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USEFULNESS AND USE OF THE SOIL MAP OF RWANDA: SCIENTIFIC AND FARMERS' SOIL KNOWLEDGE INTEGRATION FOR EFFECTIVE PARTICIPATORY INTEGRATED WATERSHED MANAGEMENT

Toward soil-specific and farmers' judgmental fertilizer utilization

Pascal NSENGIMANA RUSHEMUKA

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Pr. Laurent Bock
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Acronyms

AEZ: Agro-Ecological Zone

AFSIS: African Soil Information Service

AHI: African Highlands Initiative

ANOVA: Analysis of variance

ASARECA: Association for Strengthening Agricultural Research in Eastern and Central Africa

CEC: Cation Exchange Capacity

CGIAR: Consultative Group for International Agricultural Research

CPR: Carte Pédologique du Rwanda

EA: Ecological Agriculture

EDPRS: Economic Development and Poverty Reduction Strategy

FAO: Food and Agriculture Organization

FSK: Farmers’ Soil Knowledge

FSRP: Farming Systems Research Program

FYM: Farmyard Manure

GDP: Gross Domestic Product

GIS: Geographic Information System

GR: Green Revolution

IA: Industrial Agriculture

IFAD: International Funds for Agricultural Development

INEAC : Institut National pour l’Etude Agronomique du Congo belge

ISAE : Institut Supérieur d’Agriculture et d’Elevage

ISAR: Institut des Sciences Agronomiques du Rwanda

ISFM: Integrated Soil Fertility Management

ISNAR: International Service for National Agricultural Research

ISRIC: International Soil Reference and Information Centre

IUSS: International Union of Soil Sciences

MINAGRI: Ministry of Agriculture and Animal Resources

MINECOFIN: Ministry of Economics and Finances

MONAGRIS: Moniteurs Agricoles

NARS: National Agriculture Research Systems

NGOs: Non Governmental Organizations

NRM: Natural Resource Management

NUR: National University of Rwanda

PAP: Projet Agro-Pastoral

PIWM: Participatory Integrated Watershed Management

PR: Participatory Research
PR: Pedological Region
PRA: Participatory Rural Appraisal
R&D: Research and Development
RA: Reference Area
RAB: Rwanda Agriculture Board
RCBD: Randomized Complete Block Design
RSRS: Regional Soil Reference System
SFI: Soil Fertility Initiative
SOTER: Soil Terrain Database
SPPI: Science-Policy-Practice Interface
SSA: Sub-Saharan Africa
USAID: United States Agency for International Development
USDA: United States Department of Agriculture
WRB: World Reference Base

Abstract

Rwanda has a digital land resource database including a medium scale - 1:50,000 - soil map (CPR: for Carte Pédologique du Rwanda). The availability of this land resource information was expected to improve significantly the way agricultural research and extension were conducted in this country. Paradoxically, research and extension programs are still planned and implemented under a kind of trial and error approach (Multi-Environment Trials) within large and heterogeneous Agro-Ecological Zones (AEZs) without systematic consideration of different soil types within each AEZ. Overlooking the use of the CPR in this process has detrimental consequences on the overall reasoning of agricultural research and extension on the one hand, and the interpretation and extrapolation of obtained research results on the other hand. Without a broader understanding of the national biophysical environment and the systematic consideration of different soil types at watershed level it remains an illusion to expect from scientists, the development of soil-specific and transposable technologies in the complex soilscapes of Rwanda! A study was undertaken to understand how the CPR can be at the heart for Rwandan agricultural research and extension thinking towards the Science-Policy-Practice Interface (SPPI). Findings from this study show that in a country like Rwanda where the innovation model is intended to be the Participatory Integrated Watershed Management (PIWM), and where agriculture is practiced by small-scale farmers (0.5-1 ha) with an already functional Farmers' Soil Knowledge system (FSK), the usefulness and use of the CPR can be significantly improved by integration of the scientific and FSK systems through communication bridges. The communication bridges allow scientists to interpret the farmers' soil-related practice rationality and to introduce new soil-related technologies as compatible pieces of the FSK system.

In the *Akavugut*o watershed case study, the link between scientific and FSK consisted of the equivalency between scientific and farmers' land units and scientific and farmers' soil types. It has been observed that soils are distributed along the slope and that top soil properties and crop yields are more influenced by soil type intrinsic properties than by the land use. In other words, in the low input system of Rwanda, the response to the human management factor depends first of all on the fertility potential of each soil type. The soils of *Entisols* order *(Urubuye /Urusenyi)* occupy the mountainous and crests/interfluves. The soils of *Ultisols* order *(Inombe)* occupy the plateaus and shoulders. The soils of *Oxisols* order (*Umuyugu/Mugugu)* occupy the hillsides/back slopes (the largest land unit); while the soils of *Histosols* order *(Nyiramugengeri)* occupy the valleys. Except the mountainous which are constrained by the steep slopes (gradient >55%), soils with good soil properties (slightly acid and less leached) are located in the upper hill made up by hill summits, crests, plateaus and shoulders. In these land units, soils can still produce relatively good crop yields under low farmers' input system (farmyard manure). The infertile soils (extremely acid and strongly leached) occupy hillsides. To produce good staple crop yields, these soils imperatively need the combination of lime, organic manure and fertilizers. Other infertile soils (extremely acid) are found in the valley bottom. The soils in this land unit need the combination of lime and fertilizers to be productive. Thus, the integration of CPR soil resource information with the FSK system improves the accessibility of scientific soil knowledge and constitutes an effective way of achieving soil-specific technologies and a practical way of extrapolating results to analogous soil types. The most important practical implication is that the representative regional soil reference systems integrating both scientific and FSK systems at watershed level and circumscribed in the landscape context constitutes a key step towards an –ease-to-use Land Information System (LandIS) for Rwanda. The user friendly LandIS is necessary for the sound management of the Rwandan space and for more rational agronomic experimentation. The main policy implication is that the Participatory Integrated Watershed Management should be institutionalized in agricultural research and development organizations as a valid and valuable innovation model to which policy, administration and finance institutions should adapt.

Résumé

Le Rwanda possède une carte des sols (CPR : pour Carte Pédologique du Rwanda) numérique à moyenne échelle - 1/50.000 - et sa base de données. Il était espéré que l'existence de cette carte aide à améliorer significativement la façon dont étaient conduites la recherche et la vulgarisation agricoles dans ce pays. Paradoxalement, la recherche et la vulgarisation continuent d'être planifiées et exécutées dans une sorte d'essais et d'erreurs (Essais-Multi-locaux), sur base de Zones Agro-Ecologiques (ZAE) vastes et hétérogènes et cela sans considérations systématiques des différents types des sols dans chaque ZAE. La non prise en compte de la CPR a bien évidemment des conséquences néfastes sur la philosophie et l'organisation générale de la recherche et de la vulgarisation d'une part, et sur l'interprétation et l'extrapolation des résultats obtenus d'autre part. Sans compréhension intégrale du milieu biophysique à l'échelle nationale et sans prise en compte systématique des différents types de sols à l'échelle du bassin versant, il restera certainement illusoire d'escompter, de la part de chercheurs, le développement des technologies pertinentes, efficientes et transposables! Une étude a été menée en vue de comprendre comment la CPR peut être au cœur de la philosophie de la recherche et de la vulgarisation agricoles du Rwanda vers une interface science-politique-pratique fonctionnelle. Cette thèse montre que, dans un pays comme le Rwanda où le modèle d'innovation se veut la Gestion Participative et Intégrée des Bassins Versants et où l'agriculture est pratiquée par les petits paysans (0.5-1 ha) avec une connaissance profonde de leurs sols, l'utilisation de la CPR peut être améliorée par l'intégration des connaissances des sols définies scientifiquement et celles reconnues par les paysans. Cette intégration passe par l'intermédiaire de liens de communication entre les deux systèmes de connaissance. Ces liens améliorent le flux d'information et permettent d'ancrer l'intervention scientifique dans la connaissance pédologique paysanne.

Dans le bassin versant de l'*Akavuguto*, ces ponts de communication ont consisté à faire l'équivalence entre (1) les unités paysagiques définies scientifiquement et celles appréhendées au niveau paysan (2) le type de sol identifié au sens pédologique et le type de sol reconnu par le paysan. Il a été observé que les sols, au niveau du bassin versant, sont regroupés en associations selon les unités géomorphologiques et que les propriétés de sols des échantillons de surface ainsi que les rendements de cultures sont beaucoup plus influencés par les propriétés intrinsèques de chaque sol que par le type d'utilisation des terres. En d'autres termes, dans le système de faible taux d'utilisation d'intrant longtemps pratiqué au Rwanda, la réponse au facteur 'gestion par l'homme' est avant tout fonction du potentiel de fertilité de chaque sol. Les sols de l'ordre des *Entisols (Urubuye/Urusenyi)* occupent les massifs montagneux et les crêtes/interfluves. Les sols de l'ordre des *Ultisols (Inombe)* occupent les plateaux. Les sols de l'ordre des *Oxisols* (*Umuyugu/Mugugu)* occupent les versants, tandis que ceux de l'ordre des *Histosols (Nyiramugengeri)* occupent les vallées humides. Exception faite pour les massifs montagneux qui sont limités par les fortes pentes (>55%), les sols relativement fertiles (légèrement acides et moins lixiviés) se trouvent dans la partie sommitale constituée de sommets de collines, de crêtes et de plateaux. Les sols dans ces unités géomorphologiques peuvent encore produire de bonnes récoltes sous le système paysan d'intrants, composé essentiellement de fumier de ferme ou de compost. Les sols infertiles (extrêmement acides et fortement lixiviés) occupent les versants. Pour avoir de bonnes récoltes, ces sols exigent la combinaison de chaux, de fumure organique et de fertilisants inorganiques. Une autre catégorie de sols infertiles occupe les vallées. Les sols dans cette unité paysagique exigent la combinaison de chaux et de fertilisant inorganique pour être productifs. La conclusion principale est que l'intégration de l'information pédologique offerte par la CPR avec la connaissance pédologique paysanne constitue un moyen de mener les interventions adaptées à chaque type de sols et une modalité pratique de transférer les technologies sur les sols analogues.

L'implication pratique la plus importante est que le système régional et représentatif de références sur les sols intégrant la connaissance scientifique et celle paysanne et circonscrit dans leur contexte géomorphologique constitue, pour le Rwanda, une étape clé vers un système d'information sur le sol (LandIS) plus accessible à l'échelle d'un bassin versant. Un LandIS plus accessible est nécessaire pour une gestion saine de l'espace rwandais ainsi que pour une expérimentation agronomique plus rationnelle. La principale implication politique est que l'approche par Gestion Participative et Intégrée des Bassin Versants devrait être officialisée, dans les institutions de recherche et de développement, comme modèle d'innovation valide et valable auquel les institutions politiques financières et administratives devraient s'adapter.

Table of contents

Chapter I: General introduction

1.1 Problem statement

Rwanda is subdivided into different and sometimes spatially overlapping Agro-Ecological Zones (AEZs) (Delepierre, 1974; Prioul and Sirven, 1981; Gasana, 1990; Verdoodt and Van Ranst, 2003a). These natural regions are well covered by a 'representative' network of experimental research stations (ISNAR, 1982). However, syntheses of 30 years (1960-1990) of agricultural research in crop fertilization and crop variety selection (Rutunga, 1991) and 15 years (1980-1995) of green manuring and improved fallow (Drechsel et al., 1996) show that many trials undertaken in different sites (on station or on-farm trials) within one AEZ and between different AEZs (Multi-Environment Trials), yielded inconsistent and most of the time, contradictory results when it comes to synthesize and extrapolate results over the entire AEZ. Indeed, given the variations of soil types and their characteristics over short distances and in complex manner common in the mountain landscapes of Rwanda, the soil types and soil parameters vary significantly within AEZ as they do between AEZs (Birasa et al., 1990; Steiner, 1998). Therefore, many studies undertaken under the conventional research approach were not soil-specific[1]: hence the contradictory results.

On the other hand, because of small-scale variations of soil types in mountain agriculture, soil suitability maps for the entire AEZs (1:250,000) (Verdoodt and Van Ranst, 2003a) have been rendered irrelevant for farmers and the Agro-Ecological Zone-based crop regionalization and specialization have not yet been adopted (Steiner, 1998). Consequently, the medium scale soil map of Rwanda -1.50, 000- (CPR: for Carte Pédologique du Rwanda) (Birasa et al., 1990), which was expected to be the foundation of the Rwandan agriculture transformation reasoning has since its completion been a *sleeping beauty*.

A quick analysis on the use of the CPR suggests that the little exploitation of this soil map in agricultural research and extension could be a communication issue in terms of level of perception (scale) and legend (*Soil Taxonomy* and pedogenetic legends). It is true that these factors are considerable constraints for many soil map potential users, especially in Rwanda where the soilscape is very complex on the one hand, and where there is little experience of the use of soil maps on the other hand (Steiner, 1998). However, these are not enough to explain all problems that undermine the use of soil maps in agriculture research and extension.

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[1] Soil-specific refers to the fact that the soil on which the intervention is undertaken should be well known in terms of its name and spatial distribution and characterized in terms of its properties so that the results obtained are transposable to analogous soil types in other areas. The spatial distribution of the analogous soil types should be known in the planning area. In other words, the soil-related interventions should systematically take into account different soil types at watershed level within each AEZ.

A deep analysis shows, however, that the most acute problem with the use of soil maps begins with a policy misconception that has institutionalized the linear model of innovation[2] with its compartmentalized research based on academic disciplines and crop commodities (Bock, 1994[3]; Leeuwis and van de Ban, 2004; Raina et al., 2006). The above mentioned model postulates that innovation starts with basic research, followed by applied research and development, and ends with production and diffusion (Leeuwis and van den Ban, 2004; Godin, 2005). In the context of this model, the overwhelming majority of the soil map potential users do not know (are not aware) that they need the soil map! This lack of awareness is a big problem, because it prevents the necessary positive attitude towards the soil resource information. Indeed, soil maps are produced by soil surveyors for non-soil survey specialist potential users (Dent and Young, 1981). However, many soil maps potential users maintain that they do not understand how they can use them for their own application (Bui, 2004). In these conditions, it becomes clear that the first fundamental problem in using soil maps in agricultural research and development is the fact that those who should be working with them seldom understand the logic of their use whether they are detailed or not, with technical or utilitarian classification systems (Wielemaker et al., 2001; Niemeijer and Mazzucato, 2003; Bui, 2004).

A second fundamental problem about the use of many soil maps is the fact that the landscape context in which soils occur, which helps to form the soil surveyor mental model is not represented as part of the final soil map legend (Wielemaker et al., 2001; Omuto et al., 2013). The information lost by not representing the landscape context in which soils occur hampers the capacity of soil surveyors to fully communicate the soil resource information so that the soil surveyor mental model is clear for all potential users (Wielemaker et al., 2001). Indeed, there are traditionally two mapping approaches in soil survey: the pedological approach and the physiographic or geomorphological approach. In the pedological approach (soil-centred approach), maps and legends present only soil information. Soil-landscape relations are usually described only for representative profiles in the report/booklets. In the physiographic/geomorphological approach, soils are mapped as part of the landscape (Figure 1.1). In this approach, high categories of map legends are expressed in geomorphological terms. Lower categories are often landscape components in which the soils are described as patterns or associations. Examples of such soil maps are the Australian Atlas soil map units (Bui, 2004) and the Soil Terrain (SOTER) model of the International Soil Reference and Information Centre (ISRIC). Although in both mapping approaches landscape is used to delineate soil mapping units, the pedological map legends do not usually provide information on the landscape context (Wielemaker et al., 2001). Much useful information can still also be retrieved from the soil-centered soil maps and much application can be

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[2] This model is called 'the linear model of innovation' because it draws a straight and one directional line between various actors (see Chapter 2, Figure 2.1). In this model some actors are supposed to specialize in the generation of innovations, other concentrate on their transfer, while the farmers' role is merely to apply innovations (Leeuwis and van den Ban, 2004).

[3] Bock (1994) observed that *'le cloisonnement des structures éloigne le chercheur du praticien' ainsi que le cloisonnement de la science tend à dissocier la mesure de l'observation'*.

deduced from them, but only by users who understand how soil maps are done (Bui, 2004). Thus, the pedological map (two dimensions), is more directed to a peer audience of other soil survey specialists rather than to a large group of its potential users (Wielemaker et al., 2001).

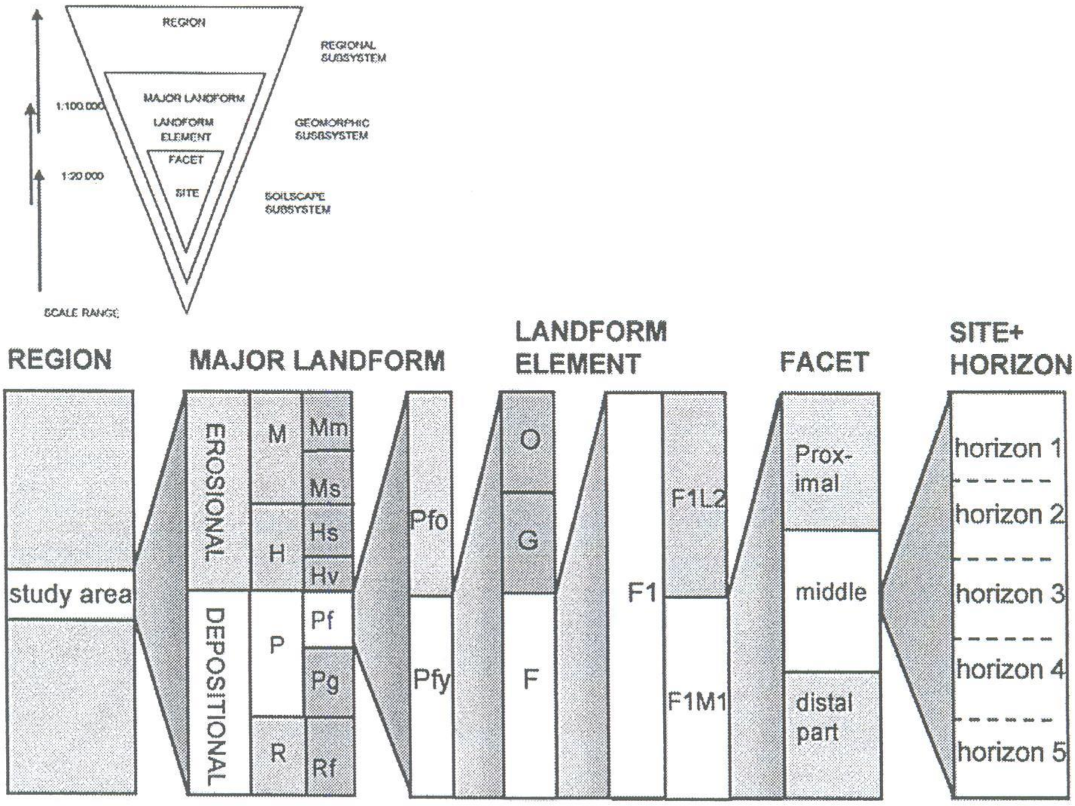

Figure 1.1 An example of a land system approach with nested multi-scale objects of the land unit hierarchy with an illustration of the desegregation and classification procedure zooming (white coloured units). Source: (Wielemaker et al., 2001).

The presented case study (Figure 1.1) has five levels: the region, the major land form, the landform element, the facet and the site or pedon. Each level has its scale range. The levels are grouped into three subsystems: the region subsystem, the geomorphological subsystem and the soilscape subsystem. The levels in this case study were clearly defined. In our case, the different hierarchies are the national territory, Agro-ecological zone/Pedological region, watershed, benchmark, land unit and soil type (see Figures 1.5a, b; 1. 8).

The CPR is a soil-centered soil map. Its digitized database and its report (booklets) show three types of legends: the cartographic[4], the narrative and the taxonomic legends. The hard copy (printed version) of the CPR shows only the narrative legend. In the three types of legends, the landscape context in which

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[4] Cartographic legend is made up by a set of symbols used by the soil surveyor at field level to record soil profile characteristics. It is a basis for pedogenetic narrative legend: a soil forming factor-oriented legend. The taxonomic legend is a soil classification-oriented legend. Soil Taxonomic is itself a pedogenetic soil classification system.

soils occur is not explicitly represented as part of the soil map legends. This is only done in the soil map report (booklets/"notice explicatives"). The problem with the soil map reports is that they are considered too academic, too riddled with incomprehensible jargon or too remote from the practical decision and action which are needed for successful development and management of agriculture enterprises (Landon, 1991). The fact that the landscape context in which the soils occur is not explicitly incorporated in the final soil map legend together with the inaccessible international soil classification systems hamper the capacity of non-soil surveyor to capture the soil surveyor mental model (Wielemaker et al., 2001; Bui, 2004). Hence the persistence of the idea that soil maps are not efficient communication tools (Hudson, 1992 cited by Bui, 2004). The consequence is that the many potential users of the soil maps merely overlook them and plan their actions without systematic consideration of different soil types within each AEZ (Nachtergael., 2000; Raina et al., 2006). The penalties of this situation are many: (1) persistence of the incoherent and contradictory results and the confusing extrapolation framework, leading to lack of soil-specific technology recommendations (2) developers imposing improvised and generic technology recommendations – e.g. blanket fertilizer recommendation (3) inefficient allocation of the limited financial resources (4) high yield risk[5] and therefore, low adoption rate of the proposed technologies (5) persistence of low productive agricultural systems and, (6) persistence of food insecurity and poverty.

In view of the above situation, it is up to soil scientists to take the leadership not only in soil fertility management but also in the set up of soil fertility management policies (Brigdes and Catizzone, 1997; Hartemink and Bouma, 2012). This means that they must work more closely with practitioners of other disciplines, and also take legal, economic and social conditions into account so that sustainable land management systems are developed and used (Brigdes and Catizzone, 1997). Because soil scientists have been less influential in the agricultural development circles at global and continental levels (Muchena, 1995; Brigdes and Catizzone, 1997; Hartemink and Bouma, 2012), scientists from other disciplines, mainly agricultural economists have been leading the international agriculture institutions like the CGIARs[6] (Mackay and Horton, 2003), but with less consideration/understanding of the biophysical environment (Nachtergaele, 2000). For example, soil scientists hardly understood the fact that the soil as such was not given specific mention in the United National Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992 as an understanding of soil

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[5] Yield Risk is defined as the probability of obtaining yields lower than or equal to the control across similar conditions of soil, climate and management (Sileshi et al., 2010).

[6] For instance, key positions, both in individual centres and in system-level bodies (such as Technical Advisory Committee, the interim Science Council, the CGIAR Secretariat and the Executive Council) have been occupied by economists, who have fostered the use of economic frameworks and quantitative methods in planning, priority setting and evaluation (Mackay and Horton, 2003). It is in this context that the CGIAR has developed a deeply rooted 'hard-science' culture and an unquestioning belief in the value of applying modern, positivist scientific methods to the solution of agriculture, environment and related problems. The problem is that in this context where the science is virtually synonymous of quantitative analysis, the alternative approaches such as qualitative methods, participatory approaches and constructivist logic are regarded as highly suspect – 'soft science'- at best (Mackay and Horton, 2003).

management underlies so many declarations (Brigdes and Catizzone, 1997). Another example is that more recently and in the context of the Millennium Development Goals (MDGs), much emphasis has been placed on stimulating the use of fertilizers without critically examining where fertilizer is efficient and where it is not and why (Sileshi et al., 2010). A last example is the way that genotypes are traditionally evaluated using multi-environment/location trials without systematic consideration of different soil types in these different locations (Matthews et al., 2002). This implies that greater effort is still needed to bridge the gap of understanding between soil science and the rest of the community (Brigdes and Catizzone, 1997).

Elsewhere, in the new context of research for development, and under the influence of Chambers (1985), different international institutions that backstop the National Agricultural Research System (NARS) of developing countries have initiated more Participatory and Integrated research and development approaches. These approaches were recognized to complement the discipline-based and commodity oriented academic agricultural research and to substitute the linear and top-down technology transfer approach. In the discipline-based and top-down technology transfer, soil science and its sub disciplines constituted an independent compartment with its own sophisticated communication jargon. In the new research and development model, it is called to play a leading role and consequently, to adopt a user-friendly communication language, to guarantee maximum accessibility of the information it holds.

It is from this new research and development context that scientists realized that farmers have deep soil knowledge in their own perspective. The Farmers' Soil Knowledge (FSK) was recognized to form a much better starting point for interactive communication than the international classification systems during the participatory integrated innovation process (Niemeijer and Mazzucato, 2003). Thus, many authors found that Rwandan farmers, like many others worldwide, possess such detailed soil knowledge that enables them to exploit any soil difference in agricultural production (Habarurema and Steiner, 1997; Steiner, 1998; Rushemuka et al., 2009). This detailed soil knowledge has been strongly recommended to be the starting point of scientific intervention in adaptive research and development (Habarurema and Steiner, 1997; Steiner, 1998). These authors advise scientists to directly build recommendations on FSK and rely on farmers' '*accurate and precise mental soil maps'* (Barrera-Bassols et al., 2006b) and farmers' flexible soil nomenclature to cope with the complex soilscape of Rwanda. Despite all these works, the problem of soil-specific interventions and replicable research results is still unresolved.

In this thesis I argue that the usefulness and use of the CPR at watershed level, and in the new context of agricultural research for development, can be enhanced by explicitly representing the land units in which soils occur as part of the CPR legend and by establishing communication bridges between the scientific and FSK systems. Linking the scientific and FSK is a mean of offering an executive framework that permits the scientific interventions to be introduced as pieces of the already functional FSK system. This is very important because technologies proposed by researchers from small experiment plots, rely on farmers to adapt them on different soil types of their own fields. The originality of this thesis is the fact that it offers effective mechanisms to build soil fertility management technologies on the synergism between the existing soil resource information database (CPR) and FSK system. In doing so, it contributes to fill the communication gap observed between those developing technologies and these being asked to use them (Niemeijer and Mazzucato, 2003). It adds value to the works of Habarurema and Steiner (1997) and Steiner (1998) who recommend the use of FSK by scientists in adaptive research and development. The FSK helps validate scientific soil knowledge to ensure that it is not only scientific but also relevant and functional (Barrera-Bassols et al., 2006b).

1.2 Justification to the problem

The new arena of agricultural research for development consisting of more participatory and integrated approach is shaped by the concept of Sustainable Development - matching human well-being and ecosystems preservation. This new research framework is complex and is likely to be achieved only by teamwork from different disciplines, cooperating within them and with farmers through interactive communication, to solve a concrete problem in a given location in an innovative way (Laker, 1981; Leeuwis and van den Ban, 2004, Weichselgartner and Kasperson, 2010). The participatory, integrated approach, though good in theory, is still difficult to implement. Hence, many authors have suspected a methodological gap or a fundamental problem which is not yet solved (Leeuwis and van den Ban, 2004; Quinlan and Scogings, 2004; Mafuka et al., 2005; German et al., 2006).

It is expected that this thesis will provide a framework to improve the collaboration between different stakeholders in the food production system. In fact, the accessibility and intelligibility of soil resource information (both scientific and FSK) will improve the interaction between (1) bio-physical disciplines among themselves, (2) the bio-physical and socio-economic disciplines and (3) the researchers -scientific community- and the farmers. The communication then established will re-start the re-thinking about the methodological gap and will boost the institutional reform to make the approach more effective. The renewed approach will allow the functionality of the “Science-Policy-Practice Interface” (SPPI) towards a “knowledge-action continuum” in research for development. At policy level, this thesis is expected to contribute to more biophysical environment understanding that is necessary to objectively revisit some relevant challenges and pitfalls observed in many land-related policy documents of Rwanda and their implementation (see Ansoms, 2008; Pritchard, 2013) and perhaps easily and exclusively attributed to some political reasons. It is a fact that the biophysical environment (the land in its broader sense) understanding is a pre-condition to its relevant and efficient management! Currently, there is much emphasis on policy and laws as tools for shaping society without sufficient understanding of biophysical and institutional environments into which new policies and laws are to be implemented (Ansoms, 2008).

1.3 Research question

How can the soil map of Rwanda 1:50,000 effectively play its role as the foundation of agricultural research and development to allow the agriculture sector to be really, an engine of the country's economic growth? The above research question can be subdivided into the following research sub questions:

1. How have the Rwandan agricultural research and development institutions and organizations evolved to cope with the innovation models that have evolved over time, and what has been the place and role of the soil resource information in this process?
2. How has soil science, as a sub-discipline of science and agriculture technology been effectively used in agricultural research and development and what has been learnt?
3. How can the scientific and the FSK be integrated for watershed level effective participatory and integrated agricultural research and development?
4. Can the scientific-farmer soil type based Regional Soil Reference System (RSRS)[7] help to analyze and interpret soil properties and soil-related experimental results to ensure soil-specific interventions and replicable technologies?
5. Can the farmers' soil nomenclature be a useful communication language in agricultural research and development to cope with short distance variability of the soils of Rwanda?

1.4 Hypothesis

The usefulness and use of medium scale soil map of Rwanda, at watershed level and in participatory and integrated research approach, can be enhanced by explicit representation of the landscape context in which soils occur as part of the soil map legend and by the integration of the scientific and FSK. This hypothesis can be subdivided into 5 sub-hypotheses:

1. The usefulness and use of the soil map depend on the research and development approach/innovation model adopted within a country: the more integrated the research and the more interactive the extension, the more useful the soil map becomes.
2. The impact of soil science, as a sub-discipline of science and technology, to the country's development is more a matter of the adopted research and development approach and the existing institutions and their capacity to allow the necessary interaction among its own sub-disciplines on one hand, and its sub-disciplines and other disciplines on the other hand; in other words, the impact of soil science depends on conducive research and development context within a given country.
3. Linking scientific and FSK might be an appropriate way of getting advantages from the two knowledge systems and is likely to contribute significantly to the effectiveness of the Participatory Integrated Watershed Management (PIWM).

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[7] A RSRS can be defined as a multi-hierarchical land information system where a set of geo-referenced representative soil profiles and land use suitability are described, in relation to the soil forming factors and the soil-landscape relationship in precise geographic scope (for more detail, see chapter V).

4. The RSRS is an appropriate way to understand, interpret and monitor soil properties and is likely to ensure soil-specific interventions and replicable experiment results.
5. The farmer soil nomenclature is rational and can be used in agriculture research and extension to enhance communication between scientists and farmers.

1.5 Objectives

1.5.1 Overall objective

The overall objective of this thesis is to contribute to the effectiveness of the Participatory Integrated Watershed Management (PIWM) approach by highlighting the central role of the soil resource information in this process.

1.5.2 Specific objectives

The specific objective is to demonstrate how the CPR can be used as the foundation of small scale farmers' technology development like soil-specific fertilizer use. This objective can be subdivided in 5 sub-objectives.
1. To discuss the conceptual framework in which the soil map of Rwanda is expected to be used in agricultural research and extension of this country.
2 To identify and capitalize on positive lessons learnt from many years of soil science interventions in agricultural research and extension in Rwanda.
3. To improve the capacity of scientists to capture the farmers' rationality by linking the scientific and FSK systems at watershed level.
4. To set up a regional soil reference system as a mean of overtime interpreting, monitoring and evaluating soil properties and crop yields.
5. To demonstrate how the farmer soil nomenclature can be used in agricultural research and extension to achieve soil-specific soil fertility management recommendations.

1.6 Methodological approach overview

1.6.1 Biophysical milieu description

Rwanda is a small (26 000 km^2) and a landlocked country isolated in Central Africa over more that 1000 Km from the Indian ocean and 2000 Km from the Atlantic Ocean (Roose et al., 1993). Its neighbors are Uganda in north, Tanzania in east, Burundi in south and Democratic Republic of Congo in west. This highland and hilly country lies between 1°4' and 2°51' of southern latitude and between 23°53' and 30°53' of eastern longitude. Figure 1.2 shows that altitude ranges from 923 m (plain of Bugarama in South-West) to 2,800 m with some peak at 4,507 m (top of Volcano Mountains in the North-West). Because of the high altitude, this equatorial country is characterized by a sub-equatorial climate. Mean temperature is relatively stable during the year, and ranges between 15 and 25°C (Verdoodt and Van Ranst, 2003a).

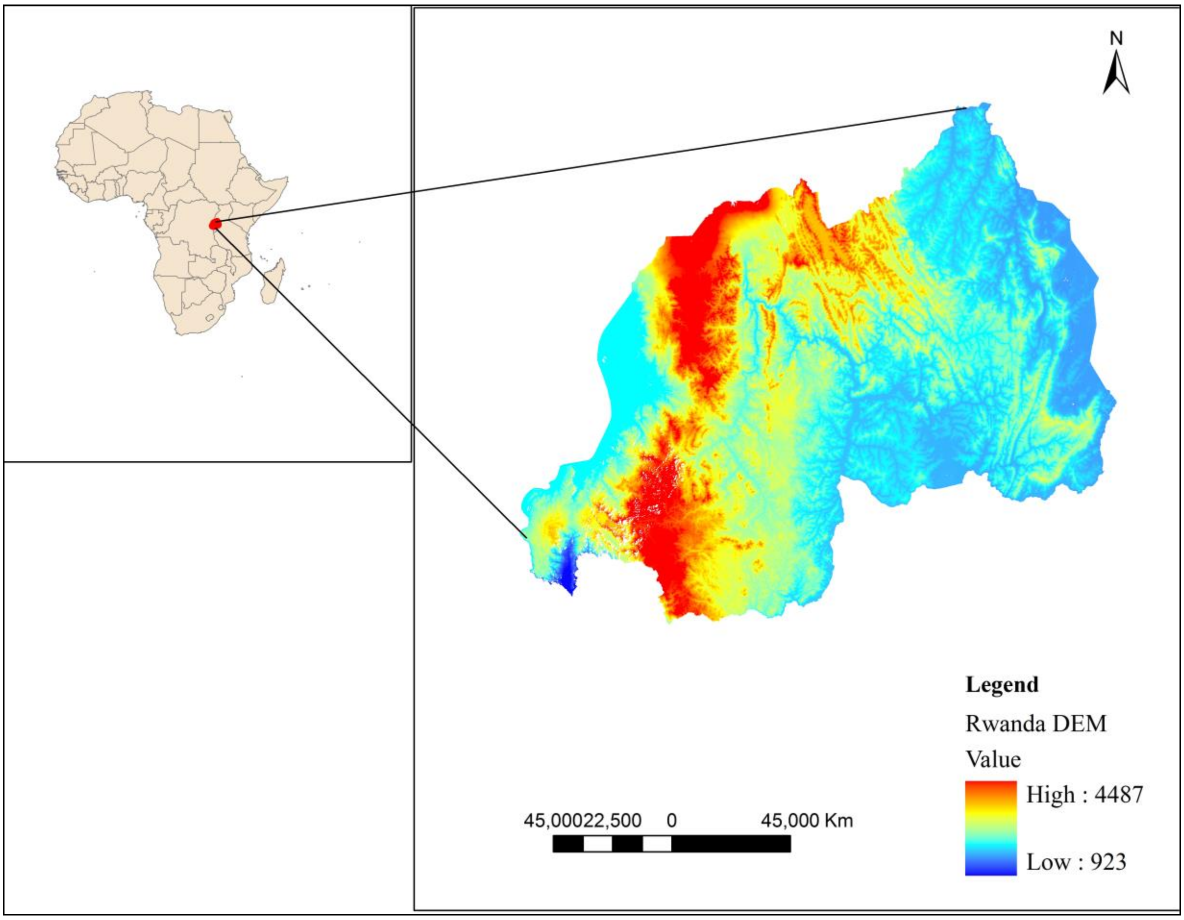


Figure 1.2 Rwanda Digital Elevation Model.
Source: Centre GIS of the National university of Rwanda.

From East to West, rainfall regimes vary from semi-humid to humid, with a bimodal rainfall regime. On the basis of relief, elevation and climate, a first perception allows subdividing the country into three agro-ecological zones (AEZs) most known as altitudinal zones: *highlands, midlands and lowlands* (Van Wambekeke, 1963; ISNAR, 1982, Verdoodt and Van Ranst, 2003a). The highlands, midlands and lowlands occupy 17, 32 and 38% of the territory respectively (Verdoodt and Van Ranst, 2003a). The remaining 14% are constituted by escarpment (1%) and marshes, islands and lakes (13%) (Verdoodt and Van Ranst, 2003a). The main common features in this first level of perception of AEZs are presented in Table 1.1.

Table 1.1 First level of AEZs perception, climatic characteristics and major limitations.

AEZ (level 1)	***AEZ (level 2)***	***Elevation (m)***	***Relief***	***Temperature (C°)***	***Rainfall (mm)***	***Dry season (month)***	***Major limitation***
Highlands	*Birunga**	*> 1,900*	*Mountainous*	15-17	*1,250-2,000*	*1 to 2*	*Slope*$^{+++}$ *Acidity*$^{+++}$
	Buberuka						
	CNWD						
Midlands	*Impala*	1,600-1,900	*Dissected Plateaus*	*17-20*	*1,000-1,250*	*3 to 4*	*Slope*$^{++}$ *Acidity*$^{++}$
	Kivu lake borders						
	Central Plateau						
	Granitic Ridge						
Lowlands	*Imbo*	< 1,600	*Pediplains*	*20-21*	*700–1,000*	*4 to 5*	*Slope+* *Erratic rainfall*$^{+++}$
	Mayaga						
	Bugesera						
	Eastern Plateau						
	Eastern Savanna						

+++: high, ++: medium, +: low limitation; CNWD: Congo-Nile Watershed Divide;

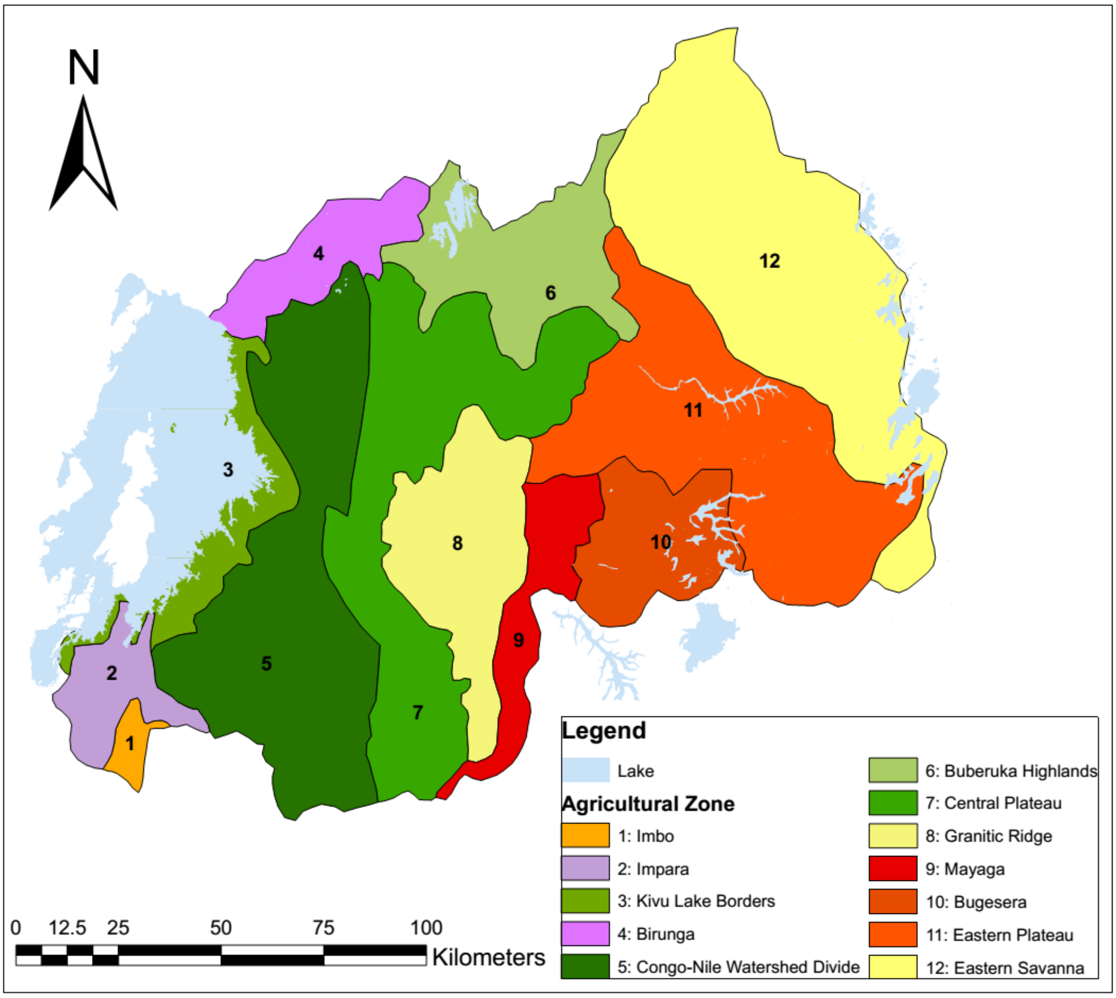
** note: The Birunga (Volcanic) AEZ is not limited by acidity and the relief is generally less mountainous compared to other AEZs in the Highlands.*

This generalization does not consider the volcanic mountains that culminate at 4507 m of elevation.

Source: synthesized from different sources by the author of this thesis.

At a second level of perception, the three AEZs were empirically subdivided into 12 natural regions known as agricultural zones (Delepierre, 1974) (Figure 1.3). They were later refined into 18 AEZ (Gasana, 1990). The diversity in climatic conditions allows an important diversification from crops suited for tropical areas to crop adapted to temperate climatic conditions (Figure 1.3).

From a pedological point of view, the experience of soil science team of the “Institut des Sciences Agronomiques du Rwanda” (ISAR), working since 1955, was synthesized into a soil association map of 18 Pedological Regions (PR) (Prioul and Sirven, 1981) (Figure 1.4). In general, soil fertility declines as one climbs up in altitude except for the highland volcanic AEZ. A closer examination of the soil map of Rwanda, established by the project ‘Carte Pédologique du Rwanda’ (Birasa et al., 1990), shows extreme variability of Rwanda soils within one AEZ or one PR. At watershed level, soil parameters change in a characteristic way from the hilltop/upper slope to the lower slope and valley bottom (Steiner, 1998).



Crop	*Introduction period*	*Adoption*	*National policy*	*Coverage*	*AEZs*											
					1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Banana	*1930*	*Perfect*	*Encouraged*	*High*	+	+	+	+		+	+	+	+	+	+	
Cassava	*1930*	*Perfect*	*Encouraged*	*High*	++	+	+	+				+	+	++	+	+
Sweet potato	*Traditional*	*Perfect*	*Discouraged*	*High*	+	+	+	+		+	++	+	+	+	+	+
Potato	*1930 (1903)*	*Perfect*	*Encouraged*	*Low*				++	+	+						
Soybean		*Moderate*	*Encouraged*	*Low*	+	+	+ +					+	+	+	+	+
Common bean	*Traditional*	*Perfect*	*Encouraged*	*High*	+	+	+	*		+	+	+	+	+	+	+
Climbing bean	*-*	*Perfect*	*Encouraged*	*Medium*				*	*	*	*					
Sorghum	*Traditional*	*Perfect*	*Discouraged*	*High*		+	+	+		+	+	+	+	+	+	+
Maize	*Recent*	*Moderate*	*Encouraged*	*Medium*	+	+	+	+	+	+	+	+	+	+	+	+
Rice	*1962*	*Perfect*	*Encouraged*	*Low*	*						*	*	*		*	*
Wheat	*1977 (1920-1930)*	*Perfect*	*Encouraged*	*Low*					*	*						
Coffee	*1927 (1905)*	*Perfect*	*Encouraged*	*Low*		+	++				+	+	++		+	*
Tea	*1946*	*Perfect*	*Encouraged*	*Low*		++	+	*	++	*						

+= reported by Delpierre (1974) but of no importance after crop regionalisation (Verdoodt and Van Ranst, 2003)

+ = reported by Delpierre (1974) and regionally important after crop regionalization (Verdoodt and Van Ranst, 2003)

++ = reported by Delpierre (1974) and nationally important after crop regionalization (Verdoodt and Van Ranst, 2003)

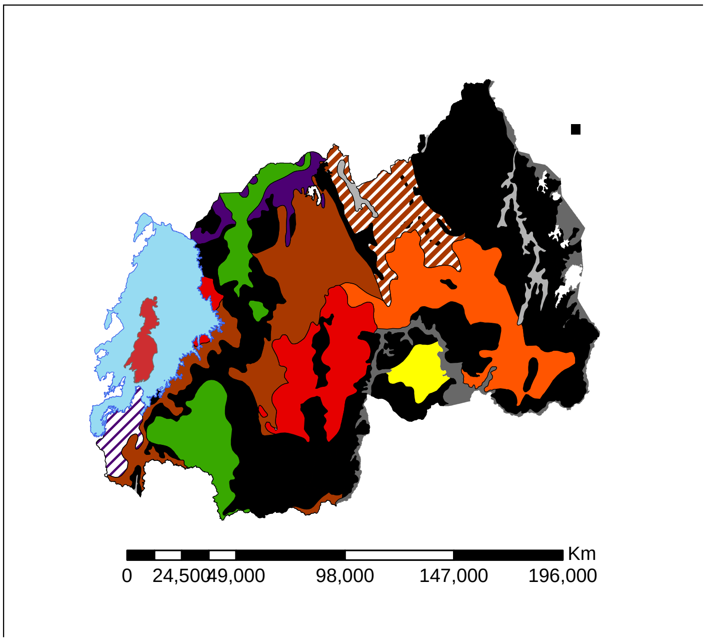
+ = not reported by Delepierre (1974) but regionally important after crop regionalization (Verdoodt and Van Ranst, 2003)

++ = not reported by Delepierre (1974) but nationally important after crop regionalization (Verdoodt and Van Ranst, 2003)

** = not reported by both group of authors but judged by the author of this thesis regionally or nationally important*

Source: Adapted from Verdoodt and Van Ranst (2003)

Figure 1.3 Agro-Ecological Zones of Rwanda and related suitable crops.
Source adapted from Delepierre (1974) and Verdoodt and Van Ranst (2003a).



