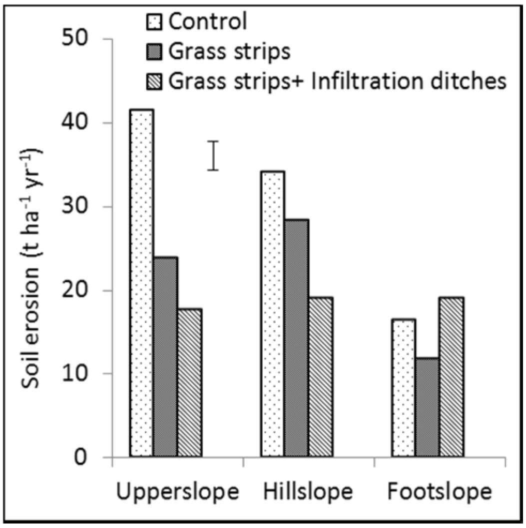

Figure 3.5. Soil loss (t ha^{-1} yr^{-1}) from plots between grass strips with and without infiltration ditches compared to plots without soil conservation measures for three landscape positions in the Northern highlands of Buberuka, Rwanda. The error bar is the average standard error of the difference.

3.3 Results and discussion

3.3.1 Effects of erosion control practices on soil loss

Significant differences (at the 5% level of significance) in soil loss were recorded among soil conservation treatments and landscape positions (Figure 3.5). Soil loss on plots of grass strips with infiltration ditches was about 18 t ha^{-1} yr^{-1}, 57% less than the control plots. Soil loss on sole grass strip plots was 24 t ha^{-1} yr^{-1}, 43% less than the control plots. Results of similar magnitude were reported on fields protected with grass strips of *Pennisetum purpureum* in the northern highlands (Lewis, 1988; Lewis and Nyamulinda, 1996). However, a weak performance of grass strips was reported by Konig (1992) and Roose and Ndayizigiye (1997) where grass strips of *Pennisetum purpureum* reduced runoff by less than 4% after 3 years of establishment. Similarly unsatisfactory results were obtained in the highlands of Kenya (Angima et al., 2002). These authors found greater soil loss in the first two years of the existence of grass strips, and attributed the differences in performance of the grass strips to the age of the evaluated strips. In this study, evaluated grass strips were 20 years old, with well-developed banks in both height and width. Poudel et al. (1999) reported that the effectiveness of grass strips in reducing soil loss increases as they become more established. This could explain the low values of soil loss reported in this study, and clearly shows that well established grass strips with infiltration ditches can make a significant contribution to soil erosion control on steep slopes, although they are considered most efficient on land with relatively low slopes (Roose and Ndayizigiye, 1997).

Considering the landscape positions, soil erosion rates varied significantly ($p=0.05$). Higher and lower rates of soil erosion were recorded on the Upperslope and the Footslope respectively (Figure 3.5), suggesting that slope length was not the dominant factor affecting soil erosion. Unexpectedly, on Footslope landscape positions, soil erosion rates were higher in plots with grass strips combined with infiltration ditches. This is partly because during heavy rainfall events, uphill infiltration ditches were quickly filled with sediment and the run-off could easily overflow into the successive terraces, thereby increasing the soil erosion rates in the lower terraces.

3.3.2 Soil fertility gradients

In Rwanda, most of the existing terraces are old and less fertile. Terraces that are formed gradually between two grass strips over 20 years showed a large difference in soil fertility indicators between the upper and lower parts of the terraces. The ANOVA residual soil organic carbon, total nitrogen, and available phosphorous values were significantly correlated with the relative distance (D_r), as presented graphically in Figures 3.6a, 3.6b and 3.6c. Organic carbon, total nitrogen, and available phosphorous values were always greater in the lower parts of the terraces, and declined towards the upper parts. Similar results were reported by Vancampenhout et al. (2006) on fields between stone contours in the Ethiopian highlands, by Poudel et al. (1999) on contour hedgerows in the Philippines, and by Dercon et al. (2003) on hedgerows in the Andes region of Ecuador.

Due to soil erosion, the fertile top soil is eroded and the infertile subsoil comes to the surface. Human activities such as hoeing may also cause a soil fertility gradient (Dercon et al., 2003; Dercon et al., 2006; Lewis and Nyamulinda, 1996; Vancampenhout et al., 2006). In addition, hedgerows composed of grass strips such as *Pennisetum purpureum* have been reported to compete with crops for soil fertility and moisture, negatively influencing the crop yield in the lower parts of the terraces (Dercon et al., 2006; Niang et al., 1998; Poudel et al., 1999). This explains the comparable results between the 0.0 and 0.25 equidistance of the relative distance (D_r) of the slow-forming terraces (Figure 3.6). Similar results were reported on contour ridge benches in Tunisia, where insignificant differences in organic carbon content were observed between the lower two parts of the relative distance of the contour ridge benches (Khlifi et al., 2010).

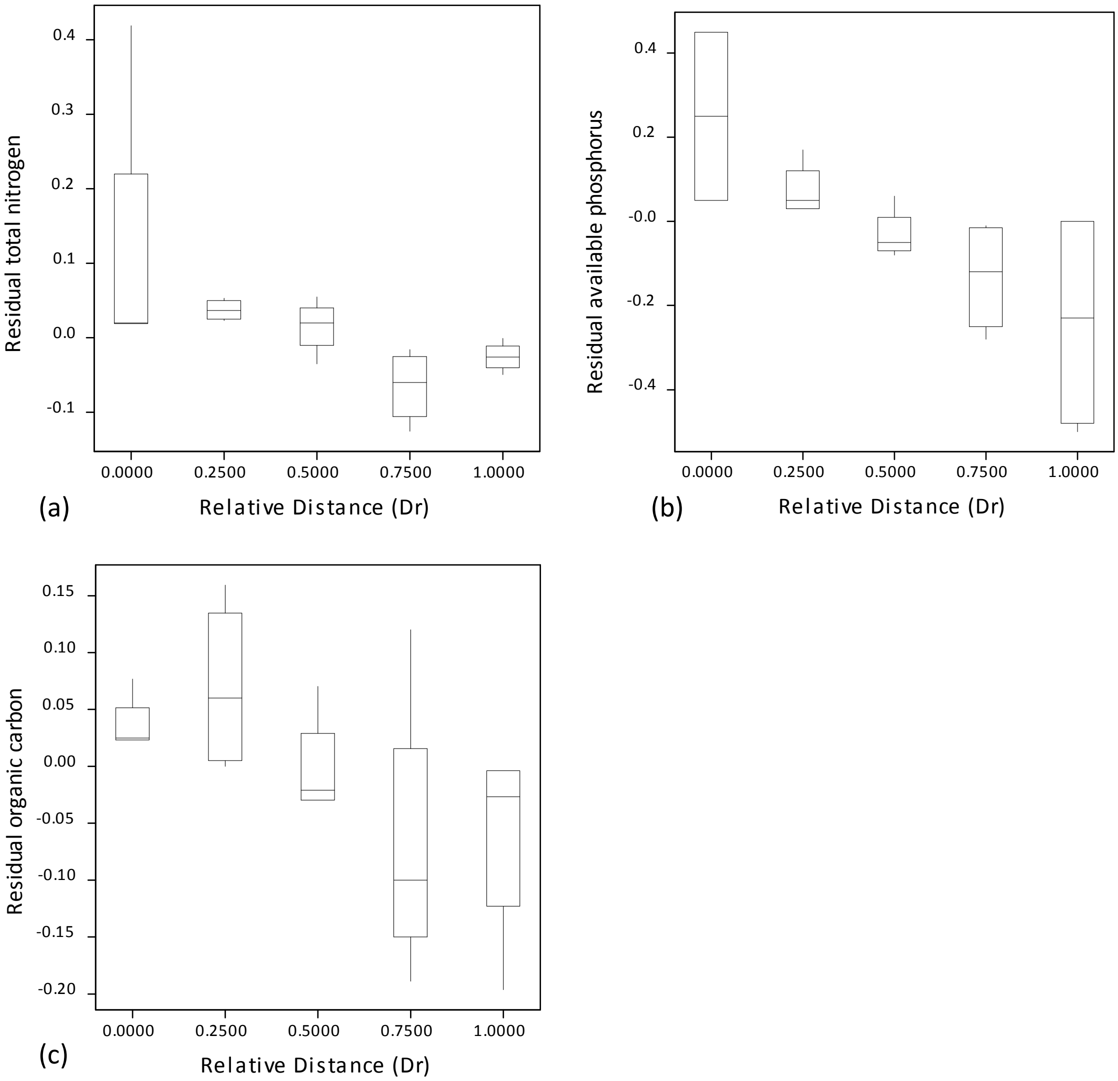

Figure 3.6. Relationship between ANOVA residuals of soil fertility indicators and relative distance (D_r) of terraces formed between grass strips with infiltration ditches. (a) total nitrogen, (b) available phosphorus, and (c) Organic carbon.

Conservation measures like grass strips with or without infiltration ditches were intended to both trap sediment and facilitate the slow formation of terraces. However, farmers cultivating steep lands in the northern highlands of Rwanda usually remove a small portion (10 cm deep) of the grass strips' lower edge each growing season (Lewis, 1992; Lewis and Nyamulinda, 1996) and spread this more fertile soil over the upper parts of the lower terraces, thus using it as a fertilizer (Lewis, 1992). As a result, grass strips in many parts of this region progressively move up- slope as the removed soil moves, as a substitute for fertilizer, down-slope (Lewis and Nyamulinda, 1996). Through this process the development of natural terraces is hampered, suggesting that if it continues, the long-term viability of agriculture on these steep slopes may be jeopardized.

3.3.3 Crop response to soil fertility gradient

The impact of the soil fertility was manifested by large significant differences (p=0.05) in crop yields between landscape positions and soil conservation practices (Figure 3.7). On average 60% of the total yield of both potato and maize crops was recorded on the lower parts of the terraces, referred to as the sediment deposition zone. Less than 10% of the total yield was recorded on the uppermost parts of the terraces. The major reason for the fertility gradient is the erosion from the upper parts of the terraces. Hence there is a relationship between grain maize and potato fresh tuber yield and soil loss characterized by a mean correlation coefficient of 0.68 and 0.61 respectively (Figure 3.8).

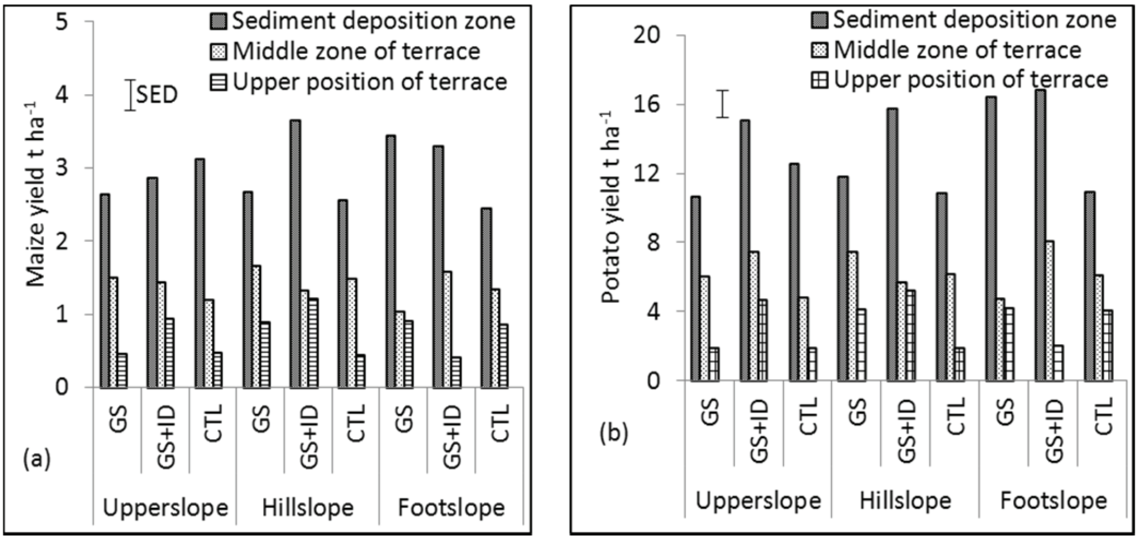

Figure 3.7. Crop yield at the sediment deposition zone, central zone and upper position of terraces. Maize grain yield (a) and potato fresh tuber yield (b) for Rwerere, Rwanda. GS is terrace between grass strips, GS+ID is terrace between grass strips combined with infiltration ditches and CTL is the control treatment (without soil conservation practice). The error bar is the average standard error of the difference.

Similar results were reported by (Niang et al., 1998), where yields from the bottom parts of the terrace plots made up 64% of the total plot yield for wheat and 61% for beans. Yields increase of 36% for maize, 40% for tomato, and 78% for cabbage were obtained on the lower position of terrace formed between two successive hedgerows in the Philippines (Poudel et al., 1999).

Except for Phosphorous (P), slow-forming terraces formed by either sole grass strips or in combination with infiltration ditches did not show any difference in soil quality parameters between land positions (Table 3.1). P was significantly greater in the Footslope land position, probably resulting from a high concentration of P in eroded sediment deposition. Poudel et al., (1999) also reported soils enriched in P from deposition in the lower parts of a landscape. Higher extractable P contents were also reported on terraces located in the lower part or at the toe of the landscape (Ni and Zhang, 2007). The interaction between land position and soil conservation technologies resulted in large differences in soil quality of C, N and K between land positions. In contrast, P does not appear to be influenced by soil conservation technologies, as no statistical significances were evident (Table 3.1). Without additional erosion control strategies, the presence of high concentrations of P in Footslope land positions may lead to the degradation of ecosystems downstream.

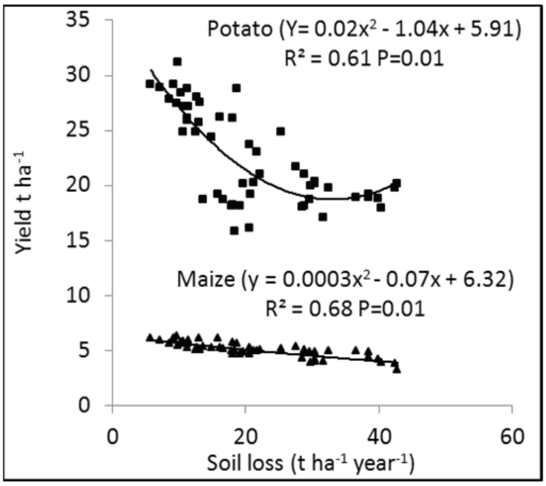

Figure 3.8. Relations between soil loss and yields of maize and potato for Rwerere in the highlands of Buberuka, Rwanda.

Table 3.1. Statistical significance of organic and mineral nutrients in cultivated fields as affected by soil erosion and slow forming terraces on three land positions at Rwerere, Rwanda.

Source of variation	Soil nutrients	C			N			P			K		
	Land position	-- (%)--						(ppm)			cmol kg^{-1}		
		Footslope	Hillslope	Upperslope	Footslope	Hillslope	Upperslope	Footslope	Hillslope	Upperslope	Footslope	Hillslope	Upperslope
Soil conservation technology		1.993ns	2.094ns	1.856ns	0.1838ns	0.2176ns	0.2096ns	26.84ns	29.04ns	28.84ns	0.3076ns	0.3073ns	0.3253ns
Land Position		1.96ns	1.9ns	2.083ns	0.224ns	0.2ns	0.1869ns	30.24*	26.36*	28.13*	0.3013ns	0.3276ns	0.3113ns
SED		0.1101			0.01581			1.478			0.01153		
Land position X Soil conservation technology													
Grass strips		1.853	1.893	2.133	0.188	0.1967	0.24	27.07	33.53	30.13	0.2573	0.3173	0.3293
Grass strips + infiltration ditches		2	2.067	1.633	0.1913	0.268	0.2127	26.6	25.73	26.73	0.328	0.3067	0.348
Control		2.127	2.322	1.8	0.172	0.188	0.176	26.87	27.87	29.67	0.3373	0.298	0.2987
SED		0.1908*			0.02738*			2.559ns			0.01998***		

**P<0.001; *P<0.05; ns – not significant at P<0.05. SED Standard Error of Difference

3.4 Conclusions

Well established grass strips alone or combined with infiltration ditches are clearly effective at reducing erosion. In this study, they reduced soil loss by 43 and 57%, respectively, when compared with plots without soil conservation practices. Grass strips showed strong resilience, being 20 years old and still effective by providing continuous barriers for soil movement. The gradually formed natural terraces between grass strips showed a marked spatial difference in both soil quality and crop yield from their upper parts downwards. The soil in the lower parts of the terraces showed as much as 57% more organic carbon content and 31% more available phosphorous than the soil in the upper parts of the terraces. Similarly, potato and maize yields were 60% greater on the lower parts than on the upper parts of the terraces. Given the age of the terraces (20 years of formation), it is surprising to see such large differences in soil quality on terraces that were expected to have homogenized over the course of time (Poudel et al., 1999). For the sustainability of these terraces, the current practice of “harvesting” the fertile soil from the lower edge of the grass strip and using it as fertilizer for the nutrient deficient upper parts of terraces needs to be stopped. It is essential to develop a site-specific fertilizing strategy that mitigates the soil fertility gradients on terraces and increases overall crop yields without chasing the grass strips upwards. One strategy that could be agronomically and economically effective might be to fertilize more the upper part of a terrace. Supporting measures would give more value to established structures and enhance the sustainability of slow-forming terraces over the long term.

Chapter 4

Integrated soil fertility management for improving potato productivity in the Rwandan highlands

This paper will be submitted as:
Kagabo, D.M., Vanlauwe, B., Visser, S.M., Musana, B.S., and Stroosnijder, L. (2012). Integrated soil fertility management for improving potato productivity in the Rwandan highlands.
Nutrient Cycling in Agroecosystems

Integrated soil fertility management for improving potato productivity in the Rwandan highlands

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Abstract

Agricultural intensification in the densely populated tropical highlands of Rwanda is hampered by substantial soil fertility constraints. Promoting Integrated Soil Fertility Management (ISFM) practices could increase the agronomic efficiency of mineral nitrogen application (N-AE) and improve crop productivity. Researcher-managed trials were established in two contrasting agro-ecological zones in Rwanda (Rwerere and Gataraga locations), during two consecutive cropping seasons of 2010 into farmers' fields in three different landscape positions, namely on upper-slope, hill-slope and on foot-slope. A factorial design was adopted and comprised a rotation of bean and potato (B-P) and a continuous cropping of potato (P-P) and ISFM component treatments. ISFM component treatments contained four treatments: T1 (local seeds + manure), T2 (improved seeds + manure), T3 (improved seeds + manure + Diammonium Phosphate (DAP)) and T4 (improved seeds + manure + DAP + Urea as a top dressing). In all landscape positions, application of manure and N fertilizer in combination with improved seeds increased potato tuber by 4457 kg ha^{-1} in Rwerere and 5905 kg ha^{-1} in Gataraga relative to the farmers' practice. Bean grain yields were generally lower in Rwerere (1145 - 2273 kg ha^{-1}) compared to Gataraga (1640 – 3142 kg ha^{-1}). Growing potato after beans resulted in (i) increased potato tuber yield compared with growing continuous potato and (ii) in a significant increase in net benefit that varied between 400 and 822 USD ha^{-1} in Gataraga and between 1100 and 1560 USD ha^{-1} in Rwerere. The combination of fertilizer, FYM and improved seeds significantly increased yields but resulted (i) in a lower N-AE across sites and on relatively fertile foot slopes and (ii) in a lower marginal rates of return (MRR) due to the high cost of seeds and N fertilizer.