Legend

- 🟦 Lake Kivu
- 🟪 Association à Andepts sur cendrées grossières, Lithosols sur laves, Histosols dans les vallées
- ☐ Association à Andosols sur cendrées fines, Andepts sur cendrées grossières, Lithosols sur laves
- ☐ Association à Sols bruns de cendrées volcaniques, Ferrisols humifères, Histosols enrichis
- ☐ Association à Ferrisols et Ferralsols humifères sur basalte, Histosols de vallées
- 🟩 Association à Umbrepts forestiers et tourbières
- ☐ Association à Umbrepts désaturés des prairies d'altitude
- 🟫 Association à Ferrisols humifères intergrades sols recents sur schistes et phyllades, Lithosols sur crête
- ☐ Association à Lithosols sur crêtes, Ferrisols humifères intergrades sols recents sur schistes et phyllade
- 🟥 Association à Ferrisols intergrades Sols recents et Collivions de concavite sur granite
- ☐ Association à Lithosols sur crêtes quartzitiques et Ferrisols intergrades Sols recents de bas versants
- ☐
- 🟧 Association à Ferralsols de glacis et Ferrisols de crêtes
- ☐ Association à Ferralsols de collines, Histosols de vallées
- ☐ Association à Ferralsols sur intercalations basiques
- 🟨 Associations à Xeroferralsols a pan, Cortisols dans les vallées
- ☐ Associations à Xeroferralsols de pentes, Vertisols de vallées
- ☐ Associations à Xeroferralsols orthotypes, lithosols de crêtes, Vertisols de vallées
- ⬛ Histosols
- ▒ Vertisols

Figure 1.4 Pedologic regions of Rwanda. Source (Prioul and Sirven, 1981).

1.6.2 Population pressure and land use

With a land size of 26,338 km^2 and a population of more than 10 million, Rwanda is the most densely populated country in Africa. At an annual population growth of 3%, the Rwandan population has doubled every 20 years since the Second World War. Indeed, the Rwandan population of 1.9 million in 1948 increased to 4.8 million in 1978 and 5.5 millions in 1982 (ISNAR, 1982). After the 1990-1994 war and genocide, the last census (Xinhuanet, 2012) shows that the population has increased from 8.2 million in 2002 to 10.5 million in 2012 and that the population growth has fallen from 2.9 to 2.6

during the same period. This dramatic population growth has resulted into all the national territory being occupied and cultivated. Indeed, 86.5% of Rwandan population is constituted by rural households living from agriculture. The later sector contributes 36 % to the country's Gross Domestic Product (GDP) (World Bank, 2010).

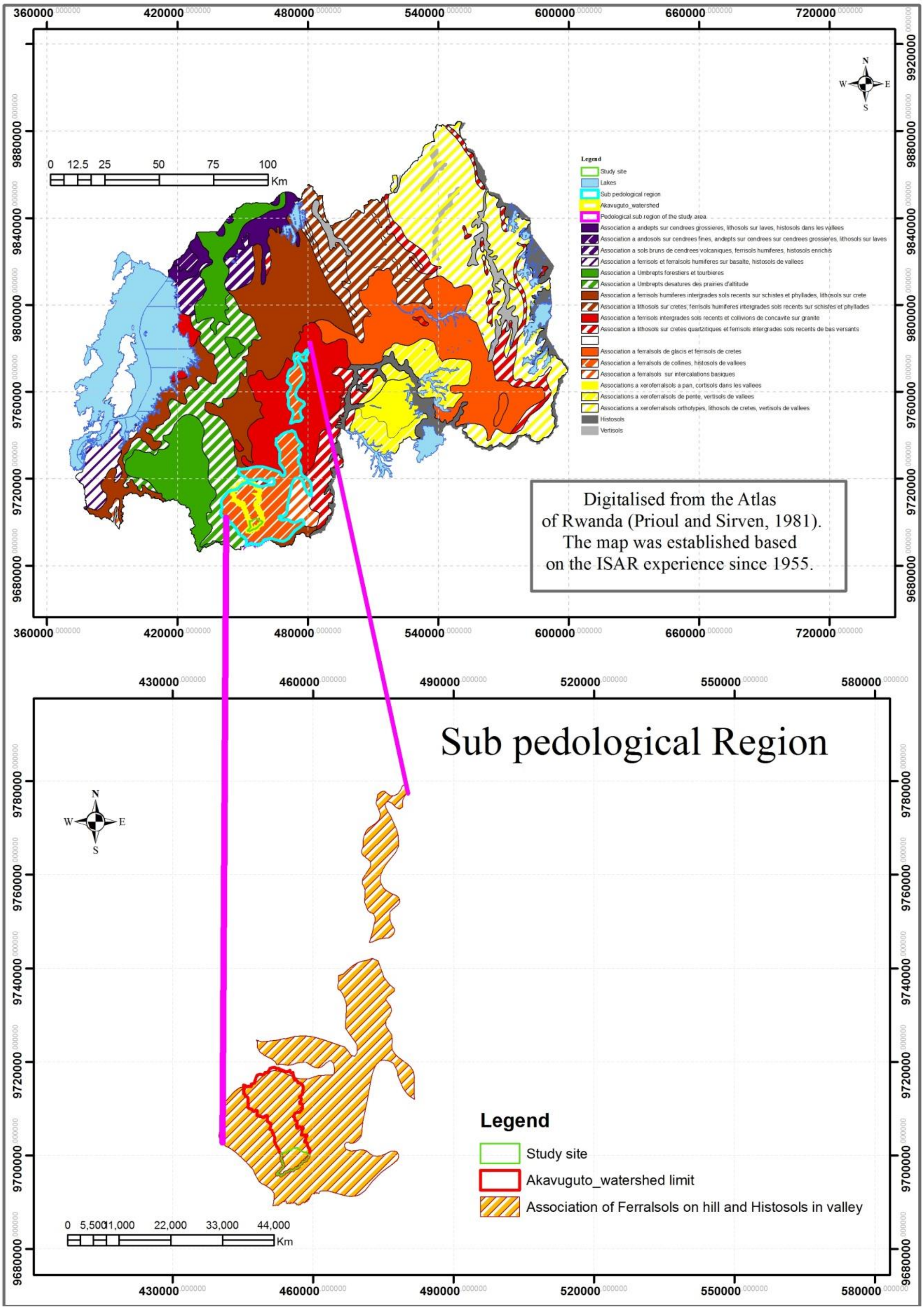
Historically, the first human settlements were in the hilly region (dissected plateau) of the Mid Altitudinal Zone. In this region, Rwandan farmers settled along the interfluves of their hillsides, where soils were more fertile than further down on the steeper slopes and where cultivation was easier than in the marshy valleys (Clay and Lewis, 1990). The households exploited three main ecological sites: (1) the interfluve/upper ridge (2) the hillside and (3) the valley bottom (ISNAR, 1982). On the interfluves and plateaus immediately surrounding the household compound, farmers planted groves of banana and other strategic crops like sorghum and beans. Further down on the back slope, they grew less demanding crops like sweet potato and cassava with frequent fallow periods. The steep slope beyond the sweet potato and cassava plots was reserved for pasture and woodlots. At the base of the slope and in swampy valleys, they raised sweet potato and vegetables along ridges that were built to facilitate water drainage (Clay and Lewis, 1990).

In a more recent past (sixties and seventies), Rwanda farmers exploited other areas of the country in response to population pressure (Drechsel et al., 1996). From the central plateau, they colonized the north and west which were under forest (ISNAR, 1982) and the eastern and less humid savannahs (lowlands) that were previously the domain of the pastoralist population (Verdoodt and Van Ranst, 2003a). Today, with nearly all the land occupied, farmers cultivate the same holdings year after year and in increasingly labor intensive fashion. Land scarcity has now compelled farmers all over the country to depart from their traditional system and convert unproductive pastures and woodlots into cropland and cultivate steep sloping fields and marshlands which were traditionally reserved for livestock grazing. The livestock is kept under zero grazing.

1.6.3 Site selection process

The site selection was inspired from the multi-scale and nested hierarchy land system reasoning (Wielemaker et al., 2001). Therefore, at national level - 1:250,000 – the pedological regions (Prioul and Sirven, 1996) were considered. At this level, while any pedological region could be chosen as an example, the "*Ferrasols on hills and Histosols in valleys*" sub-pedological region was preferred because of four main reasons: (1) a pedological region with poor soils (Neel, 1972; 1973; 1974. Birasa et al., 1990; Rutunga and Neel, 2006), therefore, more appropriate for demonstration purposes, (2) need of contributing to the alleviation of poverty in Nyaruguru, the poorest District of Rwanda (MINECOFIN, 2013), (3) existence of an ongoing project that could help field visits, (4) existence of historical data (Neel, 1972; 1973; 1974; Rutunga and Neel, 2006). In this sub-pedological region, the Akavuguto watershed was selected. The later was expected to be representative of land units, soil parent materials and soil sequences of a large area in the above sub-pedological region. For more detailed study, the benchmark site was chosen by opening a window/zoom in Akavuguto watershed

(Figure 1.5a & Figure 1.5b). At the site level, and using both technical and FSK, the soil forming factors (Jenny, 1941) and the soil-landscape relationship (Lagacherie et al., 1995;Wielemaker et al., 2001; Park and van de Giesen, 2004) were used to determine auguring points and soil pits. Composite soil samples were taken for each soil and land use type. Pot experimentation was undertaken to test the relevance of FSK as the basis for new technical intervention like efficient fertilizer use.



Digitalised from the Atlas
of Rwanda (Prioul and Sirven, 1981).
The map was established based
on the ISAR experience since 1955.

Sub pedological Region

Figure 1.5a Pedological Regions of Rwanda and the “*Ferrasols on hills and Histosols in valleys*” *Sub-pedological region.*

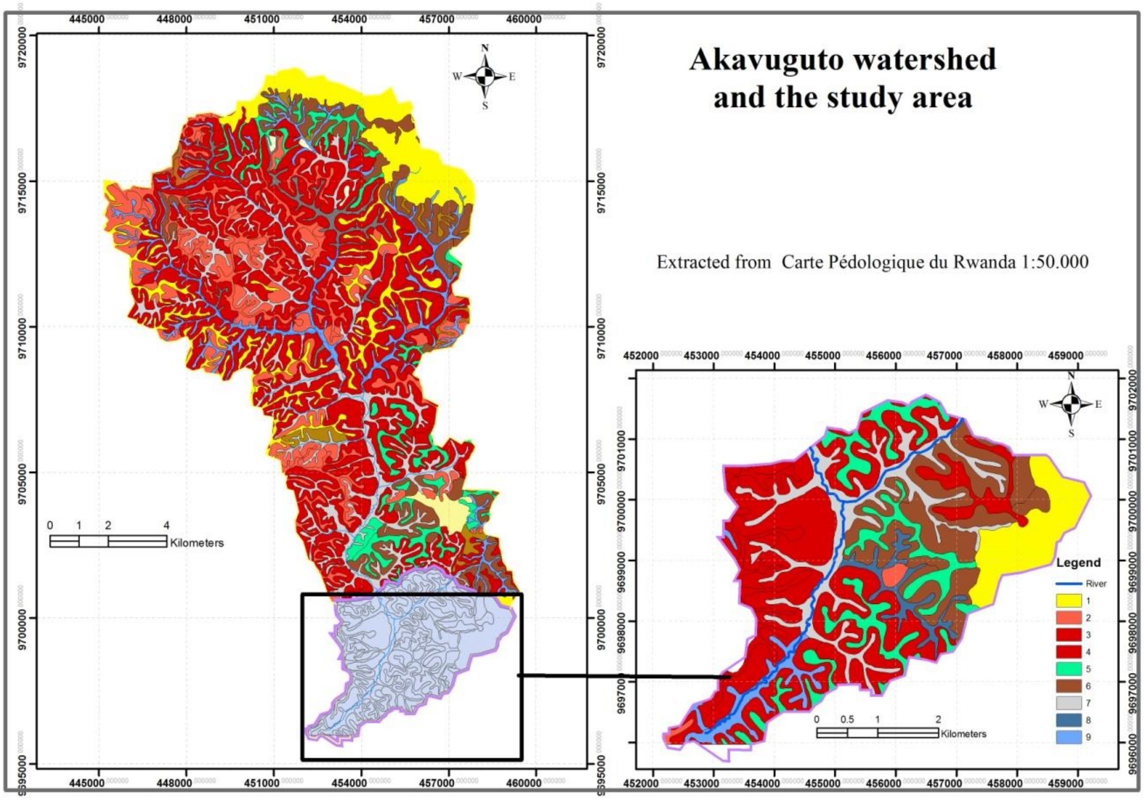


Figure 1.5b Akavuguto watershed and the study area/benchmark.

1.6.4 Study area description

Akavuguto watershed (Figure 1.6) is located in southern Rwanda, Southern province, Nyaruguru District and cut cross 4 administrative Sectors. The climate of this region is described as Cw2-3 (Neel, 1974); which means a temperate climate with 2 to 3 months of dry season, with a mean temperature in the coldest month of less than 18°C. The annual rainfall is above 1500 mm. The area comprises many hills, separated by valleys, with some mountains above 55-80% slope (Figure 1.7). From the hill summits to the valley bottoms, altitude ranges between 1800-1700 m with some mountainous mass at 2,200 m.

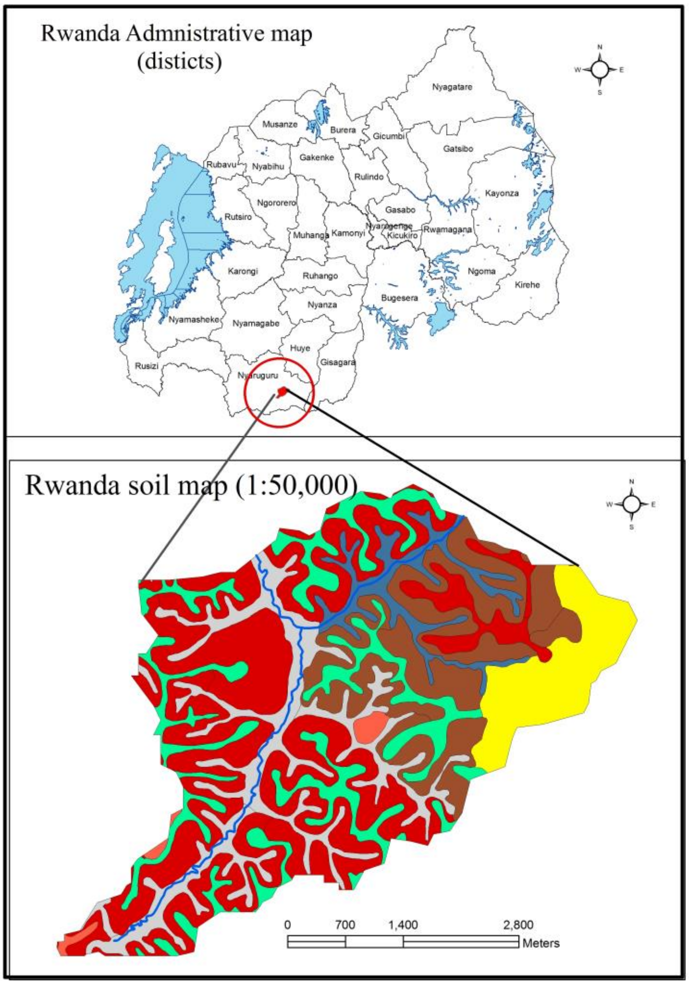


Figure 1.6 Akavuguto watershed benchmark in Administrative map of Rwanda (soil legend is explained later).

From a pedological point of view, the watershed belongs to the 'Pedological Region' of *Entisols* on crests, *Ferralsols* on hills and *Histosols* in valleys – INEAC[8] classification system (Prioul and Sirven, 1981). The parent material is described as Butare Complex – "metaquarzites, mylonites, micaschists, graphitic schists, pegmatites, amphibolites" (Dehandschutter and Buyagu, 1991).

The traditional crops grown in the watershed are sweet potatoes (*Ipomea batatas* (L.) Lam), peas (*Pisum sativum* L.), beans (*Phaseolus vulgaris* L.) and sorghum (*Sorghum vulgare* Pers.).

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[8] INEAC. Institut National pour l'Etude Agronomique du Congo belge (a former Belgian classification system for Congo, Rwanda and Urundi).

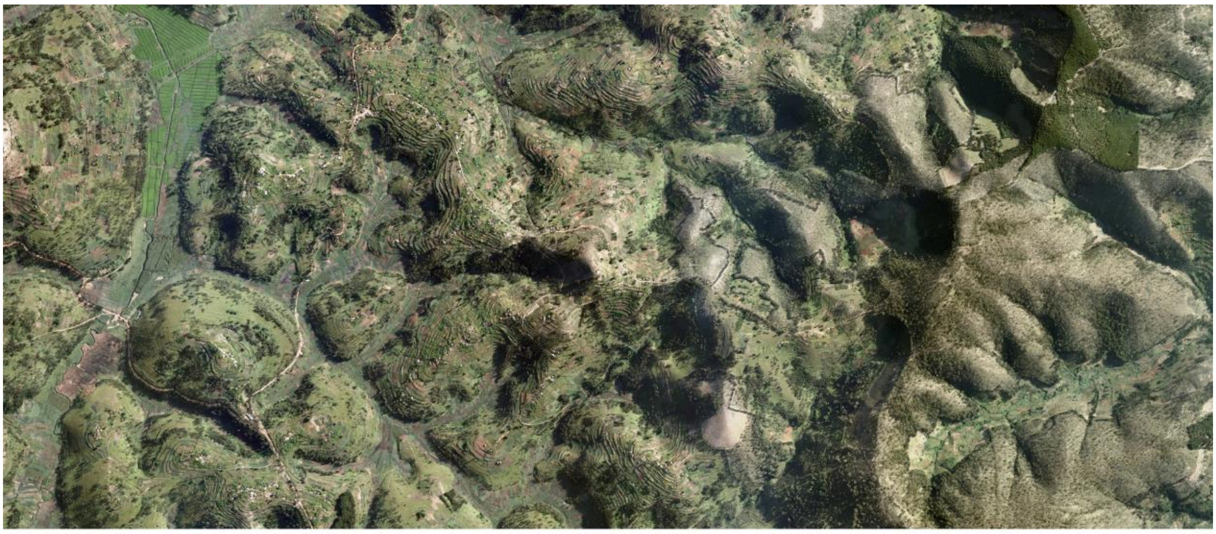

Figure 1.7 Orthophotos (5 x 5 m) showing major land units of Akavuguto watershed:
From left (West) to right (East):
the gradual evolution is from hills and valleys, to mountainous and boxed-valley land units.
Source: Swedesurvey (2008)

1.7 Thesis outline

This thesis begins by an abstract, in both English and French. The abstract states, briefly, the problem and presents the main results and practical implications. The thesis per se consists of seven chapters. Chapter 1 starts with the problem statement, followed by justification to the problem, research questions, hypothesis, objectives, overview of the methodology and ends with this outline. Chapter 2 presents and analyses the innovation model (planning environment context) in which the soil map of Rwanda is expected to be used and highlights the key role of the soil resource information in this process. Chapter 3 analyses the contribution of soil science – research and extension - to the Rwandan agriculture development to understand what can be the new perspectives to achieve sustainable development. Chapter 4 demonstrates how the FSK can be formalized and integrated with the scientific soil knowledge and how the integrated scientific and FSK can be used to interpret the rationality of farmers’ practices as a prerequisite for any new intervention at watershed level. Chapter 5 establishes the Soil References System as a mean of understanding the soil spatial distribution law, overtime interpreting and monitoring soil properties and crop yields in relation to different soil types in the watershed. Chapter 6 presents results from a pot experimentation aiming at demonstrating that different soil types occurring in the same AEZ along the catena, may need different types of soil fertility management strategies and that the farmers’ soil nomenclature captures those differences and, therefore, can be used to achieve soil-specific fertility management and replicable technologies in the complex soilscape of Rwanda. Chapter 7 presents the general conclusion and draws some policy and research implications for more effective PIWM. The general framework summarising the philosophy of this thesis is diagramed in Figure 1.8.

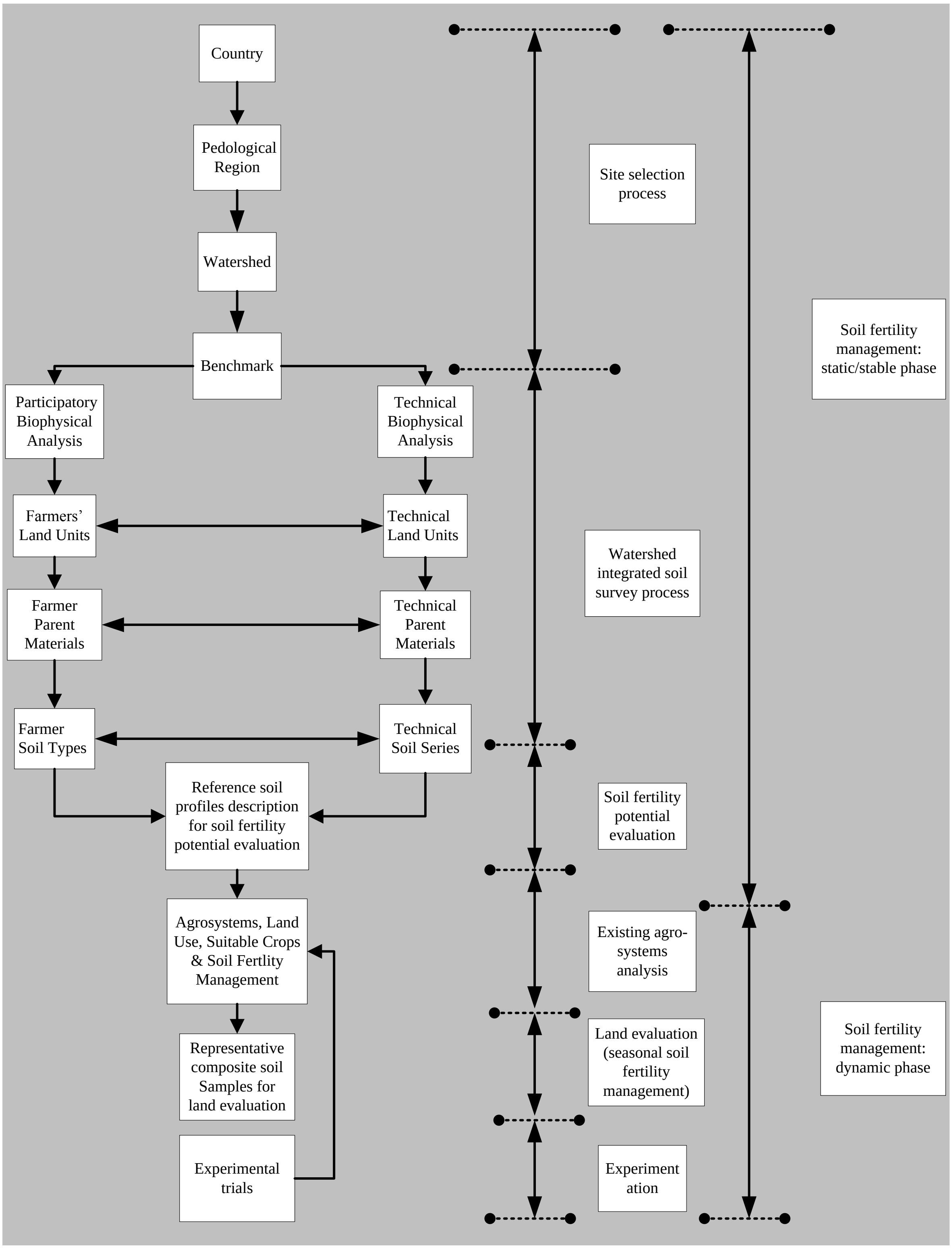

Figure 1.8 A general framework illustrating the multi-scale and nested hierarchy soil fertility management procedure as used in this thesis. Source: adapted from Rushemuka et al. (2014a).

Chapter II: Agricultural research and extension in Rwanda: evolution of concepts and the need for capturing the soil factor

Abstract

A retrospective analysis was undertaken to understand how agricultural research and extension reasoning/conceptualization in Rwanda have evolved over the last 80 years, and how they have been fed by the Rwandan biophysical environment understanding. The objective was to appreciate the innovation model in which the soil map of Rwanda is expected to be used. Findings from this study showed that the agricultural research and extension conceptualization has undergone significant progress in relation to the advances in the understanding of the complexity of farmers' agricultural problems. Among the developed concepts are the Participatory, Integrated Watershed Management and the Mother-Baby trials. However, these models though relevant, have experienced difficulties to be really effective. The fundamental problem appears to be the poor consideration of the soil factor as a natural body and the failure to take into account different soil types when designing experiments, when evaluating data and when extrapolating results. The establishment of communication bridges between scientific and Farmers' Soil Knowledge (FSK) systems and the catalytic role of the soil scientist at watershed level are likely to alleviate this understanding and minimize the communication problem. In the context of research for development, the watershed should become at the same time, the really world "laboratory" and "experimental site". The extension should no longer be about a discipline-based or a commodity oriented technology, but a successful integrated watershed model. It was concluded that the soil map of Rwanda, properly complemented with the FSK and circumscribed in the current innovation models, constitute a fundamental contributor to Rwanda' potential green revolution.

Key words: *Research mode, Linear Research & Development model, Participatory Integrated Watershed Management, Communication language, Rwanda*

2.1 Introduction

Green Revolution (GR) as known in Asia was largely made possible by investment in fertilizer, crop responsive varieties and irrigation (Dethier and Effenberger, 2012). With the GR advent (1961-2008), food production increased more rapidly than population growth in all major regions except sub-Saharan Africa (SSA) (Brady and Weil, 2002, World Bank, 2008). In this world region, despite all efforts furnished by different stakeholders (national and international agricultural research, development and research projects and Non Governmental Organizations), the adoption of such inputs and technologies has remained very low and the productivity per land unit has even declined (Keating et al., 2011; Dethier and Effenberger, 2012).

In front of this paradox, common questions in many multi-disciplinary debates and planning meetings are: why should SSA not be like Asia', why should what went well in other regions fail only in SSA? What have others done?

Because of the differences in the biophysical environment between the Asia regions where green revolution occurred and SSA on the one hand, and taking into account the progress realized in the field of sustainable development on the other hand, the GR in this world region needs a different and updated approach (Herren, 2011; Dethier and Effenberger, 2012). Moreover, the large regional differences within the SSA sub-continent (Vlek, 1995; Kolawole, 2012; Giller et al., 2011) call for several geographically separate GRs (Dethier and Effenberger, 2012). In view to the above considerations, SSA countries, on the basis of the research and development experiences so-far noted, should recalibrate the Asian GR 'equation' to adapt it to their own planning environments (biophysical constraints and socio-economic conditions). This will be possible if they understand that they need an education system more appropriate to their biophysical and socio-economic problems (Papadakis, 1975; ISNAR, 1982). From the experience of other continents, the African upcoming GRs must be sustainable in terms of nutrient and water cycles and agro-ecological functions (Keating et al., 2011).

With regard to the above described situation, the mode of research and extension thinking and the institutional arrangements are vital factors to transform existing biophysical and socio-economic information into usable knowledge and technologies (Rhoades, 1999; Raina et al., 2006; Weichselgartener and Karsperson, 2010; Kolawole, 2012).

At national level agricultural research and extension should be based on a clear understanding of the ecological context (climate and soils) in terms of the relatively natural homogenous entities, such as Agro-Ecological Zones (AEZs) and the different soil types within each AEZ. The logic of these two conceptual levels (AEZ and soil types) should be clearly perceived by planners/decision-makers, researchers (crop breeders, agronomists, fertility experts and crop modelers) and extensionists to ensure the required consistency between the soil type where a given technology is developed (e.g. on-station experiment or on-farm experiment) and the analogous soil types where the same technology is transferred (e.g. large up scaling of the best fit technology). We call this soil-specific and transposable intervention. This concept is essential if a GR is to be achieved in the very complex biophysical environment of SSA in general and of Rwanda in particular. To date, the attempt to draw fertilizer recommendations for the entire AEZ has been problematic (Rutunga, 1991; Drechsel et al., 1996, Steiner, 1998; Giller et al., 2011). However, to the author's knowledge, in Africa, few authors (e.g. Mathieu et al., 1995; Steiner, 1998; Zingore et al., 2007; Sileshi et al., 2010) have clearly noted compelling reasons for systematic consideration of different soil types in the result extrapolation strategy.

In Rwanda, after 30 years (1933-1962) of agricultural research during the pre-independence period and 50 years (1962-2012) of the independence period, the questions posed here are: (1) have the agricultural research and extension approaches progressed to cope with the requirement of soil-specific and transposable intervention and, (2) what has been learnt from the past and what can be the place and role of the CPR in the way forward? This questioning is based on the acknowledgement that likely technical constraints cannot be solved without broad-based institutional innovation' (Keating et al., 2011). Paradoxically, appropriate institution innovation could hardly occur without clear understanding of its own biophysical and socio-economic conditions that determine the planning environment.

The objective of this chapter is to discuss the conceptual framework in which the soil map of Rwanda (1: 50,000 with its Soil Taxonomy language) is expected to serve the agricultural development in the complex soilscape of Rwanda, knowing that in this country, 86.5% of the population is constituted by small-scale farmers (0.5-1 ha on average) with an already functional soil knowledge system. This kind of study is very important because the consideration of the soil map as the foundation for an agricultural development has received little attention in many SSA countries since the 1970s and because few SSA countries benefit from a whole territory soil map. It is argued that the failure of the systematic consideration of different soil types in agricultural research and extension is the major reason for the contradictory results obtained in the field of soil fertility management observed throughout Rwanda (Rutunga, 1991, Dreschsel et al., 1996) and across SSA in general (Sileshi et al., 2010; Giller et al., 2011; Marenya et al., 2012). While there are a number of functional, structural and social factors that hamper the efficiency of agricultural research and extension of many developing countries (Lal, 1995; Rhoades, 1999; Leeuwis and van den Ban, 2004; Raina et al., 2006; Weichselgartner and Kasperson, 2010; Keating et al., 2011), the little understanding of the biophysical environment (mainly different soil types and their complex spatial distribution) and the role and place of a soil resource information in agricultural development would be the root cause.

Following the introduction, Section 2, presents a brief historical background of agricultural research and extension in Rwanda. Section 3 presents and analyses the research and extension approaches with its first sub-section highlighting the drawbacks of the persistent discipline-based, commodity oriented, and instrumentalist problem-solving of the R&D approach. The second sub-section presents and analyses the Participatory Integrated Watershed Management model. Section 4 highlights the general debate about the difficulties encountered when implementing the approach in sub-section 2 of section 3 above. Section 5, discusses what the author feels is the bottleneck of the PIWM approach and the way forward. The chapter ends with a conclusion in Section 6.

2.2 Brief historical background

Since its origins from the 1930s, the role of the Rwandan agricultural research, like in any other newly colonized country, was to understand the biophysical environment and to develop new and productive crop varieties and animal breeds to improve the agricultural systems of this country (Iyamuremye, 1983). Research was mainly undertaken in research stations distributed in the main AEZ of the country and has been compartmentalized into independent programmes organized around scientific disciplines (e.g. breeding, phytopatology, soil conservation, soil fertility management) and oriented towards commodities (crop species and animal breeds). At station level, technologies or approaches were tested at plot scale and research results were expected to be recommendable to the entire AEZ.

Until 1962, the pre-independence agricultural research was undertaken by the "Institut National pour l'Etude Agronomique du Congo belge" (INEAC). During this period, the research and extension were thought very close together and financed by the same administration (Muchena and Kiome, 1995). Usually, research was conducted either at the request of extension section or as a national need. At independence, the INEAC experience was judged very positively vis-à-vis its objectives: main soils of the country known (Van Wambeke, 1963), agriculture regions defined (Delepierre, 1974), many crop varieties selected and many animal breeds introduced (Iyamuremye, 1983). At this earlier period however, under the influence of the positivism philosophy, farmers were seen as recipient of agricultural technologies (e.g. crop varieties, erosion control and soil fertility management recommendations) and the extension approach was a top-down technology transfer. In such a system, there was little room for farmers to appreciate the relevancy of proposed technologies (ISNAR, 1982, Schörry, 1991).

After independence, the INEAC activities were inherited by the "Institut des Sciences Agronomiques du Rwanda" (ISAR), now the Rwanda Agriculture Board (RAB). The ISAR retained the Belgian financial, scientific and administrative support until 1982. Subsequently, since 1976, many programmes of ISAR began to benefit from the financial and scientific support of many centres of the Consultative Group for International Agricultural Research (CGIAR). As the CGIAR centres became more engaged in supporting the national agricultural research systems of developing countries, the Belgian scientific and financial support reduced after 1977, and ended in 1982. With The CGIAR advent, the agricultural research thinking (fundamental research) was the role of these international research organizations. The role of the National Agriculture Research Systems (NARS) was to serve as a relay of the international research and adapt the research results to their biophysical and socio-economic environment (adaptive research). The CGIAR research in Rwanda was mainly and, for long time, concentrated on crop commodities.

At the end of the Belgian cooperation, agricultural research in Rwanda, as a foundation of the development of this country, was in crisis (ISNAR, 1982). A similar situation was observed in east Africa (Kenya, Tanzania and Uganda) (Muchena and Kiome, 1995). Indeed, agricultural research and extension in these countries and Rwanda faced a lot of problems (ISNAR, 1982, Lal, 1995): (1) the link between the research and extension was non-existent, (2) little operating budget, (3) inadequate number of appropriately trained personnel, (4) lack of prioritization of issues, (5) lack of continuity in the research program, (6) symptomatic and piece-meal approach to solving practical problems, (7) dependence on external technical and financial help, and therefore, lack of initiative and innovativeness, (8) decision on critical issue made by external donors, (9) the quality and type of training non relevant – very far from the national (biophysical and socio-economic) realities, (10) inexistence of intellectual infrastructure.

To date, the Rwanda agricultural research and development crisis of the 1980s (ISNAR, 1982) seems not to have been properly addressed yet (Schörry, 1991; Drechsel et al., 1996; Ansoms, 2008; Pritchard, 2013). Currently, under the auspice of the Millennium Development Goals and other long and mid-term development strategies such as Vision 2020 (MINECOFIN, 2000) and the Economic Development and Poverty Reduction Strategy (EDPRS) (MINECOFIN, 2007) respectively, the government of Rwanda has opted for an indicator-based development system. This development strategy that is purely growth-led has turned out to be detrimental to the development learning process. As a consequence, while Rwanda might be progressing (economic growth), the chances of building science are seriously reduced: science is the capacity to take the best advantage of existing information, understanding facts and solving problem (Papadakis, 1975). In addition, the highly centralized and institutionalized tender processes (focusing essentially on the financial accountability and less on the activity efficiency and learning process) have emerged as new strong impediments that undermine the ability of the agricultural research and extension to use the little research resource timely and efficiently. The persistent crisis in agricultural research and extension suggests that the fundamental problem (of the poor performance of the Rwandan agricultural development sector) is not yet clearly identified.

2.3 Evolution of research approaches and development concepts

2.3.1 The linear Research & Development model

During the decades of CGIAR support to Rwandan agricultural research, there was a clear division of roles. In the CGIAR institutionalized linear R&D model (Figure 2.1), it was basically assumed that innovations originate from CGIAR scientists (fundamental research), are tested for adaptability by NARS scientists (adaptive research), and then transferred by communication workers (extensionists), and other intermediaries, to be applied by farmers (Leeuwis and van den Ban, 2004). This would reflect the tenacity of two CGIAR ideologies (Mackay and Horton, 2003): (1) a deeply rooted "hard-science" culture and unquestioning belief in the value of applying modern, positivist scientific methods to the solution of agricultural, environmental and related problems. In this context, science was virtually synonymous with quantitative analysis. The alternative approaches which included qualitative methods, participatory approaches and constructivist logic were regarded as highly suspect – 'soft science at best'. (2) Insufficient critical view of the value of the CGIAR centres themselves, which were often referred to as "Centres of excellence". For instance, the CGIAR maintained that "there could be no long-term agenda for eradicating poverty, ending hunger, and ensuring sustainable food security without the CGIAR" (CGIAR secretariat, 1998 cited by Mackay and Horton, 2003).

During the CGIAR period, the NARS maintained compartmentalized and independent research programmes. This is the case of the research organizations of the East Africa Community countries (Burundi, Kenya, Rwanda, Tanzania and Uganda). It is also the case in India (Raina et al., 2006).

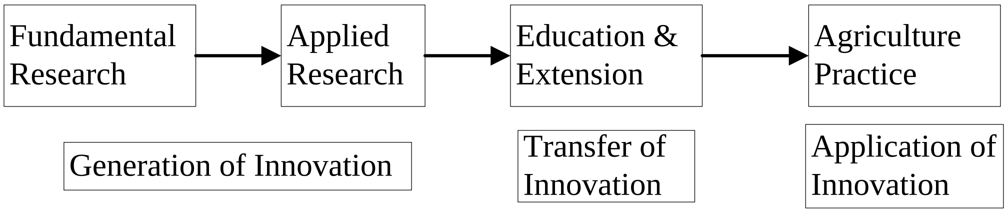

Figure 2.1 Linear R&D model. Source: adapted by the author of this thesis from Leeuwis (2004) and Godin (2005).

In Rwanda and over the last 50 years, ISAR undertook adaptive agricultural research using the multi-environment/location approach and considering the AEZ as a ‘recommendation zone’ (Rutunga, 1991; Drechsel et al., 1996; Steiner, 1998).

The extension service, for its part, has been under the responsibility of the Ministry of Agriculture. Due to weak links between agricultural research and extension (Schörry, 1991) and the lack of adapted and soil-specific technologies from the NARS (Rutunga, 1991, Drechsel et al., 1996; Steiner, 1998), the extension service, in its ambitious wish of serving the society, imposed discipline-based or more generic technologies, in many cases, non-adapted to Rwandan bio-physical environment and socio-economic context (ISNAR, 1982; Drechsel et al., 1996). Some examples are the blanket fertilizer use (Rutunga, 1991), blanket green manuring (Drechsel et al., 1996), obligatory erosion control (Roose et al., 1993) and obligatory coffee mulching and prohibition of associating other crops (Schörry, 1991) in disconnection from specific niches (soil type within each AEZ) where they can have positive impact on crop yields. The result was the poor adoption of those technologies. The poor adoption is explained by the evident absence of fitting technologies rather than the deficiency in extension message or any farmers’ resistance to change (ISNAR, 1982; Rutunga, 1991; Roose et al., 1993; Drechsel et al., 1996; Steiner, 1998). This is rather a general problem in SSA countries (Sileshi et al., 2010; Giller et al., 2011). Apparently, unaware of the fundamental reason for the poor adoption of proposed technologies, for long-time, the international research has focused on the adoption process (Rhoades, 1999). In the extreme case (Rhoades, 1999; Leeuwis and van den Ban, 2004), the linear process of R&D innovation model led to irrelevant studies suggesting that the knowledge communication chain or the farmer resistances to change were the problem for poor adoption (Figure 2.2). This was because many people attributed the fact that yields were low in developing countries to inaccurate farming, unwillingness to apply “scientific methods”, and lack of education; and they thought that the remedy was to teach farmers to work better (Papadakis, 1975). It is in this context that in Rwanda for instance technology transfer has been always, either before independence, either after independence, either after the 1994 genocide, a top down technology transfer, according to priorities decided by the leadership with little or insufficient consultation of farmers (Schörry, 1991; Pritchard, 2013). This is also reflected in the concept of “moniteurs agricoles”/ “agricultural teachers” given to extensionists in the past (Kabiligi, 1985). These ‘teachers of agriculture’ had the power of fining the “poor adopters” of technologies. The fines for “poor adopters” were abandoned only after the 1994 genocide. This long history of imposed extension has led the farmer to a reluctant behavior vis-à-vis the authorities and to adopt a tactic behavior that can avoid him with problems (Schörry, 1991). As noted by Papadakis (1975) those who criticized farmers for not working well were in general people who did not understand farming; and they pretended to teach farmers what they should do. What they failed to understand was the holistic nature of the farmers' problems (Roadhes, 1999). It is in this context that, in their effort to understand the attitude of the farmer vis-à-vis the poor adoption of 'improved technologies', the international research centers and development circles have gradually added new blood in terms of disciplines (from agronomist, to political scientist via sociologist and anthropologist) to the research and development process (Figure 2.2).

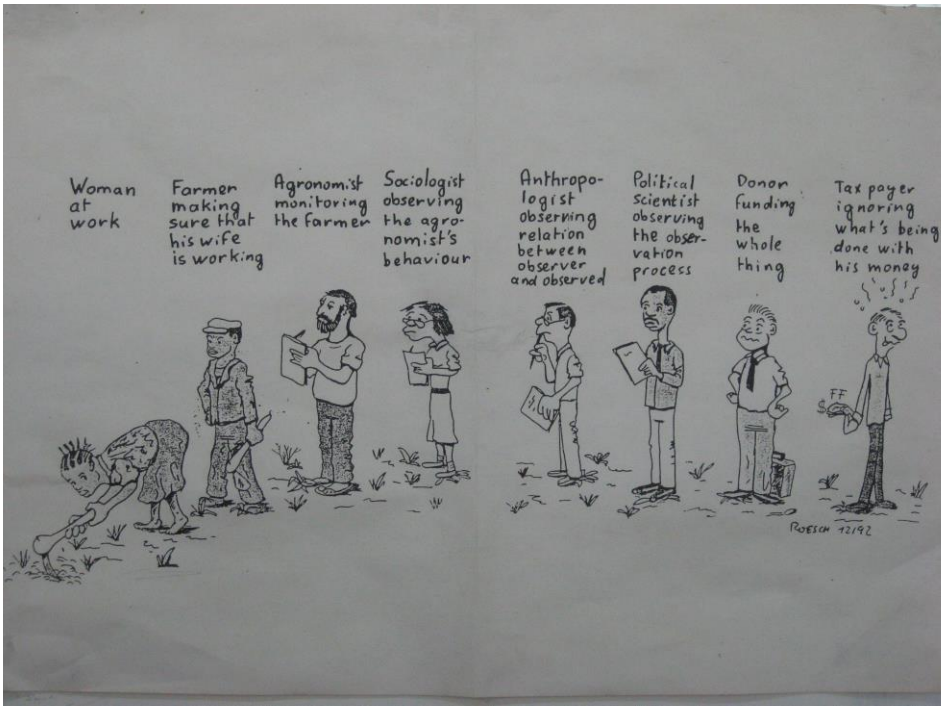

Figure 2.2 Schematic representation of deviation of the top down extension system and the poor results harvested. Source: (Roesch, 1992).

It is within such a context that ISNAR (1982) supported the view that the agricultural research of Rwanda should shift its focus and transform its methods. (1) The focus should be more the identification and resolution of concrete development problems by means of multi-disciplinary approach and less the discipline-based and commodity oriented agricultural research. (2) Its task should not just be limited to proposing new improved technologies (crop varieties or soil fertility management recommendations), but also to be fully involved in the transformation of the Rwandan agro-systems in order to improve farmers' livelihoods and soil health as well. This was the birth of the on-farm research.

2.3.2 On-Farm Research

Since the ISNAR period, the majority of agricultural research and development projects in Rwanda have promoted on-farm research experimentation as alternative to the on-station research (Yamoah and Grosz, 1988; Drechsel et al., 1996). First large field experiments were conducted by the PAP Nyabisindu in its mandate area as well as many ISAR projects, throughout the country (Drechsel et al., 1996). On-farm experiments and surveys were initiated in order to test the adaptation of green manuring or fertilizers to varying farm conditions as well as acceptance of such methods and inputs by farmers (Drechsel et al., 1996). Trial types varied from researcher-managed to farmer-managed and farmer-executed trials. According to Drechsel et al. (1996), this approach (with field days, individual and group interviews) increased the coverage to a wider range of ecological and socio-economic conditions. Other large field experiments were undertaken by the project Soil Fertility Initiative (SFI-FAO) during the period of 1980-1990 (Coursier, 1985).

During the course of agricultural research and development process, the international community has focused on four historical steps: (1) production, (2) economy, (3) ecology and (4) institutions (Table 2.1). Today, the fact is that these are not exclusive processes but should constitute the four pillars of an effective agricultural research and extension (Rhoades, 1999; Keating et al., 2011). Currently, the weak stimulation of workable institutional development is recognized as the key challenge to agricultural development (Rhoades, 1999; Raina et al., 2006; Keating et al., 2011).

In Rwanda, a closer examination of the projects that introduced the on-farm research such as the PAP Nyabisindu and the USAID supported Farming Systems Research Program (FSRP) in northern Rwanda, would indicate that researchers in these projects were aware of the above mentioned four pillars of an effective agriculture development. On production and economic issues, they aimed at improving farm productivity. On ecological point of view, they chose organic farming in terms of planted fallow or green manure in rotation as the sustainable option (Drechsel et al., 1996). On institutional aspects, researchers from different universities (e.g. Institute of Soil Science and Soil Geography of the University of Bayreuth, University of Arkansas) with their own budget and financing procedure and free of any institutional constraints, collaborated with national researchers at station level and with farmers in their own fields.

In these projects, despite the on-farm research approach and the consideration of the four pillars of effective agricultural development, the anticipated positive effects of organic farming on nutrient cycling, soil protection, crop yields, fodder and firewood production were not forthcoming (Schörry, 1991; Drechsel et al., 1996). The on-farm method had been undermined by variable soil types with different suitability occurring over short distances and in a complex manner and the incapacity of scientists to capture those soil differences (Steiner, 1998). In these conditions, green manuring proved to be risky enterprise with uncertain residual effects. The high yield risk and the uncertain residual effect were entirely inconsistent with farmers’ strategy of risk minimization (Drechsel et al., 1996).

Table 2.1 Four overlapping stages of awareness and perception of problems in agricultural research.

Intellectual movement/	***Popular movement***	***Period***	***Leading discipline***	***Innovation model***	***Expected outcomes***	***Perceived role of Farmers***	***Feedback***
Production stage	Green Revolution	1950-1975	Breeding, genetics, phytopathology and physiology	Linear R&D	Adoption of high yielding varieties, fertilizers, pesticides and irrigation	Recipient of technology	Lack of equity: green revolution favored more the rich than small and margin farmers in rainfed areas
Economic Stage	Farming System Research	1975-1985	Economics and Agronomy	Linear R&D	Equity, gender issues and role of agriculture policy	Source of information for technology design	Lack of long-term sustainability plans: ecological considerations
Ecological stage	Sustainable development	1985-1995	Anthropology, Agro-ecology, Agroforestry, integrated pest management, Geography	Participatory research	Sustainability: good balance between production - economy-environment	Simultaneously victim and cause of ecological destruction, contributor of indigenous knowledge	Lack of viable and practical social and political institutions on local and global scale: poor impact/adoption.
Institution stage	Pro-poor and equitable development and Millennium development goals	1995-up to now	Management organization sociology, political science and education	Participatory Integrated Watershed Management	Effective national programmes and networks closely linked to end users	Full co-operators in research, emphasizing households and farmers groups within national food systems	A gap in understanding how to build effective national programmes and their link with farmers on one hand and with international centres and donor agencies on the other hand

Source: adapted by the author of this thesis from Roadhes (1999).

Consequently, the concept of improving soil fertility and crop yields with the aid of planted fallow or green manure in rotation failed (Schörry, 1991; Drechel et al., 1996).

The experience which emerges from these projects is that while the institutions may be a serious constraint in many agricultural research and extension organizations of many developing countries, they might not be the fundamental issue. The inconsistence between the soil type on which a given soil-related technology is developed (on-station or on-farm) and the ones where it is transferred (on farmers' fields) is likely to be the fundamental problem (Zingore et al., 2007; de la Rosa et al., 2009). The lack of systematic consideration of the soil type during the experiment design and results extrapolation is likely to explain why scientists in Rwanda have been unable to develop soil-specific technologies in both inorganic fertilizers (Rutunga, 1991) and organic fertilizers (Drechsel et al., 1996) despite the move from the on-station to the on-farm experiment approach.

2.3.3 Participatory Integrated Watershed Management approach

At international level, the period between the mid 1980s and the mid 1990s saw much emphasis on involving farmers in agricultural research and project design and implementation (Chambers, 1985). Among the recent examples in Rwanda is the Participatory Integrated Watershed Management (PIWM) (German et al., 2006). The PIWM is closer to and built on the Integrated Natural Resource Management (NRM) model (Figure 2.3). It is made up by a set of three concepts, each of which worked alone in the past without really inducing the desired agricultural development. In the new research approach, each concept has its own contribution area which makes it indispensable and synergetic to the other two in the whole system. The goal of the PIWM approach was to stimulate interactions between farmers, scientists and the biophysical environment to design and implement a project that is socially acceptable, ecologically sustainable and economically viable (Mugendi et al., 2011). The ultimate objective was to improve the ability of local people to become effectively and efficiently linked to their land, water and other natural resources to sustainably meet their own needs (Gregersen et al., 2007).

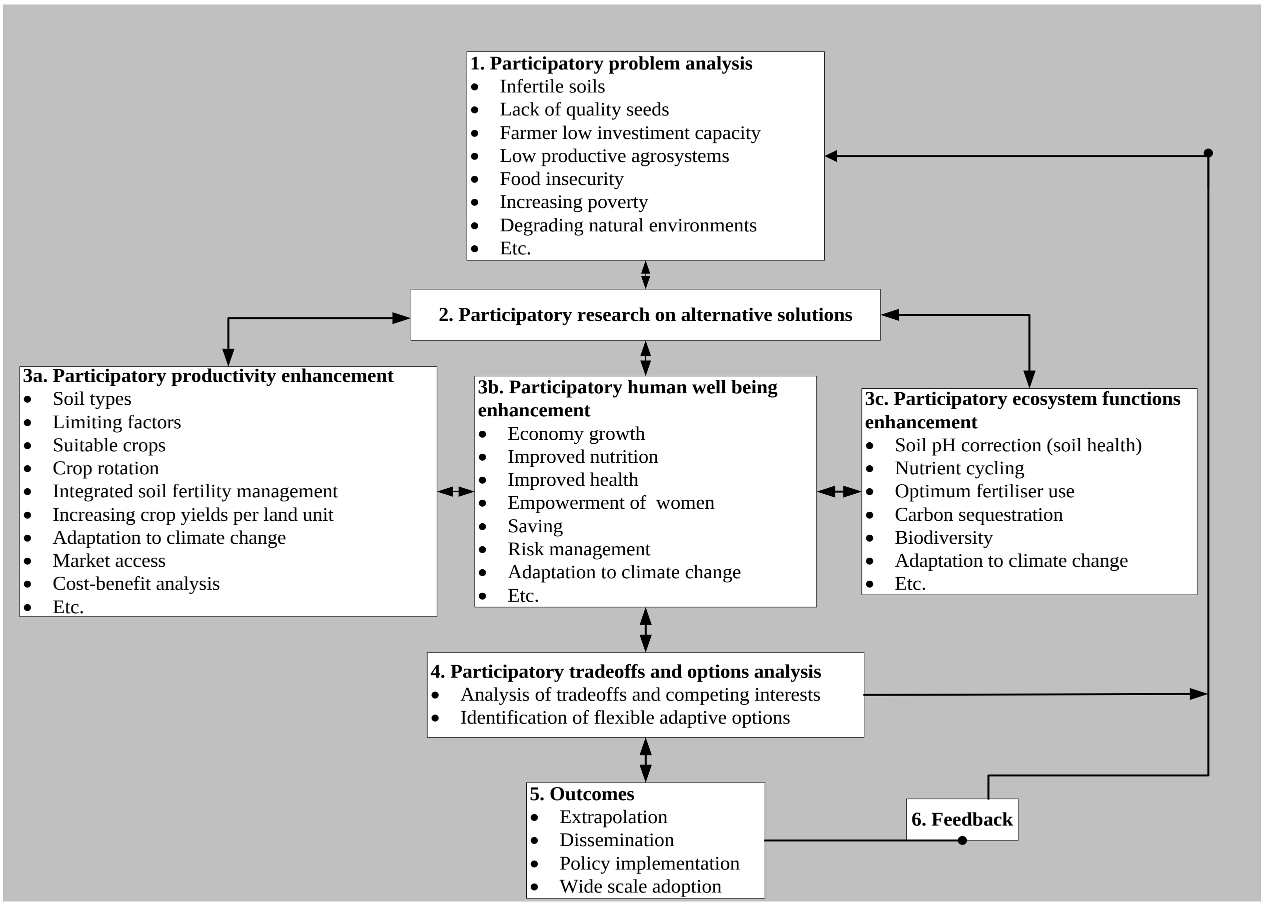

Figure 2.3 Participatory Integrated Watershed Management model.
Source: Modified from CIFOR (2000).

(1) The Participatory Research (PR) was a way of integrating the farmers' knowledge and objectives into agricultural development agenda, and was justified from the realization that successful innovations require as much input from farmers themselves as from scientists (Osbahr and Allan, 2003; Leeuwis and van den Ban, 2004). The PR promoted a research-development continuum mode (Figure 2.4) which can be defined as a farmer research model from the beginning to the end (Chambers, 1985). It means that the development of new technologies by the team of different disciplines begins with a farmers' identified problem, in farmers' fields and ends with a solution in the farmers' fields. Moreover, the PR involves farmers as intelligent driving forces that will collaborate with scientists to develop practical research agendas (Rhoades, 1999). The rationale is that building new technologies on existing synergism between the scientific and farmers' knowledge will speed up the adoption process (Kolawole, 2012).

(2) Integrated Agricultural Research is a problem-oriented research (e.g. low productive agrosystems and persistent low adoption of proposed soil fertility management technologies) and emphasizes the cross-disciplinary cooperation. The term cross-disciplinary co-operation includes related terms such as 'inter-disciplinary (between two or more disciplines), 'multi-disciplinary (involving multiple disciplines) and trans-disciplinary co-operation. The later term refers to a situation where disciplinary

boundaries are transgressed (Leeuwis and van den Ban, 2004). They are transgressed to establish new form of science that can reveal alternative way of doing development (Quinlan and Scogings, 2004). Put differently, they are transgressed to form a social interface. A social interface is defined as a critical point of intersection between life-worlds, social fields or levels of social organization where social discontinuities, based upon discrepancies in value, interests, knowledge and power are most likely to locate. It is a venue whereby different ideologies come in contact with each other (Long, 2001 cite by Tesfaye, 2005). This interaction facilitates generation of knowledge that result from a cross fertilization of different life-words (Tesfaye, 2005). The concept of interface contributes to minimize the gap between scientific and farmers' knowledge which serves little the purpose for holistic development (Tesfaye, 2005). *Holistic* approach from a soil science point of view is defined as the task of all people concerned with the soil to direct their interest, not just towards the physical, chemical and biological aspects, but also to these environmental economic, social, legal, and technical aspects that affect the soil use (Bridges and Catizione 1996). This means that the practice in interdisciplinary projects, with each discipline working away with a share of research funds and reporting back at the end of the project period or for a mid-term review with discipline specific research result, does not provide opportunities for interactions among disciplines, learning or modification in research (Raina et al., 2006). Put differently, the idea of selling pre-defined packages becomes perhaps even less appropriate: innovation can only grow and emerge out of the interactions between various stakeholders (Leeuwis and van den Ban, 2004). The aim is to identify and substantiate alternative ways of tackling a problem by looking closely at the interaction between biophysical (soil, climate, crops, livestock) and socio-economic variables (investment capacity, spending power, income generation, livelihood, institutions) (Rhoades, 1999; Quinlan and Scogings, 2004). The integration refers also to the combination of objectives (e.g. erosion control, soil fertility management, profitability) (German et al., 2006). The rationale for the integrated research is that the farmers' agricultural problems are usually complex and that only a combination of different scientific disciplines and objectives can bring relevant and innovative development solutions (Papadakis, 1975; Rhoades, 1999).

(3) Integrated Watershed Management stresses the need to consider the watershed as an elementary biophysical entity from which the soil spatial distribution and the existing agro-systems are likely to be understood in order to achieve soil-specific and transposable interventions in similar watershed. The understanding of the biophysical constraints, at watershed level, is likely to contribute to the set up of workable research and extension institutions (German et al., 2006).

The essence and purpose of this innovation model (PIWM) is not to remove disciplinary boundaries and to become all the 'same', but rather to combine and make use of expertise in a more useful manner (Leeuwis and van den Ban, 2004). Indeed, there would not be successful integrative teams without good disciplinary specialists (Ruellan, personal communication). The expertise of different specialists is necessary to contribute different scientific ideas that can spur alternative ways to achieve development (Quinlan and Scogings, 2004). From the above perspective, it is clear that the PIWM is not the opposite of the discipline-based and commodity oriented research but its complement (Figure 2.4). In the PIWM approach, scientists can still withdraw temporarily to their own disciplines, libraries and/or laboratories (Leeuwis and van den Ban, 2004).

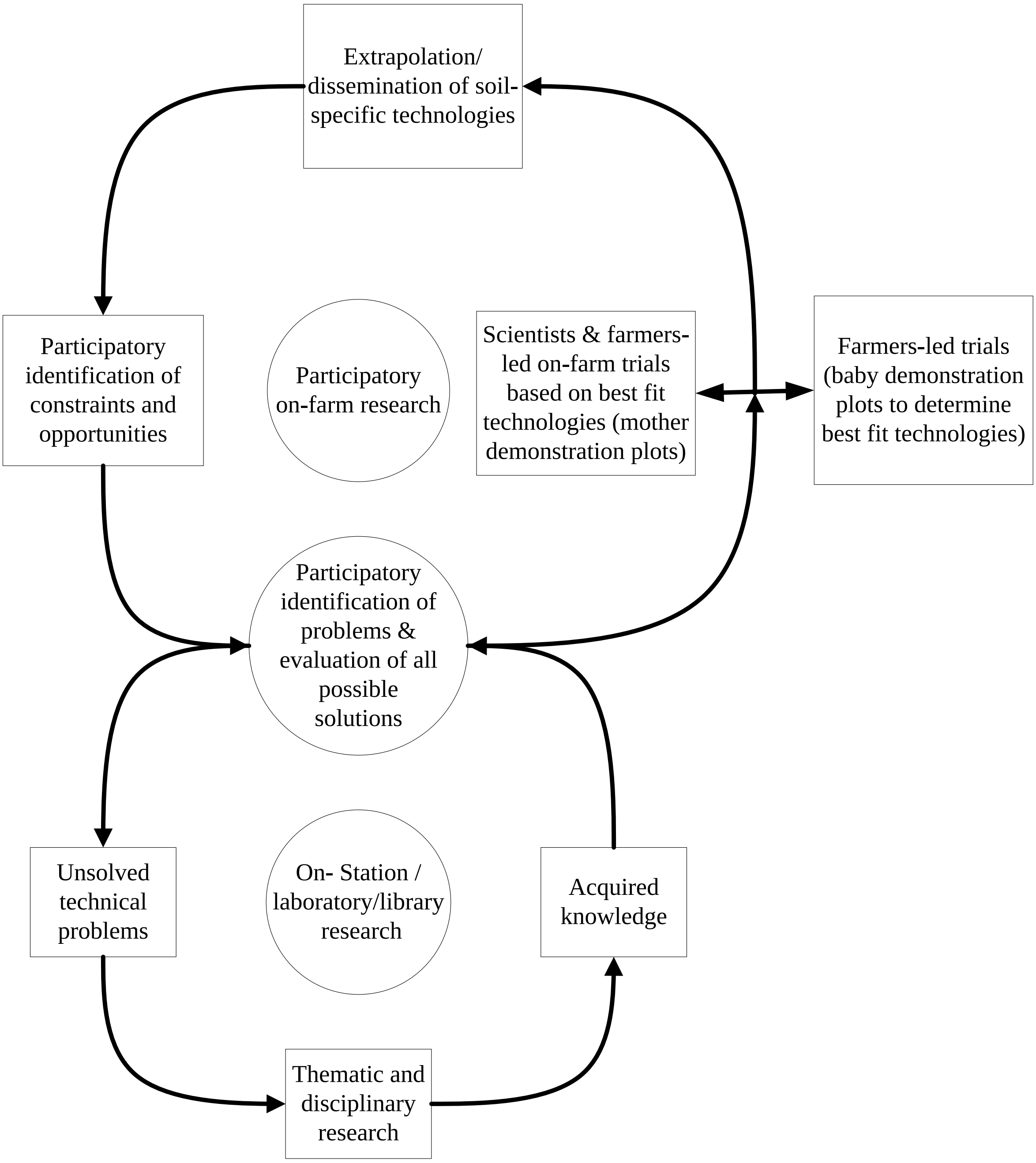

Figure 2.4 Relationship between thematic and disciplinary on-station research and participatory and integrated on-farm research. Source: modified from Steiner (1987).

2.3.4 Mother-baby approach

The mother-baby approach is an upstream participatory and integrated research approach in the area of field crop experimentation and integrated soil fertility management. It is an updated version of the many on-farm research approaches like the Farming Systems Research promoted in Rwanda (Yamoah and Grosz, 1988). The mother-baby methodology was initially developed and implemented to test legume-based soil fertility management technologies in Malawi and was later extended to Zimbabwe. The mother-baby trial model is designed to create more interactions between farmers and researchers about technology performance and appropriateness in farmers' biophysical conditions. The trial design, in this approach, consists of two types of trials: mother and baby. The mother trial (all treatments of the experiment) is a researcher-designed trial, at watershed level, and conforms to the scientific epistemological[9] framework. A baby trial consists of a single replicate of one or more technologies (treatments) on different farmers' fields at watershed level and respects the farmer's epistemological framework. The treatment selected by a farmer is called "baby" and should by no means be interpreted as inferior because it is called "baby". It is called "baby" to mean a limited number of treatment chosen/born from a 'basket' of treatments/ "mother" proposed by scientists. The mother-baby methodology has three goals (Johnson et al., 2003 cited by Mugendi et al., 2011): (1) to complement the agronomic trial data with farmers' assessment of the adoption potential of proposed technologies (2) to encourage farmers to actively participate in the trials and make their own judgment for adoption and (3) to generate data on which to assess the technology performance under realistic farmers' conditions. The interest for scientists is to understand the farmers' biophysical and socio-economic environment (walking in farmers' shoes) and to generate more relevant questions and problem definitions and to use these as entry points into several disciplines. From the mother-baby trials and through field days, individual farmer visits and data analysis, best fit technologies (soil-specific and user tailored) are identified and disseminated into analogous soil types.

2.4 Some identified challenges to the PIWM

Some challenges to the effectiveness of the PIWM research approach were highlighted by Leeuwis and van den Ban (2004) and German *et al.* (2006). These include (1) managing a complex and ambitious agenda in which diverse trades-offs and synergies must be identified and managed - both social and bio-physical (2) gap between current institutional arrangements which foster disciplinary planning and action, and which isolate research from development, and those required to operationalize the integrated planning and action research and development (3) failure to stay integrated when moving from system thinking to system action; experience has shown that in PIWM process, the system approach to planning generates considerable interest among site teams, yet, when moving to operationalize research, there is a tendency to divide up tasks along disciplinary lines and to loose integration in the process and (4) failure to forge a strong link between research and development, to raise the status of development and action-based research.

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[9] Different cultures and groups of people may not only be characterised by different knowledge and perceptions of the world, but they may also have different ideas as to how new knowledge can be produced and validated; that is they may have different epistemological framework: different 'theories of knowing' (Leeuwis and van den Ban, 2004. p1005).

With regard to the above constraints, many authors have suspected some fundamental problems that are not yet identified (Quinlan and Scogings, 2004; Raina et al., 2006). As a consequence of the impasse, the PIWM approach has resulted into frustrations and occasional acrimony among natural and social scientists at project planning and inter-disciplinary workshops (Papadakis, 1975; Quinlan and Scogings, 2004). However, because the theoretical framework of this approach seems relevant but not yet operational (Rhoades, 1999; Quinlan and Scogings, 2004; Mobjörk and Linnér, 2005), Sub-Saharan Africa researchers have enhanced the ability to talk and write (research proposals and development projects) in system terms, but have failed to modify their research behavior (German *et al*., 2006). This might have occurred as a tacit compromise between them and many development partners and/or sponsors who may be aware of the ineffectiveness of the approach but want to keep the research system ongoing despite the bottleneck.

2.5 Discussion

2 5.1 The PIWM bottleneck

Compared to the simplistic visions of earlier positivist development models (Figures 2.1 and 2.2), advances in the understanding of the complexity of farmers' agricultural problems have been accompanied by progress in the conceptualization of more constructivist agricultural research and extension approaches (Figures 2.3 and 2.4). Likewise, over the last 50 years, different key disciplines have led the agricultural development thinking and have contributed their principles and expertise (Table 2.1). It is throughout this long research and development experience that the four pillars of agricultural development (Table 2.1) have come to the awareness of scientists. The soil resource information in terms of soil types, their spatial distribution and their suitability should be at the heart of the PIWM model (Figure 2.3). The understanding of the soil resource information at watershed level is likely to play an essential role in undertaking soil-specific interventions and in transferring soil fertility management technologies from one experimentation level (on-station, mother and baby demonstration plots) to another (dissemination) like in the case of Figure 2.4. The soil resource information has finally a central potential role to play in each of the four pillars/intellectual movements of agricultural development described in Table 2.1. Ironically, since the GR years, the soil resource information has been invariably absent in most of agricultural research and development discussions of many SSA countries. The marginalization of the soil science in agricultural research and extension is explained by the fact that GR was perceived by many influential decision makers as forthcoming plenitude and a dominion of nature and that, therefore, the world could produce its food without reference to complicated sciences like pedology (Wojtkowski, 2008). Today, it is a fact that the failure to tailor soil fertility management technologies to specific soil types is among the major reasons for poor adoption of fertilizer use and high yielding crop varieties promoted throughout Africa (Steiner, 1998; Sileshi et al., 2010; Giller et al., 2011; Rushemuka et al., 2014a).

In Rwanda the CPR is also under utilized if not ignored. The proof is that the recent strategic planning documents such as Vision 2020 (MINECOFIN, 2000), the nation agriculture policy (MINAGRI, 2002) and the EDPRS 1&2 (MINECOFIN, 2007, 2013) which recognize the agriculture sector as the engine of Rwanda economic growth do not mention this soil map as a strategic planning tool toward this economic growth. One of the major reasons is that the underlying principles of the use of the soil resource as the foundation of practical agriculture as they were described by Erhart (1937), and its use in the technology transfer are not clear to many soil resource information potential users such as policy makers, agronomists, soil fertility management experts and extensionists. As a consequence, in a country like Rwanda, the value of the soil resource information in agriculture research and extension seems not to attract many potential users (Figure 2.5). The above situation has a negative impact on the effectiveness of the PIWM approach because it relies on multi-disciplinary teams that jointly study complex phenomena, members of which need to find a way to cooperate with each other and society's stakeholders (Leeuwis and van den Ban, 2004). We argue that the fundamental problem which hampers the effectiveness of the PIWM process and other on-station and on-farm approaches is the poor perception of the logic of the use and the language of the soil resource information in agricultural research for development (Figure 2.5). Indeed, the soil science/pedology has made little effort to supply its potential users with practical guides to highlights their potential as information support tools (Bock, 1994). As a result of this communication gap, many workers in other disciplines still tend to regard, at best such studies of only peripheral value to their work (Landon, 1991). As a consequence, the systematic consideration of soil types is perceived by soil fertility experts as a very challenging task (Giller et al., 2011). This is consistent with Nachtergael (2000) who observed that in many SSA countries, even though it is generally recognized that soils are important resource, in practice, it appears that available soil information is underutilized or even ignored. In Rwanda, the little consideration of different soil types within and between AEZs explain why the effort of many authors (e.g. Rutunga, 1991; Drechsel et al., 1996) to transform soil fertility experiment legacy data into practical soil fertility management recommendations has failed. Without clear perception of the soil resource as a natural body (soil individual), the job of agronomists, socio-economists and statisticians is less useful in agricultural research for development. This would help to understand why the agricultural research in Rwanda has failed to equip farmers with appropriate and convincing soil-specific technologies after so many years of research.

The figure below illustrates how inoperative information has been among different stakeholders who are supposed to interact for innovation. (1) Agronomists (crop scientists, fertility experts etc.) do not have the required prerequisite to understand the international soil classification systems/special vocabulary used in Rwanda: Soil Taxonomy (the language of the CPR),

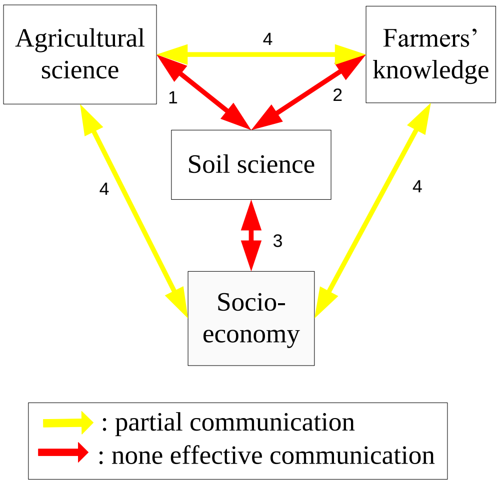

Figure 2.5 Communication barriers in PIWM model: inaccessibility of soil information. Source: conceptualized by the author of this thesis.

the INEAC classification system (the language of PR of Rwanda) and the World Reference Base (WRB) (the international soil correlating system): hence the red arrows between the 'soil science' and the 'agricultural science' to mean that agronomists do not understand the terms such as *Alfisols* (Soil Taxonomy), *Ferrisols* (INEAC) and *Alisols* (WRB) and that therefore, they intervene without understanding the soils. This is likely to be rather a general problem and is explained by the gap between pedology and soil fertility management (Papadakis, 1975; Hartemink, 2002). The gap has become even bigger with the evolution of soil science during which it has been observed that fertility experts in the tropics may relate more to crop scientists than to pedologists, while pedologists in temperate regions may find they have more in common with geologists and geographers than with soil fertility and plant nutrition specialists (Brevik and Hartimink 2010). This gap leads to divergent interest in what is supposed to be a single, united natural science field (Brevik and Hartemink, 2010): hence many authors have called for a holistic approach of the soil science (Brigdes and Catizzone, 1997; Churchman, 2010). However, while the holistic nature of soil science is usually captured in soil maps, the later are reputed cumbersome for non-soil scientists (Bui, 2004). It is in this context that Bock (1994) called for a geomorphopedological approach. This approach allows displaying the soil surveyor mental model which is highly needed for non-pedologists like fertility experts and agronomists to understand and use the soil maps (Wielemaker, 2001). In the same vein, Hartemink and Bouma (2012) called for reconnecting soils and agriculture. (2) There are no communication bridges between scientific and FSK, therefore, the farmers' soil terms (which guide the farmers' land use, crop allocation and soil fertility management), such as *Urusenyi*, *Inombe*, *Umuyugu/Mugugu etc*. (see Chapter 4), make sense for farmers only and are, therefore, not used by scientists on the one hand. The international soil classification systems used by soil scientists are not understood by farmers on the other hand: hence the red arrows between 'farmer knowledge' and 'soil science' to highlight the absence of any interaction about soils between soil scientists and farmers. (3) For the socio-economists (economists, social scientists, policy-makers, politicians etc.), the soil science makes sense only through its contribution to the transformation of research findings into policies and programs conducive to more sustainable productive agro-systems. Since soil science is not used by agronomists and farmers, it is therefore meaningless for them as well: hence the red arrow between ‘socio-economy’ and ‘soil science’ to mean that the soil science does not help this group of scientists to understand the interaction between human being with their environment (4) In these circumstances, any communication between farmers, agronomists and socio-economists is only partial/speculation because the core (the soil resource information) is omitted: hence the yellow arrows between ‘socio-economy’, ‘agricultural science’ and ‘farmers’ knowledge’, to refer to the partial contribution of the scientific information due to the ignorance of soil science (the foundation of agriculture) in the agricultural research for development. This means that the SPPI is imperfect because the existing policies and the scientific recommendations (practices) are not rooted in the biophysical constraints understanding (ISNAR, 1982). The yellow arrows indicate the superficiality with which the participatory research is undertaken and, the inaccessibility of the soil factor shares some light on why the PR is more perceived as ‘social science only or a political tool - a kind of diplomacy - and less as a scientific methodology’ (Quinlan and Scogings, 2004).

The low accessibility of the soil resource information can explain, at least partially, why many attempts to reform agricultural research and development institutions manage to change only the organizations’ names but not really the institutions’ behavior (norms and rules) (Raina et al., 2006). Effective institutional reform needs soil science arguments, which, for the moment, stay only accessible to soil scientists! The partial communication, or the ignorance of the soil resource information, might explain also the existence of many myths in the field of soil fertility management in Africa, many of which have been denounced by Vanlauwe and Giller (2006). It is also the source of many speculations. For instance, regardless of their good intentions, many development initiatives led by continental global programmes promoting intensive use of fertilizers have been reported to meet with popular resistance and in many cases, scientific skepticism, as people suspect them to be market-oriented and technology driven in favor of certain interest groups in the West, at the expense of Africa (Kolawole, 2012). This negative perception of inorganic fertilizer is due to the fact that its intensive use is presented as a must in addressing the diverse problems of soil fertility without critically examining where fertilizer is efficient and where it is not and why (Sileshi et al., 2010). Even the much advertized Asian GR has been recently subjected to strong criticism (Raina et al., 2006). If it has been judged as successful in terms of food production compare to SSA, it is likely because the limiting factor in Asia was more the water shortage than soil acidity and soil variability and their consequences on fertilizer use efficiency as it is a case in many parts of SSA (Donovan and Casey, 1998). The fact that the Asian GR was not based on clear understanding of the soil resource information (Raina et al., 2006) has two major consequences: (1) the technological spillovers from Asian to other developing countries in Africa and Latin America are unlikely (Dethier and Effenberger, 2012), (2) several consequences of Asian green revolution technologies and the ultimate impact of these consequences on the development goals of the nation pose difficult questions, often directed at policy, research and extension organization (Raina et al., 2006). In these conditions, despite excellent research, the soil sciences in India, as part of agricultural science has confronted uncomfortable and complex questions from ecological and social constituencies (Raina et al., 2006). Hence, the soil scientists in India have been among the firsts to call upon for more partnership and learning research and extension approaches and more conducive institutions (Raina et al., 2006).

2.5.2 Toward effective PIWM

While attempting to improve the collaboration between different stakeholders in the PIWM process, many scenarios may happen depending on the quality of available soil resource information.

(i) The scientific soil information is accurate and precise (e.g. soil consociation level) and an appropriate soil database is available. In this planning environment, the model takes the form of Figure 2.6.

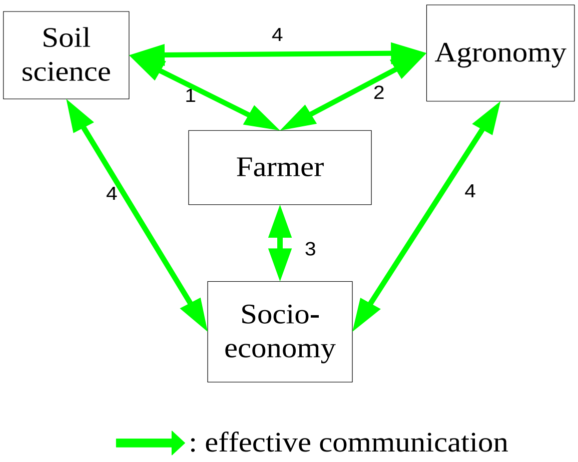

Figure 2.6 Effective communication: accessible and accurate scientific soil information.

Source: conceptualized by the author of this thesis.

This figure shows a situation where the scientific soil information is accurate with practical and understandable legend. The farmer's level of education permits him to use efficiently the available data in soil science (soil map e.g.) and agricultural science (suitable crop varieties, appropriate fertilizer recommendations) and socio-economic information (e.g. cost benefit analysis, market prices): hence green arrows between (1) 'farmer' and 'soil science', (2) 'farmer' and 'agronomy' and (3) 'farmer' and 'socio-economy'. The research findings (from soil science, agronomist and socio-economy) are intelligible to decision-makers in policy and practice and, therefore, transformed into policies and programs: hence the green arrows between (4) 'soil science' and 'agronomy' and between 'soil science' and 'socio-economy' to mean the existence of a functional SPPI. This situation is likely to be met in developed countries where accurate information exists and the agriculture is practiced by educated farmers. But again, even in this planning environment, the difference in farmers' and scientists' perspectives about soils is a fact and the understanding of both perceptions is important (Ingram et al., 2010).

(ii) The scientific soil information is not accurate at farm level, but can be complemented by the FSK. It is acknowledged that farmers have an accurate mental soil map (Barrera-Bassols et al., 2006b). Under their low input system, they exploit any soil differences. For instance, farmers' strategy for degraded fields is to replace cereals and grain legumes by less demanding root and tuber crops such as cassava and sweet potato (Drechsel et al., 1996). Moreover, they have a practical soil nomenclature which is flexible enough to cope with the complex soilscape (Habarurema and Steiner, 1997; Steiner, 1998). Indeed, for interactions, it would be helpful for agronomists, soil fertility experts and farmers in Rwanda to use the farmers' soil terms such as *Urusenyi* (Entisols), *Inombe* (Ultisols), *Umuyugu* (Oxisols) etc. In this context, the FSK can be formalized and linked to the scientific soil knowledge (knowledge system integration). In this case, the soil science becomes the hub (Figure 2.7). Full communication between different stakeholders (soil scientist, agronomist, farmer and socio-economist) depends on the catalytic role of the soil scientist. The catalytic role will permit them to serve as interface between themselves (soil survey/soil map and other soil science sub-disciplines) on the one hand, and between them and life scientist, socio-economist and farmer, on the other hand.

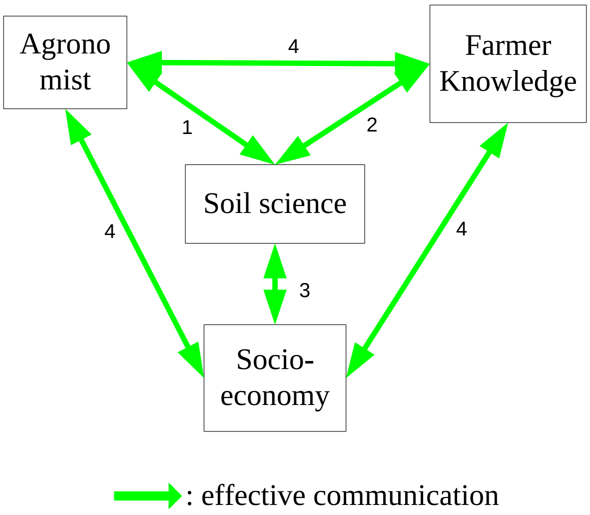

Figure 2.7 Effective communication: complementarities and synergies of scientific and local soil information. Source: conceptualized by the author of this thesis.

In fact, the soil scientists, in addition to their technical contribution (biophysical environment understanding), must play an interpretation role in the broad epistemological (biophysical, social and economic assumptions that have framed the farmer's knowledge and practice) and cultural context, rather than a narrow linguistic sense of the word (Thomasson, 1981). In doing so, they will automatically enable the communication between (1) soil scientist and life scientist, (2) soil scientist and farmer, and (3) soil scientist and socio-economist, and will (4) improve the communication among all stakeholders; hence the overall green arrows, refer to the existence of effective communication and, therefore, to a functional SPPI.

The communication bridges between scientific and FSK would be a good starting point to foster effective institutional reform in the field of agricultural research and extension. We argue that the more the soil resource information/logic is understood by all watershed stakeholders, the less complicated will be the effective institutional reform and the more effective the PIWM approach will be. In these conditions, it is important for the soil scientists to see themselves as one of the key actors in a wide network of innovators, adapters and adopters, with crucial linkages with other actors and innovation processes (Raina et al., 2006).

2.6 Conclusion

This study has argued that the shift from the "positivism" to more "constructivism" approaches constitutes a real progress in the conceptualization of the agricultural research and extension modes. However, the constructivism series of approaches, though old of more than 20 years, have failed to be really effective and the top-down technology transfer tends to survive as a default model. Many authors have identified the lack of workable agricultural research and extension institutions as the major constraint that hampers effectiveness constructivist approaches. In Rwanda, while there are good reasons to blame the agricultural research and extension institutional framework, the fundamental problem appears to be the poor integration of the soil factor (both scientific and FSK) in the PIWM reasoning and in the mother-baby trials. The study has argued that the effectiveness of the PIWM and the mother-baby models can be significantly improved by focusing on the accessibility of the soil resource information to all stakeholders. One way to achieve this is to establish communication bridges between scientific and FSK. The communication bridges would be an effective way of liberating the soil science from the jail of the linear R&D model's institutions which prevent it, the opportunity to communicate and to interact with key partners for effective agricultural institutional reform, which in turn, would allow an operational SPPI, towards soil-specific GR. The major recommendation is that in the context of research for development, the watershed should become, at the same time, the true "laboratory" and "experimental site". On-farm experimentation approaches are valuable if only they take into account the required consistence between the soil type where a technology is developed (mother-baby trials) and the ones where results are extrapolated (best fit technologies). In this context, the extension cannot continue to be about a simple scientific discipline-based or a commodity oriented technology like crop varieties but a successful integrated watershed model as result of the understanding of the required interactions between biophysical, agronomical, socio-economical and institutional factors. A clear perception of the place and role of the soil resource information in agricultural research and extension by all watershed stakeholders is a must if Rwanda is to achieve its GR.

Chapter III: Soil science and agricultural development in Rwanda: The state of the art[10]

Abstract

A critical analysis was undertaken of the contribution of soil science to Rwandan agricultural development. The objective was to explore if any trend could be observed from the past and the current situations to orient future interventions. This study has demonstrated that a positive trend of the soil science can be identified which can promote an “eco-efficient” “green revolution”. In practice however, the soil resource information remains underutilized, mainly because of its inaccessibility to its potential users. For its effective use, the following recommendations were formulated: (1) Rwandan soil scientists need to remobilize to increase the public awareness and positive attitudes about the usefulness of soil map of Rwanda (CPR) (2) the approach to agricultural research needs to adapt from the conventional approach to a truly participatory integrated approach (3) the CPR should improve its capacity to serve in trans-disciplinary cooperation by integrating the land units in its legend and by bridging the scientific and farmers’ soil knowledge (FSK). This implies the need for the urgent training of Rwandan soil scientists in mastering both Soil Taxonomy (the language of the CPR) and the FSK so that they can serve as interpreter between scientists from other disciplines and farmers. At the same time, Rwandan soil scientists also need to receive more training in the use of Geographic Information System (GIS) software so that they are able to exploit the soft copy of the CPR and become familiar with the Rwandan biophysical environment.

Key words: *Research, development, soil science, communication, agriculture, Rwanda*

3.1 Introduction

The soil is studied from both a fundamental and an applied point of view (Ruellan, 2007). The knowledge acquired by the basic soil science is published into scientific journals and books. However, the way the information generated by this scientific sub-discipline is used to formulate sound policies, and is translated into soil-specific and user-tailored technologies in applied soil science, is complex and remains controversial.

While Hartemink (2006) maintains that soil science has contributed to the increase in world agricultural food production over the last 50 years, several other authors (Papadakis, 1975; Leeuwis and van den Ban, 2004; Ruellan, 2007) find that this increase in agricultural food production in the industrialized world was made possible more by agronomic sciences (responsive fertilizer varieties, irrigation, pesticides and intensive use of fertilizers, agricultural engineering, value chain development and

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[10] This chapter is a revised version of: Rushemuka N. P., Bock L., Mowo G. J. (2014). Soil science and agriculture development in Rwanda: The state of the art. Biotechnol. Agron. Soc. Environ. 18(1), 142-154.

markets), rather than by progress in soil science and academic research. The problem is that this capital-led (purely economic growth-oriented food production) has occurred at the expense of the capacity of the soil to sustainably produce food and support life (Raina et al., 2006; Ruellan, 2007; Herren, 2011).

However, despite the above concern, in those developing countries where the increase in food production has been problematic and, therefore, has remained at a low level over the last 50 years, there is a great temptation to “imitate” the developed world. For instance, in the African fertilizer summit (whose conclusions were endorsed by the African Heads of States at Abuja, Nigeria, in 2006), it was argued that for a GR to take place in Africa, fertilizer use must be increased from the then average of 8 Kg ha^{-1} to around 50 Kg ha^{-1} by 2015. Accordingly African governments were encouraged to take conducive measures to increase the use of fertilizers. It is in this context that Rwanda is promoting a policy of agricultural “modernization” and “crop intensification” (land consolidation, mechanization, mono-cropping, high yielding crop varieties, intensive use of fertilizers and irrigation) (MINECOFIN, 2000; MINAGRI, 2002).

Agro-ecologists, while sharing the same worries regarding low agro-system productivity, would prefer not to see developing countries repeating the past errors of the developed world. Within this context, they consider “agro-ecological solutions” or Ecological Agriculture (EA) (minimum use of fertilizers and investment in agroforestry, etc.) to be superior to conventional agriculture based on chemicals or the Industrial Agriculture (IA) and propose measures for governments to lead the development and adoption of such approaches (Altieri, 2002; de Schutter, 2010; Herren, 2011). Soil scientists, for their part, argue that “agro-ecological solutions” are unable to contribute significantly to food security and poverty alleviation within the context of the inherently poor and acid soils, such as those found in many parts of sub-Saharan Africa (Rutunga and Neel, 2006, Breman, 2011; Keating et al., 2011)

Several questions arise: is this debate new? Has any progress been achieved? Given these conditions, what position should governments take? Should they wait for scientists to reach a compromise?

The objective of this chapter is to analyze how soil science has evolved in Rwanda, what has been achieved, how these achievements have contributed to agricultural development, what the constraints have been, and what might constitute the way forward. The chapter is organized as follows: Section 2 presents the methodology. Section 3 presents the Rwandan experience of soil surveys, erosion control and soil fertility management. Section 4 provides a discussion in three points (1) connectivity between soil survey, soil conservation and soil fertility management (2) EA and IA in Rwanda and (3) usefulness and use of the CPR. Section 5 offers some conclusions.

3.2 Methodological approach

A critical literature review was the main source of information for this chapter. This included articles, maps, and unpublished reports. A historical perspective approach was used to analyze the contribution of soil science to agricultural development in Rwanda. The historical time frame covers a period of about 80 years (1930-2010). A three year (2010-2013) iterative field observation of activities of an

Integrated Soil Fertility Management project was undertaken to support the literature review with concrete and recent examples. Figure 3.1 presents, the AEZs of Rwanda and the main sites frequently cited in the text.

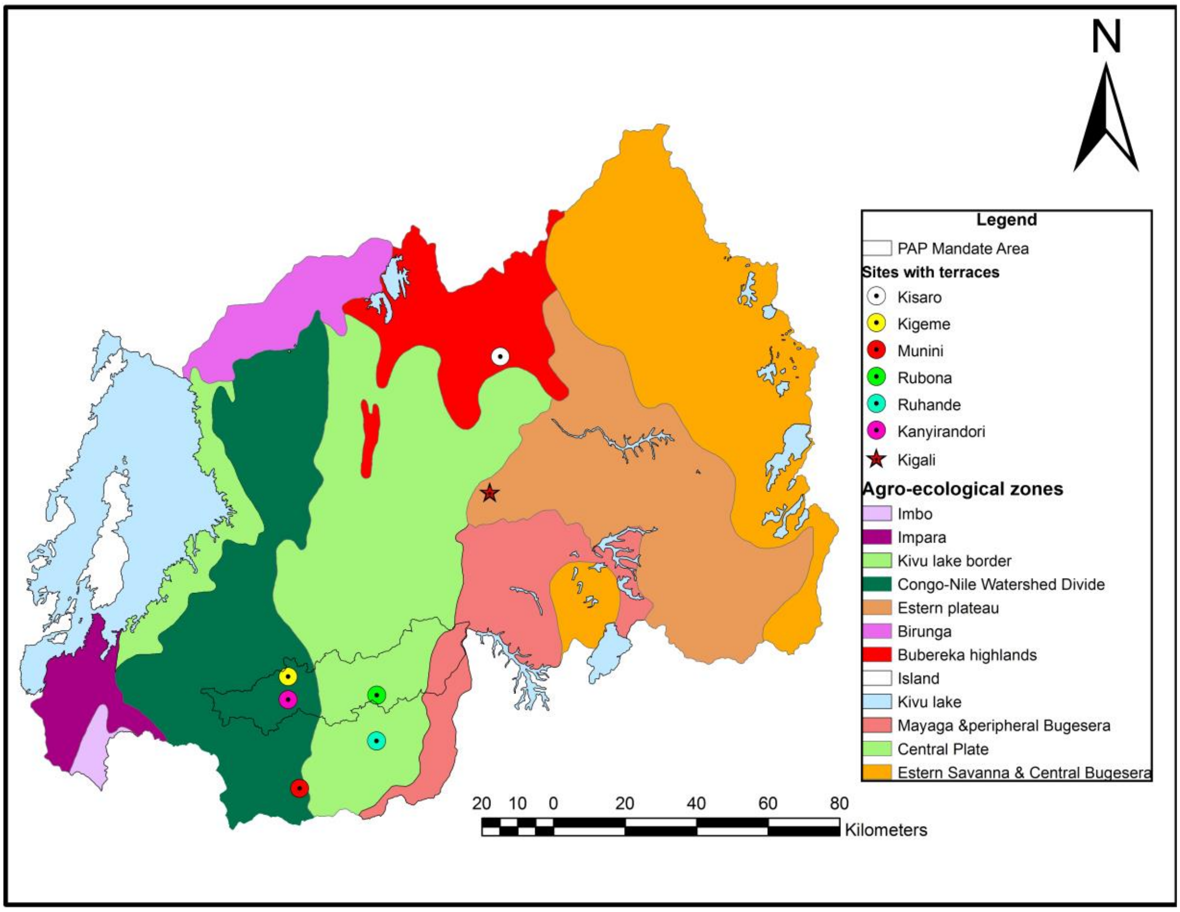

Figure 3.1 Rwanda Agro-Ecological Zones and cited sites in this chapter.