4.1 Introduction

Inherent low soil fertility combined with limited use of both organic inputs and mineral fertilizers in the sub-Saharan Africa (SSA) has resulted in a gradual depletion of soil nutrients (Sanchez et al., 1997). Higher depletion rates on smallholder farms have been reported in highly populated highlands of East Africa (Stoorvogel and Smaling, 1990), particularly in Rwanda. Factors such as, high population density and the size of the land holdings of about 0.5ha per household (Mukuralinda et al., 2011) are forcing the farmers to over-exploit the available natural resource base. As a result, soil nutrients of smallholder farms in the northern highlands of Rwanda are being depleted to an estimated rate of -9 kg N, -2 kg P2O5 and -18 kg K2O ha^{-1} year^{-1} (Kagabo et al., under review).

Integrated Soil Fertility Management (ISFM) components can help smallholder farmers confront these challenges. ISFM is defined by Vanlauwe et al., (2010) as "a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity". For instance, ISFM components can enhance the use of inherent soil nutrient stocks, mineral fertilizers and locally available organic inputs. Research conducted in several sub-Saharan countries demonstrated that ISFM components implemented on smallholder farms can substantially improve soil fertility, crop yield and maximize the agronomic efficiency (AE) of applied nutrient inputs (e.g. Bationo et al., 2007; Lunze et al., 2012; Nabahungu et al., 2011; Vanlauwe et al., 2010).

With the recent growing recognition by policy makers that enhanced farm productivity is a major entry point to break the vicious cycle underlying rural poverty (Vanlauwe et al., 2011), there is hope that more investments would be oriented to rural farm management. Hence, use suitable and affordable technologies that are accessible to resource-poor farmers including ISFM components. Recent studies

(Kagabo et al., under review; Mugabo, 2010) show that more than 70% of farmers use Farm Yard Manure (FYM). However, these FYM are of poor quality (0.79% of N) and are used in small quantities, especially on acidic soils of Rwerere (Kagabo et al., under review). Only 7.5kg of N from FYM is applied on potato in Rwerere while much more N (42kg) from FYM is applied on potato in Gataraga (Kagabo et al., under review). Elsewhere in the Southern Africa, organic inputs obtained in poor farm households were classified as often of poor quality (Nyamangara et al., 2009). Poor quality of FYM leads to insufficient sources of N for plant growth in the short term and should therefore be supplemented with mineral N to reduce N immobilization and consequent N deficiency in plants (Nyamangara et al., 2009).

The most recent Crop Intensification Program (CIP) policy launched in Rwanda to boost agricultural productivity acknowledges that sustainable agricultural intensification requires the use of external nutrient sources, in particular improved germplasm and inorganic fertilizers. CIP fails to highlight the role of organic inputs traditionally used throughout the country. Vanlauwe et al. (2011) propose that organic resources of poor quality (class II and III) to be mixed with fertilizer to obtain optimal yields. This combination is seen as a sound management principle since neither of the two inputs is usually available in sufficient quantities or at affordable prices and both inputs are needed in the long-term suitability of farms (Vanlauwe et al., 2011). These scientific evidences show that there is a need to follow a judicious policy by simultaneously building a strong promotion for the use of inorganic fertilizer and also enhance the use of FYM for sustainable crop intensification in Rwanda.

Optimal potato yield cannot be achieved only with the combined use of soil fertility management and improved germplasm unless a proper cropping system such as rotation is practiced (Juárez et al., 1999). In the highlands of Rwanda, cereals occupy land for more than three quarters of a year and this hampers options of rotating these cereals with potato. The prevailing high altitudes (1700 to 2500 m above the sea level) and low temperatures affect the growing length (6 to 9 months) of cereals (wheat, sorghum and maize). However, grain legumes such as beans can attract farmers' interest in the potato rotation system. This is partly because beans, especially climbing beans have been traditionally cultivated in the higher altitude zones beyond 1700 m above sea level with a relatively short growing period (4 to 5 months) and are positively associated with a high yield potential of 3 to 5 t ha^{-1} (Sperling and Muyaneza, 1995). Furthermore, beans are a precious food in the Rwandan diet and the annual per capita consumption is estimated to be 50 – 60 kg, one of the highest in the world (Lunze et al., 2012). In this context, a rotation cropping system of improved potato and beans has a large scope for increasing potato crop yield by incrementally applying different ISFM components, namely (i) use of improved germplasm of beans and potato, (ii) combination of inorganic and organic inputs and (iii) timing of fertilizer application.

The objectives of this study were: (i) to evaluate the impact of ISFM components on common climbing bean and potato yields at different land positions in the toposequence (i.e. upper-slope, hill-slope and foot-slope), (ii) to assess the agronomic use efficiency on mineral N fertilizer and (iii) to evaluate additional benefits obtained against additional input and labour costs, and marginal rates of return of ISFM components.

4.2 Materials and methods

4.2.1 Description of the study area

The study was conducted in two contrasting agro-ecological zones of the Northern highlands of Rwanda, namely; Gataraga and Rwerere (Figure 4.1). Gataraga is located in Musanze district (01o 32' S, 29o 31' E), Northern Province and is part of the volcanic agro-ecological zone lying about 2400 m above sea level. Rwerere is located in Burera District (01^{o} 32' S, 29^{o} 52' E), Northern Province and is located in the highlands of Buberuka agro-ecological zone of Rwanda at around 1650 m above sea level.

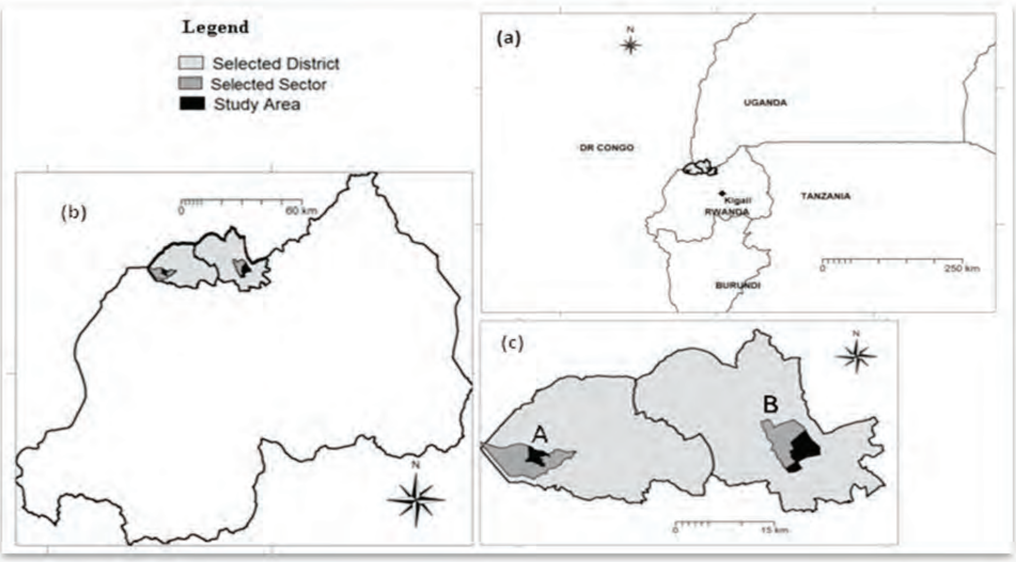

Figure 4.1. Localization of the study areas. (a) Rwanda in East African region, (b) Rwanda with selected districts, (c) selected sectors with A the Gataraga site and B the Rwerere study area.

The sites have a bimodal distribution of rainfall (Figure 4.2) which allows crop cultivation during two subsequent cropping seasons. The average annual rainfall is 1584 mm in Gataraga and 1219 mm in Rwerere. Both sites are highly populated but present differences in soil erosion risk and in soil fertility potential (Byers, 1991). In Gataraga, fertile Andosols are found because of volcanic ashes deposits that contain relatively high organic matter content, favourable pH and vast nutrient reserves (Table 4.1). The soils in Rwerere are predominantly Ferralsols, interspersed with lithic Entisols on quartrite ridges (Yamoah, 1985). These soils have a moderate soil fertility status (Table 4.1) and are highly vulnerable for erosion (Yamoah et al., 1990).

Table 4.2. Treatment structure of the experimental trials laid out in the Gataraga and Rwerere sites in the highlands of Rwanda. Mineral and organic N inputs are applied at each season.

Cropping system		Code of ISFM component treatments	ISFM component treatments	N (kg) applied per treatment from organic and inorganic fertilizer sources	N (kg) applied per treatment solely from inorganic fertilizer sources
Season 1	Season 2				
Continuous potato*					
Potato	Potato	T1	FYM + Local Seeds	72	0
Potato	Potato	T2	FYM + Improved seeds	72	0
Potato	Potato	T3	FYM + DAP+ Improved seeds	91.8	19.8
Potato	Potato	T4	FYM + DAP + Urea as top dressing + Improved seeds	120.4	48.4
Bean-potato rotation**					
Bean	Potato	T1	FYM + Local Seeds	72	0
Bean	Potato	T2	FYM + Improved seeds	72	0
Bean	Potato	T3	FYM + DAP +Improved seeds	91.8	19.8
Bean	Potato	T4	FYM + DAP + Urea as top dressing + Improved seeds	120.4	48.4

DAP= Diamonium phosphate containing NPK (18-46-0) and FYM = Farmyard manure, application rate was 3 t ha^{-1} dry mass basis. * Continuous potato means a second potato crop right after the first one. **Bean-potato rotation means potato after bean.

Table 4.1. Soil characteristics of the studied sites. Numbers in bracket represent standard deviations

Sites	Landscape positions	pH water	pH KCl	Bray^{-1} P	Exchangeable K	Organic C	Total N	Clay	Silt	Sand	Density (g cm^{-3})	Porosity (%)
				mg kg^{-1}	cmol kg^{-1}	%						
Rwerere											1.2	24.6
	Upper-slope	4.6(0.2)	4.1(0.2)	20.9(6.4)	0.5(0.2)	2.4(0.1)	0.18(0.06)	20.2(10.7)	9.3 (5.1)	70.0(12.5)		
	Hill-slope	4.3(0.2)	3.8(0.2)	17.1(4.4)	0.5(0.2)	2.1(0.9)	0.16(0.03)	24.0(11.3)	7.3 (3.7)	68.1(10.0)		
	Foot-slope	4.8(0.3)	4.2(0.2)	23.7 (5.7)	0.8(0.4)	3.7(1.2)	0.29(0.1)	29.6(12.4)	23.8(10.3)	46.6(16.0)		
Gataraga											0.63	50.6
	Upper-slope	5.5(0.1)	5.1(0.1)	12.0(20.3)	1.2(0.3)	4.9(1.8)	0.36(0.16)	27.3(5.0)	8.7(4.5)	64.0(8.3)		
	Hill-slope	5.8(0.2)	5.3(0.2)	6.9(21.6)	1.6(0.1)	4.2(1.9)	0.35(0.07)	27.8(6.2)	17.5(3.8)	54.7(4.2)		
	Foot-slope	5.9(0.2)	5.2(0.2)	22.1(18.2)	1.9(0.4)	4.5(1.3)	0.37(0.14)	29.0(6.0)	17.0(6.0)	54.0(9.0)		

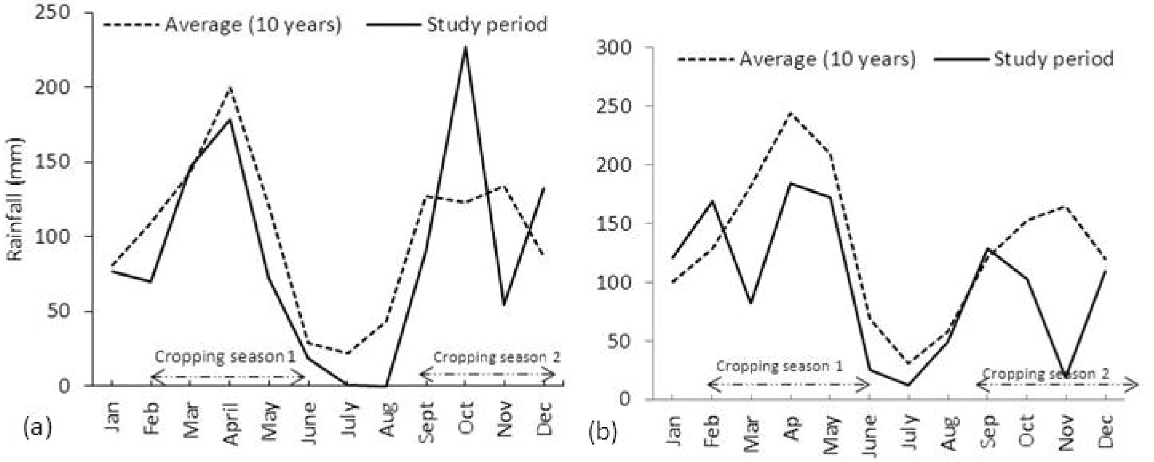

Figure 4.2. 10 years average (2000-2010) of monthly rainfall showing the bimodal pattern and cropping seasons: (a) Rwerere and (b) Gataraga.

4.2.2 Trial establishment and management

Researcher-managed trials were established in farmers' fields during two consecutive cropping seasons of 2010. Prior to trial establishment, composite soil samples were collected from the top 0–15 cm soil layer, air-dried, sieved to pass 2 mm and analysed for standard physico-chemical properties (Table 4.1). A factorial design was used with cropping system and ISFM components as factors in three different landscape positions, namely on upper-slope, hill-slope and on foot-slope. Trials of plots measuring 48 m2 (6m X 8m) were replicated 8, 16 and 18 times on upper-slope, hill- slope and foot-slope respectively in Rwerere whilst in Gataraga the replications were 9, 14 and 16 times respectively on upper- slope, hill-slope and foot-slope. Experimental plots were obtained from farmers' fields. Therefore on some landscape positions the targeted number of replicates (18) could not be obtained, especially on the upper-slope. As fields on upper-slopes are closer to homestead gardens, most of them are usually cropped in association with perennial crops such as banana. Furthermore these fields are in competition with other homestead crops, hence less fields were available for our study.

Table 4.2 shows the experimental trials structure laid in Rwerere and Gataraga in two consecutive cropping seasons. All treatments received 3t ha−1 of manure from a research managed cattle manure containing on average 20% C, 2.4% N, 0.2% P and 2.3% K. In the first treatment, local planting materials of potato (Solanum tuberosum L.) and common climbing beans (Phaseolus vulgaris L.) were grown following farmers' common practice. In this treatment potatoes were planted in both seasons with a between row spacing of 0.80m and a within row spacing of 0.30m. Bean seeds were planted using two seeds per hill at an inter and intra-row spacing of 75cm and 30cm, respectively. Manure was distributed in holes established prior to potato planting. For beans manure was broadcasted and incorporated in the field prior to planting. The second treatment consisted of improved germplasm with manure. In the third treatment, improved bean and potato germplasm was used with manure combined with 110 kg ha^{-1} of Diammonium Phosphate (DAP) containing NPK (18-46-0). In the fourth treatment, improved germplasm was used with manure combined with 90 kg of DAP while an additional application of 70 kg of urea (with NPK 46-0-0) were applied before flowering stage for beans and before tuber initiation for potato. Local agronomic practices were followed and Gasirida variety of bean (Phaseolus vulgaris L.) and Mabondo variety of potato (Solanum tuberosum L.) were cultivated. The plots were kept weed-free by weeding twice during each season. Potato late blight was controlled by Ridomil MZ 72 and Dithane. Ridomil MZ 72 was used every season by one time application at 1 or 2 weeks after full emergence, depending of the prevalence of the late blight. Dithane was used at a fortnightly basis or each time it was deemed necessary depending on the prevalence of late blight. Beans were harvested at full maturity, when pods had dried in the field. Potato was harvested 125 days after planting.

Table 4.3. Parameters used in the economic analysis of the different ISFM management technologies.

Parameter	Actual prices at local market in 2010
Price of bean seed (USD kg^{-1})	0.67
Price of potato seed (USD kg^{-1})	0.67
Price of DAP (USD kg^{-1})	0.83
Price Urea (USD kg^{-1})	0.83
Labor cost (USD day^{-1})	1.67
Price of bean grains (USD kg^{-1})	0.50
Price of potato tuber (USD kg^{-1})	0.20

4.2.3 Economic analysis

Economic analysis was done using a partial budget analysis model (CIMMYT, 1988) to evaluate the profitability of tested ISFM component treatments. Only costs that were significantly affected by alternative treatments were considered for economic analysis to make the comparison of benefits and costs across different treatments with respect to farmer practices. Detailed data on labour requirements were collected each season for land preparation, planting, fertilizer application, thinning, weeding, disease control and harvest. Other input and output prices, derived from the farm gate prices in the area, and values used in the economic analysis are presented in Table 4.3. The time taken to perform every activity was recorded and the labour was valued at the local wage of Rwf 1000 (USD 1.67) for a 8 hours working day.

4.2.4 Agronomic use efficiency of N (mineral) fertilizer

To estimate the agronomic N use efficiency (N_{AE}) by ISFM technologies, a methodology developed by Vanlauwe et al. (2011) was used. N_{AE} values were calculated according to equation 4.1.

$$N_{AE} = (Y_{Mix} - Y_O) / \mathrm{F_{appl}} \qquad [4.1]$$

Where Y_{Mix} refers to the yield [kg ha^{-1}] in the treatment with both N fertilizer and organic N inputs,
Y_O refers to the (calculated) yield (kg ha^{-1}) with only organic N inputs at a dose that is equivalent to the N dose in the treatment with both N fertilizer and organic N inputs, and
$\mathrm{F_{appl}}$ is the amount of fertilizer N applied (kg N ha^{-1}).

4.2.5 Statistical analysis

Data analysis of variance (ANOVA) was conducted using the MIXED procedure with farm location, farm landscape position, cropping system and ISFM component treatments as fixed factors and farm (famer's fields) as the random factor in the Genstat statistical package, (GenStat 14th Edition). In all figures in this paper, error bars represent standard errors of the differences (SED) of means. The effects of various factors and their interactions were compared by computing least square means (LSMEANS) and standard errors of differences (SED). Significance of difference was evaluated at $P < 0.05$.

4.3 Results

4.3.1 Potato tuber yields and bean grain yields during first season

There were interactions among the factors (landscape, location and IFSM components) for bean grain yields (Figure 4.3a), but there was no interaction of the three factors on potato tuber yields (Figure 4.3b, c and d). Potato tuber and bean grain yields were lower in Rwerere; but potato tuber yield was higher by 8% in the Upper slope of Rwerere than in the Gataraga (Figure 4.3d). For inputs use T2, T3 and T4 in all locations, potato tuber yields as well as bean grain yields from the footslope fields were generally higher

(Figure 4.3a and c). In Gataraga, the use of DAP and improved germplasm (T3) significantly ($p<0.05$) increased bean grain yields relative to the farmers' practice and to other ISFM component treatments. Combined use of improved germplasm, manure, DAP and Urea (T4) resulted in potato tuber yield increase of 4330 kg ha^{-1} in Rwerere and 5894 kg ha^{-1} in Gataraga relative to the farmers' practice. Beans grain yields were generally lower in Rwerere (1167 to 2288 kg ha^{-1}) compared to Gataraga (1606 to 3145 kg ha^{-1}) (Figure 4.3a).