3.3 Soil science components and achievements in Rwanda

Soil science, as applied in agricultural research and development in Rwanda, is traditionally subdivided into three main components: (1) soil survey, (2) soil conservation, and (3) soil fertility management.

3.3.1 Soil survey

The first soil survey in Rwanda was undertaken by the team of the *INEAC*, beginning in 1955 at Rubona Station (Figure 3.1). After independence, INEAC activities were continued by the ISAR, being integrated more recently (2012) into the RAB. By 1963, the major soil types of the country had been described (Van Wambeke, 1963). In the 1980s, all soil knowledge acquired by the INEAC-ISAR team was synthesized into a soil association map at a scale of 1: 250,000 (Prioul and Sirven, 1981). During the same period, Pietrowicz (1985) undertook a soil survey in the mandate area of the project "*Projet Agro-Pastoral* (PAP) *Nyabisindu*" (Figure 3.1).

During the period 1981-1990, the project CPR (Birasa et al., 1990) conducted a comprehensive soil survey of Rwanda. The CPR project produced a soil association at a medium scale (1:50,000) soil map (43 sheets) under the "*Soil Taxonomy*" classification system. The CPR database was created between 1990 and 1994. In 2002, the soil map was digitalized and the associated database was established (Verdoodt and Van Ranst, 2003b). In 2003, a set of soil suitability maps was published (Verdoodt and Van Ranst, 2003a).

3.3.2 Soil conservation and erosion control

Erosion control has been formally practiced in Rwanda since 1937 at INEAC research stations (Kabiligi, 1985). In 1947, the program was widened to the whole country and many extensionists (mostly known as "MONAGRIS"[11]) were recruited. In 1947, the colonial administrative "resident" decree made the creation of ditches and the planting of grass and trees obligatory for all land holders.

After independence (1962), the first republic (1962-1973) did not immediately insisted on erosion control. As consequence, farmers abandoned erosion control and many erosion infrastructures were even deliberately destroyed as sign of liberation from this coercitive work (Kabiligi, 1985). In 1966, the Ministry of Agriculture and Live Stock (MINAGRI) raised the awareness about the danger of erosion countrywide and revived a national program of soil erosion control (MINAGRI, 1971). Following this, several compulsory five year programs (1966-1970; 1971-1976; 1977-1981; 1982-1986 etc.) were implemented. It is especially under the second republic (1973-1994) that much effort was furnished in a more coercitive manner with fines for 'poor performing' farmers. During the second republic, the erosion control was highly politicized and was the core of the state discourse. The message of the president of republic to the nation at the beginning of each year contained erosion control message and each year had its denomination and key note (e.g. 1980: year of soil conservation; 1982: year of erosion control; 1983: year of reforestation etc.) (MINAGRI, 1985).

The third republic (1994 up to know), because of many priorities, after the 1994 genocide, during its first decade did not insist on erosion control. During this decade, once again farmers progressively abandoned the erosion control. It is only in 2005, as the country was recovering from the 1990-1994 civil war and genocide that the erosion control program was re-started with almost the same approach except the fines for 'recalcitrant farmers'. Since 2005, many bench terraces have been constructed. As a result, in many regions of the country, the landscape has changed remarkably. At the same time, the old infiltration ditches were renewed.

- *Infiltration ditches*

One of the most ancient and most common examples of erosion control infrastructure in Rwanda can be seen in the use of infiltration ditches ("*imingoti*") stabilized by grass verges along contour lines (Figure 3.2). The reasoning behind was that ditches cut the slope length and reduce the speed of runoff water. Moreover, the stabilizing contour grasslines were expected to barrier colluvions in the runoff

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[11] Monagris refers to "moniteurs agricoles".

water and therefore, to progressively diminish the field slope. However, the experience has shown that at the beginning of the rainy season (bare land), cultivated soils (60 cm deep) with low organic matter content (less infiltration) on steep slopes are exposed to the highest risk of erosion. Indeed, in Rwanda, on bare plots on slopes of 23-55%, the erosion is high: 300-500 t/ha/an (Roose et al., 1993) or 300-700 (Roose and Ndayizigiye, 1997). Most of Rwandan soils are well drained and their erodibility is rather low to medium (Wischmeier K index < 0.20), however, the rainfall erosivity index is high (R varies from 250 to 700). This means that the high rates of erosion are mainly explained by the high rainfall erosivity, the steepness and length of slopes and the tillage practice. Given these factors of erosion in Rwanda, in general infiltration ditches with grass lines are not enough to reduce erosion significantly. Indeed, in Rwanda, 50 % of cultivated lands have more than 18 % of slope; 20% have more than 40 % of slope, 6 % have more than 60 % of slope and 1 % has more than 80% of slope (Roose et al., 1993). In these conditions, ditches easily fill up within few days and the accumulated runoff water overflow and aggravate the erosion along the whole hillside (Roose et al., 1993). This situation is exemplified in Figure 3.2. Therefore, this erosion control method was poorly accepted by farmers as it requires a lot of labor for installation (100 to 350 days) and maintenance (20 to 50 days/year) without increasing crop yields (Roose and Ndayizigiye, 1997). As reported by Roose and Ndayizigiye (1997), the combination of infiltration ditches and agroforestry practices (hedgerows along contour lines and biomass incorporation) was able to reduce runoff to less than 2% and erosion to 2 t/ha/year on a slope of 23% but not to restore soil fertility of an unproductive soil ($pH_{water} = 4.0$).

Figure 3.2 Farms on a steep slope with infiltration ditches and grass verges along contour lines for erosion control.

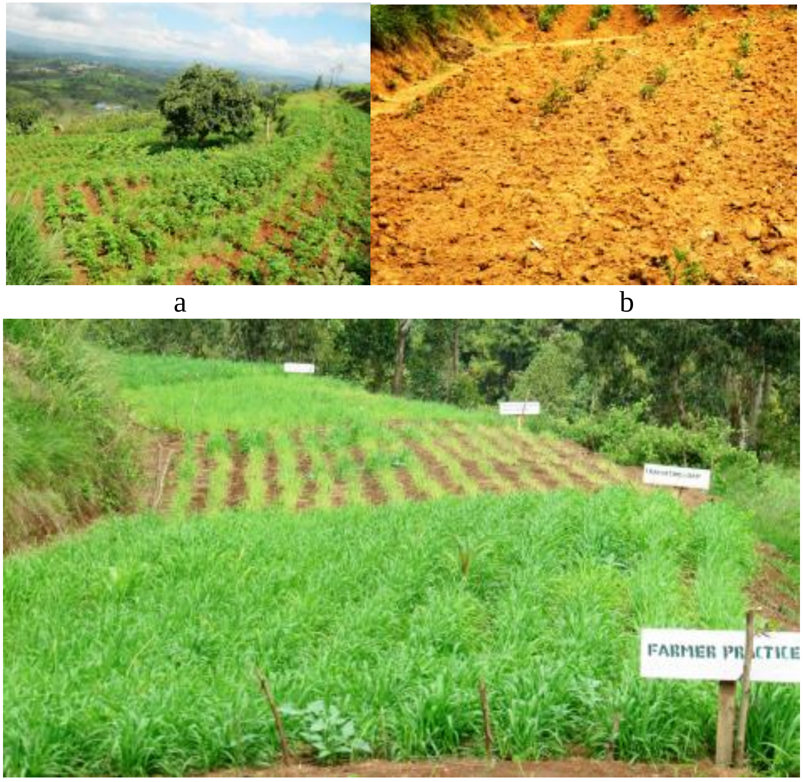
The soil productivity was restored by the supply of 2.5 t/ha/3 years of lime, 10 t/ha/2 years of farm manure and inorganic fertilizers.

- *Bench terraces*

Bench terraces (Figure 3.3) were introduced in Rwanda in 1973, in the mountainous region of *Buberuka* AEZ at *Kisaro* hill (Figure 3.1). In this region, terraces have been greatly appreciated as an effective way of controlling soil erosion and of maintaining or progressively improving soil fertility. Since 1992, the use of bench terraces has been expanded to the unproductive soils of the similar (topographically) mountainous region of the Congo-Nile watershed divide AEZ, at *Kigeme* hill (Figure 3.1). In this region, however, bench terraces on those unproductive soils and underused lands have not been adopted and the terraced terrains were abandoned. More recently (2006), under the "food for work system", many Districts and Non Governmental Organizations (NGOs) have created bench terraces on large areas in all AEZs. However, both anciently and recently constructed terraces have led to a situation where some terraces are used effectively while others were totally abandoned. The situation of some terraces being used and other being abandoned has been reported as embarrassing for policy-makers and other non-soil scientists who are interested in the adoption of terraces (Bizoza, 2011). However, for an informed soil scientist, in order for terraces to be used effectively, they would need to be constructed on productive soils, which can still be responsive to farmer input (organic input or organic input + fertilizers).

Figure 3.3 Photo of bench terraces with farmers harvesting Irish potatoes at Munini.

Alternatively, effective terraces would be constructed on the unproductive soils (very strongly acid and depleted soils) but with appropriate input supply (limestone, organic input, fertilizers and improved seeds). Terraces that remain unused would be those constructed on unproductive soils (already under utilized) without adequate input supply. Indeed, it has been demonstrated that where appropriate inputs are well combined, high yields of various crops are being obtained (Figure 3.4a and 3.4c -1st and last plots) on bench terraces constructed on the otherwise unproductive soils of southern Rwanda (Rushemuka et al., 2012). In this region, zero yields have been obtained when there was low input (Figure 3.4b and 3.4c- 2nd and 3rd plots).



a b

c

Figure 3.4 Bench terraces on extremely acid and depleted soils of southern Rwanda (a. Irish potatoes with travertine + manure + fertilizers; b. Irish potatoes without any input/control; c. layout of four plots: the first and last plots correspond to the farmer's treatment made up of travertine + DAP+ manure; the second plot corresponds to treatment with travertine + DAP. The third plot corresponds to treatment with travertine + manure).

3.3.3 Soil fertility management

Soil fertility may be examined either from a conventional perspective or from a more integrated approach.

- *Conventional soil fertility management*

In the 1970s, a series of pot experiments was undertaken on more than 500 soil samples in order to diagnose soil fertility limiting factors (Iyamuremye 1983). Results showed that the major soil fertility limiting factors were (in order of importance) P, K, N and, in some soils, Ca^{2+} and Mg^{2+}. Following these initial experiments, a nine years period (1971-1980) soil fertility experiment was undertaken (Rutunga and Neel, 2006) at Mata hill in the Munini region (Figure 3.1). Many other studies have been undertaken by ISAR, in different AEZs, on the main crops grown in the country. Since its creation in 1979, other soil fertility-related research has been conducted by the Faculty of Agriculture at the National University of Rwanda (NUR) (Ndoreyaho, 1985). Another important study on fertilizer use was undertaken by the project SFI[12]-FAO (1980-1990) in collaboration with ISAR and NUR (Coursier, 1985). The project undertook simple on farm fertilizer trials countrywide for the most

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[12] SFI: Soil Fertility Initiative.

widely grown crops. Pietrowicz and Neumann (1985) adopted a more “ecological” approach (green manure or farmyard manure plus fertilizer) in the PAP mandate area. Unfortunately, due to the 1994, the raw data of the SFI-FAO and the document produced by Pietrowicz and Neumann (1985) are no longer available in Rwanda and therefore, their experiences might not be fully capitalized. The access to those data and documentation will need additional efforts abroad.

While, in many cases, experiments were undertaken assuming the homogeneity of AEZs, results from those experiments, whatever the AEZ, enabled Rwandan soils to be categorized into three fertility classes (Rutunga, 1991): (1) fertile soils, (2) medium fertility soils and (3) infertile soils. The characteristics of each of these fertility classes are summarized in Table 3.1. Fertile soils are unresponsive to fertilizers. They need manure for fertility maintenance. Medium fertile soils are highly responsive to fertilizers. They require manure + fertilizers. Infertile soils are unresponsive to fertilizers alone and need a combination of lime, manure and fertilizers in order to be productive. Similar soil fertility classes were reported through many SSA regions (Giller et al., 2011). Most of the experimental trials that allowed Rutunga (1991) to draw these conclusions were however generally undertaken by agronomists and soil fertility management experts without systematic consideration of different soil types at watershed level (Rutunga, 1991). This is one of the main obstacles to the adoption of soil-related technology recommendations in Rwanda (Steiner, 1998).

Table 3.1 Rwanda soil fertility classes, their characteristics and their proportion vis-à-vis the arable land.

Fertility classes	**Limitation level**	**pH (water)**	**Al**	**SEB**	**PROPORTION**
			Cmol/Kg soil		**%**
Fertile soils	Low	> 5.5	< 1.5	> 3.0	27.4
Medium fertility soils	Medium to high	5.2-5.5	1.5-3.0	1.0-3.0	29.5
Infertile soils	Very strong to extremely strong	< 5.2	> 3.0	< 1.0	43.1

Al= Exchangeable Aluminum, SEB: Sum of Exchangeable Bases. Source: abstracted from Rutunga (1991) and Birasa et al. (1990).

❖ *Agroforestry: integrated soil fertility management*

Agroforestry as an integrated soil fertility management practice and scientific discipline was introduced in Rwanda by the PAP *Nyabisindu* in 1975 (Neumann and Pietrowicz, 1985). The PAP *Nyabisindu* was a long term (1969-1989) integrated project run under the auspice of the German Cooperation and the Rwandan ministry of Agriculture. In this project, Agroforestry was conceived as part of a wider philosophy of EA and was introduced under the concept of agriculture adapted to the conditions of the environment (Schörry, 1991). The aim of Agroforestry, as promoted by the PAP *Nyabisindu*, was to anticipate, as far as possible, the abusive use of imported fertilizers in a land locked country where their cost is normally beyond the economic means of resource-poor farmers (Neumann and Pietrowicz, 1985). The problem was not the stigmatization of fertilizers, but their doubtful efficiency and sustainability in the inherently poor and acid soils with very low organic matter content and, on high gradient slopes unprotected against erosion (Schörry, 1991). Moreover, in the acidic highlands (> 1800 m), with high C content (3-16 %), fertilizer use efficiency was not guaranteed because correcting pH of such soils requires much more lime (2-4 t/ha) due to low base concentrations and high content in aluminum (Roose et al., 1993; Roose and Ndayizigiye, 1997) and probably also because of the buffer effect of organic matter (Rutunga and Neel, 2006; Chapelle, personal communication). The strategy was, therefore, to stabilize and eventually improve soil fertility through the use of different, but complementary, measures available at farm field level. The PAP *Nyabisindu* promoted an integrated system whereby trees and shrubs, livestock and crops were intended to be associated within one farm of about 1 ha, known as a "*fermette*". Within this system (1) trees were primarily envisaged for their role in soil fertility management under the nutrient recycling hypothesis, but also, for collateral multipurpose functions such as erosion control (hedgerows), fodder, fire wood, stakes for climbing beans etc., (2) livestock was primarily seen as a source of manure and was assumed to be kept in zero grazing and, nourished from the on-farm produced leguminous and herbaceous fodder.

With the same token, during the period of 1980-1995, many research and development projects experienced the concept of improving soil fertility and crop yields with the help of planted fallows with wood and herbaceous legumes or green manuring in different AEZs of Rwanda (Drechsel et al., 1996). The fallows were planted over one or more growing seasons as pure green manure, hedgerows on contour lines or on fields as seasonal inter-or relay-crop.

Although the concept of EA was exciting in its appeal, the technological packages proposed were surprisingly not adopted (Schörry, 1991; Drechsel et al., 1996). In the PAP *Nyabisindu* for instance, only some components of the system proposed were selectively chosen by farmers. The tree component was the most widely 'adopted'. At the end of the project (1990), 80% of farmers had trees on their farms; but only 10% had respected the project management prescription (biomass pruning and composting or green manuring). 70 to 80% of farmers had dug infiltration ditches in their fields, but only 1 to 2% had respected the project prescriptions (stabilization with well managed hedgerows). Only 5% of farmers had practiced zero grazing. Thus, a contrast could be seen between the apparent high adoption of trees and infiltration ditches and the extremely low rate of farmers adhering accurately to the specified requirements. The selective adoption is explained by the poor effect and residual effect of green manure or improved fallows on soil properties and crop yields (Drechsel et al., 1996). Indeed, the green manure residual effects on soil fertility parameters and crop yields revealed to be highly variable and in general low. In these conditions, trees were only accepted as firewood, stakes for climbing beans and fodder and not as source of inorganic fertilizers or erosion control infrastructures (Drechsel et al., 1996).

Surprisingly, in Rwanda, the effect of green manure on soil properties and crop yields revealed to be smaller and more variable than those observed in other African countries from where the concept of EA was inspired. For instance, it was reported that the rotation of maize and *Mucuna* green manure was able to maintain maize yields for 20 years or more (Vine, 1953 and Rattray and Ellis, 1953 cited by Drechsel et al., 1996). In Zimbabwe, the yields obtained were more than able to compensate the fallowing season (Drechsel et al., 1996). However, the sustainable residual effects of green manure seem to be restricted to rather fertile soils, as they allowed on the control plots continuous maize cropping over 22 years (Drechsel et al., 1996). In Rwanda, green manure effects on unproductive *Oxisols* were insignificant where continuous cropping of maize followed by beans, for a period of 8 years gave no yield in control plots (Rutunga et al., 1998). In the complex soilscape of Rwanda, green manuring proved to be a risky enterprise due to unpredictable and in most cases unsatisfactory residual effects (Drechsel et al., 1996). The low residual effect in fertile soils might be explained by the rapid leaching of N and K or inappropriate foliage incorporation; while in the infertile soils, it is likely to be explained by the very low nutrient reserves and virtually no nutrient available to recycle (Drechsel et al., 1996). Roose and Ndayizigiye (1997) concluded that in the unproductive soils of Rwanda, agroforestry cannot increase the productivity significantly. They observed that for this to happen, it is essential to correct soil acidity, the aluminum toxicity and the phosphorus deficiency. This strategy allowed to multiply the soil productivity by two or three and was a good option to interest farmers in efforts for rural environment protection (Roose and Ndayizigiye (1997). This highlights the need of understanding its own biophysical environment and clearly identifying the limiting factors in their hierarchy for appropriate soil fertility management strategies. In the complex soilscape of Rwanda, the main practical problem seems to be the failure to systematically take into account different soil types and their limiting factors, given the over short distance soil variations and, to find out soil-specific solutions. This has resulted into confusing situation on the scientist side. While the positive effects of green manure were observed on productive soils (without limitation in basic cation concentrations), farmers were reluctant in allocating their few productive fields to fallows. On productive soils, farmers preferred to maintain soil fertility management by the traditional application of farmyard manure on a seasonal basis. In this, they are supported by research results which show that in any case, the green manure residual effects did not last for a second season and was not able to compensate the ‘lost’ season (Drechsel et al., 1996). In addition, farmyard manure has showed promising results in comparison with green manure (Drechsel et al., 1996) and is traditionally adopted by Rwandan farmers.

Whilst farmers accepted to allocate fallows to the only fields already out of production, where yield turn to zero and economic risks are low, unfortunately, the wood legumes and biomass appear to be unable to transform these unproductive soils into productive ones. On those soils, even the combination of green manure with fertilizers was not able to increase crop yields significantly (König, 1992; Roose and Ndayizigiye, 1997). The explanation is that while the principal limiting factors of those soils are the basic cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), research results showed that, these elements were not significantly affected by green manure (Drechsel et al., 1996). Thus, according to Rwandan experience, the concept of improving soil fertility management at large scale with the aid of improved fallow or green manure in rotation - the fundamental focus of EA - failed so far (Raquet and Neumann, 1995 cited by Drechsel et al., 1996; Drechsel et al., 1996). With this experience, it was clear that, under the Rwandan household economic conditions, soil fertility constraints cannot be solved with farm-produced input only (Drechsel et al., 1996). The recommendation was that the production and availability of farmyard manure and country own mineral fertilizers, such as travertine and volcanic ash should be supported (Drechsel et al., 1996)

According to Drechsel et al. (1996) and based on research results (König, 1992; Drechsel et al., 1996; Roose and Ndayizigiye, 1997), in the conditions of Rwanda, agroforestry species might have a future in wide spacing hedgerows on contour lines (progressive terraces), mainly for erosion control, biomass production, firewood and climbing bean stakes. Thus (1) in fertile soils, the green manure, under the form of hedges, should continue (2) in medium fertile soils, green manure should be combined with fertilizers (3) in infertile soils; green manure should be combined with lime and fertilizers.

In this context, more recently, with agroforestry hedgerows on contour lines, at the Kanyirandoli RAB research station, the combination of lime/travertine (lime/travertine + manure + fertilizers) on poor and extremely acid soils has generated spectacular crop yields (Figure 3.5). However, the adoption of the Kanyiradori model has not yet become widespread. The frequently given explanation is that such Agroforestry system is knowledge-demanding, labour-intensive and high investment technology (Drechsel et al., 1996). Lack of adequate tools to prune or cut the shrubs as well as of transport facilities are seen as additional constraints (Drechsel et al., 1996). This means that designing an on-site experimental sustainable agroforestry system might be relatively simple in comparison with the necessary understanding of the contributing factors to ensure its replicability (Rhoades, 1999). Effective adoption depends on factors such as (1) farmers’ investment capacity (2) appropriate technology transfer (3) input accessibility (price and distance) (4) crop product market and (5) perhaps most important, a positive input/output ratio (Coursier, 1985).

On view of the above considerations, contrary to what some agroecology proponents maintain, manure alone may not be a cheaper option for soil fertility management for over one to two third of Rwandan soils (Breman, 2011). If it has been some times described as low-input technologies, it was to emphasize its local availability in comparison to external inputs such as inorganic fertilizers (Altieri, 2002). Concerning the real cost, the amount of labor, skills and management that is necessary as input to make land and other factors of production most productive is quite substantial (Drechsel et al., 1996; Altieri, 2002).

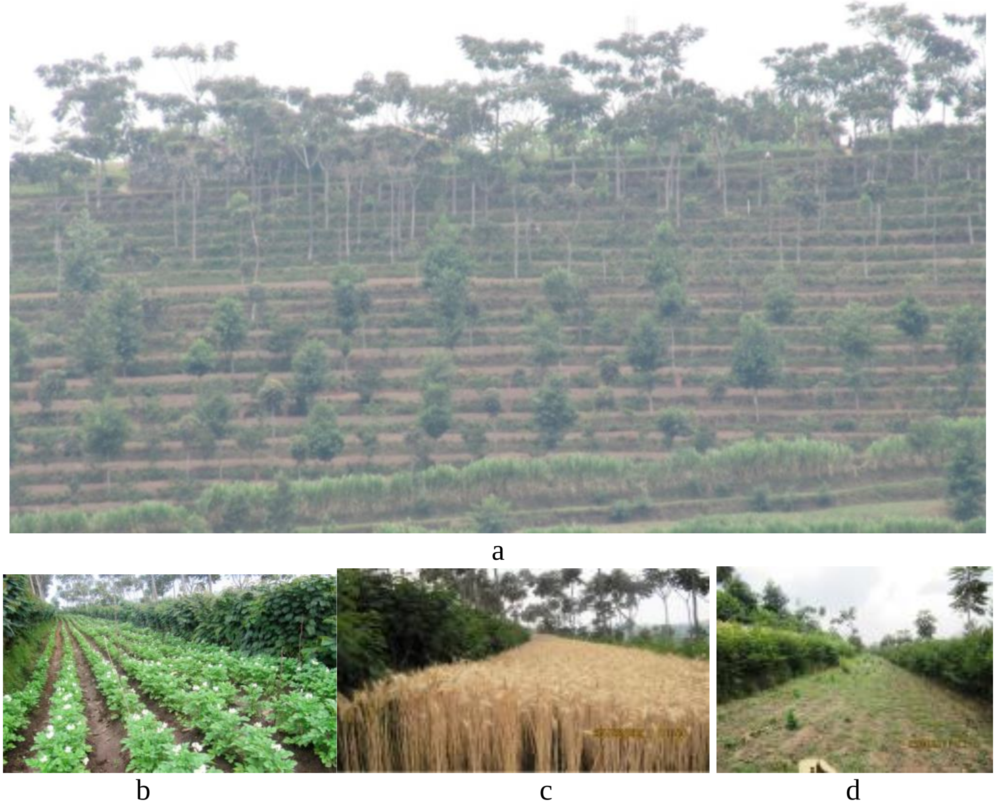

Figure 3.5 Kanyirandoli model: Agroforestry hedgerows – progressive terraces – on acid soils with high input system – lime + manure + fertilizers. a. General overview of progressive terraces; b. Irish potatoes; c. wheat; d. plot after harvesting.

3.4 Discussion

3.4.1 Soil survey, soil conservation and soil fertility management

Due to the fact that Rwanda is a hilly country, with steep slopes, and because of the long exposure of the population to erosion control campaigns since the 1930s, policy-makers have come to perceive soil erosion as the major cause of poor productivity in most Rwandan soils. However, despite the different erosion control methods and extension approaches used over the last 80 years, the adoption of proposed erosion control measures in terms of knowledge, persuasion, decision, implementation and confirmation has remained very low (Schörry, 1991; Bizoza, 2011). The reason for this lies in the fact that, on most Rwandan soils, underlying the problem of soil erosion is a serious problem of soil fertility (mainly linked with soil parent material), requiring high-level investment in soil amendments (lime, organic input and fertilizers) (Roose et al., 1993; Roose and Ndayizigiye, 1997; Rutunga and Neel, 2006, Rushemuka et al., 2012). With such soil types, it is not sufficient to control erosion, as productivity is already very low: in many cases, zero yields of cereals and legumes (Roose et al., 1993; Rutunga et al., 1998; Rushemuka et al., 2012), and only marginal yields of sweet potatoes or cassava (1-3 t/ha) (Roose and Ndayizigiye, 1997) are obtained. In these conditions, it is wiser to focus on a win-win solution: erosion control as part of Integrated Soil Fertility Management (ISFM[13]) with crop yields and farm productivity as indicators (see, for example, Figure 4 and Figure 5). In most cases, the initial investment to convert unproductive soil into productive soil is beyond the financial capacity of the farmer (Drechsel et al., 1996; Bizoza and de Graaff, 2010; Giller et al., 2011). Thus, the low productivity of a Rwandan farm is primarily due to poor soils, and a lack of resources among farmers is the main cause of the low level of adoption of proposed ISFM technologies. However, farmers and extensionists lack a good understanding of how best to manage resources (lime, organic input and fertilizers) when they become available (Giller et al., 2011). It is here that decision-makers need to listen to soil scientists so that appropriate investment in soil fertility management may be made and farmers helped to use efficiently the limited available financial resources.

3.4.2 Ecological versus Industrial agriculture

In Rwanda, many projects have experimented with fertilizers (IA, concept) in the different AEZs (Rutunga, 1991; Coursier, 1989). The EA concept, as now proposed by de Schutter (2010) is not new: this was the focus of PAP *Nyabisindu* intervention for more than 20 years. This was also the main concern of several projects during more than 15 years (Drechsel et al., 1996). It is now known from this long experience of both EA and IA that regardless to AEZ, soils in Rwanda can be subdivided into three fertility classes (Table 3.1). Rutunga (1991) recognized that it is a challenge to identify them on the fields and suggested using criteria such as chemical soil properties, indicator plants, and crop health and crop yields. However, he acknowledged the limits of such criteria in practical agriculture. Clay and Lewis (1990) observed that farmers in Rwanda traditionally distinguish three main land units corresponding to three agro-ecological niches: the upper ridge with fertile soils, the hillside with infertile soils and the marshy valley difficult to work. This suggests that land units may help to communicate with farmers about their farming systems. The findings of Clay and Lewis (1990) were corroborated with Steiner (1998) who found that, at watershed level, soil properties vary in a characteristic way from the hilltop/upper slope to the lower slope and valley bottom. He observed that variations in soil parameters are reflected in crop yields: on average, the lower slope yielded 20-50% less compared with upper slopes depending on the season and crop rotation. He noticed that trials series along the toposequence was a valuable method of experimentation. In this highly complex biophysical environment, he recommended to use the farmers' soil names to communicate with farmers for fine-tuned cropping recommendations. Consistently with these three studies, Rushemuka et al. (2014a) have shown that at watershed level, the land units, farmers' soil types and the chemical soil properties are key factors to identify the three

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[13] ISFM is defined as the application of soil fertility management practices, and the knowledge to adapt these to local conditions. ISFM aims to maximize both the efficient use of fertilizers and organic resources and crop productivity. The practices necessarily include appropriate fertilizer and organic input management in combination with the utilisation of improved germplasm (Adesina, 2009 cited by Sanginga and Woomer, 2009). In the hilly country with acid soils, erosion control and liming (travertine and volcanic ash) are important component of ISFM.

fertility classes and to communicate soil information to a large audience (e.g. policy makers, soil fertility experts, agronomists and extensionists, farmers as well)

From the experience of different interventions in Rwanda and elsewhere, it has become clear that the IA and EA concepts are not necessarily opposed but are rather convergent. Indeed, when well understood, both terms aim at reaching a sustainable “GR” through optimal investment in soil amendments (e.g. lime and organic input), fertilizers and germplasm/improved seeds. This is the true EA and the only one which deserves to be referred to as modern agriculture (Schörry, 1991; Keating et al., 2011). In this sense, as noted by Breman (2011), EA and IA have become synonymous with ISFM.

Concerning ISFM, the challenge becomes how to systematically take into account soil variations when designing experiments, when evaluating data and when extrapolating ISFM technologies. This is normally the role of the soil survey and, in Rwanda it was the aim of the CPR. However, since its completion, the CPR has not really been able to be used for this purpose.

3.4.3 Constraints in using the CPR

This study highlights five reasons hampering the usefulness and the use of this soil map in the agricultural research for development of Rwanda.

- *Historical reasons*

As with all other sectors of life in Rwanda, the CPR and its use did not escape the negative consequences of the 1994 genocide. This sad event meant that almost all personnel involved in the production and use of the soil map were either killed or driven out, and much information was lost. It took 8 years (1994-2002) to rebuild the database and then publish the digitalized version. The absence of input from Rwandan personnel in the implementation stage led to the loss of valuable experience in terms of soil map scientific and philosophical understanding, and policy-makers awareness regarding the role of a soil map in agricultural research and development planning. Today, 18 years after the genocide, only a small number of Rwandan soil scientists, are interested in its use. Moreover, policy-makers awareness and a positive attitude towards the usefulness of the CPR seem to restart from zero. While, on the one hand, the absence of the Rwandan project team is significant, on the other hand, this is not enough, in itself, to explain all the difficulties that undermine the use of soil maps in developing countries like Rwanda. Indeed, in the region and throughout Africa, examples of the successful use of the soil maps in small farmers’ agricultural development are few. In West Africa, Nachtergael (2000) noted the confusion between soil fertility potential identification and land evaluation and the relationship between the two. Muchena and Kiome (1995) and Lal (1995) discussed this situation for the countries of East Africa (Kenya, Uganda and Tanzania). Habarurema and Steiner (1997) and Steiner (1998) discussed this for Rwanda. The soil suitability maps produced in Burundi (Tessens, 1991) are not used. The recent debate over EA and IA demonstrates, if it were needed, the small consideration paid to soil maps in discussions on soil fertility management. It is also due to the difficulty of using traditional soil maps in soil fertility management that African Soil Information Service (AFSIS) is still experimenting with a global integrated soil information service (Shepherd and

Vagen, 2010). The above considerations mean that beyond the historical reasons in Rwanda, there are other fundamental causes for the low-level use of soil maps, causes that deserve to be examined more deeply.

- *A complex biophysical environment*

Due to the complexity of relief and parent materials, soils in Rwanda vary across very short distances (Dressler, 1983; Pietrowicz, 1985; Birasa et al., 1990; Steiner, 1998). Farmers respond to variations in soils with apparently complex farming systems. In these circumstances, Steiner (1998) noted the limitation of defining a small, well defined and representative recommendation zone. He observed that soils vary between AEZs as they do within one AEZ. This is consistent with the results of the CPR (Birasa et al., 1990). Within one AEZ, soils of different suitability vary from hill to hill (Dressler, 1983) and on one hill, soils vary from the hilltop/upper hill to the lower slope and valley bottom (Steiner, 1998). From a suitability point of view, under the same soil fertility management system, lower slopes can yield 20-50% less in comparison with upper slopes (Steiner, 1998). However, the forms of slope are so complex that the slope criterion is not practical for defining a “recommendation zone” (Steiner, 1998). Thus, scientists face a dilemma in this complex biophysical environment. On the one hand, soil fertility management recommendations need to be as soil-specific as possible in order to be replicable to analogous soil types. On the other hand, because of the biophysical complexity, it has been impossible to define a “recommendation zone”. Under these circumstances, conventional research and extension approach become less appropriate to develop and transfer ISFM technologies (Steiner, 1998).

- *Research mode and research institutions*

The main constraints hampering soil maps from being the foundation of soil-specific and replicable ISFM technologies begin with a research policy misconception and a biased funding system, leading to research programs oriented towards scientific disciplines or crop or livestock commodities (Raina et al., 2006). In Rwanda, for instance, under RAB, and its predecessors ISAR and INEAC, each crop such as maize, rice, sorghum, bean, cassava, etc. is considered as a research program. By the same token, biophysical sciences such as soil science and forestry are also subdivided into programs such as erosion control, soil fertility management, agroforestry, etc. These are autonomous research programs governed by rigid institutions (funding system, research agenda, experimental sites, reporting system, incentives, etc.). This research context prevents the soil scientist (pedologist) from taking the opportunity to partner with soil fertility experts or crop and animal production specialists. As part of this philosophy, even soil fertility management and erosion control practices are still being implemented as separate programs, disconnected from the soil resource information (CPR). Today, the realization is that no one research program is likely to be able to make much progress on its own in the light of the 21st century drivers and needs and that the technical constraints cannot be solved without broad-based institutional innovation (Keating et al., 2011). There is a clear need of reorganizing applied sciences (Quinlan and Scogings, 2004; Wiechselgartner and Kasperson, 2010).

The fact that the CPR is not headed by relevant institutions like RAB is explained by the fact that policy makers in the Ministry of Agriculture and external donors do not have clear perception of the role of research in influencing policies and that they have become skeptic about the capacity of conventional research to contribute significantly to poverty alleviation in line with the millennium development goals. In other words, policy makers in developing countries rely on more continental development framework traced by external donors at expense of their own research institutions (Lal, 1995). In these conditions, the agricultural research in general and the soil science in particular are reduced to research tactics for augmenting intensive yield enhancement practices (Raina et al., 2006). The dependence on external financial help in a pre-established development framework has resulted in lack of initiative and innovativeness in the chief of the local researchers (Lal, 1995). Therefore, it is important that policy makers and external donors understand that if contextualized within a wide innovation system, the CPR can become a strategic alliance to understand natural resource systems and manage them to meet the diverse demand of the new millennium (Raina et al., 2006).

It was within the context of reorganizing applied agricultural science institutions that the International Service for National Agricultural Research (ISNAR) (1982), after observing that Rwandan agricultural research and development was entering a crisis phase, strongly recommended a deep reform of this area. The limitation of the conventional agricultural research and development framework, in the context of Rwanda, was recognized by the PAP *Nyabisindu*, in its time, when it introduced the concept of "agriculture adapted to the biophysical and socio-economic environments". PAP *Nyabisindu* worked hand in hand with the CPR in the 1980s (Chapelle. personal communication).

More recently, ISAR appropriated from AHI[14], the concept of Participatory Integrated Watershed Management (German et al., 2006). Although this innovation model was seductive in its appeal for overcoming the problem of the conventional research and its top-down extension approach, it has faced the institutional rigidity of the linear R&D model and has fallen into the category of other development concepts frequently promoted by international research (see Rhoades, 1999; Keating et al., 2011). In this planning environment, the soil map finds no place. In this context, soil surveyors cannot continue to expect others to recognize and find themselves the appropriate framework to use the soil maps (Nachtergaele, 2000). It is a challenge for them to influence policy and opinion so that decisions with regard to the effective use of natural resources can be made more rationally (Nachtergaele, 2000). If they fail to address the problem with the skill at their disposal, then other will do but with less knowledge and authority (Nachtergaele, 2000). This suggests that soil sciences must relocate from the organizational confines of research to a wider range of partners and systems of innovations in agriculture. It is important for soil sciences to see themselves as one of the key actors in a wide network of innovators, adapters and adopters, with crucial linkages with other actors and

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[14] African Highlands Initiative (AHI) was an eco-regional program of the Consultative Group of International Agricultural Research (CGIAR) and the Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA).

innovation process. This can be facilitated through excellence in science, relevant partnerships, and internal learning process (Raina et al., 2006). Meeting this challenge will require that soil science broadens its constituency beyond traditional agriculture partners, that it applies itself to develop solutions to problems of soil and land management, that it breaks through a reductionist approach, that it enhances communication with different users (Nachtergaele, 2000).

❖ *Internal limitations of soil maps: complex knowledge*

In the current arena of participatory integrated research framework (e.g. German et al., 2006), and because traditional soil maps (soil-centered approach) are only understood by users who know the way surveys are made/process that soil surveyors undertake to produce soil maps (Bui, 2004), soil scientists have realized the challenge of using these maps to work in a trans-disciplinary fashion (Bock, 1994; Wielemaker et al., 2001; Bui, 2004). Indeed, a soil-centered and multipurpose soil map like the CPR is more directed to a peer audience of other classifiers than outward to a larger group of non-soil surveyor potential users (see Wielemaker et al., 2001). It is true that the CPR report and the soil suitability maps were produced. However, the different soil suitability maps for an entire AEZ do not help to overcome the problem of small-scale variations in soil properties from topography and farming practices (Steiner, 1998). In these conditions, extension recommendations for entire AEZs or administrative regions are hardly relevant for farmers and consequently not adopted (Steiner, 1998). Soil classes/soil types, on the contrary are often misinterpreted even by researchers and extensionists, who confound them with suitability classes (Steiner, 1998).

To solve this communication problem, Wielemaker et al. (2001) propose a multi-hierarchical land system approach. In this approach, higher categories of map legend are expressed in geomorphological terms. Lower categories are often landscape components in which soils are described as patterns or associations. This approach is closer to the geomorphopedological approach of the Gembloux School (Bock, 1994); approach which was applied by Li Y. (2004) in her thesis co-supervised with Mike Fullen at the University of Wolverhampton (UK) about the establishment of a generic protocol for an Integrated Land Information System (LandIS). It is also similar to the Land Information System of Cranfield University, UK. The LandIS is a substantial environmental information system designed to contain soil and soil-related information including spatial mapping of soils at a variety of scales, as well as corresponding soil property and agro-climatological data (Cranfield University, 2014). The LandIS is recognized as the definitive source of national soils information (Cranfield University, 2014). In agriculture, and specifically for Rwanda, this is very important because each landscape unit has its own specific soil and related level of productivity (Steiner, 1998). The communication problem implies that there is clearly additional work to do, if the CPR is to be used in a more participatory and multidisciplinary manner at watershed level. For instance, its legend should improve its communication capacity by explicitly representing the landscape context (which for the moment is only described in the soil map report) in line with the multi-hierarchical land system approach (Wielemaker et al., 2001; Park and van de Giesen, 2004). Following this logic, there is much to be gained in intelligibility by using spatial land information such as AEZ-watershed-hill-land units, before moving onto soil types and soil properties.

- *Reliance on Soil Taxonomy and the neglect of farmers' soil knowledge*

Soil classification systems, both scientific and farmers', provide a common means for talking about soils (Krasilnikov and Tabor, 2003). They simplify the complexity and continuum of the real world into more easily understandable discrete classes (Krasilnikov and Tabor, 2003). Soil Taxonomy is the US Department of Agriculture (USDA) soil classification system. It is a hierarchical one and is based on both genetic (presumptions) and natural (observations) principles. From a scientific point of view, Soil Taxonomy provides a good model to combine the simplicity of a rule-based hierarchical system (e.g. order, to family categories) with the specificity of nominal classification systems like soil series (Krasilnikov and Tabor, 2003). However, the fact that Soil Taxonomy uses special vocabulary (pedo-genetic jargon) means that it makes sense to the only appropriately trained soil scientists. Soil Taxonomy is the language of the CPR (Birasa et al., 1990). From a practical point of view, for many potential users of the CPR and farmers, the special vocabulary becomes a communication constraint. For example, it would be very difficult for an non-specialist to understand the terms such as: (1) "*Loamy-skeletal, mixed, non acid, isothermic lithic Troportents", (2) "Clayey, kaolinitic isothermic Sombrihumox, (3)* "*Euic*[15]*, isohyperthermic typic Troposaprits"* In addition, without understanding these terms, the soil series' names (names of localities) like Gatonde (GAT), Mata (MAT), Ruli (RL) do not convey special meaning for soil map users. In the meantime, Habarurema and Steiner (1997) and Rushemuka et al. (2014a) have observed that farmers in Rwanda have maintained their soil knowledge system with a very practical soil nomenclature. Farmers' soil names are much like the nominal system of Soil Series but without the rigor of scientific descriptions and engineering capabilities (Krasilnikov and Tabor, 2003). Because it would be unrealistic to expect non-soil scientists to adapt to the special vocabulary of Soil Taxonomy (Thomasson, 1981), Steiner (1998) recommends that Rwandan scientists build ISFM technologies based on the synergy between scientific and FSK systems. He also recommends using farmers' soil nomenclature to transfer ISFM technologies to analogous soil types. The disconnection between farmers' soil nomenclature and scientific soil classification and the resulting land management decisions that occur have wasted resources and caused severe economic hardship of communities (Krasilnikov and Tabor, 2003). On view of the above considerations, the soil scientist must be prepared to understand both scientific (Soil Taxonomy) and farmers' soil nomenclatures and to use these as an interface between non-soil scientists and farmers. This task can be described as a translation process, in its broad biophysical

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[15] Histosols with soil pH 4.5 or higher are called *euic*, and those below 4.5 are named *dysic*. In Greek, *euic* means "good" and *dysic* means "bad." This is not to suggest that *dysic* Histosols are bad soils, but rather that *euic* soils are less acid than *dysic* ones (Uehara and Ikawa, 2000).

environment meaning and cultural context rather than in a narrow linguistic sense (Thomasson, 1981). In this process, farmer should be a full partner in research process.

3.5 Conclusion

The objective of this study was to outline the past and current contribution of soil science to Rwandan agricultural development and to propose the way forward.

Our findings show that the existing CPR is an important planning document that can help to understand the complex Rwandan biophysical environment and to make decisions regarding its sound management. However, due to its inaccessibility to many potential users, the CPR completed in 1990, has been little used from the 1994 genocide to date. Moreover, the soil suitability maps and the crop regionalization for entire AEZ have been hardly relevant for farmers at watershed level (Steiner, 1998).

In the field of ISFM, the challenge ahead is how to use this soil map to implement soil-specific ISFM technologies, in the complex biophysical environment of Rwanda where: (1) soil scientists are expected to use the CPR with its Soil Taxonomy language (2) agriculture is practiced by smallholder farmers with their own soil knowledge system and (3) ISFM technologies are expected to be transferred by extensionists with little understanding of both soil knowledge systems. Two, but complementary, alternatives that emerge from this study are: (1) to present the CPR legend in relation to the landscape context and (2) to build ISFM technologies based on the synergy between scientific and FSK and to use the farmers' land and soil nomenclatures for technology transfer. This will require two important changes in the conduct of agricultural research and extension: (1) the research mode and institutions will need to effectively change from following the current top-down extension approach to pursuing more participatory and integrated approaches (2) the gap between the existing scientific and FSK will need to be bridged, in order to allow interactive communication between scientists and farmers. This will require the Rwandan soil scientists to master both Soil Taxonomy and the farmers' soil nomenclature so that they can serve as interpreter between scientists from other disciplines and the farmers. Soil scientists also require more training in the use of a Geographic Information System (GIS) so that they are able to use the soft copy of the CPR and to become familiar with the Rwandan biophysical environment.

In conclusion, a clear understanding of Rwanda's own biophysical environment (and effective communication of the acquired knowledge) and the adoption of appropriate research and extension approaches and conducive institutions is the most reasonable way of achieving sustainable agriculture development in the country. The CPR has a key role to play in this process.