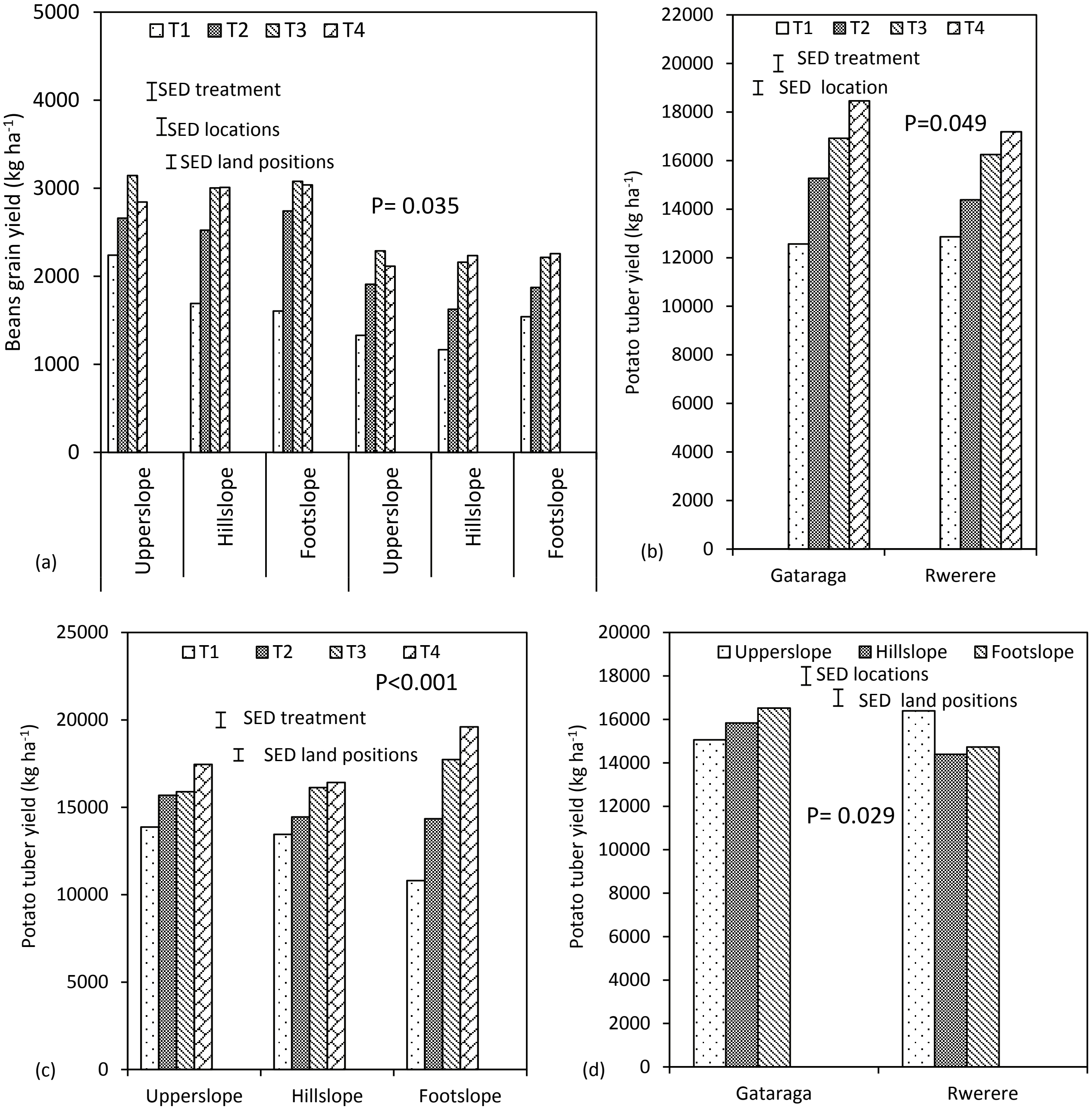

Figure 4.3. (a) First season bean grain yields from the upperslope, hillside and footslope positions in Gataraga and Rwerere as affected by treatments (T1, T2, T3 and T4), (b) first season potato tuber yields from Gataraga and Rwerere for different treatments, (c) first season potato tuber yields from the upperslope, hillside and footslope positions as affected by treatments, and (d) first season potato tuber yields from the upperslope, hillside and footslope positions in Gataraga and Rwerere. T1, T2, T3 and T4 are treatments and are described in details in Table 2. "SED" refers to standard error of the differences for the respective factor or interaction presented.

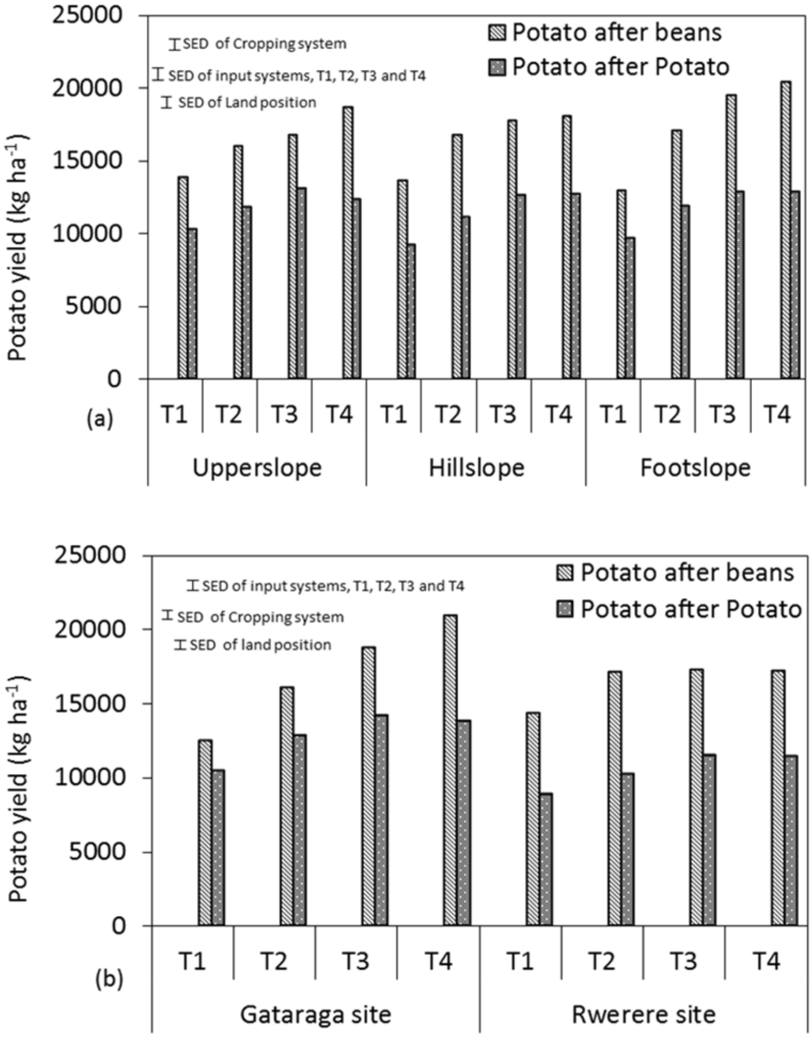

Figure 4.4. Influence of cropping system, landscape positions (a) and locations (b) on potato tuber yield in 2010. Where T1, T2, T3 and T4 are ISFM component treatments and are described in details in Table 4.2. "SED" refers to standard error of the differences for the respective factor or interaction presented.

4.3.2 Potato tuber yield as affected by the preceding bean crop and ISFM component treatments

The results indicate that potato tuber yield remains greater in the rotation with bean as a preceding crop and the lowest in continuous potato cropping system (Figure 4.4a and b). Mean potato tuber yield differences across the locations were highly significant ($P < 0.0001$). Potato tuber yield was more than 9% (i.e. 1386 kg ha^{-1}) as high in the Gataraga location than in the Rwerere (Figure 4.4b). In general, the mean tuber yield of potato grown following previous bean was 30% (5124 kg) higher than the continuous potato cropping system. A rotation of bean and potato supplied with manure, DAP, Urea and improved seeds (T4) gave over 27% (i.e. 4285 kg) the yield obtained with farmers 'practice (T1). When analysed by location vis à vis to previous bean, significant differences in potato yield was obtained between ISFM component treatments (Figure 4.4b). Potato yield on landscape positions was not influenced by the bean-potato cropping system; but potato yield was highly influenced by the interaction between landscape positions, ISFM component treatments and locations (Figure 4.4a and b).

4.3.3 Agronomic N use efficiency as affected by mixing fertilizer with organic inputs

The efficiency of N fertilizer in combination with manure varied significantly with landscape positions and sites (Figure 4.5). Except for upper-slope landscape position in Gataraga, the N-AE of potato in both Rwerere and Gataraga was positively influenced by the use of manure and DAP (T3). The use of manure and DAP (T3) resulted always in higher N-AE of potato across landscape positions and locations (Figure 4.5).

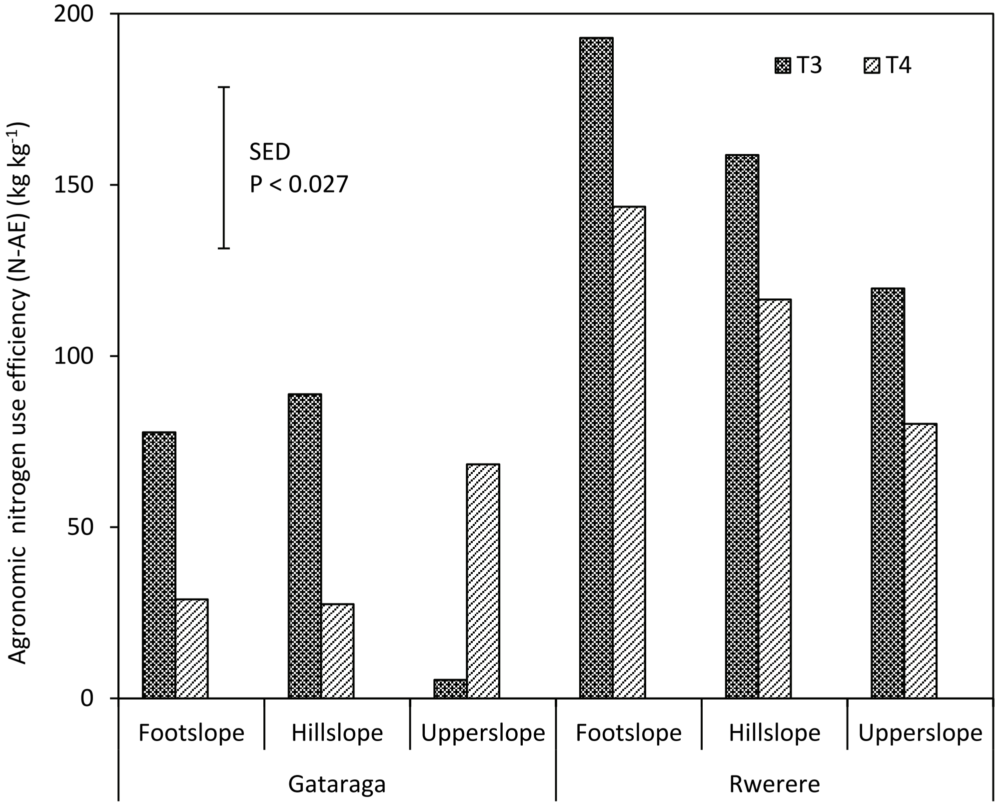

Figure 4.5. Agronomic nitrogen use efficiency (N-AE) at different landscape positions as affected by ISFM component treatments on potato in Rwerere and Gataraga sites, 2010 A. T3 is an ISFM component treatment comprising improved germplasm, manure and DAP and T4 is an ISFM component treatment comprising improved germplasm, manure, DAP and Urea applied as top dressing fertiliser. "SED" refers to standard error of the differences for the respective factor or interaction presented.

N application of 19.8 kg of N ha^{-1} (T3) in potato's plots in Gataraga site gave N-AE ranging from 5 to 89 kg kg^{-1} of N (average 53 kg kg^{-1} of N), while N application of 48.4 kg of N ha^{-1} (T4) had a N-AE that varied between 28 and 68 kg kg^{-1} of N (average 48 kg kg^{-1} of N) (Figure 4.5). N-AE of potato grown in Rwerere ranged between 120 and 193 kg kg^{-1} of N (average 157 kg kg^{-1} of N) when only 19.8 kg of fertilizer N ha^{-1} was applied (T3) but when 48.4 N ha^{-1} was applied (T4), the N-AE varied between 80 and 144 kg kg^{-1} of N (average 113 kg kg^{-1} of N).

4.3.4 Economic analysis

The ISFM component treatments allowed higher benefits but with an increase in costs, relative to the farmer's practices (Figure 4.6a and b). Labour costs slightly differed between ISFM components and varied on average between 29% to 40% of the total cost. Non-labour costs were higher because of the higher seed prices and the higher cost of fungicides used in the treatment and prevention of potato late blight. In both Gataraga and Rwerere, the bean as a preceding crop to potato (B-P) resulted in an increase of net benefits. However the increment of the net benefits in Rwerere due to growing bean as a preceding crop to potato (B-P) was higher in treatments with lower inputs in the following order: 38%, 47%, 54% and 66%, respectively for T4, T3, T2 and T1 (Figure 4.6a and b).

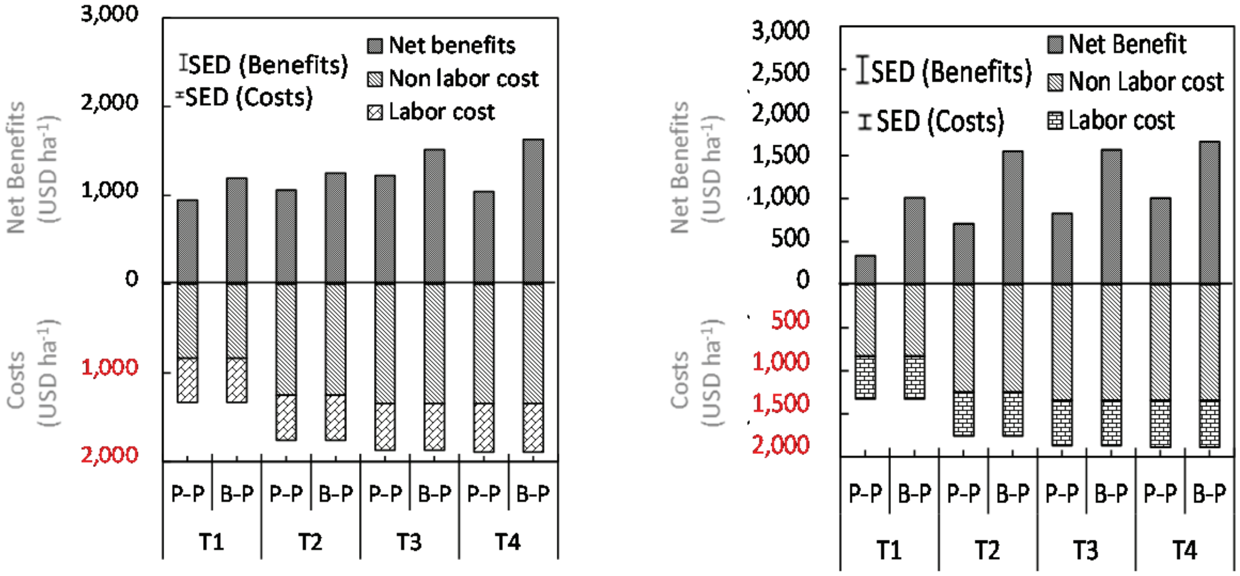

Figure 6. Costs and net benefits as affected by ISFM component inputs and cropping systems including P-P (continuous potato) and B-P (potato after beans) in (a) Gataraga site and (b) Rwerere site. Non-labour costs include purchase of seeds, fungicides or pesticides and fertilizers. T1, T2, T3 and T4 are fertiliser inputs as described in Table 2. SED represent standard errors of differences in total costs and net benefits for the interaction of cropping system and fertiliser inputs.

4.4 Discussion

The average N-AE value (48 kg kg^{-1} of N) observed under farms with degraded soil of Rwerere was close to the average N-AE (56 kg kg^{-1} of N) obtained by Essah and Delgado (2009). High application of N fertilizer during the growing season did not improve N-AE values in Gataraga site, but the application of specific ISFM components resulted in substantial increases in N-AE. Vanlauwe et al. (2010; 2011) demonstrated that the combination of inorganic and organic fertilizer as well as the use of improved germplasm increases the N-AE of crops. However, the N-AE can be low for excessive fertilizer N application rates or when fertilizer is applied to fertile or unresponsive soil (Vanlauwe et al., 2011). We observed a lower N-AE especially for potato crop in foot slopes fields which were relatively more fertile compared to hill and upper slope fields. However, the low N-AE of potato crop in Rwerere got improved when with the treatment comprising the most ISFM components (manure combined with DAP, improved seeds and the use of the N strategic fertilizer or fertilizer timing). These results partly corroborate with the findings of Sitthaphanit et al. (2009) who reported that fertilizer timing and splitting strategies conducted in sandy soils under high rainfall regimes improved nutrient use efficiency.

Because of variability found within farms, Vanlauwe et al. (2011) recommended to always adjust for site-specific soil conditions to maximize the N-AE. Titonnel et al. (2008) demonstrated that relative response of maize to NPK fertilizers tended to decrease with increasing soil quality and they reported that soil heterogeneity affected resource use efficiencies mainly through effects on the efficiency of resource capture. This concurs with our findings: N-AE increase was largest when nutrient resources were in short supply and in less soil fertile fields. Variability of soil fertility within and across farms in Rwanda has been reported due to preferential application of available inputs, especially composted manure or FYM to parcels of land around homesteads (Roose and Barthès, 2001) but also by the biophysical conditions that vary within short distances due to relief, parent material and altitude (Nizeyimana and Bicki, 1992).

ISFM component treatments resulted in increased bean and potato yields and economic benefits across and between sites and with landscape positions. Nabahungu et al. (2011) demonstrated that the

ISFM components of the combined use of organic and inorganic fertilizers increased beans grain yield in both the South and Eastern of part Rwanda. Similar results were reported by Pypers et al. (2011) in the South Kivu of the Democratic Republic of Congo where fertilizer application comprising a combination of manure and inorganic fertilizer increased beans yield. However, Pypers et al. (2011) observed that the improved germplam did not increase beans grain yield unless ISFM components were simultaneously implemented. We observed increases in beans grain yield due to the use of improved germplasm only but the yield increment of beans grain was further increased when other ISFM components were simultaneously implemented. However, on relatively fertile soils of Gataraga the use of Urea as a top dressing fertilizer on beans resulted in a lower yield (Figure 4.3a). Bean may not respond to additions of nitrogen (N), especially under the right soil conditions (Jansa et al., 2011). Bean usually recover less than 50% of applied N fertilizer and this phenomenon is probably related to the ability of bean to modify the root environment (Jansa et al., 2011) to maximize nutrient uptake, especially when the soil pH is 6.0-6.5 (Wortmann, 1998).

Bean grown as a preceding crop significantly increased potato yield as compared to a continuous potato cropping system but this increase in potato yield significantly varied between sites and landscape positions (Figure 4.4a and b). An on-farm experiment in Uganda demonstrated that potato is highly responsive to bean rotation if used before or after cereals (Lemaga et al., 2001). Climbing bean presents a better option in potato rotation system as an early maturing crop (120 to 130 days) in the highlands of Rwanda vis à vis to cereals that occupy land for more than three quarters of a year. The increase of potato yield is partly attributable to rotational effect of bean, other than N contribution as reported for other legume crops (Lunze et al., 2011; Nabahungu et al., 2011; Pypers et al., 2011). The rotation effect could be, reduced pests and diseases (Lemaga et al., 2001) and improved nutrient availability (Vanlauwe et al., 2010). The potential of crop rotation with potato in eradicating potato pests and diseases in short-season rotations are limited, particularly if the field is heavily infested (Lemaga et al., 2001). According to Lemaga et al. (2001), an one-season rotation could only reduce potato bacterial wilt and increase potato yields to acceptable levels on mildly infested soils. Potato production in smallholder farmers in the highlands of Rwanda faces huge biotic constraints such as late blight and bacterial wilt that reduce crop productivity (Muhinyuza et al., 2008). We obtained a lower average potato yields 15126 to 16477 kg ha^{-1}, especially in Gataraga with its high potential soil fertility. Experimental plots used in our study were selected into farmers' fields previously grown in a rotation cropping system with cereals. Because of low temperatures, cereals take 7 to 9 months to reach the physiological maturity. To cope with this situation, farmers have developed strategies by allowing potato volunteers to grow under these cereals. These potato volunteers are harvested along the season until cereals are matured as an alternative of getting quick food for household consumption. These practices are additional compounding factors to potato production, they may increase the incidence of potato diseases to the next potato growing season.

Averaging across locations for bean, T3 (manure+ DAP + Improved seeds) produced the highest grain yield of 2642 kg ha^{-1}. When averaging across locations for potato, the highest tuber yield of 17907 kg ha^{-1} was obtained with T4 (Manure + DAP + Urea as top dressing + Improved seeds). This implies that potato responded better than bean to the nitrogen applied as a top dressing input. The proper time of application of N fertilizer is important in crops, particularly in bean production systems in order to maximize N2 fixation (Lunze et al., 2012). It is suggested that only 0.2% of N fertilizer is accumulated by climbing bean at the late stage of pod-filling while 84% of N is derived from fixation and 16% of N from soil (Kumarasinghe et al., 1992).

Data in Table 4.4 indicate that as ISFM components were cumulatively added to subsequent treatments this increased the financial returns, relative to the traditional farmer's practice. In both Rwerere and Gataraga the rotation beans-potato was highly profitable, as it resulted in a significant increase in net benefit that varied between 400 and 822 USD ha^{-1} in Gataraga and between 1100 and 1560 USD ha^{-1} in

Rwerere. The economic benefits of crops such as beans are due to their high market value (Halloran et al., 2005). These economic benefits can attract farmers to adopt a bean-potato rotation farming system. Particularly in Rwanda, climbing beans have been traditionally cultivated in higher altitude zones beyond 1700 m asl with a relatively short growing period (4 to 5 months) and are positively associated with high yield potential of 3 to 5 t ha^{-1} (Sperling and Muyaneza, 1995).

In Rwanda most studies used value cost ratio (VCR) for analysing economic benefits and financial considerations of inorganic fertilizer combined with organic amendments in potato and bean crops (Kelly and Murekezi, 2000). They found that fertilizer use was highly profitable on potatoes and beans in the highland zones of Rwanda with potato yield responses up to 9000 kg ha^{-1} and VCR ranging from 10-12. Their results corroborate our findings. Our analysis showed that both beans and potato responded significantly well to fertilizer use although the high cost of improved potato seed as well as the fungicides increased the cost of production.

4.5 Conclusions

Results from this study have shown distinct benefits of ISFM component treatments in increasing crop yield and profitability. Application of organic and inorganic N separately or in combination together with improved germplasm increased potato tuber and beans grain yields at all sites and land positions. High agronomic N use efficiency (N-AE) was obtained with low fertilizer application as well as in fields less fertile. This implies that there is an option to save on mineral N fertilization which has potential effects on sustainable agricultural intensification in soils low in organic matter. Growing potato after beans resulted in increased potato tuber yield compared with growing continuous potato. Although the use of combined organic and inorganic fertilizer together with improved germplasm increased the system productivity, the high cost of inputs in potato cropping system, especially improved potato seeds can overshadow generated benefits. Therefore effort should be made to mitigate the high cost of improved potato seeds, especially for resource-poor farmers. Measures to promote fertilizer use among farmers by reducing transaction costs or improving their accessibility should be accompanied with strategies to improve the use efficiency of the applied nutrients.

Table 4.4. Economic analysis of beans and potato rotation with ISFM components in two distinct agro-ecological zones of Rwerere and Gataraga, Rwanda. Dominated treatments (D) were used in the calculation of the Marginal Rates of Return (MRR).

Farming system	Treatments	Additional	Additional	Net	MRR
			(USD ha^{-1})		
Rwerere Season 2010 A					
Bean	T1	490	493	-4	
Bean	T2	615	515	100	4.8
Bean	T3	759	631	128	0.2
Bean	T4	762	686	75	D
Potato	T1	2430	2461	-31	
Potato	T2	2654	2471	183	21.6
Potato	T3	2923	2584	339	1.4
Potato	T4	2926	2614	312	D
Rwerere Season 2010 B					
Continuous potato	T1	2477	2461	16	
Continuous potato	T2	2679	2471	208	7.7
Continuous potato	T3	2851	2585	266	1.7
Continuous potato	T4	2553	2615	-61	D
Potato after bean	T1	2460	2461	-1	
Potato after bean	T2	2893	2471	422	42.3
Potato after bean	T3	3255	2585	670	2.2
Potato after bean	T4	3436	2615	821	5.0
Gataraga Season 2010 A					
Bean	T1	598	293	305	
Bean	T2	898	315	583	1.0
Bean	T3	1029	431	598	12.9
Bean	T4	978	486	491	D
Potato	T1	2487	2162	325	
Potato	T2	3102	2171	931	0.2
Potato	T3	3544	2284	1260	67.3
Potato	T4	3882	2315	1567	2.9
Gataraga Season 2010 B					
Continuous potato	T1	2324	2162	162	
Continuous potato	T2	2755	2172	583	42.1
Continuous potato	T3	3157	2284	872	2.6
Continuous potato	T4	3206	2315	891	0.6
Potato after bean	T1	2642	2162	480	
Potato after bean	T2	3333	2172	1161	68.1
Potato after bean	T3	3683	2284	1399	2.1
Potato after bean	T4	3880	2315	1565	5.5
SED (within site X treatment)		79		149	
SED (between site X treatment)		157		106	

Chapter 5

Impact of participatory integrated watershed management on productivity and efficient use of natural resources in the north-western highlands of Rwanda

This paper is a revised version of:

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Impact of participatory integrated watershed management on productivity and efficient use of natural resources in the northern highlands of Buberuka, Rwanda

Abstract

For two decades, Integrated Watershed Management (IWM) has been suggested and tried in the East and Central African highlands, as an effective way to address complex natural resources (NRs) challenges. However its implementation has not been successful in most cases, due to various barriers. This study used a methodological innovation whereby concepts of participation are integrated with watershed management activities. This participatory integrated watershed management (PIWM) approach is defined as a process whereby users define problems and priorities, set criteria for sustainable management, evaluate possible solutions, implement programs, and monitor and evaluate impacts. The "*Agasozi ndantwa*" approach which started in Rwanda in 2008 is one of the few large scale experiments that comes close to what PIWM should be. An analysis of its impact was conducted in the northern highlands of Buberuka, Rwanda using a data set collected from households in two villages between mid-2008 and end-2010. The two villages belong each to a single watershed and consist of 80 and 110 households respectively. One village was benefiting from the "*Agasozi ndantwa*" approach here referred to as "treated village" whereas the second village did not, here referred to as "untreated village". The impact of watershed development activities such as bench terraces, contour bunds and grass strips was assessed using the net present value (NPV), the internal rate of return (IRR) and the economic surplus method. Beans and potato yields were obtained from a research experiment conducted in the two villages in three consecutive seasons. Assessment of soil erosion was done using locally made Gerlach troughs in both treated and untreated village on grass strips and contour bunds along a toposequence on three slopes (<25%, ≥25 to <45% and ≥ 45%). The results suggest that an IWM approach has the potential of improving farmers' livelihoods and increasing the resilience of a degraded environment. The economic surplus method shows that watershed development activities benefited the agricultural producers, especially for those growing potato and wheat. Grass strips showed strong resilience, being 20+ years old and still effective in providing continuous barriers against soil loss. Grass strips, combined with trenches have significantly less soil loss than the without soil conservation situation. In the treated village, livestock played a significant role in maintaining soil fertility by providing 5,320 kg of manure per household which contributed to replenish a substantial share of soil nutrients. Grass strips and contour bunds were financially attractive only on slopes less than 45%. Bench terraces were financially attractive even when constructed on slopes steeper than 45% thanks to the related higher use of agricultural inputs. Watershed development activities changed the farming system through more integration between livestock and crops. Our results suggest that a PIWM approach has the potential of improving farmers' livelihoods and increasing the resilience of a degraded environment. What remains to be created are institutions that use wisely the additional income (e.g. from milk and manure) and improve the quality and quantity of manure.

Key words: watershed, participatory, natural resources, land degradation and Rwanda

5.1 Introduction

With its favourable climate, the highlands of the northern region of Rwanda offer a strong potential for agricultural production. However, the prevailing high population density leads to over exploitation of the natural resource wealth. Nearly 90% of the population is deriving their livelihood from agriculture and other enterprises based on natural resources leading to rapidly deterioration of productivity and profitability of these enterprises. Apart from a high human pressure on natural resources, farm land degradation is exacerbated by soil losses through water erosion (Clay et al., 1998; Lewis and Nyamulinda, 1996).

In the past two decades in the East and Central African highlands only minimum efforts were undertaken to participatory planning for the management of natural resources to ensure its effective management while minimizing conflicts between different resource users (German et al., 2012). More often, in a top down approach, attention focussed on how to limit surface runoff and improve soil infiltration on individual farmer's fields (e.g. Lewis, 1992; Lewis and Nyamulinda, 1996; Roose and Ndayizigiye, 1997). To this end, a wide range of soil and water conservation technologies and interventions have been proposed for the highlands region of Rwanda. Many of these technologies retain water and improve infiltration. Examples include mulching, organic inputs, terracing and hedgerow barriers (Drechsel et al., 1996). Also integrated soil fertility management (ISFM) practices have been successfully tested at farmers' fields in the highlands of Rwanda (Kagabo et al., forthcoming). ISFM is defined as a set of management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm. Similarly, technologies on the use of multi-purpose legume trees (MPTs) and herbaceous species in soil conservation and soil fertility management have been successfully tested (Yamoah and Grosz, 1988).

Successful results in mitigating soil erosion and improving soil fertility were reported in numerous projects. However, farmers' adoption have been hindered by a top-down approach (Critchley et al., 1994) in which farmers' knowledge on NRM has often been ignored in projects' inception and implementation (Tripathi and Bhattarya, 2004). As a result, most of the initiated NRM projects failed and the adoption of soil and water conservation technologies by farmers was limited. For instance in Rwanda, few promising NRM technologies had impact on the technical efficiency of smallholder farmers (Oduol et al., 2011) probably because these technologies were promoted to isolated farmers that operate as individuals hindering a wide adoption of these technologies (Mowo et al., 2010). The flow of resources like water, soil and nutrients transcend farm boundaries and the consequence of decisions about resource management and use extends beyond the individual land user (Swallow et al., 2006).

Currently the Government of Rwanda is building institutions that promote wider participation of farmers. One example is locally known as *Agasozi ndantwa.* The concept *Agasozi ndantwa* is based on a theory that each administrative entity in Rwanda should have a development model community that have all the features that make human livelihood meaningful including soil conservation and best agricultural practices. The *Agasozi ndantwa* approach is implemented at watershed scale and involves both private as well as governmental investment in establishing soil and water conservation structures and other development related activities. It has been argued that realistic mitigation of land degradation can only be achieved if there is public investment that is complemented by institutions that promote good governance and enforce rules (Stroosnijder, 2012).

The *Agasozi ndantwa* approach uses a watershed as the planning unit while integrating social, economic, ecological and policy concerns (German et al., 2012) to develop the best plan (De Steiguer et al., 2003). Farmers' role in the *Agasozi ndantwa* is through participation in a platform of stakeholders to discuss and negotiate conflicting interests and objectives on the same basis (Bousquet and Le Page, 2004) and through collective action; executing activities that are beyond the farm level. This collective action contributes to bring formal research to bear on demand-driven NRM agenda (Bekele et al., 2008; German and Taye, 2008; Mazengia and Mowo, 2012). A combination of innovative NRM technologies to the watershed approach can greatly address priority issues of farmers that bring quick benefits (Mowo et al., 2010). The "Agasozi ndantwa" approach is one of the few large scale experiments that integrates participation with IWM. We consider this as participatory integrated watershed management (PIWM). Participatory integrated watershed management (PIWM) approach is defined as a process whereby users define problems and priorities, set criteria for sustainable management, evaluate possible solutions, implement programs, and monitor and evaluate impacts (German et al., 2012). The "Agasozi ndantwa" approach is certainly not the most ideal example of PIWM but the best that could be found in Rwanda. As an integral part of the existing "Agasozi ndantwa" program, a monitoring process of PIWM activities was set up since 2008 with the objective to quantitatively assess the impact of PIWM activities on NRM resources, crop and livestock productivity and on the socio-economic situation of households.

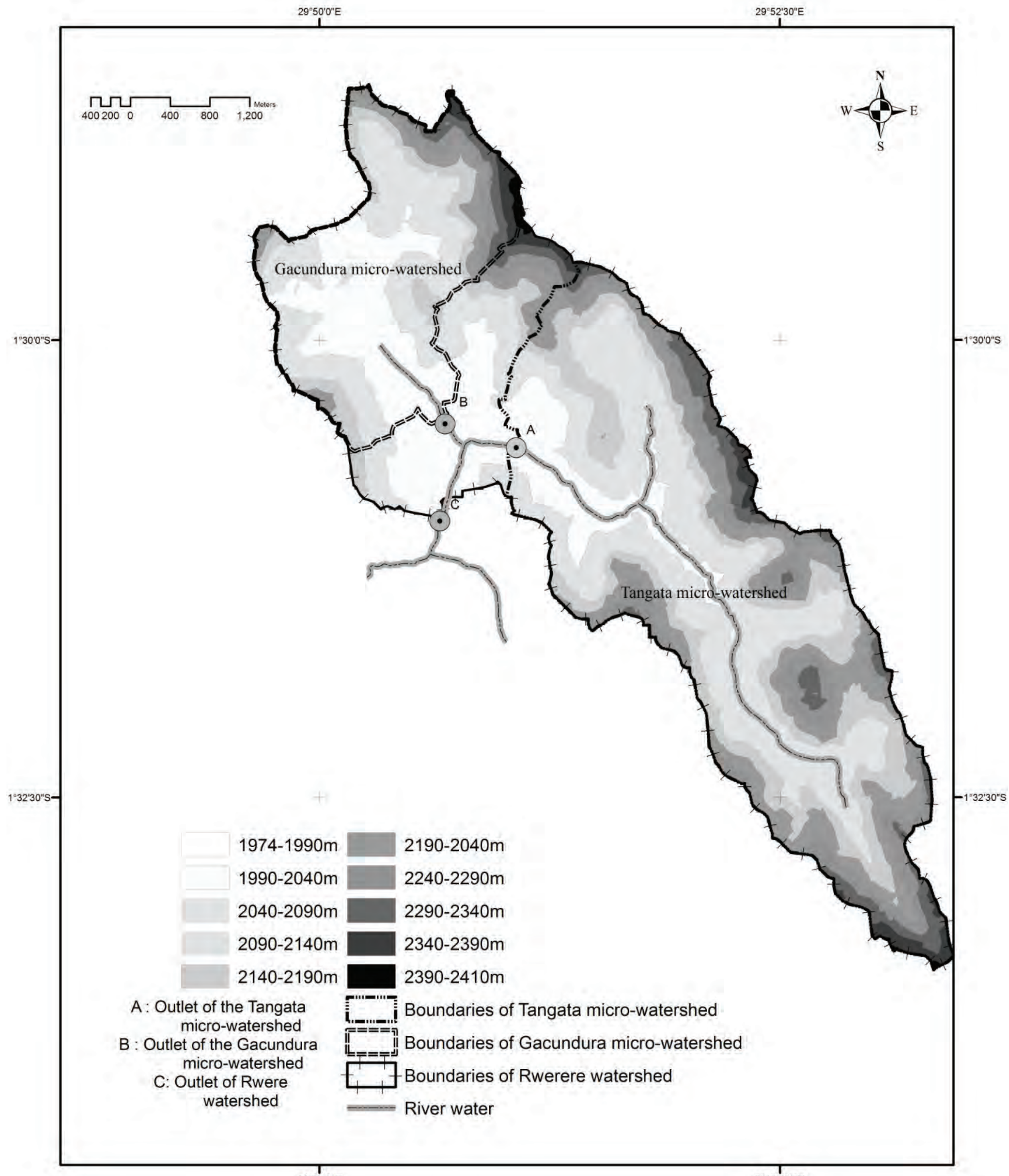

Figure 5.1. Digital elevation map illustrating hydrological boundaries and features of Rwerere watershed, Rwanda

5.2 Material and methods

5.2.1 *The intervention approach*

This study used a methodological innovation whereby concepts of participation are integrated with watershed management activities as developed by the African Highlands Initiative (German et al., 2012). Three approaches were used: (1) an approach that combines hydrological/landscape and administrative data to delineate watershed boundaries, (2) a watershed characterization where biophysical and socio-economic baseline data are collected prior to intervention. This enables research and developement teams and communities to identify socio-economic and environmental "hotspots" and opportunities for intervention and to measure progress during implementation, and (3) an approach for watershed development that uses a watershed as an entry point for developement through local leadership and local NRM structures.

By employing both watershed-level and administrative criteria it was possible to accommodate both biophysical and social processes, thus facilitating participation and implementation. The resulting provisional boundary served to guide a baseline study and a participatory diagnosis of the watershed by addressing landscape-level problems whose spatial dimensions may extend beyond the hydrological boundaries of the watershed. Local government agencies with ultimate responsibility for service provision and natural resource governance were included in the process of diagnosis. Prior to watershed development, a household survey using pre-tested questionnaires were carried out with a representative number of households (as described in section 5.2.3) in the watershed to gather basic information on the five capital assets (human, social, natural and physical capital), and on household livelihood portfolios and related constraints.

An approach that uses a "watershed as an entry point for development through local leadership and local NRM structures" was used. This approach entails working through established leadership structures and existing local NRM institutions with a history of involvement with development agencies to inculcate responsibility on their behalf for mobilizing communities for improved NRM (German et al., 2012). This "watershed entry through local leadership and local NRM structures" was built through an existing institution that promotes participation of farmers locally known as *"Agasozi ndantwa"* to boost the adoption of NRM practices. As described in section 5.1, "Agasozi ndantwa" operates at watershed level to build a local governance structure in supporting communities and ably fulfilling their responsibilities towards their constituents. It also strengthen the capacity of local institutions in articulating and addressing local concerns. Building on this existing institution of "Agasozi ndantwa", a quick mobilisation of watershed development stakeholders was possible and areas experiencing severe degradation were identified and selected. Similarly, a package of technologies including soil conservation structure, integrated soil fertility management component (ISFM) and the "one farm, one cow" program were implemented through the existing "Agasozi ndatwa" program.

The "Agasozi ndantwa" approach does not follow a 'classical research setup' but is more of the action research type. Nevertheless, it is one of the few large scale experiments that followed what PIWM should be. It is certainly not the most ideal example but the best that could be found in Rwanda. Therefore, we considered it valuable enough to describe its experiences.

5.2.2 *Description of the study area*

This study was conducted in Rwerere watershed (Figure 5.1) in the framework of "Agasozi ndatwa" referred here to as an example of the PIWM approach. Two villages, namely; Tangata and Gacundura were selected from Rwerere watershed (Figure 5.1). Tangata village is located in the "Agasozi ndatwa" program area referred as "treated village" while Gacundura village was not under the "Agasozi ndatwa" development program referred as "untreated village". Both Tangata and Gacundura are located in the agro-ecological zone of Buberuka highlands, Northern Province, Rwanda with a latitude of 01° 32' S and longitude of 29° 52' E, and an altitude of around 2190 masl (Figure 5.1).

5.2.3 Sampling procedure

In this study area, people are organized on the basis of villages. Therefore participating with them as a community requires using the village as the primary project unit rather than the watershed. To be able to reconcile the village-based approach with the watershed orientation of the technical plan, two villages namely; Tangata and Gacundura with boundaries that nearly coincided with that of the Rwerere watershed were selected. The watershed selection followed a stratified random sampling design under the following two categories of communities; (i) PIWM referred to as "treated village" and (ii) no intervention of PIWM referred to as "untreated village". The purpose of the 'treated'- 'untreated' village approach was used to assess the impact of PIWM activities on land management and farmers' livelihoods. This approach requires a minimum of two villages/watershed; "control and treatment" and two periods of study; "calibration and treatment". The basis of the paired village/watershed approach is that there is a quantifiable relationship between paired data for studied indicators such as water quality, crop productivity increase for the two villages/watersheds, and that this relationship is valid until a major change is made in one of the villages/watersheds.