Chapter IV: Farmers' soil Knowledge for Effective Participatory Integrated Watershed Management in Rwanda: towards soil-specific fertility management and farmers' judgmental fertilizer use.[16]

Abstract

In the complex soilscape of Rwanda, poor targeting of soil fertility technologies to soil types with different suitability is a major constraint for their adoption. A study was undertaken to understand how scientists can get insight into Farmers' Soil Knowledge (FSK) and introduce new soil-related technologies as part of the already functioning FSK system to enable soil-specific fertility management and farmers' judgmental fertilizer use. Farmer participatory research and biophysical diagnostic methods were used. Results from this study show that the FSK system is not only rational but is also practical and consistent with the scientific soil knowledge, with additional advantage of being user-friendly for local fertility experts, agronomists and extensionists compare to the international soil classification systems. The farmers' rationality is demonstrated by a clear agreement between farmers' cognitive soil knowledge (Corpus) and farmers' soil-related practices (Praxis). The farmers' practices follow clear coping mechanism and livelihood strategy in a complex biophysical environment. In the Akavuguto watershed case study, the mountains, with their *Urubuye* (*Entisols*), are limited by the slope gradient and stoniness; they are currently planted with trees. The upper hills, with their *Urusenyi* (*Entisols*) and *Inombe* (*Ultisols*), do not have major edaphic limitations; they are used for growing beans and sorghum crops that are demanding but key in the farmers' coping strategy. The back slopes, with their *Umuyugu/Mugugu (Oxisols)*, are limited by poor fertility status; they are used for growing cassava and sweet potato which are acid tolerant and less demanding crops. The valley bottoms, with their *Nyiramugengeri (Histosols)* and *Ibumba (Ultisols)*, are limited by very strong acidity; they are used for growing sweet potatoes. It is concluded that understanding the biophysical environment in terms of land units and associated farmers' soil types and farmers' practices rationality constitute an appropriate entry point to reach the above-mentioned objective.

***Key words**: Knowledge co-production, Analogous soil types, Understanding and communicate, Farmers' perspective of soils, Farmer practice rationality, Soil fertility management, Rwanda.*

4.1 Introduction

Since the 1990S, peoples' participation in agricultural research and development projects has been one of the issues of high priorities (Chambers, 1989). It is from the arena of participatory and integrated research approach at watershed level (German et al., 2006) on the one hand, and the inability of the

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international soil classification systems to be used in participatory manner (Raina et al., 2006) on the other hand, that soil scientists were alerted to the value of Farmers' Soil Knowledge (FSK) (Habarurema and Steiner 1997; Steiner, 1998; Niemeijer and Mazzucato; 2003; Payton et al., 2003; Barrera-Bassols et al., 2006a; 2006b).

The awareness of FSK worldwide has led to a new field of science which is called ethnopedology. Ethnopedology or the 'other pedology' is a hybrid discipline at the interface between natural and social sciences; it deals with the soil and land knowledge systems of rural populations from the most traditional to the modern (Barrera-Bassols and Zinck, 2003). It is distinct from anthropology, as it focuses on development issues to produce a locally informed development agenda and solutions of relevance to local people (Sillitoe, 1998 cited by Payton et al., 2003). This means that farmers' soil nomenclature can be much better at identifying soil-landscape relationship for mapping and soil fertility management problems than the hierarchical scientific classifications that are used through the developing world mainly because of problem of scale (Krasilnikov and Tabor, 2003). Even 1: 20,000 scale soil surveys can be too general where farmers' fields are small and soil variability is high (Krasilnikov and Tabor, 2003).

The FSK is also referred to as local, traditional, folk, native or indigenous soil knowledge. While WinklerPrins (1999) finds the term ''local'' the least problematic, Leeuwis and van den Ban (2004) specify that, in essence, scientific knowledge too is "local" and speak simply of scientists' versus farmers' knowledge. Since scientists compare their own soil knowledge to that of farmers as two epistemic communities/cultures (Ingram et al., 2010) and because the concept is already in use in Rwanda (Steiner, 1998), in this thesis we opt for the term FSK.

Farmers' (soil) world views are complex cultural assembles of beliefs and symbols *(Kosmos),* cognition *(Corpus)* and management practices *(Praxis)* of nature (Barrera-Bassols et al., 2006b). The usefulness of the FSK in the PIWM approach depends on its capacity to be integrated with the scientific soil knowledge (Payton et al., 2003, Barrera-Bassols et al., 2006b). Scientific soil knowledge assists to objectively understand the reasoning behind the farmers' soil-related management practices while the FSK 'helps validate scientific soil knowledge to ensure that it is not only scientific but also relevant and functional' (Barrera-Bassols et al., 2006b).

According to the bibliographic research of Barrera-Bassols and Zinck (2003), ethnopedological studies have been carried out in all continents, with most publications from Africa, America and Asia. The wide range of research covered under the umbrella of ethnopedology (Barrera-Bassols and Zinck, 2003) can be grouped into four main themes (1) the formalization of farmers' soil and land knowledge into classification systems, (2) the comparison of scientific and farmers' soil classifications, (3) the analysis of local land evaluation systems, and (4) the assessment of agro-ecological management practices.

With this much conformism to technical soil science sub-disciplines, ethnopedology scientists have been able to demonstrate that this branch is a valid scientific discipline – "the other pedology"- but not yet to create the required interaction between biophysical, agronomical and social scientists and extensionists for effective PIWM (WinklerPrins, 1999, Quinlan and Scogings, 2004, German et al., 2006). As a result, participatory research became steadily diluted over the years to become a somewhat tired discourse (Scoones et al., 2008). With these developments, the question is posed as to why the FSK is not used to make effective the PIWM approach in agricultural research and extension so that fertilizers are used efficiently and in a more functional Science-Policy-Practice Interface.

The objective of this chapter is to demonstrate how scientists involved in the PIWM can understand the FSK, exploit farmers' rationality and use the farmers' soil nomenclature to develop soil-specific technologies and to enable farmers' judgmental fertilizer use at watershed level. We argue that the introduction of any new soil-related intervention in harmony with the FSK system is likely to increase its relevancy and adoption.

4.2 Methodology

The research methods for this chapter combined an informal survey with field soil observation during transect walks. The informal survey consisted of participatory group discussion about soils and their use and interactive communications with key informants during transect walks. In this approach, the FSK gathering is completed in a few hours with informants sitting in one place and working from memory - mental soil map - (Gowing, 2004). The short list questionnaire/topic guideline interview was used as a tool to direct the debate and to collect information. The choice of the informal survey was dictated by the fact that it is noted that group meeting attended by a soil scientist are usually a more efficient way to obtain a balanced and informed opinion from the community than numerous individual discussions (Krasilnikov and Tabor, 2003). It was also consistent with Papadakis (1970) and Van Asten (2009) who sustained that direct questions should be avoided and that questionnaires are dangerous because they are susceptible to lead to biased or interested responses. The formal survey is particularly sensitive in Rwanda where the farmer has adopted a tactic behavior as adaptation to a top-down extension culture (see Chap 2, §2.3.1). This means that to undertake a participatory group discussion with farmers, the surveyor must have a great ability and good understanding of the problem studied (Papadakis, 1970).

The objective of the group discussion in this study was to identify the farmers' soil types and to predict their spatial distribution and to understand the rationality behind the existing agrosystems. The aim for transect walks was to check the farmers predictions on ground/field. In participatory discussions with farmers, topics included: (1) the physiographic analysis, or the identification of the land units in the watershed, (2) the identification of farmers' soil names (free-listing) and their classification criteria (ethno-semantic elicitation) (Niemeijer and Mazzucato, 2003), as well as the soil forming factors (Jenny, 1941), (3) the analysis of the soil-landscape relationship (Wielemaker et al., 2001), and (4) the analysis of land unit-soil type and agrosystem relationship (matching land unit, soil type and suitable crops). Based on the above information, and with consideration of the soil-landscape relationship, the farmers' soil types were compared to the dominant soil series from the soil map of Rwanda 1:50.000 (Birasa et al., 1990).

4.2.1 Participants selection process

Four sectors (a 3rd unit of a five-level administrative hierarchy) in the Akavuguto watershed were selected- *Coko, Cyahinda*, *Gasasa* and *Rusenge*. The choice of persons to participate in the study/meeting was done by random selection from a list of farmers, which was available at the sector office. Thirty farmers were invited to participate in each sector. A total of 120 farmers participated directly. During the soil information collection process, gender and age were taken into account. In each Sector, there were 15 women and 15 men; 15 of age below 35 years and 15 above 35 years. However, the focus in this study was not to compare the level of knowledge in these categories but to document the soil knowledge as a neutral body possessed by the watershed community as a whole and to understand the way they use this knowledge to solve their practical problems toward their livelihood. This was done through a dialogical process between representative categories of rural people. This is consistent with the fact that the FSK is relatively consistent between farmers' in the same village and between villages in the same cultural group in the same AEZ (Gowing et al., 2004; Barrera-Bassols, 2006b). This is possible because it is socially owned, as it is socially generated (Tesfaye, 2005). This means that the gathering of the FSK requires aggregation of knowledge through group discussion to arrive at consensus (Gowing et al., 2004).

4.2.2 Land units, soil types and soil-landscape relationship

The participatory group meeting was moderated by a facilitator (chair) using a short list questionnaire previously established by scientists and duly translated in local language – Kinyarwanda. The answers to questions were recorded on a flip chart by a secretary. Both the chair and the secretary were farmers, chosen by their colleagues. The strategy consisted of building consensus and precautions were taken to ensure that each person was allowed to express his/her knowledge. On a hilltop, with an overview on the entire landscape (Figure 1.7), participants were asked to list (free-listing) land units, soil types and parent materials in the watershed. They were later asked to elucidate the meaning (ethno-semantic elucidation) of each soil type, the limiting factors and the suitability for crop production. Finally, they were asked to link soil types to land units and existing agro-systems and their management. In this process, the role of researchers among farmers was to discreetly guide the debate to maintain the focus and to raise additional questions for more insights into FSK. The questions were raised until the consensus was reached. Researchers recorded the relevant farmers' observations in their own note books without disturbing the conversation flow. The meanings of farmers' soil terms were further crosschecked using the *Kinyarwanda*[17]- French dictionary (Jacob, 1985).

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[17] Kinyarwanda is the national language spoken in Rwanda.

4.2.3 Transect walks and field observation

The understanding gained during the participatory group discussions about land units, soil types, soil spatial distribution and suitable crops was enhanced during transect walks through field observation, interactive communication with key informants and individual farmers (Gobin et al., 2000). Three key informants/farmers were partnered with soil scientists and agronomists. Interviews/conversations were conducted, without formal questionnaire (Papadakis, 1970; Habarurema and Steiner, 1997). Six reference profiles, representative of the main soil types in different land units, were described and their diagnostic horizons identified (data considered in chapter V). Using the geographic coordinates, the farmers' soil types were compared to the dominant soil series from the soil map of Rwanda 1:50,000.

4.3 Results

4.3.1 Farmers' cognitive knowledge

- *Land units*

Based on the soil moisture regime, two main land units were distinguished: the dry upland mountains and hills and the wetland in the valley bottom. Based on geomorphologic aspects, such as slope gradient and slope length (difference in altitude between top and down slope), the upland was subdivided into the mountainous mass and hill land units. On basis of the slope, the hill land units were further split into the upper-hill (0-4% of slope) and the hill-side/back slope (12-25% of slope). The upper-hill comprises rounded hills, interfluves, and small plateaus. The back slope land unit is made up by linear slopes which link it to the valley bottom (see Figure 1.7). Each land unit is clearly identified by its local name (Figure.4.1).

- *Soil types*

Like animal and tree species, soils have vernacular names. This is a proof that farmers perceive the soil as a natural body and a biophysical entity. In the watershed, they have listed soil types/names intuitively. The criteria used are implicit in the soil's name (Table 4.1). Linguistic analysis (ethno-semantic elucidation) shows that the most obvious criteria to name soils in the watershed are: texture, soil depth, friability/consistence, structure, fertility, parent material and color.

Farmers, in the study area, have two perceptions of a soil type when it comes to the vernacular soil name. On the one hand, farmers know the soil as a natural body with horizons and other macroscopic soil attributes (as identified in scientific soil knowledge). On the other hand, horizons are identified with the same names of soil types. For instance, the dark top-soil, which is more friable - generally corresponding to the A horizon- is called *Umuyugu,* because of its friability. The red sub soil (generally corresponding to B horizon) is called *Inombe* because of its sticky properties which are mainly due to the relatively high content of clay. The weathered C horizon is called *Urusenyi, Ikigwagwa, Igishonyi* depending on the nature of the parent material. While there are some nuances with *Umuyugu, Inombe and Urusenyi/ikigwagwa/igishonyi* as soil types or as horizons, farmers make clear distinction between the two perceptions. The dominant characteristic of the profile, as determined by the texture, structure and the consistency, determines the soil type.

Table 4.1. Ethno-semantic elucidation of the farmers' soil types in the watershed.

Soil types	Derivation	Connotation	Characteristics
Urubuye	*Ibuye,* stone	Dominant presence of gravels, stones and outcrops	Extremely shallow soils generally on steep slopes of mountainous mass dominated by gravels, stones and outcrops
Urusenyi	*Urusenyi*, gravel	Dominant presence of gravels	Shallow soils on gently sloping terrains, generally on hilltops and thin interfluves on upper hills dominated by gravels
Inombe	*Kunomba,* to make mashed beans, potatoes/puree	Stickiness	Deep, stony, red, sticky (wet) and hard (dry) soils with block or prism like structure on plateaus, gently sloping and concave terrains
Ikigwagwa	*Ikigwagwa*, white and soft parent material	White and soft parent material	Shallow soils on white and soft parent material (Orthogneiss)
Umuyugu	*Kuyugumura, Kuyogoza,* Cultivate a big area	Friability, easy to work	Deep, stoniness, black (A) and yellowish (B), non sticky and very friable soil with fluffy structure on moderate slopes generally on hillsides.
Mugugu,	*Kuguuguuba, ubugugu* miserly insatiable, greedy	Extremely infertile, unproductive	More a fertility class than a soil type. All extremely infertile and poor responding soils. They are generally dusty and on hillside
Ibumba	*Kubumba, make ceramic pot*	Clay, pot material	Deep, clayey (sticky) soils with gley or pseudogley in the valley bottom
Nyiramu-gengeri	*Nyiramugengeri,* peat	Presence of organic matter in wetlands	A mixture of colluviums/alluvia and organic matter (Ap) on a layer of well weathered organic matter (Ah) over a clayey layer in the valley.

- *Parent materials*

In the watershed, farmers identified 4 parent materials (Table 4.2). Based on the rock type they observe on a given hill or land unit, farmers were able to link the land units and related soil types to the parent materials. However, for some soil types this was not obvious.

Table 4.2 Dominant parent materials in relation to land units and soil types

Farmers' geology	Scientific geology	Land unit	Soil type
Isarabwayi	Quartzite	Mountain	*Urubuye,*
Isarabwayi + *Igishonyi*[18]	Quartzite Micaschist	Hill top, interfluves	*Urusenyi*
-	Micaschist	Plateau, shoulder	*Inombe*
Ikigwagwa	Orthogneiss	Hillside	*Ikigwagwa*
Igishonyi	Gneiss	Hillside	*Umuyugu/Mugugu*
Umutsinda	Amphibolites	Hillside	*Umuyugu/Mugugu*
-	Tissue	Valley bottom	*Nyiramugengeri*
-	Alluvia & colluviums	Valley bottom	*Ibumba*

-: No parent material identified by farmers

- *Soil-landscape relationship*

Findings from this study show that there is a clear relationship perceived by farmers between a soil type and a land unit (Figure 4.1) and between a soil type and its parent material (table 4.2; see also Chapter V: poster 1 to poster 6). Farmers naturally associate the soil types to land units and to a parent material. The transect walks and the profiles description confirmed the soil-landscape relationship as predicted by farmers.

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[18] Igishonyi may refer at the same time to micaschist and to gneiss.

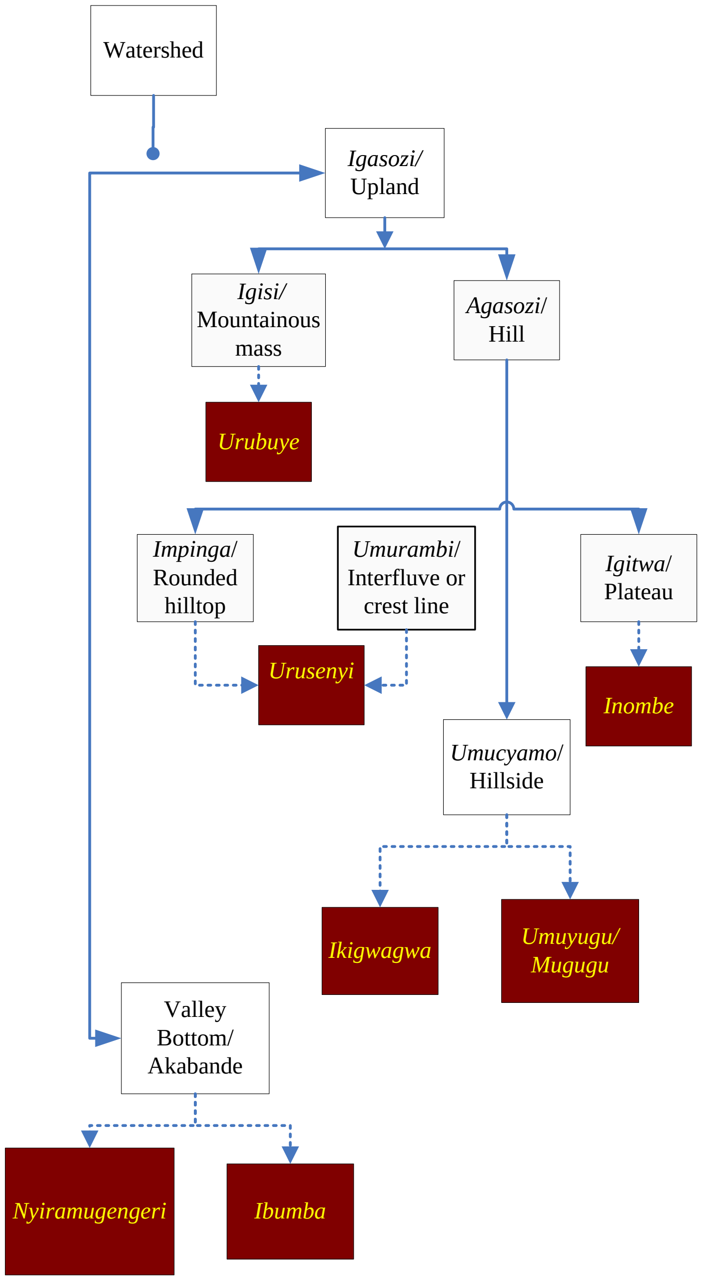


Figure 4.1 Soil-landscape relationships perceived by farmers: none shaded case= land unit; shaded case = farmers' soil type.

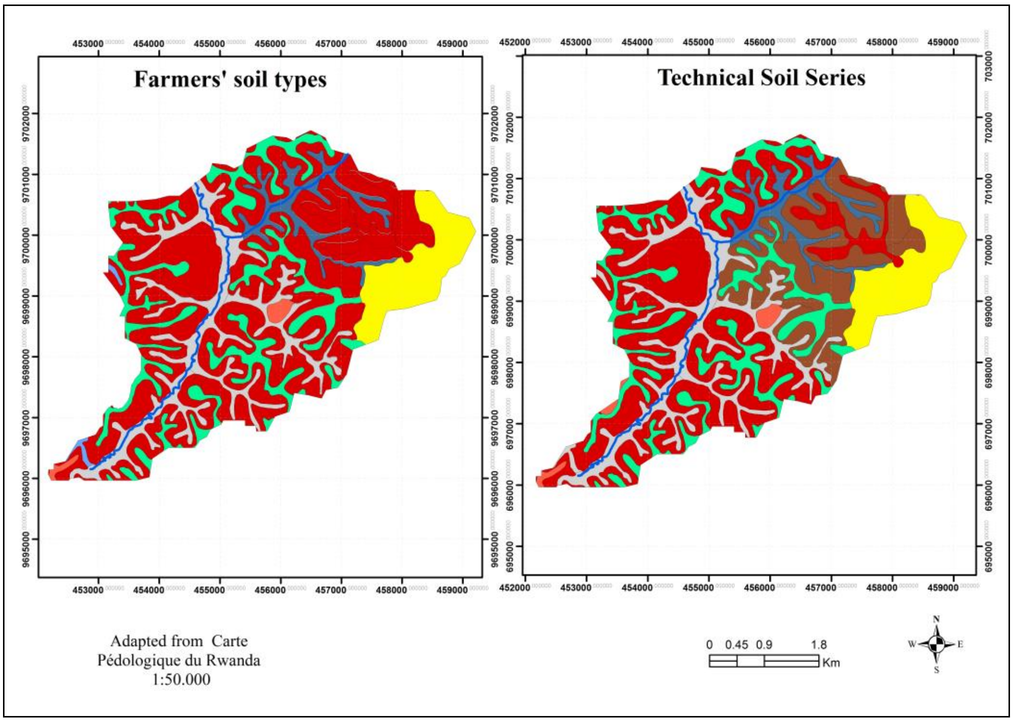
4.3.2 Link between scientific and farmers' soil knowledge

- *Farmer soil nomenclature and scientific soil classification system*

By means of land unit, diagnostic horizon of the farmers' soil type and geographic coordinates communication bridges between farmers' soil types and the scientific soil series of the soil map of Rwanda 1:50,000 were established (Figure 4.2). On the mountainous land unit, *Urubuye* corresponds to the mapping units where the dominant soil series is Bujumu (BUJ), which belongs to the *Entisols*. On the interfluves, *Urusenyi* corresponds to the mapping units where the dominant soil series is Gatonde (GAT), which also belongs to the *Entisols*. On the plateau and shoulder, *Inombe* corresponds with many secondary and tertiary soil series in different mapping units. These soils series belong to *Ultisols* and Kinombe (KNM) and Sare (SAR) soil series can be considered as their representatives. On the hillside, *Umuyugu/Mugugu,* corresponds to the mapping units where the dominant soil series are Kizi (KIZ) and Mata (MAT), which belong to *Oxisols*. In the valley bottom land unit, *Nyiramugengeri* correspond to the mapping units where the dominant soil series is Ruli (RL), which belongs to the *Histosols*. *Ibumba* corresponds to the mapping unit where the dominant soil series is Rwotso (RO), which belongs to *Ultisols*.

The established communication bridges are alternatives to taxonomic and cartographic correlations that have been problematic (Habarurema and Steiner, 1997; Niemeijer and Mazzucatto, 2003; Payton et al., 2003; Barrera-Bassols et al., 2006b). The weak statistic correlation between the two knowledge systems is explained by the differences in aims, methods and context of work (Ingram et al., 2010) or the different epistemic frameworks (Leeuwis and van den Ban, 2004). In the benchmark site, at least eight scientific soil series corresponded to six farmers' soil types (Figure 4.2). Epistemic differences are the reasons why different scientific soil series like MAT and KIZ on the one hand and KNB and SAR on the other hand can be identified by one farmers' soil type –*Umuyugu* and *Inombe* respectively. Since different scientific soil series of same suitability (according to farmers' observation and confirmed by analogous soil properties) may be grouped into one farmers' soil mapping unit, farmers' soil nomenclatures appear to be more suitability maps than soil maps/soil classes like in the scientific soil knowledge (Habarurema and Steiner, 1997). It is true that the finality of the scientific soil survey is also a soil suitability map (which also may group different soil series in one soil suitability class).

However, because of small-scale variations of soil characteristics in the complex soilscape of Rwanda, the CPR mapping units usually regroup many soil series – soil associations - such as: BUJ/GAT(MWO), MAT/KIA(FMB), KIZ/KNB(GAT), RL/RK(CR). In this association, the first soil represents the dominant soil series, the second, the secondary soil series and the third, the tertiary soil series.


Farmers' soil types

Technical Soil Series

Adapted from Carte
Pédologique du Rwanda
1:50.000

#	Land unit		Farmers' soil name	Diagnostic horizon	Geographic coordinates	Dominant soil series	Taxonomic legend (Family level) 1975
1	Mountainous mass/Ibisi	🟨	*Urubuye*	Entic Development	X= 467647 Y= 9698570	Bujumu (BUJ)	*Loamy-skeletal, mixed, non acid, isothermic LlithicTtroportents*
2	Interfluve/Umurambi	🟩	*Urusenyi*	Entic Development	X= 453413 Y = 9698870	Gatonde (GAT)	*Loamy-skeletal, mixed, non aci, isothermic Lithic Troportents*
3	Plateau/Igitwa	🟧	*Inombe*	Argilic	X= 455784 Y= 9701418	Kinombe (KNM)	*Clayey, kaolinitic, isothermic Humoxic Sombrihumult*
		🟧		Argilic	X= 455608 Y= 9701944	Sare (SAR)	*Clayey-skeletal, kaolinitic, isothermic Tropeptic* *Eutrorthox*
4	Hillside/Umucyamo	🟥	*Umuyugu*	Oxic	X= 454530 Y=9699456	Mata (MAT)	*Clayey, kaolinitic isothermic Humic Sombrihumox.*
		🟫		Oxic	X= 456934 Y=9699966	Kizi (KIZ)	*Clayey, kaolinitic, isothermic Typic Haplorthox*
5	Valley bottom/ Akabande	⬜	*Nyiramugengeri*	Histic	X = 455117 Y= 9699534	Ruli (RL)	*Euic, isohyperthermic Typic Troposaprits*
		🟦	*Ibumba*	Argilic		Rwosto (RO)	*'Fine-silty, mixed, isothermic, aeric Umbric Tropaquults*

Figure 4.2 Communication bridges (diagnostic horizons and geographic coordinated) between farmers' soil names and CPR soil series. Source: Rushemuka et al. (2014a).

When the tertiary soil series is in brackets, it means that it is an inclusion. The soil series in the same mapping unit often have different suitability as they belong to different soil orders. In these conditions, soil surveyors experience much difficulty to produce relevant soil suitability maps which takes into account the small scale variation of the soils (Steiner, 1998; Krasilnikov and Tabor, 2003). In this context, while the scientific soil survey may appear to be more detailed – soil series level - compare to the nominal farmers' soil nomenclature, the precision of the scientific soil survey - at farmer level - pose two serious problem: (1) the CPR mapping units are not pure – soil associations - and the degree of purity is not specified and the location of the associated soil series is not described within the soil mapping unit, (2) while the fact that many scientific soil series are linked to one farmers' soil type may suggest that the scientific soil survey is more accurate to the farmers' soil survey, it appears that this happen only when these soils series have the same suitability. About the precision of each system, while the scientific soil survey is restricted by the scale of printed sheet of paper and the complexity of the biophysical environment, farmers' identify precisely the soil locations in the watershed. They identify different soil within one farm and exploit any soil difference (Steiner, 1998; Ingram et al., 2010). They do this thanks to their precise and accurate "mental soil map" (Barrera-Bassols et al., 2006). This means that, at watershed level, the FSK is not only more precise but also more practical than the scientific soil survey. It is in this context that Steiner (1998) suggests that when searching for potential crop improvements, researchers and extensionists should make better use of farmers' profound knowledge of soils, work closer together with them and offer them a range of cultivars and flexible soil management recommendations. The same author sustains that giving flexible extension recommendations and relying on farmers' location-specific knowledge will help both sides to create an atmosphere of trust and to assist farmers in making optimum use of their soils.

- *Farmer soilscape knowledge and chemical soil properties*

Table 4.3 presents chemical soil properties of the A horizon for the CPR dominant soil series. It can be seen from this table that the relatively good soil properties are found on the upper hill land unit, where *Urusenyi* and *Inombe* dominate. On these land units, the pH water is > 5.2; the sum of bases is > 6 Cmol/kg soil with no aluminum toxicity. On the hillside land unit, where *Umuyugu/Mugugu* dominates, the soil series have extremely poor soil properties: pH water = 4.6, sum of bases = 0.5 Cmol/kg soil with high concentration of aluminum (3-15 Cmol/kg of soil). In the valley bottom land unit, where *Nyiramugengeri* dominates, the RL soil series seems to be limited only by the pH water= 4.1, while the RO would be limited by both pH water = 4.1 and the sum of bases: 0.8 Cmol/kg of soil.

Table 4.3. Chemical soil properties of the dominant soil series in the watershed.

Land unit	***Land-sub unit***	***S.Series***	***HZ***	***Depth***	***pHw***	***pHKCl***	***TOC***	***TN***	***Pav***	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	ΣB	***CEC***	Al^{3+}	H^{+}	***ECEC***	***Base SAT.***
				cm	***-***	***-***	***%***		***ppm***	***Cmol/kg***								***Cmol/kg***	***%***
Upper hill	*Mountain*	*BUJ*	*Ap*	*0-17*	*5.5*	*4.5*	*1.7*	*0.18*	*2.7*	*5.02*	*0.82*	*0.28*	*0.04*	*6.2*	*17.0*	*0.18*	*0.00*	*6.3*	*97*
	Interfluve	*GAT*	*A*	*0-25*	*5.6*	*4.4*	*1.1*	*0.85*	*26.0*	*4.19*	*1.41*	*0.51*	*0.02*	*6.1*	*8.3*	*0.00*	*0.05*	*6.1*	*100*
	Shoulder	*SAR*	*Ap*	*0-17*	*6.5*	*5.5*	*2.3*	*0.17*	*7.0*	*7.39*	*3.55*	*0.85*	*0.03*	*11.8*	*13.4*	*0.00*	*0.05*	*11.8*	*100*
Hillside	*Hillside*	*MAT*	*A1*	*0-15*	*4.7*	*3.8*	*3.1*	*0.16*	*-*	*0.30*	*0.10*	*0.10*	*TR*	*0.5*	*12.1*	*3.90*	*12.10*	*4.4*	*11*
		KIZ	*Ap*	*0-15*	*4.8*	*4.1*	*1.7*	*0.12*	*1.5*	*0.26*	*0.02*	*0.07*	*0.03*	*0.4*	*12.0*	*3.24*	*0.23*	*3.7*	*10*
Valley bottom	*Valley bottom*	*RL*	*Oa*	*0-30*	*4.1*	*3.9*	*23.4*	*1.93*	*-*	*36.80*	*8.70*	*0.30*	*1.00*	*46.8*	*99.7*	*-*	*66.50*	*46.8*	*-*
		RO	*A*	*0-35*	*4.4*	*3.5*	*2.6*	*0.20*	*2.5*	*0.49*	*0.09*	*0.10*	*0.05*	*0.7*	*12.0*	*3.64*	*12.10*	*4.4*	*17*

CEC à l'acétate d'ammonium, ECEC = ΣBase + Al^{3+}; SAT. = Saturation = (ΣB/ECEC)*100

Source: adapted from CPR (Birasa et al., 1990).

4.3.3 Farmers' practices: land use and soil fertility management

Farmers claim that the soils in the watershed are generally of poor fertility and with different suitability for crop production. For all soil types to be productive, farmers have, at least, to apply organic fertilizers (manure or compost) on a seasonal basis. This is consistent with the noted poor residual effect of green manuring in Rwanda soil conditions (Drechsel et al., 1996). However, soils differ in their response to organic fertilizer application depending on their natural fertility. Figure 4.3 and Table 4.4 show that the link between a land unit and a soil type is the main factor determining the land use and soil fertility management in both low input (e.g. organic fertilizers) and high input (e.g. lime + organic fertilizers + inorganic fertilizers) systems.

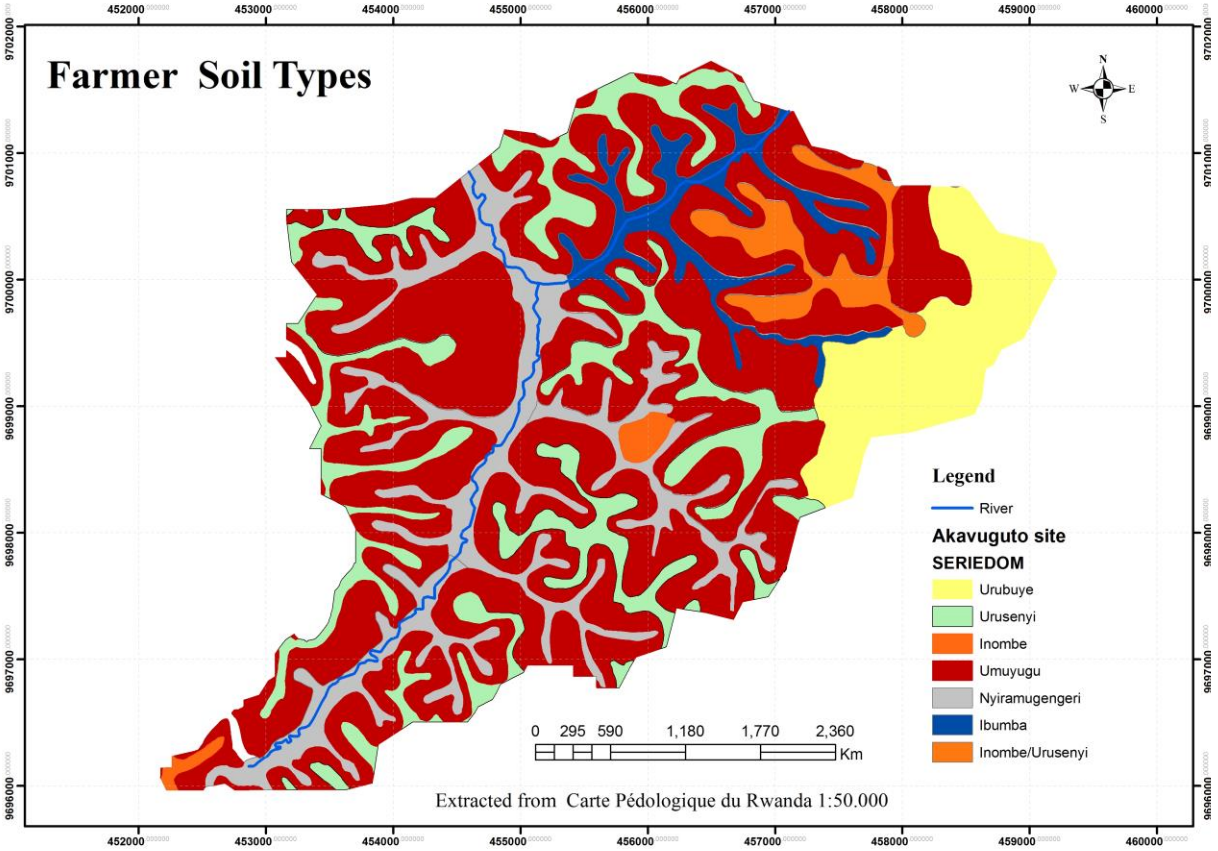


Figure 4.3. Farmers' soil types and their explicit legend (Table 4.4).
Source: Rushemuka et al. (2014a).

Table 4.4 Farmers' biophysical environment understanding and soil fertility management strategy.

Main Land unit	**Sub land unit**	Slope (%)	**chart**	**Farmers' soil name**	**Depth (cm)**	**Gravel (%)**	**Fertility**	**Limiting factor**	**Land use**	**Soil fertility management**					
										Low input			**High input**		
										Crop	**Input**	**Yield**	**crop**	**Input**	**Yield**
Mountain	Mountainous mass	>55	🟨	Urubuye	0-15	50	Poor	Slope Fertility Stoniness	W.land	Eucalyptus, Pinus	N/A	Poor	N/A	N/A	N/A
Upper hill	Interfluve and rounded hill summit	0-4	🟩	Urusenyi	30-50	30	High	No major limitation	Households + C. land	Sorghum-Beans	Farmyard manure	Good	N/A	N/A	N/A
	Plateau/ shoulder	0- 8	🟧	Inombe	>200	0	High	No major limitation	Households + C. land	Sorghum-Beans	Farmyard manure	Good	N/A	N/A	N/A
Hill- side	Back slope	12-25	🟥	Umuyugu/mugugu	>200	0	Poor	Fertility (Ibeeja) Slope	C. land + W. land + G. land	Cassava+ sweet potato Eucalyptus Eragrostis	Green manure	Very poor	Irish potato-Wheat/maize	L+ O.M + F	High
Valley bottom	Valley bottom	0-4	▒	Nyiramugengeri	100-200	0	Medium	Fertility (Ibeeja) Drainage	Tea P. & C. land	Sweet potato	Drainage	Good	Beans, Maize, Irish potato	L + F	High
		0-4	🟦	Ibumba	100-200	0	Medium	Fertility (Ibeeja) Drainage	C. land	Sweet potato	Drainage	Good	Beans, Maize, Irish potato	L + F	High

N/A=Not applicable; C. land = crop land; W. land =Wood land; G. land= Grass land; Tea P. = Tea plantation; L= lime; O.M = Organic matter; F= Fertilizer; for color column see the map (Figure 4.3).

Ibeeja syndrome is a farmers' soil fertility indicator (soil illness). It is not observed on the soils themselves, but is rather expressed through the stunted crops grown in these soils.

4.4 Discussion

This study has shown that the FSK system in Akavuguto watershed is rational and functional and that there is enough room for collaboration between scientific and FSK systems to develop relevant and soil-specific technologies in agricultural research for development. This is consistent with the findings of Habarurema and Steiner (1997) in Rwanda, Payton et al. (2003) in East Africa (Uganda and Tanzania) and in Bangladesh and Barrera-Bassols (2006) in Mexico. This means that the basic principles for both knowledge systems are the same. This is proved by the fact that the farmers' soil nomenclatures were used as the base for developing the first soil classification systems in the 1800s (Krasilnikov and Tabor, 2003). The fact that the farmers' soil names correspond to soil suitability classes (Habarurema and Steiner, 1997, Steiner, 1998) indicates that the ultimate outcome of both knowledge systems is the soil suitability. The noted differences are essentially explained by difference in epistemological framework (Leeuwis and van den Ban, 2004; Ingram et al., 2010). While it could be argued, in the case of CPR, that the difference could be also due to the difference in level of precision, Payton et al. (2003) and Barrera-Bassols (2006b) have noted that even with the same level of detail the differences subsist. What is important is that one system is transmittable into another through the established communication bridges.

4.4.1 Farmers' cognitive knowledge

From a cognitive point of view and in farmers' perspectives, findings from this study show that farmers as a community understand their biophysical environment very well. This is demonstrated by practical names for land units (Figure 4.1), soil types (Table 4.1), parent material (Table 4.2), and by the link between land units and soil types (Figure 4.1). They have also a clear perception of soil suitability based on soil quality indicators which guides crop allocation and soil fertility management in relation to their low-input system (Table 4.4). When asked for reasons for the favorable suitability in *Urusenyi*, farmers indicate that "*Urusenyi rurashyuha': Urusenyi* soil is 'hot', to mean that crops germinate rapidly and grow faster. The limitation in *Urusenyi* is the excessive drainage which makes it more sensitive to water shortage. The soil depth, < 50 cm, and the gravel status >30% are not seen as limitations. Farmers maintain that "*ifumbire y'Inombe n'imvura":* "the 'fertilizer' for *Inombe* is the rain" to mean that *Inombe* produces well if there are good rains. The limitations are the high sensitivity to water shortage and the workability. Indeed, *Inombe* soil becomes sticky when wet and hard when dry. For farmers, *Umuyugu/Mugugu* soil is sick. It suffers from *Ibeeja. Inshanya and Ubushâlire* syndrome are used interchangeable with *Ibeeja* in many acidic regions of Rwanda. The *Ibeeja syndrome* is reported on unproductive soils well known for their very strong to extreme acidity (pH < 4.7), aluminum toxicity, phosphorus fixation and low basic cation concentrations (Rutunga and Neel, 2006). *Nyiramugengeri* and *Ibumba soils* are also limited by *ibeeja*.

Compared to the scientific soil knowledge system, farmers have an accurate and precise 'mental soils map' (Barrera-Bassols et al., 2006b). In addition, the farmers' soil nomenclature, being intuitive, is flexible enough to better cope with a very complex soilscape than an international soil classification system like Soil Taxonomy (Niemeijer and Mazzucato, 2003; Cools et al., 2003). This means that at farm level, the farmers' soil nomenclature is more practical than the scientific soil survey (Krasilnikov and Tabor, 2003). This was demonstrated by the ease with which farmers listed the soil types (Table 4.1) and linked the soil types with the land units (Figure 4.1). This means clearly that the systematic consideration of soil variations, while being an insurmountable problem in practical soil fertility management in the scientific perspectives (Giller et al., 2011), is not an issue for farmers (Steiner, 1998). From a scientific point of view (soil chemistry, soil biology), it is noted that farmers may have knowledge gap regarding phenomena that they cannot see (Barrera-Bassols et al. 2006b; Van Asten et al. 2009). However, the farmers' soil nomenclature is, often, connotative of soil properties (Table 4.1). In addition, the rationality of farmers' soil fertility management (Figure 4.3 and Table 4.4) is really remarkable and supposes a high sensitivity to soil properties (e.g. *Ibeeja*). Currently, many scientists (Barrios et al., 2001; Niemeijer and Mazzucato, 2003, Barrios et al., 2006; Barrios et al., 2011; Dawoe et al., 2012) recognize a number of farmers' soil quality indicators which, in many cases, are in accordance with chemical soil properties. Based on the sensitivity of soil quality indicators (indicator plants, earthworms, soil color, smelling etc.) and in their low input system, farmers exploit any soil fertility difference of their field (Table 4.4). This is consistent with many authors observations (Habarurema and Steiner, 1997; Steiner, 1998; Niemeijer and Mazzucato, 2003). This is, sometimes, referred to as 'precision agriculture' (Barrera-Bassols et al., 2006b). It is obvious that farmers with such deep soil knowledge cannot adopt blanket fertilizers recommendations, especially when their efficiency is not evident. This is consistent with the observation of many other studies across Africa (e.g. Sileshi et al., 2010; Giller et al., 2011).

4.4.2 Crop allocation and soil fertility management strategy

Farmers' practices, in the watershed, follow a clear coping strategy in poor biophysical and socio-economical environments. This strategy is captured in the existing land use, judicious choice of crops, their spatial allocation and the corresponding soil fertility management (Figure 4.3 and Table 4.4).

In the watershed, farmers grow trees on the mountainous mass and the steep slope terrains of the back slope land unit of the hilly region. These trees are exploited for timber, stakes or charcoal. This way, farmers can still get some profit from these otherwise marginal soils. This land unit is limited by slope gradient ($\geq$ 55%), soil depth (0-15 cm) and poor fertility status (strong acidity and calcium deficiency). Farmers cultivate the strategic crops (beans-sorghum rotation) on best soils (*Urusenyi* and *Inombe)* on the upper hill land unit, where they apply, on seasonal basis, the best household soil fertility management input: farmyard manure (FYM). The limited FYM is preferably applied to these soils because it is where farmers have noted the best crop yield response compared to other soil types in the watershed. The farmers' perception is consistent with scientific soil knowledge which indicates relatively good soil properties such as $Ca^{2+,}$ Mg^{2+} and pH (Table 4.3). The non-limitation in $Ca^{2+,}$ Mg^{2+} and the moderately acid conditions allow these soils to respond favorably to FYM. This would indicate that the major soil chemical property limitations in *Urusenyi* and *Inombe* soils are C and N, which are expected to be supplied by the FYM. This would be consistent with the green manuring experiment of *Rubona (Southern Rwanda)* which showed significant difference in organic C and N between plots with and without green manure (Hargedon, 1995 cited by Drechsel et al., 1996).

The relatively good soil chemical properties (basic cations) of *Urusenyi* and *Inombe* soils compared to *Umuyugu/Mugugu* are explained by their geological origin (Table 4.2) and the slope gradient of the land unit where they occur (Table 4.4). The allocation of beans on most fertile soils is due to a comparative advantage as an important source of protein ('the meat of poor') in the household diet, in rural Rwanda. The strategic role of sorghum lies in the fact that it occupies an important place in the family food security and constitutes at the same time, a source of income for a rural Rwandan household. Indeed, sorghum is a traditional crop and its harvest is transformed into a local beer known as *Ikigage* ('the drink/milk of poor'). The *Ikigage* also plays an important social role in cultural ceremonies like wedding, baptism and other traditional feasts. This means that it has an assured local market. In the semi-humid area, it offers also the advantage of being more resilient to erratic rainfall. In acidic soils, it is more tolerant to acidic conditions than maize.

Because of its poor fertility and under the farmers' inputs, *Umuyugu/Mugugu* soils, on back slope, cannot produce legumes and cereals. Indeed, pH = 5.2 is considered as a threshold below which Al^{3+} becomes toxic to most food crops (Sanchez, 1976, Brady and Weil, 2002). They are used to produce cassava and sweet potato as sources of energy for the family food security. The allocation of sweet potato and cassava is a farmers' strategy to cope with poor soils which can no longer produce cereals and grain legumes (Drechsel et al., 1996). On this land unit, farmers try to manage soil fertility with Eucalyptus and Eragrostis green manure as the most abundant bush vegetation. When asked (during the discussion) about the eventual adverse effect (allelopathy) of such green manure on crop yields, farmers maintain that they observe no such adverse long-term effect. The scientific explanation would be the fact that, on these depleted soils (see Table 4.4), the leaf biomass is likely to serve as a source of basic cations such as Ca^{2+}, Mg^{2+} and K^+ (Parotta, 1999). The positive impact of such biomass on crop yields is more evident on poor soils than on rich soils (Mendham et al., 2003). However, because of the poor crop yields (1 t/ha) (Roose and Ndayizigiye, 1997), many farms are abandoned to *Eragrostis olivacea - K. schumach* grass land fallow in spite of the shortage of land in a densely populated country like Rwanda. The farmers' observation is, here also, consistent with the scientific information because the soils in this land unit are well known for their very strong acidity ($pH < 4.7$), aluminum toxicity, phosphorus fixation, and low basic cation concentrations (Table 4.3). The poor nutrient status makes these soils unproductive for most seasonal crops (Rutunga and Neel, 2006). Perhaps, the most limiting basic cation is Ca^{2+}. Indeed, when Ca^{2+} concentration in the soil solution falls below a critical value, as it is the case in the study area (Table 4.3), many metals including Mg^{2+}, Mn^+, and Zn^+ that are normally beneficial as nutrients become highly toxic and the roots become stunted and gelatinous (Brady and Weil, 2002). This might explain why the introduction of a high input system (limestone, organic input and fertilizers) induced spectacular yields of different crops: e.g. 30-40 t/ha of Irish potato, 3-5 t/ha of wheat, 3-4 t/ha of beans and 2-3 t/ha of soybean (Rushemuka et al., 2012). In this process, lime is expected to have raised the pH to 5.5, to supply Ca^{2+}, to avail P and to neutralize different cations toxicity (Rutunga and Neel, 2006). Organic matter is mainly known to increase the CEC and the fertilizers to supply nutrients N, P and K.

Nyiramugengeri and *Ibumba,* in the valley bottom are traditionally used to produce sweet potatoes. The major limitations are fertility (*Ibeeja/ubushalire*) and drainage. Once again, the farmers' perception is consistent with the scientific soil knowledge. Indeed, this land unit is limited by very strong acidity (pH water = 4.1) and poor drainage (Table 4.4). At pH level between 4 and 4.5 the H^+ ions themselves are of sufficient concentration to be toxic to some plants, mainly by damaging the root membranes (Brady and Weil, 2002). At pH lower levels < 4, exchangeable H^+ ions are more prominent and Al^{3+} less prominent on the organic than on the mineral soils (Brady and Weil, 2002). With improved drainage, and under the influence of high input system (lime + fertilizer), this land unit is also used for maize and Irish potato production (Table 4.4). Here, non-acid cations like Ca^{2+}, Mg^{2+} from lime are expected to substitute H^+ on the complex and fertilizers to supply nutrients (N, P and K).

4.4.3 Coping/adaptation mechanism and livelihood strategy behind crop allocation and soil fertility management practice

As mentioned above, in the crop allocation and soil fertility management process, farmers' pursue clear coping mechanism and livelihood strategy the best they can. At first level, they aim at the household's balanced diet and food security. In this logic, beans, sorghum, sweet potato and/or cassava are important elements of this food security strategy. At second level, they target any source of funds for different household's needs (e.g. school materials and school fees, health insurance, cloths). At this level, sorghum beer (*Ikigage*) constitutes a source of income. If the family can own livestock (e.g. cow, goat, chicken) it is another source of food security (protein, energy and fat), income and manure. The wood plantation on marginal soils is also an addition source of income. It is clear, from the above considerations, that Rwandan farmers are not really ignorant peasants and subsistence-oriented farmers but rational entrepreneurs, acting strategically and trying to cope with their complex and poor biophysical environment, the best they can, with limited and constraining financial resources. The problem is that, given the few fertile soils (Figure 4.3 and Table 4.4), on one hand, and the population pressure, on the other hand, many households have inherited only lands in the infertile soils where they can only produce poor yields of sweet potato and/or cassava in rupture with the farmers' livelihood strategy. This explains the chronic hunger and the malnutrition which has been persistent since many decades in the acid regions of Rwanda. In view of the above considerations, any external intervention will stand a chance if only it bears in mind the farmers' coping mechanism and livelihood strategy as a result of their interaction with their biophysical environment and socio-economic constraints. For instance, the high input system is an entry point for farmers to accept in their coping strategy, the introduction of new crops such as wheat, Irish potato and Maize (Table 4.4).

4.4.4 Practical lessons learnt

The effectiveness of the FSK system is really impressive. This is more significant as the set up of the SPPI in the scientific perspectives has been an insurmountable problem for now more than 80 years of agricultural research and extension in Rwanda (ISNAR, 1982; Rutunga, 1991; Drechsel et al., 1996). In the broader African context, this is partially explained by the well known insufficient connectivity between pedology (soil types) and soil fertility management (Papadakis, 1975, Sileshi et al., 2010; Giller et al., 2011). For the case of Rwanda, it is particularly complicated by the complex soilscape of this country (Steiner, 1998). The challenge is how to take into account systematically soil variations when designing experiment, when evaluating data and when transferring soil-related technologies, without a user-friendly communication language about soils, knowing that in the complex soilscape of Rwanda, any detailed soils map would involve prohibitive cost. In reality however, the main problem is not so much the CPR scale but the fact that the potential users hardly understand nor its philosophy neither its language (Habarurema and Steiner, 1997; Steiner, 1998). Thus, the dilemma for scientists is that on one hand, the necessary basic principles to sustainably produce food are known in all relevant scientific disciplines while on the other hand, the executive framework (in terms of SPPI) to combine these principles in a more useful manner to solve farmers' food production problems has been and is still a challenge. This is where the philosophy of bridging scientific and FSK, and using farmers' terms for land unit and soil types during the PIWM to jointly develop soil-specific fertilizer recommendations, is very practical (Table 4.4).

In this framework, findings from this study show that the major constraint to farmers, in the study area, is not the farmers' little understanding of their biophysical environment, but the inherently poor soils (*Umuyugu/Mugugu* on the hillside and *Nyiramugengeri* and *Ibumba* in the valley bottom) and the lack of resource to acquire external inputs (lime, organic and inorganic fertilizers) to build up the fertility of their fields (soil fertility domestication). Without clear understanding of the biophysical environment, researchers, policy makers and extensionists fail to build up the SPPI in agricultural research for development. The absence of a functional SPPI can explain why decision makers in policy and practice 'typically use insufficiently the research-based knowledge available and researchers typically produce insufficiently knowledge that is directly usable' (Wiechselgartner and Kasperson, 2010). The introduction of new technologies in the farmers' functional soil knowledge perspective (Table 4.4) is likely to be an alternative solution. In this framework, scientists having (jointly with farmers) developed a technology for a given soil type will rely on farmers' location-specific for adapting these technologies to their different soil types. The case of *Umuyugu/Mugugu* with their *Ibeeja* soil fertility indicator constitutes a good example. For instance, while research may recommend liming for acid soils with soil pH water < 5.2 (Sanchez, 1976), the message for farmers would be formulated that lime is required for soils suffering from *Ibeeja* like *Umuyugu/Mugugu* on back slope and *Nyiramugengeri* and *Ibumba* in the valley bottom This may help to avoid the abusive use of lime and inefficient use of other limited inputs.

4.5 Conclusion

The overall objective of this chapter was to contribute to the effectiveness of the PIWM innovation model as an appropriate framework for the SPPI. It was specifically, to demonstrate how the FSK can improve the intelligibility of the soil knowledge system and its application by non-soil specialists involved in the PIWM process. This study shows that the farmers’ land units and soil names complemented with soil chemical properties are key factors for understanding the farmers’ practice rationality. The later is a good starting point for planning sound interventions and their efficient implementation. The farmers’ soil terms are also user-friendly communication channels to enable soil-specific technologies and farmers’ judgmental fertilizer use.

Chapter V: Soil Reference System and soil properties interpretation in Rwanda: Akavuguto watershed case study

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Abstract

In Rwanda, within one agro-ecological zone, soils of different suitability vary over short distances and in a complex manner in response to relief, parent material and altitude. Under such conditions in practical agriculture, extrapolating soil-related experiment results obtained from experimental plots of one soil type to analogous soil types (soil-specific intervention) is a challenging issue. A Regional Soil Reference System was established to demonstrate a strategy of coping with this complex soilscape. Using scientific and farmers' soil knowledge along the slope (different land units), results showed that under the low input system of Rwandan farmers, soil properties are more results of the nature of the soil type than the management influence. Between soil types, relatively good soil properties of *'Urusenyi' (Entisols)* and '*Inombe*' (*Ultisols*), on the upper hill, were well elucidated by their intrinsic soil properties related to their parent materials and their topographic position. The poor soil properties of '*Umuyugu/Mugugu' (Oxisols)* and *'Nyiramugengeri' (Histosols),* on the back slope and valley bottom respectively, were also explained by their parent materials and the geomorphological position. This means that, in the study area, the interpretation of soil-related interventions needed to consider, first of all, the contribution of the soil type. The effects of other factors like the human influence were more significant within soil types than between soils types. It was concluded that, at watershed level, the farmer's soil nomenclature-based soil reference system can be used as a tool to monitor changes in soil properties and crop yields and can enhance the application of existing biophysical resource information.

Key words: *Land units, Soil types, land uses, soil property interpretation, Rwanda*

5.1 Introduction

In the mountainous highlands of Rwanda, soils vary over short distances. On the other hand, the most accurate available soil fertility management planning tool is the medium scale (1:50.000) soil map of Rwanda (CPR). The CPR is under '*Soil Taxonomy*' and has a pedogenetic legend (soil forming factor-oriented). The main challenge for soil scientists working with ISFM experts, crop production scientists, extensionists and farmers, in agricultural research for development for instance, is more the common and accessible communication language about soils and soilscape than the understanding of chemical or physical soil properties of a given soil series or composite soil sample at site level. In those circumstances, the soil properties or even the soil-related experiment results, at experiment plot level, are of little use if the plot itself is not first of all and properly related to a soil type and a land use within the soil type in a given land unit within one AEZ. Indeed, soil properties such as pH, Ca^{2+}, Mg^{2+}, K^{+}, P etc. and experiment results are better interpreted if linked to a soil type and to a land use within the soil type in relation to the land unit where the soil occurs. In practical agriculture, it is strategic to exploit the concept of “soil individual[19]” or “polypedon” (Figure 5.1), where the soil and the land unit are assimilated to other natural bodies like animal or tree species. The implication is that like in the case of other natural bodies, the soil name must be identified not only in systematic classification terms but also in the user’s friendly language (e.g. farmers’ soil nomenclature). In addition, the spatial distribution must be known (e.g. land unit) and the human influence (historical and operational management) must be indicated if soil properties are to be useful and experiment results are to be statistically properly interpreted for result extrapolation in analogous soil types at watershed level. ‘We can efficiently manage a biophysical environment/the land if only we understand it’.

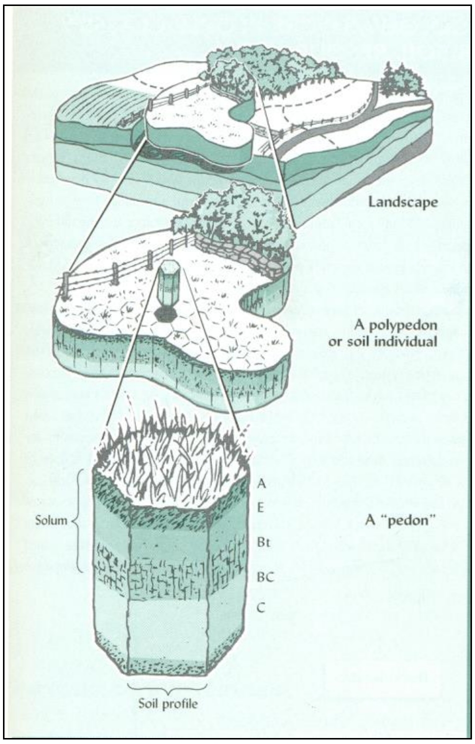

Figure 5.1 Schematic diagrams to illustrate the concept of soil individual and its implication in the biophysical environment understanding. Source: Brady and Weil (2002).

Understanding the biophysical environment is a fundamental principle and means to understand the factors that act on this biophysical environment and their respective influences on the same environment. As far as soils are concerned, this calls for an understanding of soil nomenclature, soil-landscape relationship (Wielemaker et al., 2001), soil forming factors (Jenny, 1941) and their respective influences on soil properties.

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[19] All the soil individuals in the world that have in common a suite of soil profile properties and horizons that fall within a particular range are said to belong to the same soil series (Dent and Young, 1981; Brady and Weil, 2002, IUSS Working group, 2006).

Soil forming factors and soil-landscape relationship are the two paradigms used by soil surveyors to produce soil maps. Soil survey is a kind of ‘knowledge system’ as defined in knowledge engineering and soil maps are representation of structured knowledge about the distribution of soils in the landscape (Bui, 2004). Therefore, to use them one must display the mental model used by soil surveyors. The problem is that in the soil-centred soil map, a considerable part of the context-related knowledge and data which is collected and used during a soil survey (soil surveyor mental model) is condensed in the soil map report/booklet and does not appear in the narrative legend of the final soil map (Wielemaker et al., 2001). The result is that few users outside pedologists are familiar with this ‘knowledge system’ (Bui, 2004). As a consequence of the inaccessibility of this ‘knowledge system’ to many potential soil map users, many soil maps produced in developed and developing countries, Rwanda included, are ‘sleeping beauties’ (Cline, 1981). The underuse of the soil resource information has eliminated soil surveyors (pedologists) from the debates about practical agriculture, poverty reduction and environment conservation policies and has opened a window for many speculations in the field of soil fertility management. One example is the way that the concept of the within-farm soil fertility gradients at increasing distances from the homesteads (Vanlauwe and Giller, 2006; Tittonell et al., 2007) has been overemphasized over the soil-landscape relationship or the toposequence and catena concepts. Both toposequence and catena mean a series of soil-slope relationships characterized by differential parent materials and uniform parent materials respectively but with identical differentiating topo-drainage characteristics (Okusami, 2006). This sequence, be it toposequence or catena, has come to be known in soil classification/mapping paradigms as soil association (Okusami, 2006).

From the difficulties of interpreting and exploiting soil map information by many potential users, the Regional Soil Reference System (RSRS) was developed. After the ‘Le petit Robert 1’ (Robert, 1990), the reference system - from its geometric meaning - is understood as a system of axis and points from which the position of one point is defined - with help of its coordinates. Likewise, in soil science, especially with the Geographic Information System (GIS) era and, due to the recognized importance of the terrain reality, for monitoring and evaluation purposes, it is now imperative to locate a soil sample – profile or composite soil samples– with help of its geographic coordinates and extract the existing soil information at this point (Bock, 1994).

A RSRS can be defined as a multi-hierarchical land information system where a set of geo-referenced representative soil profiles (Figure 5.2) and land use suitability are described, in relation to the soil forming factors and the soil-landscape relationship in precise geographic scope. The geographic scope may be a small area – e.g. watershed – representative of a big area – e.g. natural region. In this approach, the similar soil series – in terms of crop suitability e.g. - in the same land unit are grouped into the same geomorphopedological unit. The results are synthesized in a synoptic table which displays the landscape context in which soils occur, the soil forming factors and the synthetic parameters of soil fertility. On basis of those characteristics, the present constraints are identified and the alternative solutions or new land use may be proposed in PIWM innovation process. In this way, the soil map data is transformed into user tailored information.

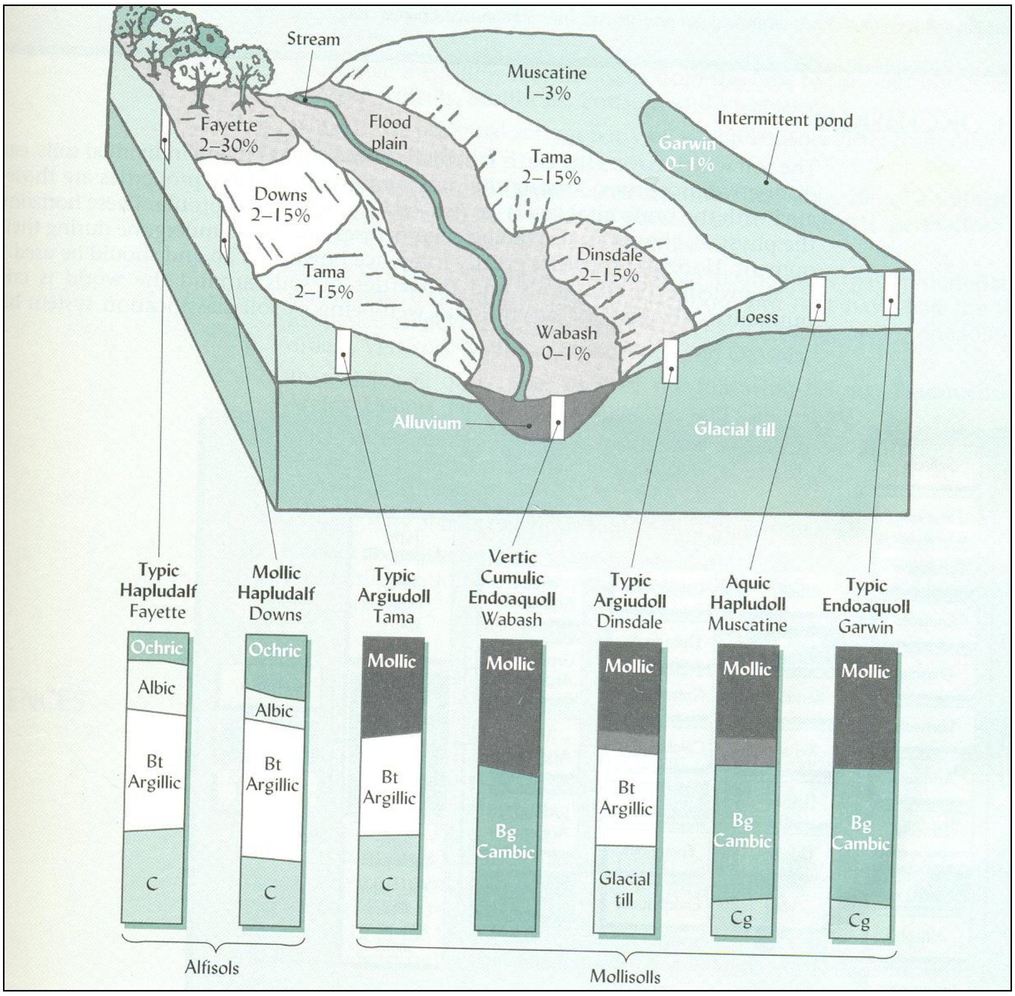


Figure 5.2 An example of a Regional Soil Reference System of Iowa/US. In this figure, each land unit is characterized by an actual soil profile. Source Brady and Weil (2002).

The RSRS is closer to the concept of the Reference Area (RA) developed by Favrot (1981) and reused by Lagacherie et al (1995) in computerized soil survey. The RA is a small but representative area of a small natural region. In the RA, a detailed soil survey defines the main soil classes of the whole region and establishes their mapping rules (Lagacherie et al., 1995). While the RA is used to map a small natural region, from a detailed survey in the RA, the RSRS in this thesis is seen as a way of recovering/recuperating the soil surveyor mental model or the landscape context or the mapping rules of an existing soil map to enhance its capacity of communicating the findings to the potential users so that the results can be used in a participatory and integrated research format. This is more practical because the fact that the landscape context information does not appear in the narrative legend of the soil-centered approach hampers the understanding of the soil maps (Wielemaker et al., 2001; Bui,

2004) and is the main cause of their little use in the research and development processes of developing countries.

The RSRS re-displays the soil properties in relation to soil forming factors and the soil-landscape relationship. In this sense, it can become a tool for overtime monitoring and evaluating changes in soil properties and crop yields in an agri-environmental changing situation. It plays the role of the base-line survey concept of socio-economists which allows identifying the initial status of a given intervention and to monitor and evaluate the upcoming changes due to different interventions. It allows relating composite soil samples or experiment results to a soil type – reference soil profile - thereby avoiding to merge (soil) samples or experiment results which could be stratified on the basis of soil type and land use (Bock, 1994). Likewise, it is an important tool to undertake soil-specific intervention and replicable technologies. Indeed, because it captures the soil mapping rules, it permits a technology developed at a given place to be extrapolated to another place where the same conditions prevail/analogous soil types. While the soil map of Rwanda (CPR) is a soil-centered soil map, no RSRS has been developed at watershed level to elucidate its narrative and taxonomic legends with the landscape context, thereby, enhancing its capacity of communicating its findings to a large group audience of non-soil scientists involved in sustainable land use and agricultural planning in particular.

The objective of this chapter was to set up a RSRS as a tool to (1) interpret and overtime monitor changes in soil properties and crop yields as a function of inherent soil properties and land management (2) distinguish the effect of soil type from the effect of management (3) interpret the existing watershed agrosystems variability.

5.2 Methodological approach

5.2.1 Transect walks and field observation

On the basis of the CPR information (Birasa et al., 1990), the farmer soil knowledge and the soil-landscape relationship (judgmental soil sampling), three transects walks were organized to verify and confirm the information previously obtained (chapter IV) and to decide the location of the soil profiles in the watershed. Six reference profiles representative of the main soil types (farmer and scientific soil nomenclature) in three main land units (upper hill, back slope and valley bottom) were described. Field book for describing and sampling soils (Schoeneberger et al., 2002) and Keys to Soil Taxonomy were used for this end: the same tool and procedure as the CPR (Birasa et al., 1990). During the transect walks, three key informants/farmers were associated with soil scientists and agronomists. During this exercise auguring was done, and interviews on soil types, agro-systems and their management in relation to the soil types and land use and crop management were carried out.

5.2.2 Composite soil samples

Except for the case of *'Urubuye'* which is permanently inapt to annual crop production, in each soil type (reference profile), composite soil samples were taken to evaluate the effect of land use on soil properties. For correct interpretation of results, the composite soil samples were connected to the soil type via the reference soil profile. In this study, three factors were considered to make sure that composite soil samples were related to the same soil type: the land unit, the CPR soil mapping unit (Birasa et al., 1990) and the farmer soil name. The reasoning behind was that both soil mapping unit and farmers' soil name correlate positively with the land unit. This procedure is a judgmental soil sampling close to the discrete approaches (Park and van de Giesen, 2004). Indeed, the later authors observed that the stratification of the hill slope gives a better estimation of soil properties with fewer samples than a random sample scheme.

5.2.3 Laboratory soil property analysis

Soil samples were analyzed in the laboratory of 'Centre Provincial de l'Agriculture et de la Ruralité' in Belgium for particle size (texture), pH (water and KCl), total organic carbon and nitrogen, exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+).

5.3 Results

Findings from this study show that soils and their properties in the study area differ from the upper hill to valley bottom. The main changing factors are parent material and land unit (geomorphology). In the farmers' low input system, the land use has more impact within soil type than between soil type. The following points present the main soils of the study area, their soil properties and the soil reference system.

5.3.1 The main soil types of the study site

- *Urubuye*

Urubuye is a farmers' name for a soil type on the mountainous land unit. The mountainous land unit is characterized by its shallow soil depth (<5 cm), outcrops, stony and gravel soil and the steep slope (> 55%). It is dominated by sand in its 2 mm soil fraction. The dominant parent material is quartzite in the 'Butare complex'. It is under *Eucalyptus camaldulensis* and *Pinus sp* tree species. The biophysical constraints make it permanently inapt to crop production. Because of the stoniness status no profile was described in this land unit.

- *Urusenyi*

This soil type is located on the rounded hill tops and on interfluves on gently sloping terrains (0-4%) of the upper hill land unit. This small unit is where both agricultural activities and households are preferably concentrated. Because of the shallow soil depth (< 50 cm) and gravel status of this land unit (> 30 %), many authors (Habarurema and Steiner, 1997, Rutunga and Neel, 2006) have mistaken '*Urusenyi'* to be eroded soils. The profile described in this land unit shows that this soil has relatively good properties (Table 5.1). In fact, its pH_{water} is above 5.2, the threshold under which aluminium becomes toxic to most plant (Sanchez, 1976; Rutunga, 1991). It has also good exchangeable base status compared to the dominant land unit in the watershed. This leads to an acceptable CEC. The situation of skeleton soil types being fertile was reported by Mathieu et al. (1995) and the good fertility status of such soils was attributed to the presence of little altered parent material at a shallow depth.

However, the soil properties of the profile described like calcium and magnesium decline as one moves deeper. This is due to the fact that the top layer of the profile of the interfluves land unit where the profile was located is covered by a thin layer (30 cm) of sediments (*Urusenyi*). These sediments are constituted by quartzite and schist materials (Dehandschutter and Buyagu, 1991). The underlying part originates in the feldspathic micaceous schist parent material (*Ikigwagwa*). Therefore, in the region, there is a geological based difference in both lateral and vertical soil properties. The gravel layer of '*Urusenyi'* soil type may be several meters deep or may repose on another type of parent material like micaceous schist *(Ikigwagwa)* (Habarurema and Steiner, 1997). The detailed geomorphological properties of the soil profile dug in *Urusenyi* soil type are given in poster 1.

Morphological profile description

Poster 1. Profile *Urusenyi*

1. Administrative location

Country: Rwanda;
Province: South;
District Nyaruguru;
Sector Cyahinda;
Cell: Coko;
Umudugudu: Gitara.

2 Geographic coordinates (m)
X = 453413;
Y = 9698870;
Z = 1915.

Profile environment: surface soil and the author testing the texture.

Profile environment: parent materials on top soil: metasediments gathered by the farmers along years

Context

Season: rainy season
Geomorphology position: summit
Geology: Feldspathic micacious schist.
Cover: Annual crops (beans-sorghum rotation)
Human influence: continual cropping

Profile description (260+ cm)

H1: dark reddish brown (5YR 2.5/2), sandy clay loam, clearly granular, plastic and friable.

H2: yellowish red (5YR 4/6), sandy clay, blocky sub-angular, plastic and friable

H3: yellowish red clay loam, blocky sub angular, plastic and friable.

H4: yellowish red clay loam, blocky sub angular, plastic and friable.

Pores: many and coarse

Stoniness: abundant

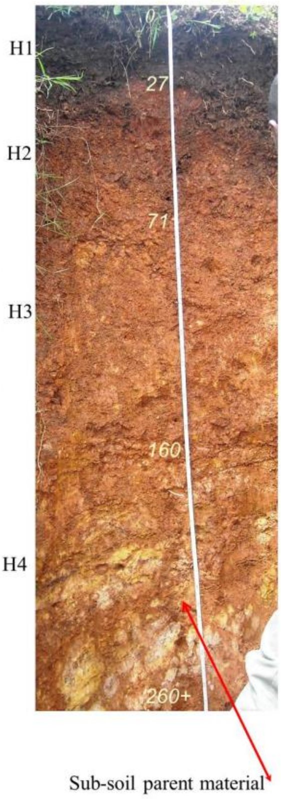
Quantity and root size: few and fine

Horizon boundary:

Abrupt (H1-H2), diffuse (H2-H3) and gradual (H3-H4)

Biological activity: weak except in H1.

Organic matter: moderate (H1) and low (H2-H4).



Sub-soil parent material

Horizon samples

- *Inombe*

In the watershed, *Inombe* soil type which is not widespread is located on the rare small plateaus or associated with *Urusenyi* soil type in relatively big interfluves and hilltops on gently sloping terrains (4-6%). The profile described on this soil type presents good soil properties: pHw > 5.2, acceptable CEC, good base status (Table 5.1). In the sub-pedological region, *Inombe* profile presents a deep dark horizon specific/characteristic of the sub-pedological region. The farming practice and dark horizon influence the soil properties trend in the profile. Better soil properties are found in H2 (50-124 cm) compared to H1 (0-50 cm). This may be attributed to the leaching process. The C content in the deep dark horizon is also high. While the pH water does not change significantly, the exchangeable bases are low. It is the same with the CEC. This is in accordance with many authors view that the high C content of the deep dark horizon is not reflected in crop suitability (Prioul and Sirven, 1981, Mutwewingabo, 1984). This implies that beyond the problem of quantity of organic matter, the quality should also be considered. The detailed geomorphological properties of the soil profile dug in *Inombe* soil type are given in poster 2 thanks to the Soil Taxonomy field book, the same tool used by the CPR soil survey.

Morphological profile description

Poster 2. Profile *Inombe*

1. Administrative location

Country: Rwanda;
Province: South;
District Nyaruguru;
Sector Cyahinda,
Cell: Rusenge;
Umudugudu: Cyuna

Profile environment: surface soil (left and right) and sorghum crops (middle)

2 Geographic coordinates (m)

x=455784;
y=9701418;
z=1870.

Profile description (260+ cm)

Texture: Clayey

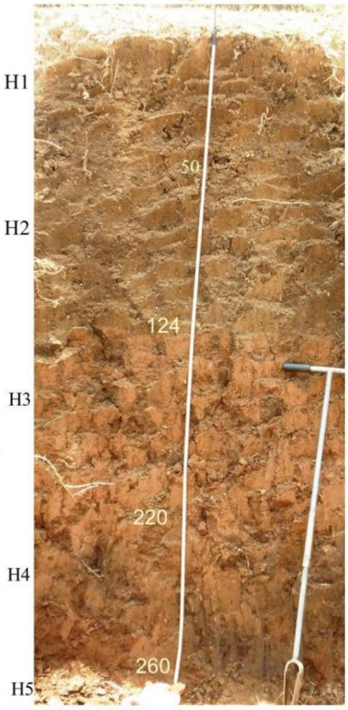
H1: brown (2.5 YR4/4) dry, clayey, blocky sub angular, firm of many coarse pores, without mottling and concretion, many fine roots, acid, diffused horizon boundary with the underlying horizon.

H2: dark reddish brown (2.5YR3/3) dry, clayey, blocky angular, firm of many coarse pores, without mottling and concretion, few roots, acid, with clear boundary with the underlying horizon

H3: reddish brown (2.5 YR4/6) dry, clayey, blocky angular, very firm, many cracks, acid, with gradual boundary with the underlying horizon.

H4: reddish brown (2.5YR4/6) dry, clayey, blocky angular, very firm without concretion, acid, with clear boundary with the underlying horizon.

H5: red (10 R4/8), clayey, blocky angular, very firm, acid.



Profile

Horizon samples

Texture

Structure

- *Umuyugu*

Umuyugu is a farmer name for a soil type which is deep, very friable and dusty. In this soil unit three soil profiles were described. Scientifically they correspond to three soil series and the CPR presents them in two soil mapping units. The MAT soil series is formed from gneiss and presents a deep dark horizon (poster 3). The KIZ soil series is formed from a mixture of gneiss and schist and does not present the deep dark horizon (poster 4). The soil series number 3 is formed from amphibolite parent material (intrusion) (poster 5). It is not described in considered CPR mapping unit; it is an inclusion. The chemical analysis (Table 5.1) show that these soils are severely limited by soil acidity (pH water = 4.5 on average) and poor base status (the sum of bases less than 2 Cmol/kg). The poor acido-basic status inhibits good organic matter and nitrogen content. One farmers’ soil type matching three CPR soil series is explained by the fact that the ultimate product of the FSK system is a suitability class (Habarurema and Steiner, 1997, Steiner, 1998). Indeed, the three soil series occur in the same land unit and have similar chemical soil properties. This means that they are in the same suitability class, even in the scientific suitability classification (Verdoodt and van Ranst, 2003a).

Morphological profile description

Poster 3. Profile *Umuyugu* on Gneiss

Administrative Location
Country: Rwanda;
Province: South;
District Nyaruguru;
Sector Cyahinda,
Cell: Coko;
Umudugudu: Gitara
Geographic coordinates
X=454530;
Y=9699456;
Z=1850.

Context

Climatic condition of previous days: rain season

Geomorphology: on regular slope, on hill side with 14 % of slope.

Geology: Gneiss.

Cover: Eragrostists fallow

Human influence : grazing and bench terraces

Profile environment: overview of the watershed and the surface soil (A)

Profile description (220+ cm)

Texture: loamy (profile)

Color: dark reddish brown 5YR3/2 (H1), 5YR 2.5/2 (H2 & H3), brown 7.5 YR4/4 (H4), dark reddish brown 5YR2.5/2 (H5) and strong brown 7.5YR4/6 (H6).

Structure: fluffy on all the profile.

Knife penetration test: very easy

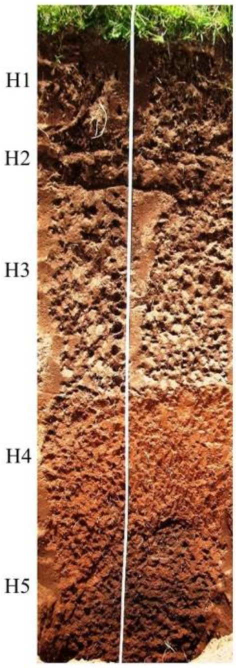
Pores: many

Gravel: zero.

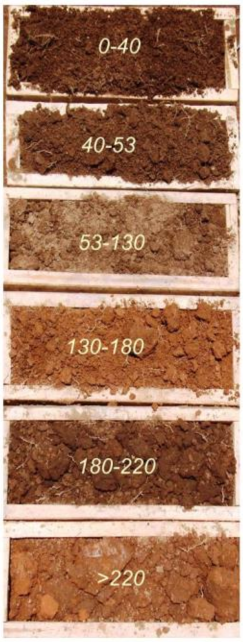
Roots: many and fine H1 (0-17cm) and absent on the rest of profile

Biological activity: moderate H1 (0-16 cm) and weak the rest of profile

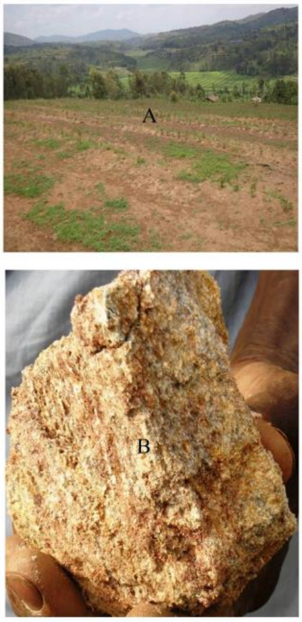
Horizon boundaries: clear (H1-H2), (H2-H3); Abrupt (H3-H4, H4-H5 and H5-H6).



profile



Horizon samples



Profile environment: surface soil (A) and parent material (B)

Morphological profile description

Poster 4. *Umuyugu*

Administrative Location
Country: Rwanda;
Province: South;
District Nyaruguru;
Sector Gasasa,
Cell: Gasasa;
Umudugudu: Kavumu
Geographic coordinates
X=456934;
Y=9699966;
Z=1820.

Profile environment: vegetation cover and surface soil

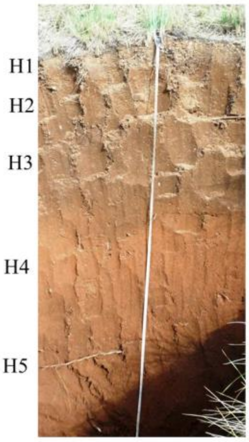
Context

Climatic condition of the previous day: rainy season
Geomorphology: hillside of 25 % .
Geology: Gneiss
Cover: Eragrostis
Human influence: anti-erosion structure

Profile environment: vegetation cover

Profile description (200+ cm)
Color: brown 7,5 YR 4/4 (H1, H2) ; very dark brown 7.5YR2.5/3 (H3), reddish dark 5YR4/4 (H4) dark very reddish brown 5YR3/4 and dark reddish brown 5YR3/4 (H6).
Structure: fluffy H1 & H2, granular H3, blocky sub angular H4, H5, H6.

Knife penetration test: very easy on all the profile
Pores: many
Gravel: absent
Roots: many and fines in H1 and H2, few to absent elsewhere
Biological activities: moderate (H1 et H2)
Horizon boundaries: diffuse H1-H2, clear H2-H3 and diffuse H3-H4, H4-H5 and H5-H6.



Profile

Horizon samples

Profile environment: parent material

Morphological profile description

Poster 5. *Umuyugu* on Amphibolite

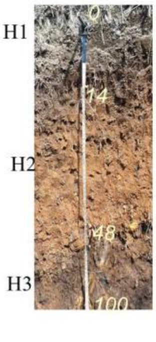
Administrative Location
Country: Rwanda; Province: South;
District: Nyaruguru; Sector: Cyahinda,
Cell: Coko; Umudugudu:Cyahinda

Geographic coordinates (m):
X=4554780;
Y=9698374;
Z=1765.

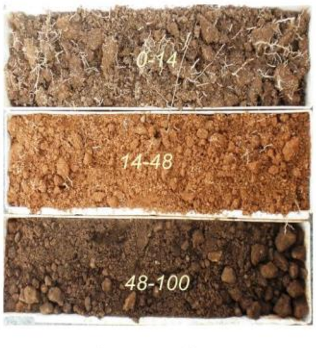
Profile environment:
Microtopography: hilly
Slope form: convex
Slope angle: 20%
Parent material: Amphibolite
Land use: Eragrostis fallow

Profile description (100 cm)
Texture: Loamy (H1, H2, H3)
Color: H1 (0-14 cm) Dark reddish brown – 2.5YR3/2
H2 (14-48 cm): reddish brown-5YR 4/8 and H3 (48-100): brownish black 10YR 2/2
Structure: granular (0-14 cm) and blocky sub angular H2 (14-48 cm) and unstructured H3 (48-100).
Knife penetration test: easy
Pores: many
Gravel: H1= none, H2= few, H3=Many
Roots: many and fine in H1 (0-14cm), few in H2 (14-48 cm) and very few in H3 (48-100)
Biological activities: moderate H1 (0-14 cm) and weak H2 (14-48 cm) and H3 (48-100)
Organic matter: high in H1 and H3(4 et 10%) and weak in H2
Horizon boundaries: H1-H2 diffuse and H2-H3 clear

Profile environment: vegetation cover



Profile



Horizon samples

Profile environment: parent material

- *Nyiramugengeri*

Nyiramugengeri is a farmer soil name which refers to the peat bog. This soil type occupies the valley bottom land unit. The valley bottom land unit is naturally imperfectly drained. Currently, this land unit has been managed/drained for tea plantation and seasonal crops (poster 6). The results show that this soil is extremely acid. The detailed soil profile description of *Nyiramugengeri* soil type and the profile environment are given in poster 6.

Morphological profile description

Poster 6. Profile *Nyiramugengeri*

Administrative location:
Country: Rwanda
Province: South
District: Nyaruguru
Sector: Cyahinda
Cellule: Gasasa
Umudugudu: Ryamarembo

Geographic coordinates
X =455117
Y=9699534
Z=1742 m

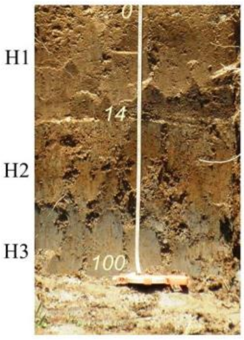
Profile environment: perennial crops: tea plantation

Context

Climatic condition of previous days: rainy season
Geomorphology: valley bottom in a hilly region
Slope: 4%
Parent material: tissue + alluvia
Cover: tea plantation

Profile environment: seasonal crops: Irish potatoes

Profile description (100 cm)
Texture: loam (H1 & H2)
Color: dark brown 10YR 3/4 (H1), dully yellowish (H2) and gray 5Y 4/1.
Structure: blocky sub angular none clear (H1), blocky angular (H2) and blocky angular very clear (H3)
Consistancy of the structure: very friable/loose (H1 and H2), sticky (H3)
Mottling: none (H1), many (H2) and moderate (H3)
Knife penetration test: easy H1, H2 and sticky H3
Pores: many fine (H1), many coarse (H2) and many fine (H3)
Gravel: none
Roots: many and coarse H1 and absent H2 & H3.
Biological activity: moderate (H1)
Horizon limits: clear and smooth



Profile

Horizon samples

Profile environment: a layer of tissue (A) on a layer of alluvium clays (B)

5.3.2 Soil properties of the main soil types

Soil properties differ according to soil types (Table 5.1). The best soil properties are found in the upper hill land unit dominated by '*Urusenyi'* (represented by GAT soil series) and '*Inombe*' (represented by KNM soil series). These soils are characterized as slightly acidic (pH water > 5.5) and have relatively high base status and CEC. The poorest soils are found on the back slope land unit dominated by '*Umuyugu*'/'*Mugugu*' represented by MAT and KIZ soil series. These soils are characterized by their extreme soil acidity (pH water < 5) and an extreme low base status and therefore low CEC. The soils in the valley bottom are also poor. The valley bottom is dominated by '*Nyiramugengeri*' represented by RL soil series. Like in the case of '*Umuyugu*', '*Nyiramugengeri*' soils are characterized by extreme soil acidity and low base status.

5.3.3 Land use: composite soil samples

Results of 33 composite soil samples taken to assess the variability of soil properties as a function of soil type and land use are presented in Table 5.2. Findings showed that soil properties were good in '*Urusenyi*'. This was observed in some soil properties such as gravel content, soil pH, and relatively high base status. The high proportion of gravel indicated the presence of alterable minerals. *'Inombe'* also had relatively good soil properties. '*Inombe*' presented some physical soil properties like the hardness and cracking when dry and the stickiness when wet that suggested some 2:1 clay. The 2:1 clays would be the reason for relatively good soil properties of *'Inombe'*. This observation was made (Van Wambeke, 1963) in the same region for '*Ferrisols*' (INEAC classification system). All composite soil samples in '*Umuyugu*' (MAT, KIZ soil series) and '*Nyiramugengeri'* (RL soil series) were of extremely poor soil properties.

5.3.4 Regional Soils Reference System

In the watershed, four geomorphopedological/land units were distinguished (see Figure 1.7): (1) the upland mountainous mass (2) the upper hillside (crest lines and rounded hill summits on one hand and shoulders and plateaus on the other hand) (3) the hillside/back slope and (4) the valley bottom. The transect walks and the profiles described showed a clear link between land units, soil types and soil properties. The shallow and stony soils – '*Urubuye*' - occupy the steeply sloping mountains mass. The shallow and gravel soils – *'Urusenyi'* - occupied the gently sloping hill summits and crest lines/interfluves. The deep and sticky soils – *'Inombe'* - occupied the plateaus and shoulders. The non sticky, very friable and dusty soils – '*Umuyugu*'/'*Mugugu*' - occupied the back slope and the tissue dominated soils – '*Nyiramugengeri*' - occupied the valley bottom. Figure 5.3 and Table 5.3 present the main agricultural soils of the watershed as a function of the soil forming factors in relation to land units where they occur.

Table 5. 1 Soil profile properties.