The first level strata consisted of a watershed while the second-level consisted of villages. These strata represent the extent to which agricultural research and development projects have intervened in the study area. Only two villages were purposively selected because they exhibit similar agro-ecology, farming system, market linkages, culture and demography with comparable social and institutional features, thus providing an opportunity to test the impact of PIWM activities under similar social settings (Table 5.1). This avoids, to a large extent, differences that can be caused by many other factors.

Table 5.1 Baseline characteristics (2008) of Tangata and Gacundura villages in Rwerere watershed, Rwanda.

Villages	Tangata	Gacundura
No. Household members (persons)	3.85	3.35
Age household head (year)	23.6	25.5
Total farm area (ha household^{-1})	0.43	0.415
Altitude (m) watershed average	2193	2195
Annual temperature (°C)	19	19
Annual precipitation (mm)	1346	1346
Soil pH (water)	4.9	4.8
Total N (%)	0.3	0.27
% organic carbon	3.4	3.5
ECEC (cmol kg^{-1})	9.3	8.9
Base saturation (%)	59.6	59
Clay (%)	25	23
Cropping land (% of total farm area/household)	95%	96%
Pasture and others (% of total farm area/household)	3	3
Woodlots (% of total farm area/household)	2	1
Dominant lithology	Quartzite and schist complex	Quartzite and schist complex
Distance to market (km)	1.2	0.8

Prior to watershed development, a household survey was carried out in 2008 to compare the baseline situation of households and communities. The level of development and implementation of policies, which can have profound implications for the operations and institutionalisation of watershed development in the two villages were found to be similar (Table 5.1). Using a sampling frame comprising of names of household heads in the villages as provided by local leaders, 30 households per village were selected using random numbers for inclusion in the household interviews. Therefore, a total of 60 households were interviewed and monitored about the impact of bench terraces, grass strips, contour bunds, “one farm” “one cow” program and production enhancing technologies such as improved crop varieties and manure, on land management and households’ livelihood.

5.2.4 Data collection and monitoring of watershed activities and design

We used baseline and endline data collected respectively in mid-2008 and end of 2010. The household data were collected using a structured questionnaire that sought information on general household characteristics, awareness and use of SWC technologies, crop and livestock production, marketing of agricultural produce, interactions among key stakeholders in the area and access to and use of improved inputs. SWC technologies on which information was obtained include bench terraces, grass strips and contour bunds. Data on the villages were also collected using a semi-structured questionnaire and a checklist, which was administered to key informants and focus groups, respectively. The village characterisation questionnaire was specifically designed to capture information on institutional variables that are exogenous to the households but endogenous to the village, such as village linkage with financial, NRM, research and extension organisations.

In the treated village, soil loss on grass strips and contour bunds was assessed along a toposequence on three slopes (<25%, ≥25 to <45% and ≥ 45%) (Figure 5.2). Likewise, soil loss was also assessed in the untreated village. Assessments were also conducted in both villages on inputs such as manure, improved seeds and on fodder production. A contineous monitoring of manure production and use in both villages was conducted. A data sheet form was distributed to heads of househeads to record the manure production on daily basis. A similar form was distributed to farmers to record harvested fodder from hedgerow barriers and from bench terrace risers.

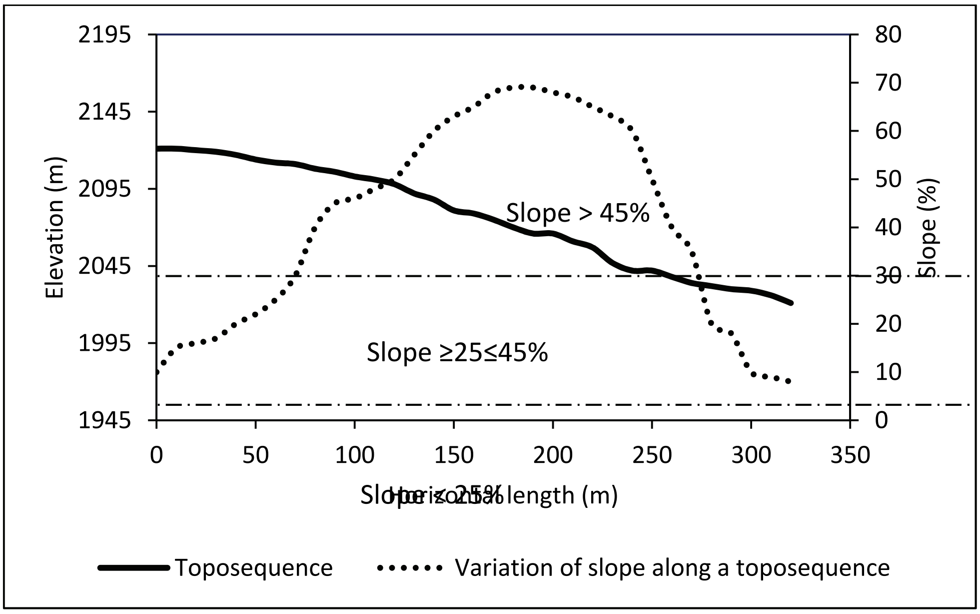

Figure 5.2. Slope gradients along a typical toposequence in Rwerere watershed, Rwanda.

5.2.5 Soil erosion assessment

Assessment of soil erosion was done using locally made Gerlach troughs as detailed in Kagabo et al. (in review). The device consists of a simple metal gutter that captures the surface runoff from the upper unbounded area. The trough was made of metal sheet, closed at the sides and with a movable lid on the top to prevent direct entry of rain. An outlet pipe runs from the base of the gutter to a collection jerrycan (Morgan, 2005; Tenge et al., 2007). The total amount of surface runoff was measured and the water and sediment mixture stored after each erosive rainfall. The soil settled at the bottom of the storage containers was dried and weighted. This gave the sediment content per volume surface runoff (Morgan, 2005).

5.2.6 Measurement of crop yield response

Beans and potato yields were obtained from a research experiment conducted in three consecutive seasons as detailed in Kagabo et al. (under review) while wheat and maize yields were measured from farmers' fields for one cropping season.

5.2.7 Financial analysis

The impact of watershed development activities such as bench terraces, contour bunds and grass strips on financial returns to farmers was assessed using the net present value (NPV), the internal rate of return (IRR) using the methodological approach developed by Gittinger (1982) and the economic surplus method. NPV is the most straight forward discounted cash flow that measures the development project worth and is estimated according to equation 5.1.

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{R_t}{(1+r)^t} \qquad [5.1]$$

Where:
R stands for revenue,
The super and sub-scripts t represent respectively future (year) and current time (year), and
r stands for the discount rate at time (t).
An alternative decision criterion to express the profitability of a project is the Internal Rate of Return (IRR). IRR is defined as the maximum interest that a project could pay for the resources used if the project is to recover its investment and operating costs and still break even (Gittinger, 1982). Or, in other words, IRR is the rate of return on capital outstanding per period while it is invested in the project (Merrett and Sykes, 1973). Internal Rate of Return was computed according to equation 5.2.

$$\text{IRR= r if } \sum_{t=0}^{n} \frac{R_t}{(1+r)^t} = 0 \qquad [5.2]$$

When the IRR of a project is greater than the discount rate, then the NPV of that project is positive. An interest rate of 13%, the lowest interest rate of agricultural projects loans in Rwanda was used in all calculations. The lifetime of the respective investments in the watershed development activities is considered to be 20 years.

The impact of the watershed development activities on the village economy was computed using the economic surplus model proposed by Pachico et al. (1987). The theory of the economic surplus model stems from shifts over time of supply and demand functions. The change in total surplus in the village economy due to watershed intervention was decomposed in to a change in consumer surplus and a change in producer surplus according to equation 5.3.

$$\Delta TS = \Delta CS + \Delta PS \qquad [5.3]$$

Where:
ΔTS is the change in total surplus,
ΔCS is change in consumer surplus, and
ΔPS is change in producer surplus.

These latter surpluses are calculated according to respectively equation 5.4 and 5.5.

$$\Delta \mathrm{CS} = P_O\, Q_O\, \mathrm{Z}\,(1 + 0.5 * \mathrm{Zn}) \qquad [5.4]$$

$$\Delta \mathrm{PS} = \mathrm{P}_0\, \mathrm{Q}_0\, (\mathrm{K} - \mathrm{Z})\,(1 + 0.5 * \mathrm{Zn}) \qquad [5.5]$$

Where:
P_0 = Price of product,
Q_0 is η is the elasticity,
K is the supply shift due to watershed intervention and is computed according to equation 5.6.

$$K = \forall * \rho * \Psi * \Omega \qquad [5.6]$$

Where:
∀ is net cost change which is defined as the difference between reduction in marginal cost and reduction in unit cost. The reduction in marginal cost is defined as the ratio of relative change in yield to price elasticity of supply (ε_s). Reduction in unit cost is defined as the ratio of change in cost of inputs per hectare (1+change in yield).
ρ is the probability of success in watershed development implementation,
Ψ represents the adoption rate of technologies, and
Ω is the depreciation rate of technologies.

Mathematically, Z represents the change in price due to watershed interventions according to equation 5.7.

$$Z = K * \frac{\varepsilon_s}{\varepsilon_d + \varepsilon_s} \qquad [5.7]$$

The information on price elasticity of demand and supply of various farm products were obtained from published sources in Rwanda.

5.3 Results and discussion

5.3.1 Farm characteristics

The production system in the treated village evaluated in an integrated crop-livestock system where livestock provide manure (on average 5,394 kg per year per household) as an input for crops. In addition, crop residues are used as animal fodder and represent about 27% of the total livestock forage (Table 5.2). Little crop-livestock integration exists in the untreated village and the share of crop residues in the total livestock feed is only 13.4%. This is similar to what Klapwijk (2011) found among three categories of farmers (wealth ranking) in the southern highlands of Rwanda. The proportion of crop residues allocated as feed depends on livestock density in the farming system and rules of access (de Leeuw, 1997). In the treated village, farmers are specialized on specific crops (thanks to the watershed management program) while in the untreated village farmers still rely on a traditional mixed farming system and only keep small stock that require relatively less feed. Livestock numbers expressed in TLU (Tropical Livestock Unit;

1TLU=250kg live weight) are high among households living in treated village (Table 5.2). In the treated village, the majority of households had two or more than two TLU. In the untreated village, 71% of the households had less than one TLU, 10% had at least one TLU, 12% had two TLU and 7% had more than two TLU. Cattle were the most dominant livestock category in the treated village whereas small stock was predominantly found in the untreated village (data not presented here). The treated village benefited from the watershed development activities such as, the 'One farm, one cow'-program initiated within the *Agosozi ndatwa* development program in 2008. This 'One farm, one cow'-program is complementary to the existing policy of the zero-grazing system. Beneficiaries (individual household farms) of the 'One farm, one cow'-program are required to have an appropriate animal housing (a 'zero-grazing unit') and sufficient animal fodder. Watershed development activities related to soil and water conservation practices create new niches (mostly bench terrace risers) for planting fodder. These new niches for fodder planting are good opportunities to farmers who on average own only about 0.45 ha (Table 5.2). Synergies from these policies (e.g. 'One farm, one cow', soil and water conservation program and zero grazing) create enabling conditions to farmers by providing simultaneously cattle, niches for fodder and terraces for soil and water conservation and management.

Table 5.2. Characteristics of four categories of households (differing in TLU) in treated and untreated villages in Rwerere watershed, Rwanda.

	Number of livestock in TLU									
	Untreated village (n=30)					Treated village (n=30)				
Variable	<1	1	2	>2	ALL	<1	1	2	>2	ALL
Share of household (%)	71.0	9.7	12.9	6.5	100.0	30.0	13.3	33.3	23.3	100.0
Use of of FYM[a] (kg)	1024	1383	3340	4643	2598	2171	3708	6519	8895	5323
TLU[b]	0.3	1.3	2.3	3.6	1.9	0.3	1.4	2.5	4.4	2.2
Share of crop residue as feed					13.4					27.2
Total farm area (ha)					0.43					0.46
Age household head (yr)					36.3					37.3
Household members					4.7					5.4

[a] Farm Yard Manure per household farm and [b] Tropical Livestock Unit (1TLU=250kg live weight)

The provision of cattle to farms present mainly two major benefits: production of milk and other indirect benefits including nutrients from manure which lead to improved crop productivity (Rufino et al., 2009). The use of manure on farmers' fields has been effective in achieving high yields in the north-western highlands of Rwanda (Kagabo et al., under preparation). Although, in highly depleted soils, crop production does not necessarily increase through the use of livestock manure, mostly because of the poor quality and small quantity of manure (Giller et al., 2011; Nyamangara et al., 2009).

In the treated village the adoption for all soil and water conservation practices is above 60% (n=30), whereas in the untreated village the adoption is only above 50% (n= 30) for tree planting in the form of woodlots and hedgerow barriers (Figure 5.3). The adoption of hedgerow barriers was similar in both villages, 80% and 79% respectively for treated and untreated village. Similar results were previously reported in the highlands of Buberuka in Rwanda where most famers either 'build terraces with live hedges' (80%) on at least some of their fields, or else they 'plant tall grasses' (83%) on the lower ends of their fields to stop erosion (e.g. Kagabo and Nsabimana, 2010; Ndiaye and Sofranko, 1994; Oduol et al., 2011).

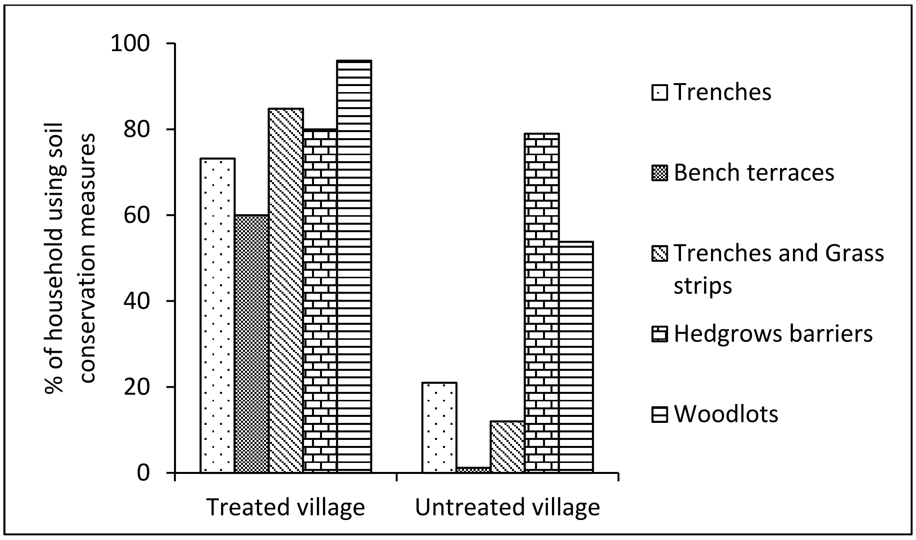

Figure 5.3. Adoption by farmers of soil and water conservation technologies from treated and untreated villages of Rwerere watershed, % of households in year 2010.

5.3.2 Farmers' perception on soil fertility change

Farmers' perception on soil fertility status is presented in Figure 5.4. Despite the steep slopes and the high erosivity of rainfall (Roose and Ndayizigiye, 1997), most respondents (68%) in the treated village perceive that soil fertility has been improved over the last 5 years. However, in the untreated village 66% of respondents perceive that soil fertility is deteriorating. In similar environmental settings, Ndiaye and Sofranko (1994) corroborate our results. In the treated village, few farmers (5.1%) do not perceive the change in soil fertility. This is probably because of the soil fertility of terraced lands that goes down in the first years after construction due to disturbances of the fertile top soil during the construction process of bench terraces. To restore the soil fertility of terraced lands as quickly as possible, additional investments are needed. For instance in the Rwandan conditions additional inputs are required, e.g. 10 t ha^{-1} of manure, 1 to 5 t ha^{-1} of lime and the recommended fertilizer rates for each crop (Bizoza, 2011; Roose, 1996).

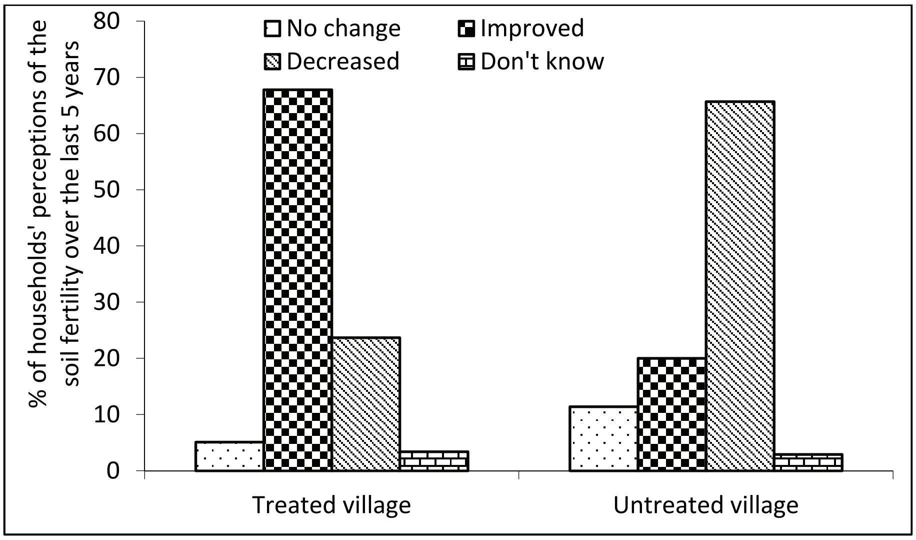

Figure 5.4. Households' perception of soil fertility change over the last 5 years in treated and untreated villages of Rwerere watershed, Rwanda.

5.3.3 Impact of livestock as a source of manure on soil fertility management

Livestock in both, treated and untreated, villages are kept under a zero grazing system. Esilaba et al.(2005) estimated that one TLU can produce about 7,000 kg of recoverable manure per year when stabled. The amount of manure production by an average per household is small, 5,323 kg and 2,598 kg, respectively for treated village and untreated village (Table 5.2). The difference may be due to inadequate skills in manure handling/management (Kagabo et al., under review-b). Another aggravating factor can be the inadequate feed supply that limits livestock production and thus the availability of manure, especially under smallholder farm conditions in Africa (Bayu et al., 2005). Manure production was double in the treated village relative to the untreated village due to differences in number of TLU (higher in treated village) and in feed quantity. In the treated village farmers use more crop residues (50% more than in untreated village) and have more access to cultivated fodder grown on risers of terraces.

The number of TLU and the amount of manure used as a soil input are highly correlated ($r^2 = 0.76$) in the treated village (Figure 5.5). This correlation is weak ($r^2 = 0.47$) in the untreated village probably due to the differences in manure management efficiency and other uses such as sale, donation or partial use of manure or the total abandonment of manure. Considering individual farmers, more manure is produced among farmers who own just less than one TLU, especially in the treated village. This suggests that farmers in a treated village have better management strategies compared to farmers living in an untreated village.

The productivity level of soils can only be sustainably improved if stocks of the nutrients in the soil are enhanced (Bayu et al., 2005). Livestock plays a significant role in maintaining soil fertility by providing manure that can contribute to replenish a substantial share of soil nutrients. In the case of Rwanda, a huge amount of manure, as much as 10,000 kg, is required to recover soil fertility of one hectare of terraced land (Roose and Ndayizigiye, 1997). Considering the amount of manure (5,323 kg per household) and the landholding size per household (0.45 ha) in the treated village, terraced lands may regain their initial fertility in two years. Hence, farmers can start benefiting from bench terraces as early as possible. This quick return of gains may increase farmers' adoption of bench terraces. The argument here, is not simply supplying the amount of nutrients in the form of N, K, P, etc. for the immediate use by crops, it is rather the improvement of biological, chemical and physical properties of the soil that is considered. Organic inputs such as manure is considered as a prerequisite for soil organic matter pool that maintains the physical and physicochemical components contributing to soil fertility (Vanlauwe and Giller, 2006). In addition, there is synergy obtained when using both organic and inorganic fertilizers together as already reported through the literature (e.g. Kagabo et al., under preparation; Nabahungu et al., 2011; Vanlauwe et al., 2011).

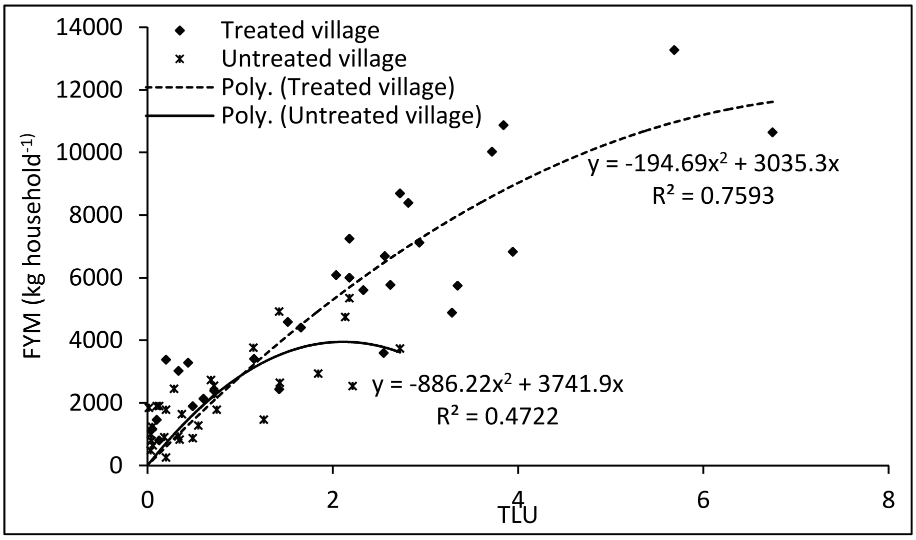

Figure 5.5. Relationship between number of TLU and FYM used per household in treated village (a), and in untreated village (b) in Rwerere watershed, Buberuka highlands, Rwanda.

5.3.4 *Fodder production on contour bunds and bench terraces*

Synergies of watershed development program known as *"Agosozi ndatwa"* that includes the 'One farm, one cow' program had a significant impact on the size and composition of the livestock sector. Closure to grazing as a result of the zero grazing policy, increased the adoption of fodder planted on bench terraces risers and on edges of most farmers' fields. This shift from free grazing to zero grazing also brought dramatic changes in the animal husbandry sector in the treated village. Fodder production on bench terrace risers and from other progressive (slow forming) terraces in both treated and untreated village is presented in Table 5.3. In the treated village, harvested grasses from bench terrace risers were estimated to be 28 kg m^{-1}. On progressive terraces, especially grass strips the yield was 22 kg m^{-1}. This lies within the range of 20 to 33 kg m^{-1} reported in Rwanda and Tanzania on bench terraces and on progressive terraces (Bizoza and de Graaff, 2012; Niang et al., 1998; Tenge et al., 2005). In the untreated village without soil and water conservation measures, little fodder was produced (8 kg m^{-1}). Similar values of the same range (6 to 15 kg m^{-1}) were reported in the southern Rwanda on progressive terraces under farmers 'management (Klapwijk, 2011).

Table 5.3 Annual fodder availability from treated and untreated villages of Rwerere watershed, Buberuka highlands, Rwanda

Soil conservation measure	Fodder yield (kg m^{-1})			
	Treated village		Untreated village	
	Farmers' fields n = 41		Farmers' fields n = 41	
	Mean	Standard deviation	Mean	Standard deviation
Bench terraces	28.0	11.6	-	-
Hedgerow barriers	22.3	11.9	-	-
Without technology	-	-	8.2	3.4

5.3.5 Effects of contour bunds, grass strips and bench terraces on soil erosion

The highest average soil loss (41.5 t ha^{-1} yr^{-1}) was observed in the untreated village at a slope steeper than 45% (Figure 5.6). Significantly higher values of aboveground biomass of grasses coupled with better root development resulted in significantly lower soil loss on plots with slopes steeper than 45%. On slopes steeper than 20%, soil loss is significantly less on plots conserved with grass strips + trenches than plots conserved with sole grass strips. Positive effects of the grass strips in reducing soil losses were significantly augmented by trenches due to higher retention and infiltration of runoff. In- situ soil and water conservation practices such as grass strips were reported to increase infiltration of rainwater in the soil (Stroosnijder, 2009). Poudel et al. (1999) reported a strong correlation between the growth of grass barriers and sediment deposition. The effectiveness of grass strips in reducing soil loss increases as they become more established (Poudel et al., 1999). In the southern Rwanda, Konig (1992) reported better conservation effects of living hedges with contour bunds (soil loss 12,5 t ha^{-1} yr^{-1}) over sole contour bunds (soil loss 30 t ha^{-1}). Supplementary erosion control measures such as hedgerows or grass strips planted along the contour lines make soil conservation practices "sustainable" (Konig, 1992).

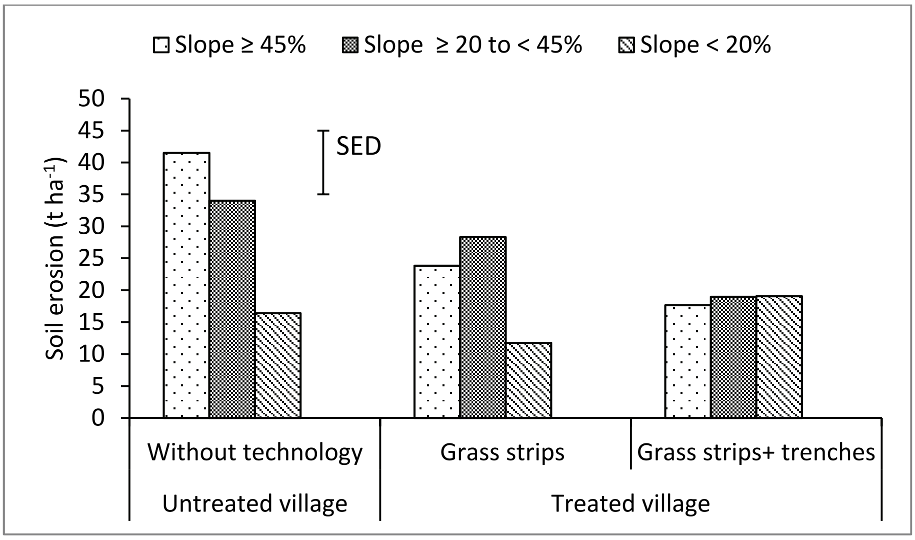

Figure 5.6. Soil loss (t ha $^{-1}$ yr^{-1}) from plots solely conserved with grass strips and plots with grass strips combined with trenches as compared to plots without soil conservation of untreated village in the Northern highlands of Buberuka, Rwanda. The error bar is the average standard error of the difference.

5.3.6 Financial analysis of watershed development activities

The financial efficiency (NPV and IRR) of contour bunds, bench terraces and grass strips implemented under watershed development activities was evaluated on three slopes (Table 5.4). The NPV and IRR vary significantly with the slope steepness. Bench terraces constructed on slopes less than 25% are financially more attractive. However, values of NVP and IRR on these bench terraces shrink as the slope steepness increases due to high cost of establishment. Findings of Tenge et al. (2005) corroborate our results. They reported that farmers benefited from bench terraces established on moderate slopes (13-25%) in the highlands of Usambara, Tanzania.

Bizoza and de Graaff (2012) found that bench terraces in the highlands of Rwanda are only financially viable when the opportunity cost of labour and manure are below their local market price levels. Similarly, Fleskens (2007) reported that bench terraces are only financially viable in highlands of Rwanda when agriculture on the terrace area can be substantially intensified. In fact investigated terraces in this study are benefiting from the prevailing integrated production system (crop-livestock) initiated by the watershed development program known as *Agosozi ndatwa* program which is complemented by the 'One farm, one cow'-program and crop intensification program as detailed in section 5.3.1. Synergies from these policies provide farmers more opportunities to easily access inputs such as improved seeds and manure for increasing the productivity of constructed bench terraces.

Table 5.4 Financial efficiency of contour bunds, bench terraces and grass strips on three slope categories in Rwerere watershed, Rwanda.

Slope	<25%		> 25% and <45%		<45%	
	NPV (US$ha^{-1})	IRR (%)	NPV (US$ha^{-1})	IRR (%)	NPV (US$ha^{-1})	IRR (%)
Contour bunds	434	19	305	17	-147	11
Grass strips	578	28	323	24	-15	12
Bench terrace	887	19	168	14	33	13

Table 5.5. Impact of watershed development activities on the treated village economy.

Crops	Total benefits due to watershed development activities (US $)		
	Change in total surplus (ΔTS)*	Change in consumer surplus (ΔCS)	Change in producer surplus (ΔPS)
Beans	823 (100)**	378 (46)	444 (54)
Maize	680 (100)	285 (42)	394 (58)
Potato	3833 (100)	2147 (56)	1687 (44)
Wheat	983 (100)	600 (61)	(9)

* The decomposition of total surplus is as follows: $\Delta\mathrm{TS} = \Delta\mathrm{CS} + \Delta\mathrm{PS}$, $\Delta\mathrm{CS} = \mathrm{P_O}\,\mathrm{Q_O}\,\mathrm{Z}\,(1 + 0.5 * \mathrm{Zn})$ and $\Delta\mathrm{PS} = \mathrm{P_0}\,\mathrm{Q_0}\,(\mathrm{K} - \mathrm{Z})(1 + 0.5 * \mathrm{Zn})$. **Values in brackets are % of change

Contour bunds and grass strips are financially attractive for slopes up to 45%. This implies that at steep slopes up to 45% grass strips or contour bunds are a viable alternative for terracing and can easily offset all engaged investments. Evaluated grass strips were 3 years old, with well-developed banks in both height and width leading to low values of soil loss, hence stabilizing the soil fertility (Kagabo et al., under review-a), although in the East African highlands contour bunds and grass strips were considered most efficient on land with relatively gentle slopes (Roose and Ndayizigiye, 1997; Tenge et al., 2007).

In Table 5.4, IRR values of bench terraces on steep slopes (> 25% and <45%) are higher (14% to 19%) indicating that farmers who are able to invest can quickly recover their investment. The IRR values of 19 and 14 (greater that 13% which is the lowest loan rate of commercial banks) from bench terraces constructed on moderate (<25%) and steep (> 25% and <45%) slopes, respectively; indicate the worthiness of the watershed development project. Bizoza and de Graaff (2012) reported higher values of IRR than the discount rate (13%) on non-subsidized bench terraces in highlands of Rwanda.

The impact of watershed development activities on crop yields using the economic surplus method is presented in Table 5.5. The change in total surplus was higher for potato and wheat than for maize and beans. This is because wheat and potato were preferentially promoted, especially on bench terraces by local extension services with high inputs, hence achieving higher yield. When the change in total surplus is partitioned into change in consumer surplus and change in producer surplus, the producer surplus is relatively a bit higher for maize and bean crops. This could be attributed to the fact that the market for maize and bean is thin or a small proportion of these are commercialized or go through the marketing system. A greater proportion being retained and consumed by the producer as maize and beans are regarded as basic food for family consumption among the rural residents. On the other hand, wheat and potato have a high market value and benefited relatively more to consumers than producers. In the case of consumers, the increased crop production in the watershed results in availability of produce at lower prices (Palanisami et al., 2011). This additional produce creates a gradual shift of supply output due to benefits from watershed development activities. The supply shift factor due to watershed development activities is known as K. This factor K was computed using mathematical equations provided in section 5.2.7 and can be interpreted as a reduction of absolute costs for each production level, or as an increase in production for each price level (Libardo et al., 1999).

5.3.7. Critical reflection on the "treated", "untreated" village approach

The selection criteria of participating villages was of critical importance to the analysis of the impact of PIWM. Numerous factors that can determine a village's performance in agricultural production and natural resource management were equally distributed across both treated and untreated villages. This implies that villages did not vary in their endowment of factors that can affect performance (Table 5.1). Hence, observed differences between "treated and untreated villages are due to differences in performance of project activities but not the effects of pre-existing village characteristics. Similar studies from India have adopted villages as the primary unit rather than the micro-watershed, which would be the logical unit of implementation in a purely technical program (Kerr, 2001). To successfully implement this village approach, PIWM projects must reconcile the village-based approach with the watershed orientation of the technical plan in two ways (Kerr, 2001 and German et al. 2012). First, select villages in which the watershed and village boundaries nearly coincide, or in which the microwatershed falls within the village. Second, watershed projects should not adhere rigidly to one set of boundaries rather they should use a flexible approach that accommodates village boundaries that fall outside watershed boundaries or watershed boundaries that fall outside the village boundary.

The approach of "treated and untreated" village produced different results in terms of improvement in socio-economic conditions, and the environment. Although the paired watershed (village) comparison is of course not ideal, the technical packages for intensification (extension services, "one farm", "one cow" programme, ISFM components, credits and subsidies, etc.) and conservation (terraces, grass strips) were, in our opinion, major reasons for the successful implementation of watershed development activities. Furthermore, the existing strong institutional organization implemented under "Agasozi ndatwa" programme to coordinate and channel development and research activities was a key to the success of PIWM activities.

5.4 Conclusions

This study presents careful evidence of the impact of PIWM activities on NRM resources, crop and livestock productivity and on the socio-economic situation of households. The economic surplus method shows that watershed development activities benefited the agricultural producers, especially for those growing potato and wheat. As part of the programme those crops were promoted on bench terraces by local extension services. Grass strips showed strong resilience, being 20+ years old and still effective in providing continuous barriers against soil loss. Grass strips, combined with trenches, showed, thanks to its significantly higher infiltration rate of runoff, significantly less soil loss than the without soil conservation situation.

Synergy was observed due a package of policies related to: (1) agricultural inputs and land management, (2) livestock husbandry management (zero grazing) and (3) farmers' livelihoods (the 'one farm, one cow'-program). This combination positively impacted on the size and composition of livestock, the availability and use of manure, the production of fodder and the reduction of soil loss. In the treated village, livestock played a significant role in maintaining soil fertility by providing 5,320 kg of manure per household which contributed to replenish a substantial share of soil nutrients. This improved farmers' perceptions on bench terraces and more than 68% of farmers saw the soil fertility improving as a result of bench terrace development. Grass strips and contour bunds are financially attractive only on slopes less than 45%. Bench terraces are financially attractive even when constructed on slopes greater than 45% because of the related higher use of agricultural inputs. The high use of inputs results from the integration of several policies that are operating simultaneously in the watershed. Watershed development activities changed the farming system with more integration between livestock and crops. What remains to create are institutions that use the additional income from milk and manure wisely and improving the quality and quantity of manure.

In our case study (the "*Agasozi ndantwa*" approach in Rwanda) the increased attention for participation in IWM did indeed embrace multi-institutional tasks and harmonize partnerships and alliances happening at different levels. The results suggest that a PIWM approach, more than IWM only, has the potential of improving farmers' livelihoods and increasing the resilience of a degraded environment.

Chapter 6

Synthesis

Synthesis

6.1 Rationale and research hypothesis

The ability of the north-western highlands of Rwanda to produce more food to keep pace with the growing population is threatened by land scarcity and land degradation. Land scarcity is the result of rapid population growth while land degradation in the form of erosion and depletion of soil fertility causes low crop production. There is a basket full of technologies that address soil and water conservation (SWC) and soil fertility management (Schwilch et al., 2012). Although reports on the potential of such technologies are abundant, their adoption by farmers is limited.

It is argued that the only way to get more insight into what farmers do (or not do) and why, is to obtain more trust between the numerous stakeholders that nowadays participate in complex agricultural systems (Stroosnijder, 2012). This trust can be obtained by building a culture of good governance in which proper institutions are created, agreed rules are enforced and corruption is mitigated. Participatory approaches where all stakeholders are involved such as Integrated Watershed Management (IWM) can be the start of building such good governance environment. However, although IWM involves improved natural resource management, it is not yet leading to widespread adoption of more sustainable land management practices at farm level. Enabling an effective participation of stakeholders requires an effective representation in decision-making at watershed level by blending the “integration” and “participation” approaches leading to a new approach here referred as Participatory Integrated Watershed Management (PIWM). This study hypothesised that PIWM is a viable tool to stimulate farmers towards more sustainable land use for improved land management and increased crop productivity in the north-western highlands of Rwanda.

Currently the Government of Rwanda is building institutions that promote participation of farmers, such as a PIWM approach, locally known as “agasozi ndatwa” to boost the adoption of NR management practices. The concept "agasozi ndatwa" is based on a theory that each lowest administrative entity in Rwanda should have a model community that have all the features that make human livelihood meaningful including soil conservation and best agricultural practices. The "agasozi ndatwa" approach is implemented at watershed scale and involves investment from the government in establishing soil and water conservation structures as well as other development related activities. The "Agasozi ndatwa" approach uses a watershed as a planning unit while integrating social, economic, ecological and policy concerns (German et al., 2012; Mutekanga, 2012). The farmers’ role in the "Agasozi ndatwa" is carried out through collective action activities that are beyond the farm level.

The study was started by assessing the ecological and economic sustainability of smallholder farms using the level of nitrogen recycling between farm activities and farm income as indicators. Hence, challenges and opportunities within the current farming systems for policy makers and other agriculture agencies were revealed. Soil fertility management components - including farm inputs and improved farming systems combined with the knowledge on how to adapt these practices to local conditions at field, farm and watershed levels - were evaluated. Following a proper participatory assessment of soil and water conservation practices, a field experiment was conducted to explore the efficiency of 20+ year old progressive (i.e slow forming) terraces in farmer’s fields. Finally, the impact of watershed development activities on NRM, crop and livestock productivity, and farmers’ livelihood was assessed.

These studies were conducted to answer the following research questions:

1. How sustainable is farming in the north-western Highlands of Rwanda? (Chapter 2)
2. Can progressive (i.e. slow forming) terraces improve ecological sustainability? (Chapter 3)
3. Can Integrated Soil Fertility Management improve economic sustainability? (Chapter 4)
4. Can a PIWM approach stimulate farmers to manage their farms more sustainably? (Chapter 5)

6.2 Answers to the research questions

6.2.1 How sustainable is farming in the north-western Highlands of Rwanda?

Ecological sustainability was assessed in Chapter 2 using the level of integration between farm household activities and nutrient flow balances. ***The majority of the smallholder farms in the north-western highlands of Rwanda are ecologically not sustainable. However, they can be sustainable under a number of enabling conditions as proven in model communities described in Chapter 5.*** Findings from Chapter 2 indicate that diversity of the flows of N to, from and within the smallholder farms differed more across sites than between farms due to the strong variation in the management of Farm Yard Manure (FYM). Higher internal flows of N were obtained in farms with large tropical livestock units (TLU) which in turn influenced the N inflows (e.g. organic fertilizer) and N recycling between farm activities. On-going policies (discussed in Chapter 5) such as “one cow per poor family” and “zero grazing” that are being implemented in the north-western highlands of Rwanda create enabling conditions for a more sustainable use of farms where both agriculture and livestock are integrated. Soil conservation practices such as bench terraces and slow-forming (progressive) terraces create niches (risers) on which grasses are grown that serve as a source of fodder for domestic animals (Chapter 5). In return, animal manure produced and collected in animal enclosures is available for use as fertilizer. Due to these integration practices, farmers’ income improved due to increased crop yield, an increased size and improved composition of the livestock. Without change, further ecological damage will occur but there are practices and programs that show promise for ecological sustainability in the area if more widely adopted.