				Texture					Soil reaction			Organic status				Exchangeable bases					
F. Soil type	**Soil series**	**HZ**	**G r**	**Cy**	**Fl**	**Cl**	**Fs**	**Cs**	**pHw**	**pHKCl**	**ΔpH**	**TOC**	**TOM**	**TN**	**C/N**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**Na^{+}**	**SB**	**CEC**
		(cm)	**%**									**%**				**Cmol/kg**					
Urusenyi	GAT	0-27	50	26.6	11.5	5.6	18.9	37.4	5.7	4.9	0.8	2.3	4.6	0.20	12	5.35	0.99	0.31	0.04	6.69	6.9
		27-71	30	39.2	12.3	7.8	17.9	22.0	5.0	4.0	1.0	0.5	1.0	0.05	10	0.70	0.25	0.08	0.04	1.07	2.6
		71-160	45	41.2	9.7	5.2	11.6	32.2	5.1	4.1	1.0	0.6	1.2	0.05	12	0.75	0.25	0.08	0.04	1.12	2.7
		160-237+	14	31.5	14.8	10.4	22.1	21.1	4.8	4.1	0.7	0.5	1.0	0.03	17	0.50	0.16	0.08	0.04	0.78	1.8
Inombe	KNB	0-50	7	34.3	11.7	4.7	16.2	33.1	6.0	4.9	1.1	1.4	2.8	0.08	18	3.8	1.89	0.13	0.04	5.86	7.1
		50-124	10	30.9	14.7	5.1	16.1	33.2	6.6	5.3	1.3	1.6	3.2	0.10	16	4.5	1.81	0.33	0.04	6.68	8.9
		124-220	6	51.6	7.7	3.2	11.9	25.2	6.4	5.1	1.3	0.7	1.4	0.05	14	2.5	1.07	0.26	0.04	3.87	5.3
		220-260	0	52.0	4.8	4.8	12.2	26.1	6.1	4.8	1.3	1.4	2.8	0.17	8	0.5	0.08	0.08	0.09	0.75	4.5
		>260	0	51.5	6.7	2.8	11.7	27.2	5.9	4.7	1.2	0.5	1.0	0.12	4	1.1	0.16	0.08	0.04	1.38	5.0
Umuyugu1	MAT	0-40	0	45.6	7.7	4.9	15.3	26.6	4.5	4.1	0.4	2.6	5.2	0.22	12	0.5	0.16	0.08	0.09	0.83	4.4
		40-53	3	47.5	8.0	3.2	11.3	30.1	5.2	4.2	1.0	2.3	4.6	0.12	19	0.5	0.16	0.08	0.04	0.78	3.4
		53-130	2	48.8	8.3	3.2	13.2	26.5	5.2	4.2	1.0	2.5	5.0	0.17	15	0.5	0.08	0.08	0.04	0.70	3.8
		130-180	0	56.5	7.0	1.9	11.3	23.3	5.0	4.2	0.8	1.3	2.6	0.10	13	0.5	0.16	0.08	0.04	0.78	3.7
		180-220	0	34.4	19.3	10.5	12.3	23.5	4.5	4.3	0.2	2.4	4.8	0.14	17	4.5	1.15	0.10	0.04	5.79	6.7
		>220	0	54.5	6.5	3.1	10.5	25.5	4.8	4.2	0.6	1.3	2.6	0.16	8	7.1	1.23	0.08	0.17	8.58	9.6
Umuyugu2	KIZ	0-13	7	26.2	4.7	3.1	18.3	47.7	4.7	4.2	0.5	2.3	4.6	0.19	12	0.5	0.08	0.08	0.04	0.70	2.7
		13-30	3	29.3	7.0	3.5	19.3	40.8	4.6	4.2	0.4	2.8	5.6	0.21	13	0.5	0.08	0.08	0.04	0.70	3.7
		30-70	2	33.9	17.4	4.7	16.1	28.0	4.8	4.1	0.7	3.2	6.4	0.08	40	0.5	0.08	0.08	0.04	0.70	2.5
		70-120	0	31.2	10.9	4.7	15.9	37.3	4.5	4.3	0.2	1.0	2.0	0.08	13	0.5	0.08	0.08	0.04	0.70	2.5
		120-160	0	28.4	10.4	6.8	16.1	38.2	4.4	4.2	0.2	0.9	1.8	0.07	13	0.5	0.08	0.08	0.04	0.70	3.4
		160-200+	2	34.9	6.4	3.0	14.2	41.4	4.4	4.1	0.3	0.6	1.2	0.05	12	0.5	0.08	0.08	0.04	0.70	2.8

Umuyugu3		*0-14*	*6*	*42.5*	*9.2*	*2.6*	*12.3*	*33.4*	*4.6*	*4.1*	*0.5*	*2.9*	*5.8*	*0.11*	*26*	*0.5*	*0.08*	*0.08*	*0.04*	*0.70*	*3.0*
		14-48	*7*	*43.9*	*12.4*	*5.1*	*11.5*	*27.1*	*4.7*	*4.2*	*0.5*	*1.4*	*2.8*	*0.24*	*6*	*0.5*	*0.08*	*0.08*	*0.04*	*0.70*	*3.4*
		48-100	*75*	*27.1*	*14.9*	*5.4*	*11.5*	*41.5*	*/*	*4.4*	*/*	*2.9*	*5.8*	*0.16*	*18*	*0.5*	*0.08*	*0.08*	*0.04*	*0.70*	*2.3*
N.Mugengeri	*RL*	*0-38*	*3*	*31.7*	*16.1*	*9.7*	*27.3*	*15.2*	*4.0*	*4.3*	*0.3*	*2.6*	*5.2*	*0.19*	*14*	*0.5*	*0.08*	*0.08*	*0.04*	*0.70*	*3.8*
		38-62	*0*	*38.1*	*25.6*	*8.6*	*23.0*	*4.3*	*4.0*	*4.4*	*0.4*	*2.0*	*4.0*	*0.11*	*18*	*0.5*	*0.08*	*0.08*	*0.04*	*0.70*	*3.0*
		62-92	*7*	*33.8*	*22.8*	*13.6*	*26.3*	*3.4*	*3.9*	*4.7*	*0.8*	*1.5*	*3.0*	*0.24*	*6*	*0.5*	*0.08*	*0.08*	*0.04*	*0.70*	*3.4*

HZ = horizon, Gr = gravel, Cy = clay, Fl = Fine silt, Cl = coarse silt, Fs = Fine sandy, Cs= coarse sandy.

Table 5. 2 Composite soil samples properties

Land unit	***Farmers' soil type***	***land use***	***Farmers' Yield appreciation***	***Names of farmers***	***gravel***	***pH w***	***pH_{KCl}***	***Δ pH***	***Ct***	***Nt***	***C/N***	***Ca^{2+}***	***Mg^{2+}***	***K^{+}***	***Na^{+}***	***SB***
					%				*%*			*Cmol/kg*				
Crest/interfluve	*Urusenyi*	*crop land*	*very good*	*Nahayo*	*34.8*	*6.1*	*5.4*	*0.7*	*2.2*	*0.18*	*12.2*	*5.40*	*1.97*	*0.41*	*0.04*	*7.82*
	Urusenyi	*crop land*	*Good*	*Niyitegeka*	*42.2*	*5.3*	*4.6*	*0.7*	*1.6*	*0.14*	*11.4*	*2.55*	*0.74*	*0.10*	*0.04*	*3.43*
	Urusenyi	*Crop land*	*Good*	*Gumiriza*	*38.2*	*5.8*	*5.3*	*0.5*	*1.8*	*0.15*	*12.0*	*4.75*	*1.56*	*0.31*	*0.04*	*6.66*
	Urusenyi+Muyugu.	*Crop land*	*Good*	*Nahayo*	*30.4*	*5.3*	*4.6*	*0.7*	*1.9*	*0.16*	*11.9*	*2.85*	*1.15*	*0.41*	*0.04*	*4.45*
	Urusenyi-Agahama	*Crop land*	*Good*	*Bizimana*	*26.5*	*4.9*	*4.5*	*0.4*	*2.8*	*0.20*	*14.0*	*2.55*	*0.33*	*0.08*	*0.04*	*3.00*
	Urusenyi	*crop land*	*Good*	*Ndayisaba*	*35.8*	*5.1*	*4.6*	*0.5*	*2.2*	*0.16*	*13.8*	*2.35*	*0.58*	*0.23*	*0.04*	*3.20*
	Urusenyi+Inombe	*crop land*	*very good*	*Nyamaswa*	*18.4*	*5.7*	*5.1*	*0.6*	*2.4*	*0.19*	*12.6*	*4.50*	*2.22*	*0.77*	*0.04*	*7.53*
	Urusenyi	*crop land*	*Good*	*Bizimana*	*36.2*	*5.5*	*5.0*	*0.5*	*1.2*	*0.09*	*13.3*	*3.20*	*0.90*	*0.20*	*0.04*	*4.34*
	Urusenyi	*crop land*	*Poor*	*Gasaza*	*29.0*	*5.4*	*4.9*	*0.5*	*1.0*	*0.08*	*12.5*	*1.70*	*0.49*	*0.13*	*0.04*	*2.36*
	Urusenyi	*crop land*	*very good*	*Nahayo*	*34.8*	*6.1*	*5.4*	*0.7*	*2.2*	*0.18*	*12.2*	*5.40*	*1.97*	*0.41*	*0.04*	*7.82*
	Mean				*32.6*	*5.5*	*4.9*	*0.6*	*1.9*	*0.15*	*12.6*	*3.53*	*1.19*	*0.31*	*0.04*	*5.06*
	SD				*6.8*	*0.4*	*0.4*	*0.1*	*0.5*	*0.04*	*0.9*	*1.36*	*0.69*	*0.21*	*0.00*	*2.17*
Shoulder and plateau	*Inombe*	*crop land*	*very good*	*Nyungura*	*8.6*	*5.8*	*5.3*	*0.5*	*1.6*	*0.13*	*12.3*	*5.15*	*1.56*	*0.26*	*0.04*	*7.01*
	Inombe	*crop land*	*very good*	*Mwenende*	*2.3*	*5.7*	*5.2*	*0.5*	*1.4*	*0.12*	*11.7*	*4.70*	*1.64*	*0.38*	*0.09*	*6.81*
	Mean				*5.5*	*5.8*	*5.3*	*0.5*	*1.5*	*0.13*	*12.0*	*4.90*	*1.60*	*0.30*	*0.10*	*6.90*
	SD				*4.5*	*0.1*	*0.1*	*0.0*	*0.1*	*0.00*	*0.4*	*0.30*	*0.10*	*0.10*	*0.00*	*0.10*
Back slope/hillside	*Umuyugu*	*crop land*	*Good*	*Nyirinkindi*	*2.4*	*4.6*	*4.3*	*0.3*	*1.5*	*0.11*	*13.6*	*0.75*	*0.33*	*0.15*	*0.04*	*1.27*
	Umuyugu	*crop land*	*Good*	*Uwayezu*	*0.0*	*4.9*	*4.4*	*0.5*	*2.3*	*0.18*	*12.8*	*1.10*	*0.49*	*0.23*	*0.04*	*1.86*
	Umuyugu	*crop land*	*Poor*	*Munyakindi*	*0.0*	*4.3*	*4.1*	*0.2*	*2.3*	*0.18*	*12.8*	*0.50*	*0.33*	*0.31*	*0.04*	*1.18*
	Umuyugu/Mugugu	*crop land*	*very poor*	*Uwakirate*	*0.0*	*4.2*	*4.1*	*0.1*	*2.8*	*0.22*	*12.7*	*0.60*	*0.08*	*0.10*	*0.04*	*0.82*
	Umuyugu	*crop land*	*Poor*	*M.ndamutsa*	*7.3*	*4.3*	*4.2*	*0.1*	*3.1*	*0.22*	*14.1*	*0.50*	*0.08*	*0.08*	*0.04*	*0.70*
	Umuyugu	*crop land*	*Poor*	*Mukabutera*	*2.2*	*4.4*	*4.1*	*0.3*	*2.1*	*0.16*	*13.1*	*0.55*	*0.16*	*0.15*	*0.04*	*0.90*
	Umuyugu	*crop land*	*very poor*	*Sahoguteta*	*0.0*	*4.3*	*4.1*	*0.2*	*2.6*	*0.19*	*13.7*	*0.50*	*0.16*	*0.08*	*0.04*	*0.78*
	Umuyugu ufashe	*crop land*	*Good*	*Kanyoni*	*0.0*	*4.9*	*4.2*	*0.7*	*2.2*	*0.19*	*11.6*	*2.10*	*0.74*	*0.67*	*0.04*	*3.55*

Land unit	***Farmers' soil type***	***land use***	***Farmers' Yield appreciation***	***Names of farmers***	***gravel***	***pH w***	***pH_{KCl}***	***Δ pH***	***Ct***	***Nt***	***C/N***	***Ca^{2+}***	***Mg^{2+}***	***K^{+}***	***Na^{+}***	***SB***
					%				*%*			*Cmol/kg*				
	Umuyugu	*crop land*	*Good*	*Rwemera*	*0.0*	*4.7*	*4.3*	*0.4*	*2.4*	*0.15*	*16.0*	*1.05*	*0.33*	*0.36*	*0.04*	*1.78*
	Umuyugu/Mugugu	*crop land*	*Poor*	*Rufatabahizi*	*3.0*	*4.5*	*4.3*	*0.2*	*3.3*	*0.23*	*14.3*	*0.10*	*0.16*	*0.15*	*0.04*	*0.45*
	Umuyugu	*crop land*	*Very poor*	*Baseka*	*2.1*	*4.7*	*4.4*	*0.3*	*2.0*	*0.14*	*14.3*	*1.35*	*0.41*	*0.20*	*0.09*	*2.05*
	Umuyugu	*crop land*	*Poor*	*Nazari*	*3.4*	*4.5*	*4.2*	*0.3*	*2.3*	*0.17*	*13.5*	*0.95*	*0.49*	*0.38*	*0.09*	*1.91*
	Umuyugu/Mugugu	*Idem*	*Idem*	*Kandi*	*8.0*	*4.3*	*4.2*	*0.1*	*1.8*	*0.12*	*15.0*	*0.50*	*0.08*	*0.08*	*0.04*	*0.70*
	Umuyugu/Mugugu	*crop land*	*Very por*	*Musabeyezu*	*2.3*	*4.5*	*4.2*	*0.3*	*1.8*	*0.13*	*13.8*	*0.50*	*0.16*	*0.08*	*0.04*	*0.78*
	Umuyugu	*crop land*	*Good*	*Mababaro*	*0.0*	*4.2*	*4.1*	*0.1*	*1.8*	*0.14*	*12.9*	*0.50*	*0.16*	*0.10*	*0.04*	*0.80*
	Mean				*2.0*	*4.5*	*4.2*	*0.3*	*2.3*	*0.20*	*13.6*	*0.77*	*0.28*	*0.21*	*0.05*	*1.30*
	SD				*2.6*	*0.2*	*0.1*	*0.2*	*0.5*	*0.00*	*1.1*	*0.55*	*0.20*	*0.20*	*0.00*	*0.80*
	Umuyugu/ Mugugu	*Fallow*	*Very poor*	*Kabarira*	*0.0*	*4.3*	*4.2*	*0.1*	*1.7*	*0.11*	*15.5*	*0.55*	*0.08*	*0.08*	*0.04*	*0.75*
	Umuyugu/ Mugugu	*Fallow*	*Very poor*	*Gashugi*	*7.7*	*4.2*	*4.1*	*0.1*	*3.1*	*0.20*	*15.5*	*0.55*	*0.08*	*0.08*	*0.04*	*0.75*
	Umuyugu	*Fallow*	*Very poor*	*Gasasa Css*	*2.0*	*4.3*	*4.1*	*0.2*	*2.9*	*0.20*	*14.5*	*0.55*	*0.08*	*0.08*	*0.04*	*0.75*
	Umuyugu	*Fallow*	*Poor*	*Karerangabo*	*0.0*	*4.4*	*4.2*	*0.2*	*3.1*	*0.21*	*14.8*	*0.55*	*0.08*	*0.08*	*0.09*	*0.80*
	Umuyugu/Mugugu	*Fallow*	*Very poor*	*Inde*	*10.2*	*4.4*	*4.2*	*0.2*	*2.4*	*0.15*	*16.0*	*0.55*	*0.08*	*0.08*	*0.04*	*0.75*
	Mean					*4.3*	*4.2*	*0.2*	*2.6*	*0.20*	*15.3*	*0.55*	*0.10*	*0.10*	*0.10*	*0.76*
	SD					*0.1*	*0.1*	*0.1*	*0.6*	*0.00*	*0.6*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Valley bottom	*Nyiramugengeri*	*Tea plantation*	*Good*	*Mata tea*	*0.0*	*3.9*	*3.8*	*0.1*	*4.5*	*0.35*	*12.9*	*0.05*	*0.08*	*0.08*	*0.04*	*0.25*
	Nyiramugenegeri	*Crop land*	*Good*	*Akavuguto Bridge*	*0.0*	*4.8*	*4.0*	*0.8*	*10.1*	*0.68*	*14.9*	*1.10*	*0.08*	*0.08*	*0.09*	*1.35*
	Nyiramugengeri	*Plantation*	*Good*	*Mata tea plantation*	*36.0*	*4.8*	*3.9*	*0.9*	*4.1*	*0.32*	*12.8*	*0.50*	*0.16*	*0.08*	*0.04*	*0.78*
	Umuyugu/colluv.	*Plantation*	*Good*	*Mata tea*	*28.9*	*4.6*	*4.4*	*0.2*	*4.2*	*0.32*	*13.1*	*4.45*	*0.25*	*0.10*	*0.09*	*4.89*
	Mean					*4.5*	*4.0*	*0.5*	*5.7*	*0.40*	*13.4*	*1.50*	*0.10*	*0.10*	*0.10*	*1.80*
	SD					*0.4*	*0.3*	*0.4*	*2.9*	*0.20*	*1.0*	*2.00*	*0.10*	*0.00*	*0.00*	*2.10*

Gr=gravel, ΔpH=difference (pHw-pKCl), TC= Total Carbone, TN= Total Nitrogen, K^{+}*= Potassium,* Na^{+}*=sodium,* Mg^{2+}*=Magnesium,* Ca^{2+}*=Calcium*

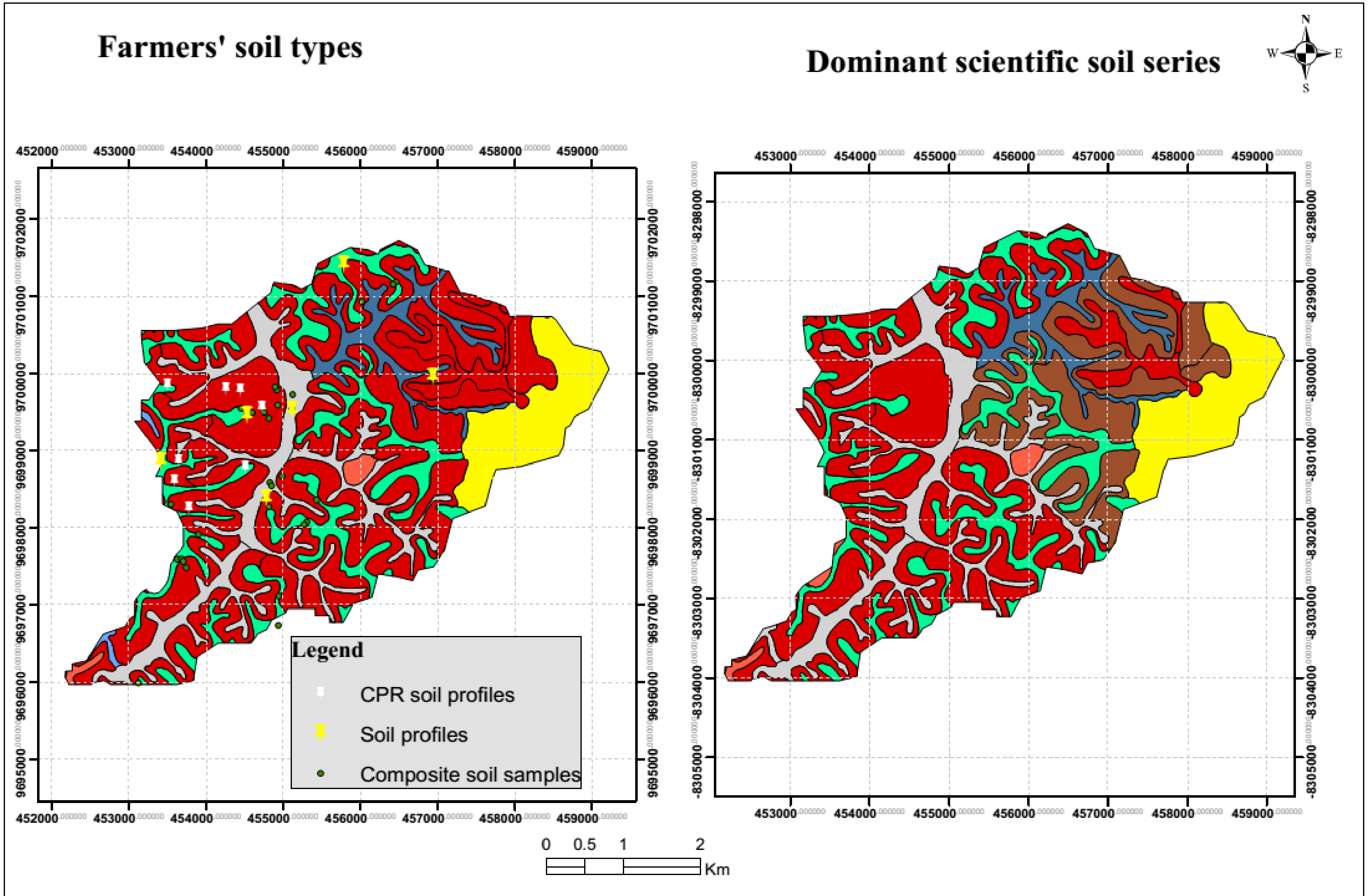


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Figure 5.3 Watershed soil map (left) farmers' soil types and (right) scientific soil series: see the explicit legend (Table 5.3).

Table 5.3 Soils Reference System (explicit and extended legend of figure 5.3)

Land unit	***Land Sub-unit***	***Dominant lithology***	***Farmers' soil type***	***soil series***		***Slope (%)***	***Altitude (m)***	***Outcrope***	***Gravel***	***Texture***	***Surface color***	***Depth (cm)***	***pH*** $_{water}$	***pH*** $_{KCl}$	***C/N***	***CEC***	***L.U***	***Constraints***	***New alternatives***
Mountainous mass	-	*Quartzitic metasediments*	*'Urubuye'*	*BUJ*	🟨	*45 to 55*	*1900-2200*	*present*	*dominant*	*Sandy*	*Dark reddish brown-*	*< 30*	*4.0*	*3.9*	*20.7*	*2.7*	*Wood land*	*Nutrient status, Slope*	*Wood land*
Upper hill	*Interfluve rounded hill*	*Micashist and quartzitic metasediments*	*Urusenyi*	*GAT*	🟩	*1 to 4*	*1800-1900*	*none*	*dominant*	*Sandy*	*Dark reddish brown*	*< 30*	*5.7*	*4.9*	*12.0*	*6.9*	*Crop land*	*Without major limitations*	*Use of organic matter (compost, green and/or farmyard manure*
	Plateau	*Micashist*	*Inombe*	*KNB*	🟧	*1 to 4*	*1800-1900*	*none*	*none*	*Clayey*	*Brown*	*> 300*	*6.0*	*5.3*	*16.0*	*8.9*	*Crop land*	*Without major limitations*	
Hillside	*Hillside*	*Gneiss,*	*Umuyugu*	*MAT*	🟥	*4 to 45*	*1700-1900*	*none*	*none*	*Loamy*	*Dark reddish brown*	*>300*	*4.5*	*4.1*	*12.0*	*4.4*	*Fallow*	*Acidity, Nutrient status, Slope*	*Combination of lime, organic matter and fertilizers*
		Amphibolite	*Umuyugu*	*Other*	🟥	*4 to 45*		*none*	*few*	*Loamy*	*Dark reddish brown*	*100*	*4.6*	*4.1*	*13.0*	*3.0*	*Fallow*	*Acidity, Nutrient status, Slope*	
		Basic rock?	*Umuyugu*	*KIZ*	🟫	*4 to 45*		*none*	*none*	*Loamy*	*Brown*	*>200*	*4.7*	*4.2*	*12.0*	*2.7*	*Fallow*	*Acidity, Nutrient status, Slope*	
Valley bottom	-	*Valley bottom tissue + alluvia*	*Nyiramugengeri*	*RL*	⬜	*1 to 4*	*1700-1800*	*none*	*none*	*Clayey*	*Dark brown*	*150*	*4.7*	*4.2*	*6.0*	*3.4*	*Crop land*	*Acidity, Nutrient status*	
			Ibumba	*RO*	🟦	*1 to 4*	*1700-1800*	*none*	*none*	*Clayey*	*Dark*	*200*	*4.7*	*4.2*	*13.0*	*3.6*	*Crop land*	*Acidity, Nutrient status*	

5.4 Discussion

The soil profile description confirmed the occurrence of various soil types at watershed level (Table 5.1). The composite soil samples taken in different plots in different soil types and under different land uses - where applicable - also showed differences in chemical soil properties (Table 5.2). These soils types and their chemical soil properties were consistent with the geomorphology or the major landforms of the watershed (Table 5.3). The mountainous mass land unit was dominated by *Urubuye* soil type. The biophysical factors such as shallow soils (≤ 15 cm), outcrops and steep slopes (> 55%) make this soil type permanently inapt to crop production. Soils with relatively good chemical properties were found on the upper hill land unit dominated by '*Urusenyi'* (on crest lines and hill summits) and '*Inombe*' (on shoulders and plateaus). These soils are characterized by moderate acidity (5.6-6.0), medium Ca^{2+} concentration (5-10 Cmol/kg soil) and low CEC (5-15 Cmol/kg soil) (Table 5.1). Soils with poor chemical properties were found on the hillside/back slope dominated by *Umuyugu/Mugugu* soil type and in valley bottoms dominated by *Nyiramugengeri* soil type. These soils are characterized by very strong acidity (4.5-5), very low Ca^{2+} concentration (< 2 Cmol/kg soil) and very low CEC (< 5 Cmol/kg soil) (Table 5.1).

In the watershed, the difference in soil chemical properties of composite soil samples was more significant between soils than within one soil type (Table 5.2). The case of soil pH and Ca^{2+} concentration is illustrative of this. The pH-water of the ten composite samples in *Urusenyi* soil type ranged from 4.9 to 6.1. The mean soil pH was 5.5. With such a mean soil pH, *Urusenyi* soil type belongs to the class of strong acid soils: pH 5.1-5.5. In the same soil type, the Ca^{2+} concentration ranged from 1.7 to 5.4 Cmol/kg soil with a mean of 3.53 Cmol/kg soil. With this Ca^{2+} concentration level, *Urusenyi* belongs to the low Ca^{2+} concentration class (2-5 Cmol/kg soil). The two composite soil samples taken in *Inombe* soil type indicated that this soil type was moderately acidic (5.6-6.0) and low in Ca^{2+} concentration. The fifteen composite soil samples taken in *Umuyugu/Mugugu* soil type, under crop land, showed that soil pH ranged from 4.2 to 4.9 with a mean of 4.5. With this mean soil pH, this soil type belongs to the very strongly acidic class (4.5-5). The Ca^{2+} concentration ranged from 0.1 to 2.1 Cmol/kg soil with a mean of 0.77 Cmol/kg soil. With such mean Ca^{2+} concentration, this soil type, under the specified land use, belongs to the very low Ca^{2+} concentration class (< 2 Cmol/kg soil). The five composite soil samples taken in *Umuyugu/Mugugu* soil type, under fallow land indicated that soil pH ranged from 4.2 to 4.4 with a mean of 4.3. With this mean soil pH, this soil type, under the specified land use belongs to the extremely acid class (< 4.5). The Ca^{2+} concentration is 0.5 Cmol/kg soil. With such mean Ca^{2+} concentration, this soil type under the specified land use belongs to the very low Ca^{2+} concentration class (< 2 Cmol/kg soil). The four composite soil samples taken in *Nyiramungeri* soil type showed that soil pH ranged from 3.9 to 4.8 with a mean of 4.5. With this mean soil pH, this soil type belongs to the very strongly acid class (4.5-5). The Ca^{2+} concentration varied from 0.5 to 4.45 Cmol/kg soil. The mean concentration of this element was 1.5 Cmol/kg soil. With such mean Ca^{2+} concentration, this soil type belongs to the very low Ca^{2+} concentration class (< 2 Cmol/kg soil).

Whilst there was distinct demarcation in soil properties of the composite samples according to different soil types to which they belonged, there was still some significant difference in soil properties within soil type as shown by the standard error (Table 5.2). For instance, a difference of one unit soil pH and 3.7 Cmol/kg soil of Ca^{2+} in *Urusenyi* was observed. Among the possible reasons are (1) the soil continuum and the central and intergrades concepts with their implication in soil property variations (2) the management factor (3) the merge/overlap of soil particles from different soil types due to lateral movement (erosion and colluvium deposits) in cultivated soils. In *Umuyugu/Mugugu*, there was a significant difference in soil pH according to different land uses. For instance, as above mentioned, *Umuyungu/Mugugu* under crop land belongs to the very strongly acid class (4.5-5) while the same soil type, under fallow land (Eucalyptus sp or *Eragrostis vidacea K. schumach),* belongs to the extremely acid class (< 4.5). However, the Ca^{2+} concentration was not affected by the land use in this example. The difference in soil pH class might be explained by the fact that in the land scarcity of Rwanda, fallows are only allocated on the already extremely unproductive soils. Another possibility is that the existing fallow is acidifying. This is corroborated by farmers' perception that the Eucalyptus or *Eragrostis* fallows do not regenerate soil fertility compared to the crop land. The farmers' opinion is that in the acidic and depleted soils, some practices such as deep tillage and bush biomass incorporation may relatively improve soil fertility than the planted or natural fallows.

The between and within soil type property variations might constitute a good explanation to the noted 'crop yields variations from field to field and plot to plot' (Drechsel et al., 1996). The implication is that while the soil fertility management strategies need to be soil-specific, at the same time, it requires being flexible within the soil type (Steiner, 1998). Indeed, scientists in practical agriculture estimate that it is neither desirable nor possible to derive 'recommendations' for each field in each farm (Giller et al., 2011). This means that, at certain level, farmers should be encouraged to 'experiment' themselves, without an authoritarian extension service, and to adapt the soil-specific fertility management recommendations to their own fields and plots (Drechsel et al., 1996, Steiner, 1998). In other words, rigid cropping systems, with fixed designs, fixed fertilizers recommendations, planting dates etc., seem to be entirely inappropriate to Rwandan farming conditions (Drechsel et al., 1996). It has been observed that, African farmers, independent of the agro-ecological zones, forest, savanna, or mountains, are 'experts' in optimizing the use of soil difference by judicious choice of crop species and soil fertility management practices (Steiner, 1998; Giller et al., 2011). This means that when aspiring to engage in experimental activities with farmers, it is important to realize that farmers, in their own epistemological framework are likely to engage already in 'experimental' activities, even if this may not be immediately clear and visible to outsiders (Leeuwis and van den Ban, 2004). In other words, engaging in experimentation with farmers should not be equated with 'turning farmers into scientists' or 'imposing scientists' epistemological culture' (Leeuwis and van den Ban, 2004). This is the essence of the mother and baby field research approach (Chapter 2, section 2.3.4) where the two epistemological cultures work together in interactive manner through field days and farmer exchange visits.

The observed difference in soil properties can be interpreted through the light shared by the concepts of toposequence and catena/soil association (Milner, 1935, Okusami, 2006), geomorphopedological units (Bock, 1994) or land system analysis (Wielemaker et al., 2001). Composite soil samples with relatively good chemical properties corresponded to the soil types (profiles) with good chemical properties: *Urusenyi* and *Inombe* on the upper hills. Likewise, composite soil samples with poor chemical properties corresponded to soil types (profiles) with poor soil properties: *Umuyugu/Mugugu* and *Nyiramugengeri* on the back slopes and valley bottoms respectively. Overall, there was a clear relationship between the parent materials, geomorphological conditions, soil types, soil chemical properties, crop suitability/land use and soil fertility management strategies (Table 5.3).

The distinct demarcation of soil properties between different soil types confirmed the existence of a clear relationship between land unit-soil type-soil properties. It is also the proof of the little capacity of existing soil fertility management practices and the locally-produced input (farmyard manure, green manure, compost) to improve soil properties, especially the basic cations. In fact, the level of input in Rwanda and Burundi has been classified as low in a three level input classification system (low, medium and high) (Tessens, 1991). Indeed, until the advent of the first installment of the seven years government program (2006-2012) mostly known as the Economic Development and Poverty Reduction Strategy (EDPRS 1) (MINECOFIN, 2007), the farmyard manure was the main source of nutrients for almost all staple food production in Rwanda. However, without systematic consideration of different soil types at watershed level, the effects of green manure under the form of planted fallow or compost turned out to be highly variable and in general non-significant (Pietrowicz and Neumann, 1987 cited by Drechsel et al., 1996). Only the large doses of 30 - 60 t/ha, applied during four consecutive growing seasons (two years), were able to raise the soil pH of very strongly acid soils (soil pH water < 5) of one unit and to suppress the aluminum toxicity (Mbonigaba, 2007). The residual effect of 35 t/ha of farmyard manure on an extremely acid soil, applied during five consecutive years, lasted only two years (Rutunga and Neel, 2006). In practice such large quantities of organic matter are not applied because they are too huge to be available to a Rwandan household (Rutunga and Neel, 2006). This illustrates how difficult it is to manage soil fertility on acidic and inherently poor soils of Rwanda with ‘low cost input’ such as organic amendments. Instead of trying to influence the soil chemical properties until a more acceptable level, farmers in Rwanda, under their low input system and investment capacity, prefer to allocate crops, farmyard manure and labor strategically (Clay and Lewis, 1990). Under this strategy, farmers concentrate their effort and inputs on relatively rich soils (where they have observed good response) compared to poor soils which receive less demanding crops, less quality inputs and less care (Rushemuka et al., 2014b). The same situation was also reported in Kenya (Tittonell et al., 2007). The above consideration means that the large variability in soil fertility at watershed level is likely to be explained by the soil type than the management factor.

The systematic variation of soils along the hill slope as result of the catena or toposequence was known long time ago (Milner, 1935). However these concepts have been less used to understand and explain the farmers' reasoning behind their heterogeneous cropping systems so that soil fertility management technologies are developed for specific soil types and transferred to analogous soil types at watershed level. For instance, some sites around the homestead (generally on the gently sloping upper hill) have been reported to be more productive than the sites far from the homestead (general on sloping terrains down slope) (Rutunga and Neel, 2006; Vanlauwe and Giller, 2006; Tittonell et al., 2007). Likewise, some ancient settlement sites (*amatongo* in central Africa and *tombondu* in West Africa) have been reported to have their soil properties improved for long time (Fairhead and Scoones, 2005). Similarly, some ancient cattle parks (*amacukiro in Central Africa*) on highlands can have their A horizon transformed into an epipedon closer to the Plaggen (A) surface diagnostic horizon. Without sufficient consideration of the soil spatial distribution law (toposequence and catena concepts) and the effect of soil type on farmers soil fertility management strategy, this soil fertility gradient has been interpreted as the result of human influence in terms of differential household manure application (Rutunga and Neel, 2006; Vanlauwe and Giller, 2006; Tittonell et al., 2007). However, the long lasting effect of organic input (farmyard manure, green manure, compost) seems to be restricted only to the fertile soils (Drechsel et al., 1996). This said, small scale human influences on soil properties and crop yields, which depend on the type and level of inputs used on the one hand and soil types and their fertility levels on the other hand, should not hide the effect of intrinsic soil fertility as explained by the natural soil forming factors and the soil-landscape relationship. This means that the concept of anthropic soils – '*sols anthropiques*' (Neel, 1972; Neel and Deprins, 1973, Neel, 1974, Rutunga and Neel, 1980, Rutunga and Neel, 2006) needs to be revisited. The problem is that agronomic experimentations (fertility and plant breeding experiments) in Rwanda (Rutunga, 1991; Steiner, 1998) and elsewhere (Matthews et al., 2002) are undertaken using multi environmental/location trials to evaluate the performance of the fertilizer technology or the genotype performance with little understanding of soil variability within one AEZ. The generalization of obtained results overlooks the soil type effect and the rationality of farmers to invest their inputs to the best responding soils and to allocate crops strategically. In Rwanda, it has been observed that farmers apply farmyard manure to the soils where they expect the best response in terms of crop yields and/or economic return whether they are near (hill top) or far from the homestead (valley bottom). A comparable situation was also observed in West Africa (Mathieu et al., 1995). In Kenya farmer resource use efficiency was strongly affected by soil fertility and the negative relationship between soil fertility factors and distance from the homestead was not evident (Tittonell et al., 2007).

5.5 Conclusion

The objective of this study was to set up a RSRS as a tool of objectively interpreting, managing and monitoring the spatial and temporal variability of soil properties and crop yields at watershed level. The RSRS was useful for undertaking soil-specific interventions, interpreting experimental results and extrapolating results to analogous soil types. This shows the need to understand the soil as a natural body in terms of its name and properties in relation to the land unit where it occurs. The site selection was done using the multi-hierarchical and nested land unit philosophy (Figure 1.8). The major results consisted of the identification of five soil types occurring in five land units at watershed level. The results showed a clear link between land units, soil types, soil properties and soil fertility management strategies. The shallow and stony soils – '*Urubuye*'/*Entisols* - occupied the steeply sloping mountain mass where the main limitation is the steep slope. The shallow and gravel soils – *'Urusenyi'/Entisols* - occupied the gently sloping hill summits and crest lines/interfluves and did not have major limitations. The deep and sticky soils – *'Inombe'/Ultisols* - occupied the plateaus and shoulders and also did not have major limitations. The non sticky, very friable and dusty soils – '*Umuyugu*'/'*Mugugu*'/*Oxisols* - occupied the hillside/back slope and were severely limited by a strong acidity and extremely low basic cation concentrations and to a less extent by the slope. The tissue dominated soils – '*Nyiramugengeri*'/*Histosols* - occupied the valley bottom and were limited by a strong acidity. Farmers allocated crops strategically and invested more effort and resources in the more productive and less risky soils on the upper hill land unit. It was concluded that the medium scale and digital soil map of Rwanda complemented by the FSK can help to objectively interpret data, undertake soil-specific interventions, and extrapolate results to analogous soil types within one agro-ecological zone. The major recommendation was that when interpreting soil properties, experimental results and agrosystems variability, soil type should be considered at first level, and other factors such as the historical and operational management and the crop species and crop variety used should follow.

Chapter VI: Strategic soil fertility management for replicable technologies development in Rwanda

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Abstract

In the complex landscapes/soilscapes like those found in the highlands of Rwanda, soil-specific fertility management and replicable technology development is a crucial issue. A pot experiment was undertaken to demonstrate the need to match soil type with appropriate inputs and the strategy to extrapolate developed technologies to analogous soil types. Using a multi-scale and nested hierarchy land system reasoning, four soil types occurring in different land units of the same watershed and eight fertilizer treatments were considered. The plant test was *Sorghum bicolor (L.) Moench.* Results showed significant differences between soil types and fertilizer treatments ($p \leq 0.001$). This confirmed the requirement of tailoring soil fertility management inputs to specific soil types in specific land positions/land units. In Akavuguto watershed case study, both *Urusenyi (Entisols)* on hill tops and *Inombe (Ultisols)* on plateaus, the effect of lime was not significant and the control in both soil types still produced relatively high biomass yields. In *Umuyugu/Mugugu (Oxisols)* on back slope and *Nyiramugengeri (Histosols)* in the valley bottom, the effect of lime was spectacular. The response in all treatments without lime was insignificant and in the same category of mean separation with the control. In these two soil types, the best treatment was the combination of lime, farmyard manure and fertilizers. The difference in soil suitability was mainly explained by different parent materials in the different land units. The conclusion was that within the same agro-ecological zones, farmers' nomenclature for land units and soil types can be an effective communication framework to develop soil-specific technologies and transfer them into analogous soil types.

***Key words**: Strategic soil fertility management, Land unit, Farmer soil nomenclature, Analogous soil types, Rwanda.*

6.1 Introduction

Conventional soil-related research findings based on the multi-environmental/location trials, without systematic consideration of different soil types within each AEZ have been less practical to draft the extension messages relevant for the entire AEZ (Rutunga, 1991; Drechsel et al., 1997; Habarurema and Steiner, 1997; Steiner, 1998; Matthews et al., 2002). To solve this problem, de la Rosa et al. (2009) proposed to adopt soil-specific agro-ecological strategies where the soil type information in decision-making is at the heart for sustainable use and management of agricultural land. In the same vein, several authors (e.g. Steiner, 1998; Niemeijer and Mazzucato, 2003; Payton et al., 2003; Gowing et al., 2004; Barrera-Bassols et al., 2006b; Rushemuka et al., 2014a) stressed the need for integrating the scientific and the farmers' soil knowledge in research and technology development in order to make use of farmers' experience, thereby ensuring greater relevance of research results for farming practice. However, examples showing the feasibility of these recommendations are still limited. As a consequence, crop simulation models have not yet contributed to solve the problem of poor farmers in developing countries (Matthews et al., 2002).

The objective of this study was to demonstrate a farm-level and user-friendly strategy of ensuring soil-specific and replicable technologies in the complex soilscape of Rwanda. This objective can be subdivided into two sub-objectives: (1) to show that regardless of crop management factors (planting date, planting density, weeding practice, resource allocation etc.) different soil types occurring along the slope (concept of catena and toposequence) within one AEZ may have different fertility potential and, therefore, may need different soil fertility management strategies (2) to demonstrate that farmers' nomenclature for land units and soil types is rational and, therefore, can be used as a communication framework in agricultural research and extension to achieve watershed level soil-specific and replicable soil fertility management recommendations.

6.2 Methodological approach

6.2.1. Soil sampling strategy

Composite soil sampling was achieved taking into account the land units, the CPR soil mapping units (Birasa et al., 1990) and the farmer soil nomenclature. Four farmers' soil types were considered in four land units along the slope (Table 6.1). Soil samples were taken at 25 cm depth with the help of an auger. Each composite soil sample was a mixture of 10 composite samples taken in 10 farmer's fields of 0.5 ha (on average) for each soil type under the same land use. The exception was made for soil number 4 - *Nyiramugengeri*- where a single grazing farm of five ha was sampled. The reason was to avoid the effect of lime and fertilizers applied to this soil type the previous season. Laboratory analysis of composite soil samples, which involved different soil properties: particle size, soil pH (water and KCl) total organic carbon, total nitrogen, exchangeable bases, was conducted in the laboratory at the 'Centre Provincial de l'Agriculture et de la Ruralité' in Belgium. Results are presented in Table 6.2.

Table 6.1. Soil type according to farmer and scientific soil knowledge in relation to the land units.

#	*Land unit*	*Soil description*		
		Farmers' Soil Types	*Connotation*	*Scientific (family) soil Taxonomy (1975) after CPR*
Soil 1	*Interfluve*	*Urusenyi*	*Gravely soils*	*Loamy-skeletal, mixed, non acid, isothermic, lithic Troportents*
Soil 2	*Shoulder*	*Inombe*	*Sticky soils*	*Clayey, kaolinitic, isothermic, humoxic Sombrihumult*
Soil 3	*Back slope*	*Umuyugu*	*Friable soils*	*Clayey, kaolinitic, isothermic Sombrihumox*
Soil 4	*Valley*	*Nyiramugengeri*	*Tissue soils*	*Euic, isohyperthermic, typic Troposaprits*

Table 6.2. Texture and chemical properties of A horizon.

Soil type	*Gr*	*Cl*	*Lm*	*San*	*pH-w*	*pH KCl*	*ΔpH*	*TOC*	*TN*	*C/N*	*Ca^{2+}*	*Mg^{2+}*	*K^{+}*	*Na^{+}*	*CEC*
	%							*%*			*Cmol/kg*				
Urusenyi	*37*	*26.6*	*17.1.*	*56.3*	*5.7*	*4.9*	*0.8*	*2.3*	*0.20*	*11*	*5.35*	*0.99*	*0.31*	*0.04*	*6.9*
Inombe	*7*	*34.3*	*16.4*	*49.3*	*6.0*	*4.9*	*1.1*	*1.4*	*0.08*	*9*	*3.80*	*1.89*	*0.13*	*0.04*	*7.1*
Umuyugu	*0*	*45.6*	*12.6*	*41.9*	*4.5*	*4.1*	*0.4*	*2.6*	*0.22*	*12*	*0.50*	*0.16*	*0.08*	*0.09*	*3.7*
N.Mugengeri	*3*	*31.7*	*25.8*	*42.5*	*4.3*	*4.0*	*0.3*	*10.2*	*0.19*	*15*	*0.50*	*0.08*	*0.08*	*0.04*	*3.8*

Gr = gravel; Cl = Clay; Lm = Loam; San = Sand; TOC = Total Organic Carbon;
TN = Total Nitrogen; CEC = Cation Exchange Capacity

6. 2. 2 Matching soil types and appropriate inputs.

A pot experiment was conducted from May 2011 to August 2011 to demonstrate the need to tailor soil fertility management technologies to specific soil types. The experiment was conducted at Mamba hill in the greenhouse of the Faculty of Agriculture of the National University of Rwanda (NUR). The experiment took place at ambient temperature in the greenhouse, which served as a shelter from rain while ensuring sunlight. The test plant was the Sorghum *bicolor (L.) Moench,* variety IS 21219, from ICRISAT.

❖ *Treatments and Experiment layout*

Different treatments were defined to test different hypothesis.

F1. Control or zero input: the reference treatment; to test the soil type’s natural fertility potential
F2. Lime/travertine; to test the need for liming
F3. Farmyard Manure (FYM): to test the response to FYM; the current farmer practice
F4. NPK: to test the response to fertilizer as new input being introduced
F5. Lime + FYM: to assess the interaction between lime and FYM
F6. Lime/travertine + NPK: to evaluate the interaction between lime and fertilizer
F7. NPK + FYM: to test the interaction between FYM and fertilizer
F8. Lime + FYM+ NPK: to test the interaction between lime, FYM and fertilizer

The trial was a factorial Randomized Complete Block Design (RCBD) three times replicated. Two factors were considered: soil type with four levels and fertilizer types with eight levels.

❖ *Input application and trial set up*

Double polyethylene pots (plastic) 14 cm deep and 16 cm wide were used to contain soils and drainage water. Each soil substrate was put into a set of two pots one containing another. In the inner pot containing the soil substrate, four little holes were made in the bottom to allow the drainage of excess water. The role of the outer pot was to collect water draining from the soil in order to return it to the soil in the inner pot to avoid nutrient loss. The total number of pots of equal size was 96. Each pot soil substrate was homogeneously mixed with fertilizers and/or other amendments according to treatments and rates of application.

For each treatment, the following inputs and their rates were used:

- 1 kg of soil/pot
- 0.15 g of NPK per pot: equivalent of (51 kg of N, 51 kg of K_2O, 51 kg of P_2O_5)/ha or 300 kg of NPK 17-17-17 $ha^{-1,}$ the blanket recommendation used for sorghum in Rwanda.
- 5 g of FYM per pot: equivalent of 10 t/ha, the general recommendation in the area.
- 4.2 g per pot of lime (Mashuza travertine: 40% of CaO.): equivalent of 8 t/ha of travertine.