Deeper insight into the economic sustainability was provided by the analysis of gross margin and net farm income of smallholder farms. ***The economic sustainability of smallholder farms is presently insufficient.*** Although where livestock and agriculture are being integrated farmers’ income improved due to increased crop yield, an increased size and improved composition of the livestock, this is not the case overall. Little of the crop yields reach the market since most of it is used for household consumption. Farm activities are mainly concerned with securing food needs for the family. Except for smallholder farms keeping TLU’s, the economic diversity of smallholder farms is also very low. Overall, increasing the economic sustainability of smallholder farmers requires changes on many fronts. In addition to controlling soil erosion which is the major source of nutrient depletion, introduced changes in cropping systems such as ISFM practices (Chapter 4), increased crop yield relative to farmers’ practices and farming systems that are more market oriented are examples of needed enabling conditions.

6.2.2 Can progressive terraces improve ecological sustainability?

The role of slow-forming terraces in conserving soil, improving soil fertility and crop productivity was the focus of Chapter 3. These terraces were built up gradually during a process of crop cultivation and simultaneous planting of grass strips. We can conclude that slow-forming terraces contribute to ecological sustainability. Thanks to significantly higher infiltration rates, grass strips combined with trenches showed significantly less soil loss than the situation without soil conservation (Chapter 3, Figure 3.5). The grass strips and slow forming terraces also showed strong resilience, still providing barriers against soil loss and strong, wide bank terraces after 20+ years.

However, a marked soil fertility gradient threatens the sustainability of these terraces (Chapter 3, Figure 3.6) and needs to be addressed. It is essential to develop site-specific fertilizing strategies that mitigate this soil fertility gradient and increase overall crop yields. While it has already been recommended that adjustments always be made for site-specific soil conditions to maximize the Agronomic Efficiency of Nitrogen (N-AE) in farms with soil fertility gradients (Vanlauwe et al., 2011), it is not yet widely practiced. One strategy that could be agronomical and economically effective, and improve the sustainability of this soil conservation practice, is to apply more fertilizer on the upper part of a terrace.

6.2.3 Can Integrated Soil Fertility Management (ISFM) improve economic sustainability?

An integrated set of soil fertility management practices including the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions was used to study this question (Chapter 4). ***Results indicate that if costs of inputs such as improved seeds can be controlled, ISFM can significantly improve crop yields, however if costs remain as high as they are at present, the apparent economic improvement is not real.*** ISFM strategies were identified and targeted to specific types of farms and to specific landscape positions. Crop yield and farm profitability increased as a result of the combination of organic inputs, inorganic fertiliser and improved seeds (Chapter 4, Table 4.4). Similarly, the cropping system in which potato is grown after beans resulted in increased potato tuber yield compared with growing continuous potato (Chapter 4, Figure 4.3a and b). Overall results from Chapter 4 (Table 4.5) indicate that financial returns increased as ISFM components were cumulatively added to the traditional farmer's practice. However, this increase in returns to smallholder farms was overshadowed by high cost of inputs, especially in potato cropping system. Therefore effort is needed to mitigate the high cost of improved potato seeds, especially for resource-poor farmers. Measures to promote fertilizer use among farmers by reducing transaction costs or improving their accessibility, accompanied by strategies to improve the use efficiency of the applied nutrients, would make ISFM a more feasible approach to increased economic sustainability.

6.2.4 Can a PIWM approach stimulate farmers to manage their farms more sustainably?

Past NRM practices in Rwanda focused on isolated farmers that operate as individuals, thus hindering wide adoption of these practices and facilitating individualized versus community decision making processes. This has led to natural resource conflicts in rural communities, poor management of resources like water, soil and nutrients that transcend farm and village boundaries, absence of collective action in addressing common concerns. This thesis (Chapter 5) explored the potential for a PIWM approach to effectively address these challenges by quantitatively assessing the effects of soil and water conservation practices and other agricultural activities implemented through PIWM on crop and livestock productivity, and socio-economic aspects of farmers' lives. ***We conclude that a PIWM approach can lead to more sustainable management of farms because, in our study, practices implemented this way led to improved farmers' livelihoods and increased resilience of a degraded environment.*** Due to *this PIWM approach,* synergy of policies was effective leading to positive impact on the size and composition of livestock, the availability and use of manure, the production of fodder and the reduction of soil loss.

The economic surplus method shows that watershed development activities benefited the agricultural producers, especially those growing potato and wheat. It was clear that assessed soil conservation practices are physically effective if implemented and maintained according to the recommendations.

6.3 Generated knowledge

6.3.1 Ecological and economical sustainability

This thesis (Chapter 2) reveals the extent to which the presence of livestock under zero grazing conditions positively affects the ecological and economical sustainability of smallholder farms in Rwanda. Higher internal flow of Nitrogen was the result of high nutrient transactions within the system due to the presence of livestock under zero grazing conditions. Our findings confirm the findings of others (e.g. van Beek et al., 2009) but under different conditions. Contrary to our findings, in a similar socio-economic environment of Ethiopia inflows depended largely on imported N (Rufino et al., 2009).

Previous to this PhD study there has been very little published information available on farmer practices in the north-west highlands of Rwandan environment. In Chapter 4 of this thesis, farming systems of smallholder farms were revealed to be complex and strongly tied to tradition. Due to low temperatures that prevail in north-western highlands of Rwanda (e.g. 15°C annual average), cereals take 7 to 9 months to reach physiological maturity. To cope with this situation, farmers have developed two coping mechanisms/management strategies: (i) allowing potato volunteers or indigenous vegetables such as pumpkins and amaranths to grow under cereal crops, and (ii) sowing tuber or legume crops in a weeded field of cereals which is still at the senescence development stage. In the case of the first, potato volunteers are harvested along the season until cereals are matured as an alternative way of getting quick food for household consumption. Yet these potato volunteers are compounding factors to crop production since they increase the incidence of potato diseases in the next potato growing season. In the case of sowing tuber or legume crops, as this field of cereals progressively matures, farmers take care to harvest plants that mature first. This process allows legumes or tubers grown under cereal crops to gain enough light (radiation). This traditional farming strategy presents three advantages: (i) minimize the risk of losing the second cropping season in a year, (ii) allow minimum tillage, hence less disturbances of soil and (iii) provide a continuous soil cover. This new information on the experiences of farmers who currently address their ecological and environmental situation through rotation of cereals with legumes/tubers is a valuable source of information that can help address some of the knowledge gaps, and provide a better focus for researchers.

6.3.2 Progressive (slow forming) terraces

Grass strips as part of slow forming terraces were revealed in this study to be efficient in reducing soil loss due to the well-established banks that form. The efficiency of soil erosion control practices for crop productivity can be well managed if the capacity of the soil to produce a good crop is not limited by fertility (Mati, 2011). Thus, the concept of “soil” and “water” conservation is not just about water availability or soil erosion control, but also about nutrient availability which enhances Green Water Use Efficiency (GWUE) (Stroosnijder, 2009). High crop yield or quick returns are obtained if soil and water conservation practices are combined with nutrient management practices (Stroosnijder, 2009). Given the age of the terraces (20+ year old), it was thought that the soil quality on terraces between alleys would have become homogenized over the course of time. However, we found (Chapter 3, Figure 3. 6) large soil fertility gradients on terraces with marked spatial difference in both soil quality and crop yield from their upper parts downwards. The soil in the lower parts of the terraces showed as much as 57% more organic carbon content and 31% more available phosphorous than the soil in the upper parts of the terraces (Chapter 3, Figure 3.6). As a result, potato and maize yields were 60% greater on the lower parts than on the upper parts of the terraces (Figure 3.7). This variability of soil fertility within terraces and across landscape positions poses a major challenge in strategizing options to improve crop productivity. In this thesis (Chapter 3) we recommend the development of a site-specific fertilizer strategy and introduce a new soil tilling technique. As an alternative to current practices, we recommend a new land tillage technique consisting of “harvesting” the fertile soil from the lower edge of the grass strip and using it as fertilizer for the nutrient deficient upper parts of terraces.

What also becomes clear in our study is that, for sustainable use of this soil conservation practice, there is a need to encourage farmers to invest in the maintenance and repair of their terraces. Previous experiences in the highlands of Rwanda show that the building of soil conservation practices was organized predominantly through collective labour arrangements (e.g. food or cash-for-work) and this led to inefficiencies and unsustainable outcomes (Bizoza, 2011a). This reveals the need for awareness raising sessions and promotion of the role of well built, well maintained, slow-forming terraces in controlling soil erosion and increasing crop productivity.

6.3.3 Integrated Soil Fertility Management (ISFM)

We found (Chapter 4) high efficiency of mineral N application with low fertilizer application even in fields with soils low in organic matter. This implies that the combination of mineral fertilizer and FYM increased the agronomic N use efficiency (N-AE). Tilling/hoeing and preferential application of available inputs, especially composted manure or FYM, was found to be the main cause of soil fertility variability within and across farms. We found that combining mineral N, FYM and improved seeds significantly increased yields but resulted (i) in a lower N-AE across sites and on relatively fertile foot slopes and (ii) in a lower marginal rate of return (MRR) due to the high cost of seeds and mineral N fertilizer. Effort should be made to mitigate the high cost of improved potato seeds, especially for resource-poor farmers. Measures to promote fertilizer use among farmers by reducing transaction costs or improving their accessibility should be accompanied with strategies to improve the use efficiency of the applied nutrients. Furthermore, crop rotation (potato after beans) resulted in increased crop yield and net benefit. In Rwanda, beans have a high market value (Halloran et al., 2005) that can attract farmers to adopt easily the rotation of bean-potato. Particularly in Rwanda, climbing beans have been traditionally cultivated in higher altitude zones beyond 1700 m asl with a relatively short growing period (4 to 5 months) and are positively associated with a high yield potential of 3 to 5 t ha^{-1} (Sperling and Muyaneza, 1995).

6.3.4 The PIWM approach

In the model village (Chapter 5), where an active PIWM process was implemented, much was learned about the potential for this approach in the Northern Province. Livestock played a significant role in maintaining soil fertility by providing 5320 kg of manure per household which contributed to replenishment of a substantial share of removed and lost soil nutrients. This increase of manure resulted in crop yield increase on bench terraces, hence improving farmers' perceptions vis-à-vis of bench terraces. More than 68% of farmers saw the soil fertility improving as a result of bench terrace development. Grass strips and contour bunds are financially attractive only on slopes less than 45%. Bench terraces are financially attractive even when constructed on slopes greater than 45% because of the related higher use of agricultural inputs. The high use of inputs results from the integration of several policies that are operating simultaneously in the watershed. These policies include: (1) agricultural inputs and land management, (2) livestock husbandry management (zero grazing) and (3) farmers' livelihood (the 'one farm, one cow'-program) using the "agasozi ndatwa" approach here referred to as PIWM. Synergy of policies was observed and positively impacted the size and composition of livestock, the availability and use of manure, the production of fodder and the reduction of soil loss. This gave new evidence that PIWM can indeed embrace multi-institutional tasks and harmonize partnerships and alliances happening at different levels.

Contrary to our findings, experiences from another similar watershed in Rwanda show that policies can be conflicting (Nabahungu, 2012). This likely occurred in that watershed because of the set of institutional arrangements for establishing watershed development activities - which was different than in the watershed studied in this thesis. Apart from the recently introduced PIWM, many interventions in NRs management in Rwanda have focused more on establishment of soil and water conservation structures rather than on their subsequent use by farmers (Bizoza, 2011b). Experiences from the Ngenge watershed in Uganda, where there was a lack government involvement in watershed management, show that varying priorities from stakeholder to stakeholder can be difficult to coordinate leading to poor management of resources (Mutekanga, 2012).On the other hand, experiences from India show that watershed projects implemented mainly by government agencies and lacking stakeholder involvement led to inequity within community members (especially poor farmers), either in terms of differential resource access rights, or of full ownership of watershed programs (German and Taye, 2008; Mula, 2008). Kerr (2001) raised the issue of equitable access and use of watershed projects outputs among stakeholders. He argued that in many watershed projects the process occurs in hierarchical power structures which strongly influence who is included and who is excluded from the process. Poor grassroots community organizations are often located towards the bottom of these power structures and therefore feel that some watershed projects are imposed upon them. Our study shows that true PIWM can be much more effective, and provides evidence of the need and potential for a participatory form of integrated watershed management to lead to more sustainable use NRs.

6.4 Limitations of this PhD study

Results indicate that PIWM can occur where there are critical conditions and suitable institutional structures established. Through well-established institutions, existing disparities of views and perspectives from different stakeholders are channelled leading to commendable results. While PIWM seems all nice and positive, a key element (payments for environmental services, (PES). was not studied. We did not attempt to assess conditions suitable for establishing PES, i.e. locally-based programmes (villages, land-user groups) designed to control soil erosion, sediment transport and water quality. Nor did we try to determine the relative contributions of institutions and individuals in controlling erosion. Future studies should focus on exploring PES options and their limiting factors. Furthermore, institutional adaptations and supports that are required for a successful implementation of PES markets should be examined. Similarly, how PES can complement existing policies is an area to investigate.

In the north-western highlands of Rwanda, farmers are conservation minded. The natural tendency is to plant grasses wherever feasible, to install necessary land improvements like terraces, to farm on the contour and to minimize tillage operations. These indigenous assets are often overlooked in development programs. This is an aspect that was also not considered in this PhD study, but which warrants attention for its potential to contribute to development of viable policies.

6.5 Recommendations for further scientific study

Nationally, little is known about the actual soil losses in Rwanda and estimates vary considerably. Additionally, what information does exist is often based on older data. In order to be able to design appropriate and cost-effective soil erosion control measures, it is important to know the realistic soil losses under various land use systems. Potential soil loss (erosion hazard), actual soil loss and erosion control are interlinked subjects that should be treated together. Studies are needed to map the soil loss based on more recent data, further improved estimation models and increased field verifications.

Erosion control and soil fertility management are interrelated. One of the “lessons” quoted in land management is that “successful erosion control is not only a question of building structures but it also requires sustained attention to restoring soil fertility”. The construction of bench terraces will not be cost-effective unless it is combined with soil fertility restoration. Options for increased soil productivity through the combination of biological erosion control and soil fertility management should be further studied. In addition to soil erosion control measures with an important element of soil loss and engineering (terraces, ditches, bunds), more scientific study should be carried out on soil erosion control through improved land use systems which aim at soil coverage and protection throughout the year along with increased soil fertility. These land use systems may have one or more elements of conservation agriculture, based on the principles of minimum soil disturbance, permanent soil cover and crop rotation as reported in Chapter 4 of this thesis. Further, the longer term environmental consequences of the Crop Intensification Programme should be studied. The mono-cultures advocated under this programme may conflict with the need for permanent soil cover and agro-forestry as part of the soil erosion control efforts. Similarly, a study should also look into the long-term effects of the use of various agronomic inputs, such as inorganic fertilizers and lime.

6.6 Recommendation for extension and policy

Although a PIWM approach has the potential for creating synergy of policies (Chapter 5), it was evidenced that the PIWM programs known as *Agosozi ndatwa* are operating only in localised sites. This may be a source of frustration for farmers in neighbouring watersheds unless serious measures are taken to develop more ambitious programs that cover a larger number of farms. Furthermore, increased farmers ownership of investments in land management would be achieved if farmers' objectives as well as their knowledge on NRM are taken into greater consideration in projects' inception and implementation. We recommend that extension staff and managers advocate a PIWM approach from the start in order to build multi-institutional tasks and harmonize partnerships and alliances happening at different levels.

While the bench terraces promoted by the extension service in the north-western highlands are financially efficient in the long term, the high investment costs limit adoption and are only financially viable when agriculture on the terrace area can be substantially intensified. Prevailing integrated production systems (crop-livestock) initiated by the watershed development program known as *Agosozi ndatwa* program which is complemented by the 'One farm, one cow'-program and crop intensification program should be reinforced by creating farmer's forums through which farmers' awareness on the existing programs is raised. These programs provide to farmers more opportunities to easily access inputs such as improved seeds and manure for increasing the productivity of constructed soil conservation structures.

To further support the on-going efforts and achieve desired developmental outcomes, there is need for a platform that includes 'all' agricultural stakeholders (researchers, extension and development agents, policy makers, farmers and the private sector) who can work together for more effective innovation in response to changes in the complex agricultural and natural resources management context. Among other things, the platform could consider the availability of credit schemes for the re-investment in land management, and facilitate access to reliable and contracted markets of farmers' produce. The economic position of smallholder farms improves with the number of tropical livestock units (TLU) (Chapter 2). However, establishment of institutions that create ways to use the additional income from milk and manure more strategically and improve the quality and quantity of manure could further improve both livelihoods and sustainable management of the land.

Additionally, we recommend that programs be established for training and capacity building on maintenance for conservation structures. The analysis in Chapter 2 showed that more than 75% of farmers have adopted either progressive or bench terrace soil conservation practices. Increasing coverage of the arable land (1,900,000 ha national wide) with erosion control measures, means that the need for maintenance of all these measures also increases. For example, if 75% of cultivable land that needs protection is protected, it means that erosion control structures on more than 1,425,000 ha have to be maintained. Because of the hilly topography, the fragmented land ownership and the low capital investment undertaken by farmers, erosion control will be a continuous challenge that can never be 100% achieved. The same holds true for maintenance of the structures, however the effort must be made. The erosion risk in Rwanda is high and unpredictable natural hazards such as exceptional high rainfall will continuously threaten existing erosion control measures. That can only be done by the farmers themselves so corresponding capacity building and organisation has to be a continuous process.

Progressive terracing is probably the most common form of erosion control. It is applicable on moderately steep slopes and is easily combined with agroforestry measures. The technique is fairly simple and can be applied individually by farmers. However, since progressive terraces do not stop erosion entirely, especially on steep slopes of the north-western highlands of Rwanda, farmers are sometimes tempted to distribute relatively fertile soil from the risers to eroded land and, in the process, damage the terraces (Chapter 3). Therefore, strategies should be put place to stop this bad practice.

In comparison with other countries also characterized by steep slopes and high (rural) population (e.g. north of Ethiopia, Eritrea), Rwanda has the advantage of high rainfall, two growing seasons and a good land cover (crops, trees, shrubs, grass) for most of the year. Two growing seasons and the absence of roaming livestock provide opportunities for many types of vegetative erosion control measures, including agroforestry and the inclusion of cover-crops into the farming system. This huge opportunity should be fully exploited by strategizing at policy level how this natural advantage can be efficiently used to increase crop productivity.

Finally, we recommend that Rwanda's Crop Intensification Program (CIP) incorporates principles and practices' of Conservation Agriculture (CA) - the use of residues of previous crops and nitrogen fixing legumes to create mulches into which seed and fertilizer are sown directly. Such no till farming will increase the sustainability of the intensification process in hills and slopes. Furthermore, there is a need of fine tuning fertilizer recommendations to conform to specific combinations of crops and soil conditions to sustain crop yields. Besides contributing to the increase in crop yields, the mineral fertilizers also contribute to the improvement of the availability and quality of soil organic matter and, therefore, eventually their own efficiency. To realize this potential, it is recommended that appropriate tools such as MonQi be used in monitoring the performance of promoted technologies in improving soil quality and livelihood of smallholder farms. If existing methods and technologies dealing with NR management are fully packaged and adapted to conditions in the north-western highlands of Rwanda and adopted by farmers, then the danger of land degradation can be mitigated. This can be enabled by creating a platform of stakeholders with diverse interests to come together to analyse problems and develop solutions. Doing this will increase chances of technology generation relevant to local conditions and acceptable to local communities, hence a better future to communities.

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Summary

This thesis explores whether integrated watershed management is a viable approach to promote best soil and water conservation (SWC) measures towards more sustainable land use. The study was conducted in two contrasting agro-ecological zones of the north-western highlands of Rwanda, namely; Gataraga and Rwerere. Gataraga is located in Musanze district (01^{o} 32' S, 29^{o} 31' E), at the border of the Western and Northern Provinces. It is part of the volcanic agro-ecological zone lying about 2400 m above sea level. Rwerere is located in Burera District (01^{o} 32' S, 29^{o} 52' E), in the Northern Province. It is located in the highlands of the Buberuka agro-ecological zone of Rwanda at around 1650 m above sea level. Both Rwerere and Gataraga have a bimodal distribution of rainfall which allows crop cultivation during two subsequent cropping seasons.

The research started with an assessment of the ecological and economic sustainability of smallholder farms in the two study areas. The level of nitrogen recycling between farm activities and the farm income were used as indicators. Challenges and opportunities within the current farming systems were revealed for policy makers and other agriculture agencies. Soil fertility management components, including farm inputs and improved farming systems were evaluated. This was done in combination with knowledge on how to adapt these practices to local conditions at field, farm and watershed level.

Following a proper participatory assessment of soil and water conservation practices, a field experiment was conducted to explore the efficiency of 20+ year old progressive (slow) forming terraces. This was done in farmer's fields. Finally, the impact was assessed of participatory integrated watershed management (PIWM) activities on natural resource management (NRM), on the productivity of crops and livestock and on farmers' livelihood. Furthermore, the integration of several policies that are operating simultaneously in the watershed was evaluated.

In **Chapter 2** the "Monitoring for Quality Improvement" (MonQI) toolbox was used to assess nutrient balances and economic performance at individual farm activity and the whole farm level. Nutrient balances and flows differed for the two agro-ecological zones due to differences in crop management and the importance of livestock. Positive nutrient balances were found for relatively fertile volcanic soils, but on steep slopes and acid soils, N, P and K stocks were declining at rates of 8.6, 1.4 and 17.5 kg ha^{-1} year^{-1}, respectively. For farms with steep slopes and acid soils, the cost of replenishment of mined nutrients was 20% of gross margin compared to only 0.2% of the gross margin of smallholder farms in the relatively high agricultural potential site. Nitrogen recycling between farm activities was low, varying between 1.8 and 6 %, which may limit the adaptability and reliability of the current farming systems. Little of the farm produce reached the market and the contribution of crop produce to the net farm income was about 90%.
This implies that the economic diversity of smallholder farms was low, with the exception of smallholder farms keeping large tropical livestock units (TLU).

Chapter 3 describes a field experiment where soil erosion rates and fertility gradients of 20+ year old terraces were compared between sole grass strips (*Pennisetum purpureum*) and grass strips combined with infiltration ditches with land without soil conservation measures. The lowest annual soil loss (18 t ha^{-1}) was recorded with grass strips combined with infiltration ditches. This is a 57% reduction in soil loss when compared with plots receiving no soil conservation practices. The terraces showed marked "within" spatial differences in soil quality and crop yield. The soil in the lower part of the terraces showed 57% more organic carbon content and 31% more available phosphorous than the soil in the upper part. The soil fertility gradients indicate that the sustainability of slow-forming terraces is threatened, unless a site-specific fertilizer strategy is developed. For the sustainability of these terraces, the current practice of

"harvesting" fertile soil from the lower edge of the grass strip and using it as fertilizer for the nutrient deficient upper part of terrace needs to be stopped.

Chapter 4 presents results from researcher-managed trials in farmers' fields during two consecutive cropping seasons of 2010. Trials were established in three different landscape positions, on the upper-slope, hill-slope and on foot-slope. A factorial design was used and comprised a rotation of bean and potato (B-P) and continuous cropping of potato (P-P) with components of integrated soil fertility management (ISFM) as treatments. In all landscape positions, application of manure and N fertilizer in combination with improved seeds increased potato yield. In Rwerere potato yield increased by 4460 kg ha^{-1} and in Gataraga there was an increase of 5900 kg ha^{-1} relative to the farmers' practice. Bean grain yields were generally lower in Rwerere (1145 - 2275 kg ha^{-1}) compared to Gataraga (1640 – 3140 kg ha^{-1}). Growing potato after beans resulted in increased potato tuber yield compared with growing continuous potato. And also in a significant increase in net benefit that varied between 400 and 822 USD ha^{-1} in Gataraga and between 1100 and 1560 USD ha^{-1} in Rwerere. The combination of fertilizer, farm yard manure (FYM) and improved seeds significantly increased yields but resulted in a lower nitrogen agronomic efficiency (N-AE)
on the relatively fertile foot slopes. And also in a lower marginal rate of return (MRR) due to the high cost of seeds and N fertilizer.

Chapter 5 describes the impact of PIWM development activities such as bench terraces, contour bunds and grass strips. Impact was assessed using the net present value (NPV), the internal rate of return (IRR) and the economic surplus method. The results suggest that a PIWM approach has the potential of improving farmers' livelihoods and increasing the resilience of a degraded environment. The high use of agricultural inputs results from the integration of several policies that are operating simultaneously in the watershed.

Synergy of policies was observed that had a positive impact on the size and composition of livestock, the availability and use of manure, the production of fodder and the reduction of soil loss. This implies that PIWM can embrace multi-institutional tasks and harmonize partnerships and alliances happening at different levels. The economic surplus method shows that watershed development activities benefited the agricultural producers, especially for those growing potato and wheat. Grass strips showed strong resilience, being 20+ years old and still effective in providing continuous barriers against soil loss. Grass strips, combined with infiltration trenches have significantly less soil loss than the without soil conservation situation.

Livestock played a significant role in maintaining soil fertility by providing 5320 kg of manure per household. This replenish a substantial share of the harvested soil nutrients. Grass strips and contour bunds were financially attractive only on slopes less than 45%. Bench terraces were financially attractive even when constructed on slopes greater than 45% because of the related higher use of agricultural inputs related to the use of these terraces. Watershed development activities changed the farming system with more integration between livestock and crops.

Chapter 6 is a synthesis of previous chapters. It briefly summarizes answers to the research questions, describes the added value of the thesis in terms of knowledge generation and provides suggestions for further research and policy making. The overall conlcusion is that integrated watershed management, provided it is executed with 'true' participation of all stakeholders, is a viable approach towards more sustainable land use.

Samenvatting

Dit proefschrift onderzoekt in hoeverre geïntegreerd beheer van natuurlijke hulpbronnen op stroomgebied niveau meer duurzaam landgebruik kan bevorderen. De studie is uitgevoerd in twee contrasterende agro-ecologische zones van de noordwestelijke hooglanden van Rwanda, te weten; Gataraga en Rwerere. Gataraga bevindt zich in Musanze district (01o 32 'S, 29o 31' E), op de grens van de West- en Noord-Provincies. Gataraga maakt deel uit van de vulkanische agro-ecologische zone, en ligt ongeveer 2400 m boven de zeespiegel. Rwerere bevindt zich in Burera District (01o 32' S, 29o 52' E), in de Noordelijke Provincies. Rwerere is gelegen in de hooglanden van Buberuka, een agro-ecologisch gebied in Rwanda op circa 1650 m boven de zeespiegel. Zowel Rwerere en Gataraga hebben een bimodale verdeling van de neerslag, die teelt tijdens twee opeenvolgende groeiseizoenen mogelijk maakt.

Het onderzoek is begonnen met een evaluatie van de ecologische en economische duurzaamheid van kleinschalige landbouwbedrijven in de twee studiegebieden. Het niveau van stikstof recycling tussen landbouwactiviteiten en het landbouwinkomen dienen hierbij als indicatoren. Uitdagingen en kansen binnen de huidige landbouwsystemen werden geïdentificeerd t.b.v. beleidmakers en landbouw-organisaties. Hierbij is zowel op bedrijfsniveau als op stroomgebied niveau gekeken. Componenten van bodemvruchtbaarheid beheer, waaronder productiemiddelen en verbeteringen in de landbouwsystemen zijn geëvalueerd. Dit is gedaan in combinatie met kennis over hoe deze componenten aangepast kunnen worden aan de lokale omstandigheden op veld, boerderij en stroomgebied schaal.

Na een 'echte' participatieve evaluatie van de bodem- en waterconservering praktijken, is er veldonderzoek uitgevoerd om de efficiëntie van de 20+ jaar oude, zich progressief (langzaam) vormende terrassen te bepalen. Dit is gedaan op percelen van boeren. Ten slotte is gekeken naar de impact van het participatief geïntegreerd beheer op stroomgebied niveau (PIWM) op het beheer van de natuurlijke hulpbronnen (NRM), de productiviteit van zowel gewassen als vee en op de leefomstandigheden van de boeren. Ook is de integratie van verschillende beleidsmaatregelen die tegelijkertijd actief zijn in het onderzochte stroomgebied geëvalueerd.

In **Hoofdstuk 2** is een toolbox voor de 'monitoring voor verbetering van kwaliteit' (MonQI) gebruikt om nutriëntenbalansen en economische prestaties te beoordelen voor zowel afzonderlijke activiteiten als ook voor een boerenbedrijf als geheel. Nutriëntenbalansen en -stromen verschilden voor de twee agro-ecologische zones als gevolg van verschillen in de landbouwmethoden en van het belang van vee. Positieve nutriëntenbalansen werden gevonden voor relatief vruchtbare vulkanische bodems. Maar op steile hellingen en zure bodems, daalden de voorraden N, P en K met respectievelijk 8,6, 1,4 en 17,5 kg ha^{-1} $jaar^{-1}$. Voor landbouwbedrijven met steile hellingen en zure bodems, bedragen de kosten van het aanvullen van de gebruikte voedingsstoffen 20% van de bruto marge. Dit in tegenstelling tot de kleinschalige landbouw-bedrijven in de gebieden met relatief hoge agrarische potentie waar dit slechts 0,2% van de bruto marge is. Stikstof recycling tussen de activiteiten op landbouwbedrijven was laag, variërend tussen 1,8 en 6%. Dit beperkt het aanpassingsvermogen en de betrouwbaarheid van de huidige landbouwsystemen. Weinig van de producten van het boerenbedrijf kwamen op de markt en de bijdrage van gewasproductie op het netto bedrijfsinkomen was ongeveer 90%. Dit betekent dat de economische diversiteit van kleinschalige landbouwbedrijven laag is, met uitzondering van kleine landbouwbedrijven met grootvee (TLU).

Hoofdstuk 3 beschrijft een veldexperiment waarbij bodemerosie en bodemvruchtbaarheid gradiënten werden vergeleken van 20+ jaar oude terrassen met alleen grasstroken (Pennisetum purpureum) of met grasstroken in combinatie met infiltratie sleuven met land zonder bodembescherming technologie. Het laagste jaarlijkse bodemverlies (18 t ha-1) werd gemeten bij grasstroken in combinatie met infiltratie sleuven, een 57% reductie in bodemverlies in vergelijking met percelen zonder bodembescherming. Binnen de terrassen werd een fors ruimtelijke verschil waargenomen in zowel de bodemkwaliteit als de gewasopbrengst. De bodem in het onderste deel van de terrassen bevat 57% meer organische koolstof en 31% meer beschikbaar fosfor dan de bodem in het bovenste deel van de terrassen. Deze opvallende bodemvruchtbaarheid gradiënt bedreigt de duurzaamheid van de 'slow-forming' terrassen, tenzij een locatie specifieke bemesting strategie wordt ontwikkeld. Voor de duurzaamheid van deze terrassen moet de huidige praktijk van het 'oogsten' van vruchtbare grond van de onderste rand van de grasstrip om die te gebruiken als meststof voor de het bovenste deel van het terras worden stopgezet.

In **Hoofdstuk 4** worden de resultaten gepresenteerd van door de onderzoeker beheerde experimenten op boerenvelden tijdens twee opeenvolgende groeiseizoenen van 2010. Deze experimenten werden gedaan in drie verschillende landschapsposities, namelijk in het bovenste deel van een helling, in het midden van de helling en aan de voet van de helling. Een factoriaal ontwerp is gebruikt met een rotatie van bonen met aardappel en een continue teelt van aardappel met componenten van geïntegreerd bodemvruchtbaarheid beheer (ISFM) als behandelingen. In alle landschapsposities werd een verhoogde aardappel productie waargenomen bij de toepassing van dierlijke mest en kunstmest N in combinatie met het gebruik van verbeterde zaden. Deze verhoging was 4460 kg ha^{-1} in Rwerere en 5900 kg ha^{-1} in Gataraga ten opzichte van de gangbare boeren praktijk. Boon opbrengsten waren over het algemeen lager in Rwerere (1145 - 2275 kg ha^{-1}) dan in Gataraga (1640 tot 3140 kg ha^{-1}). Productie van aardappelen na bonen resulteerde in een verhoogde aardappel opbrengst vergeleken met continue productie van aardappels. En ook in een aanzienlijke toename van de nettowinst welke varieerde tussen 400 en 822 USD ha^{-1} in Gataraga en tussen 1100 en 1560 USD ha^{-1} in Rwerere. De combinatie van kunstmest, organische mest en verbeterde zaden zorgde voor een sterke toename in opbrengsten maar in een lagere agronomische stikstof efficiëntie (N-AE) in de relatief vruchtbare lagere delen van de helling. En ook in een lager marginaal rendement vanwege de hoge kosten van zaden en kunstmest.

Hoofdstuk 5 beschrijft de impact van PIWM ontwikkelingsactiviteiten, zoals terrassen, dijkjes langs de hoogtelijnen en grasstroken. De impact wordt zowel uitgedrukt in netto huidige waarde (NPV), in een internal rate of return (IRR) en met behulp van de economische surplus-methode. De resultaten geven aan dat een PIWM benadering de mogelijkheid biedt om het bestaan van de landbouwers te verbeteren en de veerkracht van een aangetast milieu te vergroten. Het hoge gebruik van landbouwhulpmiddelen is het resultaat van de integratie van verschillende beleidsmaatregelen welke tegelijk actief zijn in het stroomgebied. Er werd een duidelijke synergie van het beleid waargenomen en dat had een positief effect op de omvang en samenstelling van de veestapel, de beschikbaarheid en het gebruik van mest, de productie van voedergewassen en de vermindering van bodemverlies. Dit houdt in dat PIWM inderdaad multi-institutionele taken aankan en samenwerkingsverbanden en allianties kan harmoniseren welke verschillende niveaus bestrijken. De economische surplus methode laat zien dat stroomgebied activiteiten voordeling uitpakken voor landbouwproducenten, vooral voor degenen die aardappels en tarwe verbouwen. Grasstroken vertonen een sterke veerkracht, zijnde al 20 + jaar oud en nog steeds effectief als barrières tegen bodemverlies. Grasstroken, gecombineerd met infiltratie sleuven hebben beduidend minder bodemverlies dan velden zonder bodembescherming maatregelen. Vee speelt een belangrijke rol bij het handhaven van de bodemvruchtbaarheid door het produceren van 5320 kg van mest per huishouden. Dit vult voor een aanzienlijk deel de geoogste voedingsstoffen aan. Grasstroken en dijkjes langs de hoogtelijnen zijn alleen financieel aantrekkelijk op hellingen van minder dan 45%. Terrassen zijn financieel aantrekkelijk, zelfs op hellingen van meer dan 45% als gevolg van de daarmee verband houdende hogere gebruik van agrarische grondstoffen. Ontwikkelingsactiviteiten in het stroomgebied veranderde het landbouwsysteem met meer integratie tussen vee en gewassen.

Hoofdstuk 6 is een synthese van voorgaande hoofdstukken. Het geeft in het kort antwoord op de onderzoeksvragen, beschrijft de toegevoegde waarde van de thesis m.b.t. kennisontwikkeling en biedt suggesties voor verder onderzoek en beleidsvorming. De algemene conclusie is dat geïntegreerd beheer van natuurlijke hulpbronnen op stroomgebied niveau, mits uitgevoerd met 'echte' participatie van alle betrokkenen, duurzaam landgebruik kan bevorderen.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)
- Participatory Integrated Watershed Management in the north-western highlands of Rwanda

Writing of project proposal (4.5 ECTS)
- Integrated watershed management for improved natural resource management and crop productivity in the North-Western highlands of Rwanda

Post-graduate courses (9 ECTS)
- Participatory geographical information systems in development studies; Helsinki University, Finland (2008)
- Coping with climate change in integrated watershed management; Wageningen UR (2008)
- Training on greenhouse gases mitigation assessment; Kigali, Rwanda (2009)
- Monitoring for quality improvement (MOnQI) training course; Musanze, Rwanda (2009)
- Sustainable national greenhouse gas inventory management systems in Eastern and Southern Africa; UNFCCC secretariat, Dar es Salaam, Tanzania (2010)

Deficiency, refresh, brush-up courses (3 ECTS)
- Erosion processes and modelling (2008)

Competence strengthening / skills courses (3 ECTS)
- Information literacy for PhD including EndNote introduction; Wageningen UR (2008)
- Training on questionnaire of technologies (QT) and questionnaire on approach (QA) for SLM technologies: WOCAT; Rwanda
- Writing a wining project proposal: intensifying agricultural water management interventions with proven returns to investments in East and Southern Africa; Nairobi, Kenya (2009)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.8 ECTS)
- PE&RC Introduction weekend (2008)
- PE&RC Weekend for PhD student in final year (2012)

Discussion groups / local seminars / other scientific meetings (8.4 ECTS)
- Discussion group on spatial methods and scaling issues; WUR, the Netherlands (2008)
- Annual research review meetings (2009-2011)
- Seminar on farmers ‘knowledge on land and soil degradation in the highlands of Rwanda; SLM Project; Musanze, Rwanda; (2010)
- Seminar on integrated research for development and natural resources management; Kabale, Uganda (2010)
- Seminar on MonQI: quantification of nutrient balances of smallholder farms in the tropics; Musanze, Rwanda (2010)

International symposia, workshops and conferences (6.6 ECTS)

- Regional conference on Agricultural Water Management in Eastern & Southern Africa: Investment in Agricultural Water Management Pays (2008)
- Regional workshop on Lessons Learnt from Promoting Agricultural Water Management in Eastern & Southern Africa; Nairobi, Kenya (2010)
- International conference on “Challenges and Opportunities for Agricultural Intensification of the Humid Highlands Systems od Sub-Saharan Africa; presentation: integrated soil fertility management for optimizing crop productivity in the highlands of Rwanda (2011)

Lecturing / supervision of practical ‘s /tutorials (2.4 ECTS)

- Crop water management and irrigation scheduling; 8 days (2011)

Supervision of 1 MSc student

- Quantification of the balance of nutrient flow at farm level for improved soil and land management in the Rwandan Highlands; 20 days

Curriculum vitae and author's publications

Mbarushimana Désiré Kagabo was born on May 12, 1971 in Rutshuru, Democratic Republic of Congo (DRC). He finished his secondary education from Mahano High School, DRC in 1990. Desire has obtained his BSc degree in Soil and Rural Engineering from the National University of Rwanda in 1999. From August 1999 to date he has served as a researcher in Soil and Water Management Research Program of the Rwanda Agriculture Board (RAB). In February 2000, he got a Japan International Cooperation Agency (JICA) fellowship for a professional training on Irrigation and Drainage. In February 2004, he got a World Bank fellowship for the Master program on Soil Sciences and specialised on Soil Water Balance Modelling and Crop Growth Simulation from the University of Pretoria, South Africa. From 2006 to date, he has been involved in lecturing and supervising BSc dissertations at both the National University of Rwanda and High Learning Institute of Agriculture and Animal husbandry (ISAE). Between 2006 and 2008, he has been the director of the Highland Agriculture Research Centre (HARC) of the former *Institut des Sciences Agronomiques du Rwanda* (ISAR).

In February 2008, he has got a Wageningen University Sandwich PhD fellowship at the Land Degradation and Development Group. His PhD research focused on integrated watershed management for improved natural resource management and crop productivity in the north-western highlands of Rwanda. He has published a number of peer reviewed articles and made a number of oral and poster presentations in several international meetings. Mbarushimana Désiré Kagabo is married and father of three daughters and two sons. Email: desirekagabo@yahoo.com or desire.kagabo@gmail.com.

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