Input dose per kg was calculated assuming 2,000,000 kg of soil/ha on a basis of a soil depth of 15 cm and 1.3 soil density (Brady and Weil, 2002). After mixing the soil and the input manually in a plastic basin according to each treatment's inputs, the soil was introduced into pots in two portions. The bigger portion was deposited into the pot and leveled. Ten seeds were separately placed on the soil surface of each pot and a little more soil was then added to cover the seeds uniformly to about 1 mm of soil depth above the seeds. A wooden plate was used to level and lightly cram the soil in the pots such that 3 cm distance was left between the soil surface and the upper edge of the pot. Then, the pots were watered to saturation until seeds germinated. After watering, pots were covered by their plastic covers until germination was complete. They were then grouped into three blocks. Each block was made up of 32 pots arranged and seated randomly (Figure 6.1). A permutation of pots following the blocks design was done every day (in the evening) to ensure even distribution of light and avoid biased results. After germination was complete, only seven out of the ten seeds were left and allowed to grow. The three seedlings uprooted were laid on top of the soil to decompose.

- *Trial management and data recording*

Watering of the pots was done on a regular basis every two days. The water rates were calculated considering the soil water retention capacity previously determined. Every day of watering, the drainage water collected in the outer pot was recycled into the soil. For the first 20 days after germination, watering was done to 4/9 of soil water retention capacity of each soil type, then after that period watering was done to soil saturation (full saturated soil, equivalent of effective porosity). The change in the watering doses is justified by the crop water use efficiency related to crop growth stage. Sorghum biomass yields were harvested three times on regular basis of 28 day interval after planting. Fresh weight of the plants (g) was recorded on a precision balance and the mean for the three cut was calculated.

- *Data analysis*

Statistical analysis was performed using the GenStat software, (12th editions). Differences in various treatments were tested using "two–ways analysis of variance (ANOVA2) in Randomized complete Block design, with least significant mean differences at 5% probability level.

Repetition I	S1F7	S4F2	S3F7	S1F5	S2F4	S3F2	S2F5	S4F6
	S3F6	S2F6	S4F5	S3F8	S4F1	S2F3	S1F4	S2F8
	S4F3	S1F6	S2F2	S4F7	S1F2	S4F8	S3F1	S1F1
	S2F7	S3F3	S1F8	S2F1	S3F5	S1F3	S4F4	S3F4
Repetition II	S4F1	S1F2	S2F8	S4F5	S3F4	S2F5	S2F5	S1F6
	S2F6	S3F1	S1F5	S2F2	S1F1	S3F2	S4F3	S3F6
	S1F3	S4F6	S3F3	S1F7	S4F2	S1F8	S2F7	S4F8
	S3F8	S2F4	S4F4	S3F7	S2F1	S4F7	S1F4	S2F3
Repetition III	S2F4	S3F2	S4F6	S2F2	S1F4	S4F7	S1F5	S3F6
	S4F5	S1F6	S3F5	S4F8	S3F1	S1F3	S2F7	S1F8
	S3F3	S2F1	S1F2	S3F7	S2F8	S3F8	S4F2	S2F6
	S1F7	S4F3	S2F3	S1F1	S4F1	S2F5	S3F4	S4F4

Figure 6.1. Experimental design: the arrow on the top right of the experimental design indicates that pots were subjected to a regular rotation

- *Evaluation of effect of lime on soil properties*

After the experiment, some key elements (pH, Ca^{2+} and $Al^{3+)}$ were analysed to evaluate the effect of lime on soil properties by comparing treatments with and without lime. Soil analysis was conducted in the laboratory of the 'Institut Superieur d'Agriculture et d'Elevage' (ISAE). The pH water was determined using a pH meter in a 1:2.5 soil-water ratio. The exchangeable acidity was determined by leaching with 1 M KCl and titration by 1 M NaOH. Exchangeable bases were determined by ammonium acetate extraction method, and from extracts, concentration of calcium was determined by atomic absorption spectrophotometry.

6.3 Results

6.3.1 Sorghum biomass experiment results

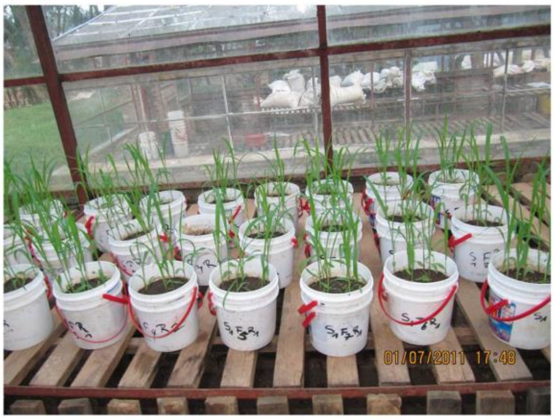
Figure 6.2 (poster 6.1) shows the effect of different input combinations (the eight treatments) in each soil type. Figure 6.2 (poster 6.2) compare the effect of each treatment on the four soil types. Figure 6.3 presents the mean sorghum biomass yields (g/kg) per soil type and treatment in each soil type. During the experimentation, the difference in crop response was clear between different soil types and treatments. Considering the factor soil type, *Urusenyi* proved to be the most productive in all treatments, followed by *Inombe*, followed by *Nyiramugengeri*, followed finally by *Umuyugu/Mugugu.* This is exactly the ranking previously done by farmers. The observed trend during the experimentation

(Figure 6.1) was confirmed by the statistical analysis. Indeed, the analysis of variance (ANOVA) showed that there were significant differences between soil types and treatments ($p < 0.001$).

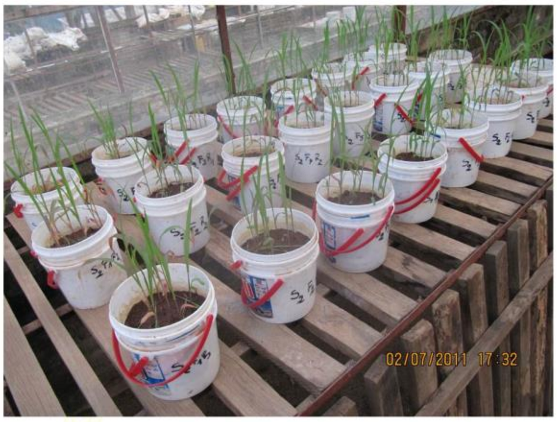
The best treatments, from the mean of the three cuts, in *Urusenyi* were the combination of lime + FYM + fertilizers (F8) and the combination of farmyard + fertilizers (F7). Treatments with lime (F2), NPK (F4) and the combination of lime + NPK (F6) showed significantly superior biomass yield compared to the control. Treatments with FYM (F3) and FYM + NPK (F6) showed significantly inferior biomass yield compared to control. The inferiority of those two treatments appeared to the second and the third cuts. It might be partially explained by the sensitivity of the sorghum plants after the first cut, to a certain fungal population observed in those two pots during the experimentation. Therefore, caution is permitted about these two treatments because of these external factors. In *Inombe*, the best treatments were the combination of lime + FYM + NPK (F8) and lime + FYM (F7) in the first category of mean separation and, NPK (F4) and lime + NPK (F6) in the second category. The remaining treatments of lime (F2), FYM (F3) and FYM + lime (F5) were in the same category with the control (F1). The high productivity of *Urusenyi* compared to *Inombe* is likely to be explained by the good status of the *Urusenyi* in basic cations such Calcium and Potassium that allow efficient use of its relatively good status of organic Carbon and Nitrogen (Table 6.2). The relatively high basic cation concentrations are likely to be explained by the high quantity of gravel (Table 6.2) which implies some alterable minerals.

In *Umuyugu* and *Nyiramugengeri* soil types, the best treatment was the combination of lime + FYM + NPK (F8), followed by the combination of lime + FYM (F6) in the same category with the combination of lime + NPK (F5). The response of the treatment which received lime alone (F2) was significant but still very low. Treatments without lime (F3, F4 and F7) had low biomass production in the same category of mean separation with the control (F1). In both soils, all treatments without lime yielded zero biomass at the 3rd cut.

Poster 6.1 Pot experimentation: comparison of the 4 soil types containing all treatments



Urusenyi*: from left to right F1 to F8*



Inombe

Umuyugu

Nyiramugengeri

Treatment: F1= control; F2= lime; F3= farmyard manure (FYM); F4= fertilizer; F5= lime + FYM; F6= lime+ fertilizer; F7= fertilizer+ FYM; F8= lime + FYM + fertilizer

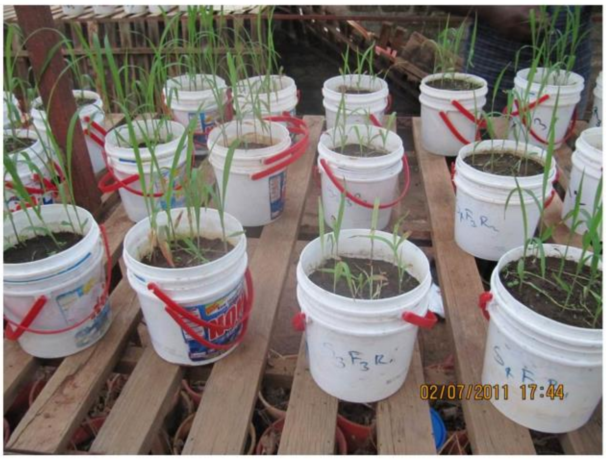
Poster 6.2 Pot experimentation: comparison of the 8 treatments in the 4 soil types


02/07/2011 17:37

F1: control: From left to right: Urusenyi, Inombe, Umuyugu, Nyiramugengeri


02/07/2011 17:42

F2: lime


02/07/2011 17:44

F3: FYM


02/07/2011 17:46

F4: fertilizer

Poster 6.2 Pot experimentation: comparison of the 8 treatments in the 4 soil types (continued)

F5: lime + FYM

F6: lime + fertilizer

F7: fertilizer + FYM

F8: lime + FYM + fertilizer

Figure 6.2 Experiment: pots ranged according to the soil types (poster 6.1) and different treatments (poster 6.2)

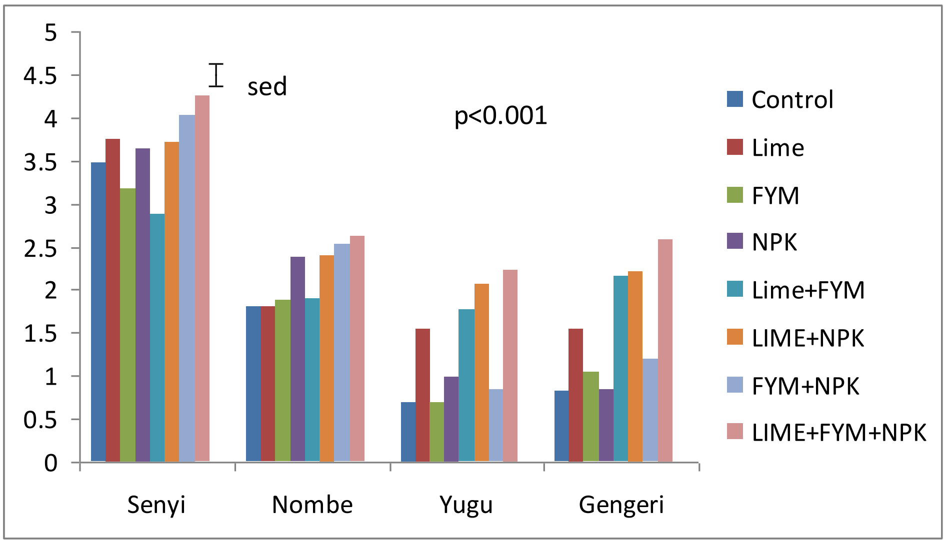


Figure 6.3 Mean sorghum biomass yields (g/Kg of soil) of three cuts: crop response to the soil type and soil fertility replenishment treatments. In this figure Senyi= Urusenyi; Nombe= Inombe; Yugu= Umuyugu; Gengeri= Nyiramugengeri; SED= Standard Error Deviation.

6.3.2 Effect of lime on soil properties

Figure 6.4 shows the effect of lime on soil pH, calcium and aluminium. All soil types responded favorably to the lime as follows: in all soil types, soil pH increased over 0.68 units on average. In each soil type the increase was as follow: *Urusenyi* (0.78), *Inombe* (1.1), *Umuyugu* (0.82) and *Nyiramugengeri* (0.68). *Urusenyi* changed from the moderately acid (5.6-6.0) to the neutrality class (6.6-7.3). The strongly acid *Inombe* (5.1-5.5) changed to the lightly acid class (6.1-6.5). *Umuyugu/Mugugu* and *Nyiramugengeri* changed from the extremely acid class (< 4.5) to the very strongly acid class (4.5-5.0). The little change of pH in *Urusenyi* suggests a little need in calcium/lime (Neel, 1973) while the greater change of pH in *Inombe* is likely to be explained by greater need in calcium/lime as these two soil types differ in their calcium concentrations and their gravel status (Table 6.2). In *Umuyugu/Mugugu* and *Nyiramugengeri* the little change is likely to be explained by the buffer effect of organic matter of these soils (Rutunga and Neel, 2006). This shows that soils in the moderately acid class can be limed towards the neutrality class, while those in the strongly and very strongly acid class can be limed towards the strongly acid class (5.1-5.5). This would suggest that the pH value of 5.5 should be the target for efficient liming of extremely and very strongly acid soils. This is consistent with many authors’ findings for acid tropical soils (Sanchez, 1976, Rutunga et al., 1998; Rutunga and Neel, 2006). Indeed, more liming of tropical acid soils to soil pH 7 causes more harmful than good (Sanchez, 1976). For instance, while a single application of 2 t/ha of lime on an acid *Oxisol* (*Umuyugu/Mugugu)* significantly decreased the level of the exchangeable aluminium and increased the soil pH, Ca^{2+} content, cationic exchange capacity ($p < 0.001$), the application of 2 t/ha every 2 years during eight years has raised the soil pH from 4.6 to 7.5 but at the same time, has led to over liming (Rutunga et al., 1998). The over liming had a negative effect on crop yields (Rutunga et al., 1998).

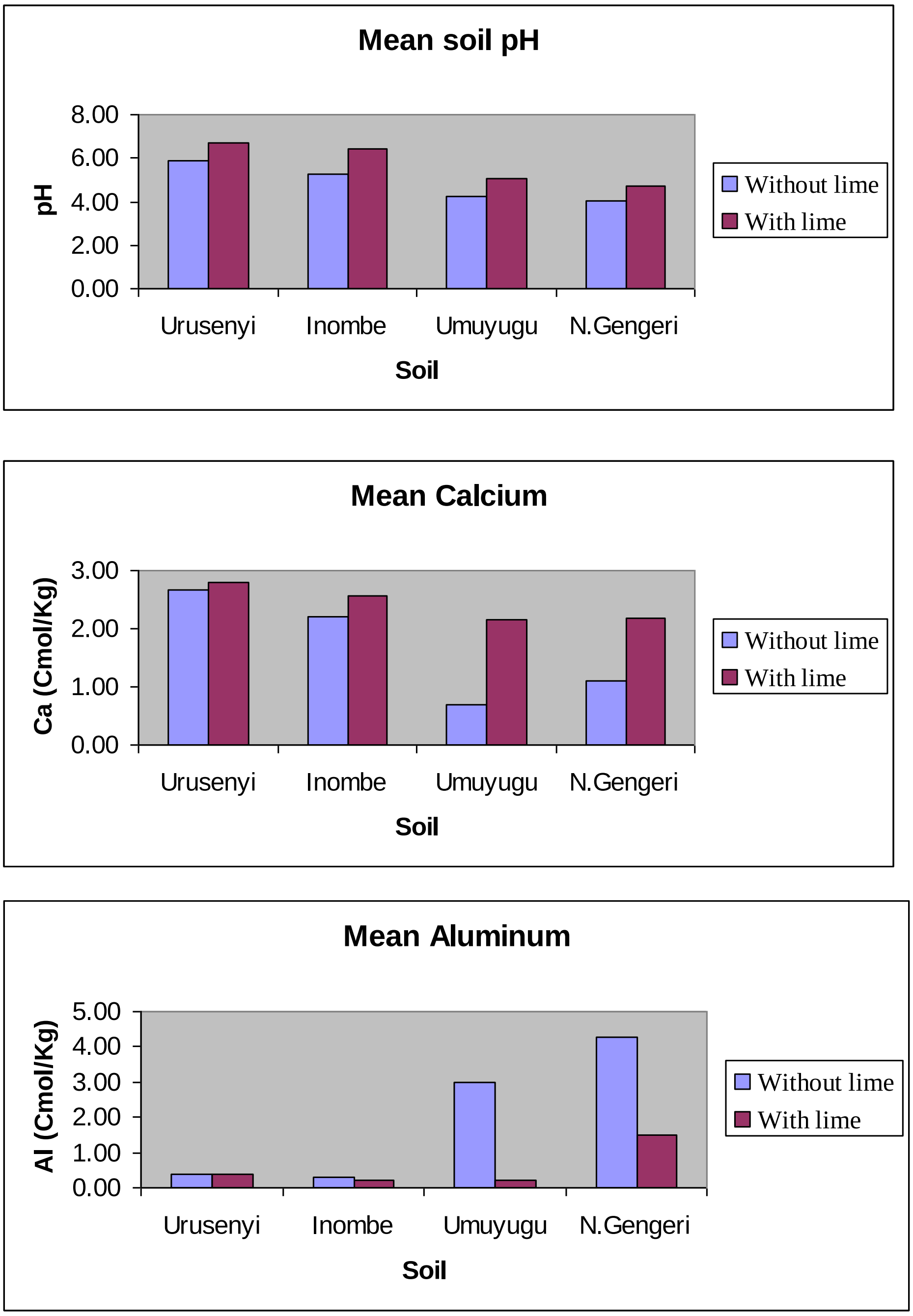


Figure 6.4 Comparison of effect of lime on some key soil properties between treatments with and without lime.

With calcium, the more a soil type is deficient in this nutrient, the more is its increase through liming. Thus, the increase was greater in *Umuyugu* (1.45), followed by *Nyiramugengeri* (1.08), followed by *Inombe* (0.35), and followed by *Urusenyi* (0.13). In these leached soils, calcium is likely to act as a nutrient and an amendment at the same time (Rutunga et al., 1998; Rutunga and Neel, 2006). Aluminium was also significantly reduced in both *Umuyugu* (2.79*)* and *Nyiramugengeri* (2.76) where it was among the limiting factors (Figure 6.4**)**. This is consistent with several authors who observed the positive effect of 2-3t/ha of lime on acidic soils of southern Rwanda (Neel and Deprins, 1973; Rutunga et al., 1998, Rutunga and Neel, 2006; Mbonigaba, 2007). The reduction of Aluminium is explained (Figure 6.5) by the reaction of lime in the Aluminium rich soils where 3 Ca^{2+} cations replace 2 Al^{3+} cations on the complex and the released Aluminium [Al $(OH)_3$] which is inactive and is eliminated in the drainage water (Sopher and Bair, 1982). In our case, the level of Aluminium reduction is shown in Figure 6.4.

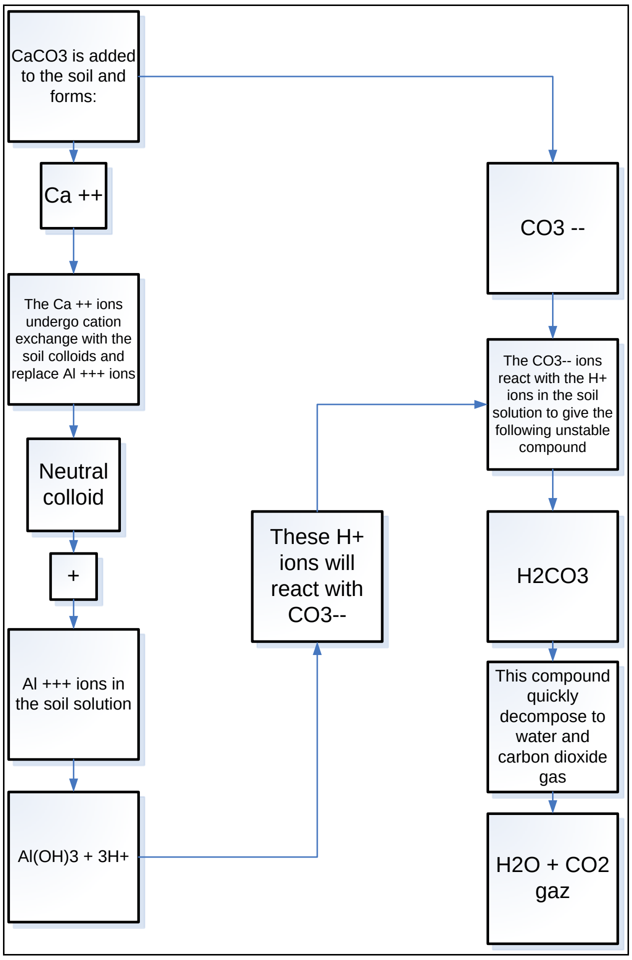


Figure 6.5. The overall net reaction of calcitic limestone in the soil favours neutral soil colloids and a reduction in the relative number of H^+ *ions in the soil solution. A consequence of this, the pH of soil is raised. Source:* Sopher and Bair (1982).

6.4 Discussion

Results showed that different soil types in relation to the land units where they occurs (Table 6.1) have inherently different fertility potential. This is proved by differences in soil properties and in biomass crop yields of the control treatments (F1) in the four soil types (Figure 6.3). Because of the different soil fertility potential (Table 6.2), the four soil types also responded differently to fertilizers and other soil amendments with the soils on the upper hill land unit being more productive than these on the back slope and valley bottom (Figures 6.2 and 6.3). This is in line with Steiner (1998) who reported that in the highlands of Rwanda, soil parameters change in a specific way from the hilltop/upper slope to the lower slope and valley bottom. The soil property variations along the slope are often reflected into crop yields. For instance, under the same management practice and on average, the lower slopes yield 20-50% less compared with upper slope, depending on season and crop rotation (Steiner, 1998). This does not mean that the effect of management is always negligible but rather that it needs to be circumscribed within each soil type as shown in Figure 6.3. This means that the management influence on soil properties and crop yields depends on soil type and the level of input. This implies that 'the use of soil type information in soil-related decision making should be at the heart for sustainable use and management of agricultural land' (de la Rosa et al., 2009).

Consistently with its favorable chemical soil properties, *Urusenyi* soil type proved to be superior in almost all treatments. In this soil, the control treatment (F1) yielded highly significant results compared to the best treatment in the rest of soils (Figure 6.3). In the same token, *Inombe* soil type was the second productive soil considering almost all treatments. In these two soils, the effect of lime (treatment F2) applied alone was not very spectacular (Figure 6.3). The reason might be that the two soil types with a pH water > 5.5 (Table 6.2) do not need the lime as an amendment or as source of nutrients (Sanchez, 1976; Rutunga et al., 1998; Rutunga and Neel, 2006). In these soils of low CEC, the relatively good basic cation concentrations would suggest that the non acid cations like Ca^{2+} and Mg^{2+} (Table 6.2) do not constitute a limiting factor. In both soils, the FYM treatment was not impressive (Figure 6.3). The reason might be the fact that the organic matter content of the control treatment was enough. Indeed, Tessens (1991) considered 2 % of TOC as sufficient in the conditions of Rwanda and Burundi. This is consistent with many other studies (Rutunga et al., 1998, Rutunga and Neel, 2006). Thus, the control treatment (F1) which represents the farmer practice was at adequate level of organic matter (Table 6.2). The general trend in both *Urusenyi* and *Inombe* soil types shows that all treatments with fertilizer component tended to respond favorably (Figure 6.3). The observed situation suggests that the limiting factor in these two soil types is low macronutrient (N, P, and K) concentrations. The little response to lime (F2) in both *Urusenyi* and *Inombe* (Figure 6.3) is more likely to be explained by a good soil pH level in these two soil types (Table 6.2). For these two soil types, the best recommendations, from a statistical point of view were the combination of FYM + fertilizer (F7) and the combination of lime + FYM + fertilizer (F8). However, because the lime in F8 has a cost without significantly increasing the biomass yield compared to (F7), the recommendable treatment at this level might be the combination of FYM + fertilizer (F7). In this treatment, FYM was expected to supply nutrients and to improve the fertilizer use efficiency by increasing the CEC (Rutunga et al., 1998). The optimum recommendation can only be determined after comparing the cost-benefit analysis of all treatments at field level (Bekunda et al., 1997).

While the effect of lime on crop biomass yields of the two previous soil types (*Urusenyi* and *Inombe*) was less spectacular, on *Umuyugu* and *Nyiramungengeri* soil type, it became impressive since the first cut. In the latter two soil types, the biomass yields of the lime treatment applied alone (F2) was statistically higher compared to all treatments without lime F1, F3, F4 and F7 (Figure 6.3). This positive effect was attributed to the fact that the lime raised the soil pH, inactivated the aluminium and supplied basic cations to the plants (Figure 6.4) and eventually increased the P availability (Sopher and Bair, 1982; Rutunga et al., 1998; Rutunga and Neel, 2006). However, the effect of lime alone was still very low compared to the combination of lime + FYM (F5), lime + fertilizers (F6) and lime + FYM + fertilizers (F8) (Figure 6.3). This would indicate that, in these soils, the acidity and the basic cation (Ca and Mg) concentrations were the most limiting factors. When these elements are supplied at adequate level, the macronutrients (N, P and K) become the limiting factors. This is proved by poor response to the treatments lime, NPK, FYM alone or their binary combinations (Figure 6.3). In these soils, the recommendable soil fertility management strategy is the combination of lime + FYM + fertilizers (F8). This is consistent with findings from other studies in the area (Rutunga et al., 1998; Rutunga and Neel, 2006). In this combination, the role of the FYM is to improve the fertilizer use efficiency by increasing the CEC and by releasing additional nutrients, especially the N (Rutunga et al., 1998). In *Umuyugu/Mugugu* and *Nyiramugengeri* soil types, the fact that the biomass yields of all treatments without lime decreased cut by cut to become zero at the third cut would mean that their little basic nutrient reserves were over and, in the mean time that the aluminium toxicity increased.

The results obtained in *Umuyugu/Mugugu,* the largest soil unit are supported by previous studies at experiment site level (Neel, 1972, Neel and Deprins, 1973; Rutunga and Neel, 1980 and Rutunga and Neel, 2006) and the current field reality. In this soil type, without lime no legume or cereal yield is possible when FYM or fertilizers are applied alone (Rutunga et al., 1998; Rutunga and Neel., 2006). With the combination lime (2 t/ha) + FYM (10 t/ha) fresh matter + fertilizers (300 Kg NPK 17-17-17) (Rutunga et al., 1998; Rutunga and Neel, 2006), yields were spectacular: e.g. 30-40 t/ha of Irish potato, 3-5 t/ha of wheat, 3-4 t/ha of beans and 2-3 t/ha of Soybean (Rushemuka et al., 2012).

The crop yields that result from the recommended high input system have been reported to be sufficient to justify the heavy investments required to transform these unproductive soils into productive ones (Bizoza and de Graaff, 2010). However, due to the low investment capacity of Rwandan small farmers, the initial stage of the soil fertility management should be supported by the government or its partners (Drechsel et al., 1996). Beyond the small farmers' credits recommended (Drechsel et al., 1996), the scientific support remains crucial. This is very important because it has been noted that farmers lack the necessary knowledge to efficiently use the newly introduced input (Giller et al., 2011). The scientific support would help to avoid existing over liming risk (Rutunga et al., 1998) and try to minimize the high yield risk associated with this high input system especially seed born diseases mainly on Irish potato, the most profitable crop. Without these precautions that ensure sufficient know-how to small farmers and minimize the yield risk, previous large scale adoption incentives like 'bank credits, feeder roads have not engendered expected outputs '(Bizoza, 2011).

The difference in biomass yields according to different soil types and different fertilizer combinations and other amendment combinations confirm the need of systematic consideration of different soil types within one watershed. It is a proof that different soil types, at watershed level, may need different fertility management strategies. These soil differences are well perceived by farmers. From a scientific point of view, they are supported with the geological map of Rwanda 1:100,000 (Dehandschuter and Buyagu, 1991) which shows different geological units mainly on the hills and the valley bottoms. They are also indicated by the soil map of Rwanda 1:50,000 (Birasa et al., 1990) which shows different soil series that belong to different soil orders of *Soil Taxonomy* (Table 6.1). However a recent literature (Tittonell et al., 2007) has associated the decrease in crop yields with the increasing distances from the homesteads suggesting that in addition to the within farm soil fertility gradients, the management factor has a greater role in such variability.

In the study area, findings from this study and previous observations (Clay and Lewis, 1990) help to understand that the household are preferably located on the upper hill where geomorphological conditions (gently slopes and well drained soils) exist and where soils are naturally more fertile compare to the hillside. In the same token, the topsoil fertility of the soils in this land unit is maintained by the household manure because their properties can still allow it. On the contrary, as told by the farmers in Akavuguto watershed, households located on the hillside/back slope (as result of demographic pressure and the subsequent land shortage) have failed to improve the fertility of the hillside soils for more than 50 years (Neel was already installing fertilizer experiments in the region since 1971). The situation of down slope hillside being less responsive to soil fertility management inputs compare to the upper slope was reported by many authors in Rwanda (Drechsel et al., 1996; Rutunga et al., 1998; Steiner, 1998) and abroad (Giller et al., 2011). The reason is the fact that those extremely acid, leached and aluminium rich soils on the lower slopes hardly respond to household organic manure or to the fertilizer alone. They need lime to boost their productivity and organic matter to increase their CEC before being responsive to fertilizers (Rutunga and Neel, 2006).

Considering the above results and the general situation of the soils in Rwanda (Birasa et al., 1990), it can be observed that the extremely (< 4.5) to very strongly (4.5-5) acidic and inherently poor soils occupy 43% of the national crop land. The poor properties of Rwandan soils are explained by their origin in ancient and acid parent materials (schists, granite, gneiss and quartzite) coupled with steep slopes and heavy rains. In normal conditions, those unsuitable soils should not be used for annual food crop production. However, given the land scarcity and the demographic pressure of this country, coupled with the lack of alternative opportunities outside the agriculture sector, there seems to be no choice. This means that agricultural development in Rwanda relies on transforming unproductive soils into productive ones. This can be termed soil fertility domestication like animal or crop/tree species domestication.

6.5 Conclusion

This study insisted on the understanding of one’s biophysical environment in terms of soil types and their spatial distribution at various scales for sustainable and soil-specific fertility management. More specifically, the study stresses the need of understanding the effect of soil type before considering the contribution of the management factor when interpreting existing agrosystems, when designing experiments, when evaluating data and when extrapolating results. The major findings confirm that different soils in the watershed require different soil fertility management strategies according to their intrinsic soil properties and that farmers’ soil nomenclature could constitute a helpful tool to systematically take into account the soil differences in a friendlier manner. The *Urusenyi* and *Inombe* on upper hill land unit responded significantly to the combination of FYM + fertilizers and to the combination of lime + FYM + fertilizers. Still, the control/farmers’ practice responded well. The combination of FYM + fertilizer would be the best option. These soils might not need liming.

The *Umuyugu/Mugugu* on the hillside/back slope and the *Nyiramugengeri* in the valley bottom responded significantly to lime either alone or combined with FYM or fertilizers. The best treatment was the combination of lime + FYM + fertilizers. There was almost no response to all treatments without lime. In these two soil types; lime is indispensable before any other intensive use of fertilizers. The study demonstrated that soil fertility response is, first of all, soil type dependent. Therefore, a technology developed in one soil type in a given land unit must be extrapolated only to the similar soil type in the same AEZ until the contrary. In the complex soilscapes such as the one encountered in Rwanda, the farmers’ soil nomenclature linked to scientific soil knowledge (soil properties) and circumscribed in a multi-scale and nested hierarchy land system (Figure 1.8) is a practical way of undertaking soil-specific fertility management and replicable technologies.

Chapter VII: General conclusion

7.1 Conclusion

Overall, the thesis has advanced the understanding about the key role of accessible/intelligible soil resource information to make effective the PIWM innovation model and to ensure soil-specific and farmers' judgmental fertilizers use. The overwhelming majority of the previous studies have recognized the PIWM as a real progress in the conceptualization of agricultural research and development and a promising innovation model to deal with the inherently complex farmers' production problem. However, until now, the holistic nature of this approach is reputed to be more cumbersome and enormously challenging. The little effectiveness of this development model calls to mind the existing impression that much of agricultural research and development models, developed by the international research overtime, seem to lack direction (Rhoades, 1999).

The underpinning problem that emerged from this thesis appears to be the fact that farmers and scientists use different frame of reference of soils on one hand, and that both knowledge systems are not accessible to scientists from other disciplines involved in the PIWM on the other hand. Yet, during the PIWM innovation process, interactive information exchange between different stakeholders is about commodities (crop species and varieties, animal breeds), socio-economic aspects (gender, poverty, input access, market and saving etc.) and institution arrangements (norms and rules that govern research and development) and this, in total disconnection from the soil resource factor – one of the foundation of all these components! Indeed, there cannot be full and deep interactive problem analysis and identification of sound solutions without common communication language about soils. This thesis, nevertheless, has shown that these two knowledge systems, though using different soil knowledge systems, can work in synergy provided that communication bridges are established and the originality of each system is preserved.

In Akavuguto watershed, as a case study, this was achieved by exploiting the soil-landscape relationship by means of land units, farmers' soil names, diagnostic horizons, geographic coordinates and the CPR mapping units. At watershed level, land units were chosen as the first integration step. Indeed, land units are visible entities and serve as a basis to determine soil mapping units. Sustained consistency of the mapping units has been observed when the same area is mapped by specialists of different disciplines (geology, geomorphology, cartography). This consistency testifies to the crucial role that the land unit can play in information exchange between scientists from different disciplines. In addition, high correlation between scientific and farmers' land units is usually observed. This means that the land unit is a natural entity which allows a first contact with the watershed and common ground for information exchange.

The soil was considered at second level. Within land unit, the soil factor is more complicated. Indeed, soil scientists and farmers use different procedures to identify and to name a soil type. The problem with the scientific soil maps is that, to use them one must understand all the process of their realization. In practice, few potential users, outside pedologists, understand how soil maps are done. Farmers, on their side, use vernacular soil names. It has been shown, in this thesis, that these farmers' soil names cope well with the special nature of the soil as a natural body, are closely related with the land units and reflect many soil properties and soil suitability. Farmers' soil names play the same communication role as the scientific soil classification systems. The soil-landscape relationship represents the soil surveyor mental model, and is equivalent to the farmers' mental soil map. Soil chemical properties are usually compared to the farmers' soil quality indicators. Although correlation between scientific and farmers soil knowledge may be possible, it might not be the best way of using the synergism between the two knowledge systems as this can significantly alter the originality of the FSK (Niemeijer and Mazzucato, 2003). The farmers' soil nomenclature linked with the scientific soil classification system, by means of diagnostic horizons, and to the CPR mapping units, by geographic coordinates, has been judged excellent communication language about soils between different stakeholders within the same watershed. Conversely, because the farmers soil quality indicators are more subjective and given the fact that farmers have a knowledge gap regarding the phenomena that they cannot see (by naked eye/microscopic level), the soil chemical and physical properties have been considered the objective way of understanding the challenge that farmers face and as the basis for proposing new interventions. For communication with non-soil specialists and farmers, the synergism between the two knowledge systems can be exploited through the communication bridges. This way, the soil factor dimension can be added to the PIWM innovation process and can contribute significantly to its effectiveness. In this process, the soil scientist serves as an interpreter in the broader biophysical and cultural context, rather than the narrow linguistic sense of the term. Once a technology is built on basis of the farmers' soil names, on small but representative plots, and given the farmers' mental soil map, its replication at watershed level, in analogous soil types would not pose many problems.

This thesis has contributed a simple, but efficient way of setting communication bridges between scientific and FSK systems. The synergism between the two knowledge systems has helped to understand that soil properties, soil fertility management and experimental results are primarily interpreted by means of the toposequence and secondly by the land use factor. The thesis has also shown that farmers' soil names are practical and can be used in agricultural research and extension. The accessibility of the soil resource information to all watershed stakeholders by means of the integration of the scientific and FSK will likely favor the emergence of appropriate institutions, conducive to more effectiveness of PIWM.

All in all, this thesis shows that the soil map of Rwanda linked to FSK is the bedrock on which to build agricultural development of this country. However, the thesis demonstrated that if the soil map is not used, it is not the fault of the soil map per se. The first responsibility lies on the persistence of the linear model's institutions in the agricultural research and extension of Rwanda that hamper the capacity of soil map to pattern with other soil science sub-disciplines and other soil-related disciplines to solve farmers' problems in a socially and environmentally relevant and efficient fashion. At this level, it is useful to mention that, if it can be possible, in the field of crop production, to rely on crop varieties developed by the international agricultural research centers, in soil and social sciences however, there is no choice; it is the task of Rwandan agricultural research community to understand its soil resource information, set up appropriate policies and adapt its institutions so that these crop varieties can make the difference!

In the near future, taking the opportunities that offer 'near infrared' technologies, the existence of large scale aerial photographs -1/5,000 – and the land registration at national level, this soil map should be the basis of development and/or calibration of soil-related agricultural models such as those in the field of fertilizer application with significant threshold at watershed level. This is the new orientation that could take agricultural research and teaching in a country like Rwanda into the 21st century. In this process, soil science must be aggressive and should be prepared to take the lead, otherwise the needed change will hardly come.

7.2. Practical implications

A critical practical recommendation that emerges from this thesis is that the soils of pH water ≥ 5.5 (fertile class) are likely to produce acceptable crop yields with organic manure input. An attentive examination of the CPR (Birasa et al., 1990) under the light shared by the soil-landscape relationship as developed in this thesis can let one realize that soil series of such pH level dominate the low lands, the volcanic agricultural zone in the highlands and the upper hill land units of both middle and highlands. Some of their corresponding vernacular names were defined by Rushemuka et al (2009) in different AEZs of Rwanda. From a point of view of systematic classification (Soil Taxonomy), these soils belong generally to (1) *Lithic Troporthent (Urusenyi)* on interfluves/crests and distributed in all altitudinal zones and *Fluventic Humitropept (Urusenyi rw'inkata)* in the valleys of middle lands (2) *Alfisols* (*Inombe ya butsima)* on plateaus, shoulders and piedmonts in the low and, to less extent, in the middle lands (3) *Andosols* (*Amakoro)* in the volcanic region and (4) Vertisols *(Ibumba)* in the valleys of low lands.

Soils with pH between 5.2 and 5.5 (middle fertility class) require the combination of organic matter and fertilizers to produce normal crop yields. Soil series belonging to this category are generally found in the low and middle lands. They are dominated by *Ultisols* intergrades *Oxisols (Inombe irekuye, Inombe ya gatuku, Inombe ivangiye Umuyugu).* Considering the spatial distribution, in the low lands they are found on the hillside/back slope land unit associated with *Urusenyi* on the crest and *Inombe* on the piedmont. In the middle land, they are found on the upper hill (shoulder) land unit associated with *Urusenyi* on the crest and *Umuyugu/Mugugu* on the back slope.

Soils with pH water < 5.2 (infertile class) can only produce marginal crop yields for some less demanding crops (cassava and sweet pototo). They belong to *Oxisols (Umuyugu/Mugugu, Ikibimba, Umucucu, and Rwona* depending on the regions*)* on back slope land unit in the middle and highlands.

Soils of this category are also found in the valley bottom of the highlands dominated by *Histosols* (*Nyiramugengeri).*

Because of the steep slopes in the hilly areas of Rwanda, all soils require a serious erosion control strategy at different degrees depending on the severity of the erosion in the region or land unit. This should not be reduced to the sole erosion control infrastructures but should include the whole process necessary for soil health. The soils in the study area have shown low Cation Exchange Capacity (CEC) (Table 5.1). The low CEC is likely to be widespread in many Rwandan soils. For instance, among 14 profiles described (Pietrowicz, 1985) in the PAP Nyabisindu mandate area only one profile with vertic properties –*Vertic Tropaquept* (Soil Taxonomy)- had the CEC > 20 Cmol/kg of soil. Other 13 profiles had the CEC between 4.45-17,63 Cmol/kg of soil.

A similar situation was noted in many watersheds of Rwanda (Rushemuka et al., 2009). It is important also to highlight the crucial role of organic manure on water use efficiency. Tessens (1991) suggests maintaining the total organic carbon at minimum of 2.1% for most seasonal crops.

In addition to organic manure, soils with pH 5.2-5.5 need fertilizers. Soils with pH < 5.2 require a combination of lime + organic manure + fertilizers except the Histosols which may need only lime + fertilizers. Fertilizer alone is not a good option and should be avoided. Overall, agroforestry based (interaction between trees, crops and livestock) and soil-specific ISFM emerges as a sound option for sustainable food production in Rwanda. The financial implication is that sustainable agriculture development of Rwanda needs heavy investment in lime and compost production to sustain its Crop Intensification Programme (CIP), currently consisting of the intensive use of chemical fertilizers and high yielding varieties. Obviously, this will need suitable policies, programs and strategic plans.

7.3 Policy implications

An important policy recommendation to ensure sustainable food production in Rwanda should be to give up the linear R&D model and its top-down technology transfer in favor of more learning and partnership based innovation system approaches such as the PIWM. This stems from the fact that farmers in Rwanda have such profound knowledge of their soils that they exploit any soil difference in agreement with scientific rationality. The interaction between scientists and farmers is more important because in the long run, a development strategy that enhances farmers’ capacity to innovate and adapt in response to development challenges is encouraged (Ingram et al., 2010; Bizoza, 2011, Kolawole, 2012). It is, therefore, accommodating to build technologies on the farmers’ soil perspectives. After all, practices proposed by scientists and technicians rely on farmers to implement them, and ultimately, the farmers actions will determine the state of development (Ingram et al., 2010). Effective PIWM needs innovative policy framework that allows for constant interactions/collaborations between the social and the biophysical sciences. In a rapidly changing economic, ecological, political and organizational context, it is obvious that jobs like system understanding, local knowledge/actor linkages, research planning/impact assessment and policy making can no longer be the exclusive domain of the social sciences/economics (Leeuwis, 2004; Quinlan and Scogings, 2004; Raina et al., 2006). In this process, the soil science community must be prepared to lead the agricultural sciences through an ecological and social re-orientation, addressing all other key concerns in the knowledge about utilization and conservation of natural resources (Raina et al., 2006).

At national scale, it is important for policy makers, planners, and agriculture production scientists to bear in mind that with its complex soilscape, highly acidic and depleted soils, steep slopes, a high population density (416 hab/km^2) and a high population growth rate (2.6%), Rwanda is a specific case in terms of its biophysical and socio-economic constraints. This means that Rwanda’s problem need appropriate solutions and that no improvised solution can make the difference! At this level, it is important to be aware that, on the basis of relief and climate, Rwanda national territory has been subdivided into different AEZs, from which representative watersheds can be identified. At watershed level, the medium scale soil map of Rwanda becomes an important planning tool. It is time, therefore, to institutionalize a real working watershed research approach, not simply to move the discipline-based or commodity oriented technologies to small farmers. Real interaction between biophysical, biological, socio-economical and institutional sciences is needed to design working production systems that are economically viable, socially acceptable and environmentally friendly in a participatory manner. In this framework: (1) the agricultural research should move away from a farmer/technology focus to innovation system perspective (2) the research must be circumscribed not only in the administrative structures but first of all, in the biophysical environment to ensure the maximum reliability and geographic scope in regard to technology transfer (3) the research needs a major degree of cross-disciplinary cooperation with full farmers participation. In this new orientation, the watershed with its representative sequence of soils represents the new framework for a research station.

In practice, in the unproductive soils of Rwanda, mainly on the back slope land unit, soil fertility domestication needs special and concomitant strategies combining erosion control (bench or progressive terraces/hedge rows along contours lines), soil amendments (lime and/or manure), fertilizers and quality seeds. The organic manure is particularly important because it has a vital function to play in soil health notably the water and nutrient uses efficiency. As a consequence, in the unproductive soils of Rwanda, investments in erosion control, liming, organic and inorganic fertilizers are recommendable options and should be combined, but not opposed.

7.4 Further Research

This thesis has demonstrated the way and importance of linking the scientific soil map of Rwanda with the FSK in making more effective the PIWM approach in agricultural research and development. This is especially important because, in Rwanda, agriculture is practiced by small scale farmers with their own frame of reference of soils. However, there are areas which are not addressed by this thesis that deserve the attention of future research in the field of agricultural research for development:

- To identify the role of the soil resource information (biophysical environment understanding) in determining appropriate research policies and institutions compatible with PIWM philosophy, in other words, the contribution of the soil resource information in the set up of a functional SPPI.
- To determine, through experimentation, the optimum level of soil properties per soil type and the crop responses to single fertilizer element as input for crop modeling
- This thesis has compared the soil suitability in different land units of the same watershed. It would be necessary to compare different watersheds in the same AEZ or altitudinal zone to see if the land unit can serve as recommendation/extrapolation zone and to test the link between the CPR and the FSK in other AEZs.
- The methodology developed in this thesis was demonstrated using pot experimentation; it would be interesting to experiment at the field level.

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