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Focus on:

Soil science and agricultural development in Rwanda: state of the art. A review

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Poor agricultural productivity remains a crucial problem in Rwanda in spite of numerous technological interventions, including aspects of soil management. The objective of this study was to draw lessons from the past with the view to better orient future interventions in soil fertility management. The literature review and iterative field observations were the sources of information. Findings from this study show that substantial progress has been made in the identification of different soil types and their spatial distribution. Factors related to low level of productivity have been identified and sustainable soil fertility management options have been developed at plot level. However, the widespread adoption of these technologies has been problematic. The main reason is the failure to tailor soil fertility management technologies to specific soil types. The study has demonstrated that the soil map of Rwanda (CPR for *Carte Pédologique du Rwanda*) – 1:50,000 – offers a remarkable potential to constitute a tool to solve this problem. In practice however, the CPR remains underutilized, mainly because of its inaccessibility to its potential users (*e.g.* policy makers, soil fertility experts, agronomists and extensionists). For its effective use, the following is recommended: Rwandan soil scientists need to increase policy makers' awareness about the usefulness of this soil map; agricultural research needs to adapt from the conventional model to a truly participatory and integrated approach; the CPR legend should be elucidated by providing information on the land units in which soils occur and by bridging Soil Taxonomy with the farmers' soil nomenclature; regional soil reference systems should be established that allow linking soil types with the fertility status of arable land and crop yields. This implies the need for training of Rwandan soil scientists in both Soil Taxonomy (the language of the CPR) and the farmers' soil nomenclature so that they can serve as interpreter for scientists from other disciplines and farmers. Rwandan soil scientists should be trained in the use of Geographic Information System (GIS) software to enable them to exploit the digitized version/soft copy of the CPR and to become familiar with the Rwandan biophysical environment.
Keywords. Soil sciences, soil map, agricultural research, information exchange, rural development, Rwanda.

Science du sol et développement agricole au Rwanda : état de la question (synthèse bibliographique). Au Rwanda, malgré plusieurs interventions techniques, en ce compris les aspects de la gestion des sols, la faible productivité agricole reste un problème crucial. L'objectif de cette étude était de tirer les leçons du passé en vue de mieux orienter les interventions futures en gestion de la fertilité des sols. La revue de la littérature et les observations itératives sur terrain ont servi de source d'information. Les résultats de cette étude montrent qu'un progrès substantiel a été réalisé dans l'identification des différents types de sols et de leur répartition spatiale. Les facteurs responsables du faible niveau de productivité des terres ont été identifiés et les options de gestion durable ont été développées à l'échelle de la parcelle. Cependant, leur adoption à grande échelle est restée problématique. La raison principale apparait être l'incapacité d'adapter les technologies de gestion de la fertilité aux différents types des sols. Cette étude montre donc que la Carte Pédologique du Rwanda (CPR) - 1:50 000 – constitue un outil possible pour résoudre ce problème. En pratique cependant, la CPR reste sous-utilisée, principalement à cause de son inaccessibilité à ses utilisateurs potentiels (planificateurs, experts en gestion de la fertilité, agronomes et vulgarisateurs). Pour son utilisation effective, les recommandations suivantes ont été formulées : les pédologues du Rwanda devraient sensibiliser les planificateurs à propos de l'utilité de cette carte des sols ; la recherche et vulgarisation agricoles devraient passer de l'approche conventionnelle à une approche réellement participative et intégrée ; la légende de la CPR devrait être explicitée en y incluant les unités paysagiques/morphologiques et en établissant des ponts de communication entre la légende taxonomique de la CPR et les noms vernaculaires des sols ; des systèmes régionaux de référence sur les sols devraient être établis, qui permettent de mettre en relation les types de sols, l'état de fertilité des terres cultivées et les rendements obtenus. Ceci implique un besoin

pour une formation des pédologues du Rwanda à la maitrise de la « *Soil Taxonomy* » (langage de la CPR) et de la nomenclature vernaculaire des sols afin qu'ils servent d'interprètes pour les non-pédologues et les paysans. Au même moment, ils devraient aussi recevoir plus de formation sur l'utilisation des logiciels de Systèmes d'Information Géographiques (SIG) afin d'être capables d'exploiter la version digitalisée/électronique de la CPR et devenir familiers avec le milieu biophysique rwandais.
Mots-clés. Sciences du sol, carte de sols, recherche agricole, échange d'information, développement rural, Rwanda.

1. INTRODUCTION

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

While Hartemink (2006) maintained that soil science has contributed to the increase in world agricultural food production over the last 50 years, many other authors (Papadakis, 1975; Leeuwis et al., 2004; Ruellan, pers. com.) asserted that the increase in agricultural food production in the industrialized world was made possible less by progress in soil science and academic research than by the agronomic sciences, which developed responsive fertilizer varieties, pesticides and intensive use of fertilizers, agricultural engineering, value chain development and markets. The problem is that this capital-led and non soil-specific intensification of 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, pers.com.; Herren, 2011).

Despite the above concerns, in those developing countries where food production has stagnated over the last 50 years, there is a great temptation to "imitate" the developed world. For instance, in the African Fertilizer Summit, the conclusions of which were endorsed by the African Heads of State at Abuja, Nigeria, in 2006, it was argued that for a green revolution to take place in Africa, fertilizer use must be increased from the then mean of 8 $kg \cdot ha^{-1}$ to ~ 50 $kg \cdot ha^{-1}$ by 2015. Accordingly, African governments were encouraged to take conducive measures to increase fertilizer use. Following these recommendations, several African countries have used subsidies in efforts to increase farm-level fertilizer applications (Marenya et al., 2012). It is also in this context that Rwanda has promoted a policy of agricultural "modernization" and "crop intensification" with land consolidation, mechanization, mono-cropping, high yielding crop varieties, intensive use of fertilizers and irrigation (MINECOFIN, 2000; MINAGRI, 2002; MINECOFIN, 2007).

Agro-ecologists, while sharing the same concerns about 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) to be superior to conventional agriculture based on chemicals or Industrial Agriculture (IA). They thus propose measures to governments to lead the development and adoption of such approaches (Altieri, 2002; de Schutter, 2010; Herren, 2011; Marenya et al., 2012). Soil scientists, for their part, maintain that "agro-ecological solutions" are unable to contribute significantly to food security and poverty alleviation within the context of acid and inherently poor soils, such as those found in many parts of sub-Saharan Africa (Drechsel et al., 1996; Rutunga et al., 2006; Breman, 2011; Keating et al., 2011).

Several questions arise: is the debate about IA *versus* EA new? Has any progress been achieved? What position should governments take? Should they wait for scientists to reach a compromise, or is even any compromise possible?

The objective of this study 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.

2. METHODOLOGICAL APPROACH

A literature review, including unpublished reports, maps and journal articles, was the main source of information for this study. 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 ~ 80 years (1930-2010). Three years (2010-2013) of iterative field activity observations were undertaken to support the literature review with concrete and recent examples. **Figure 1** presents the location of Rwanda within Africa, the Agro-Ecological Zones (AEZs) of Rwanda (Verdoodt et al., 2003a) and the main sites cited in the text.

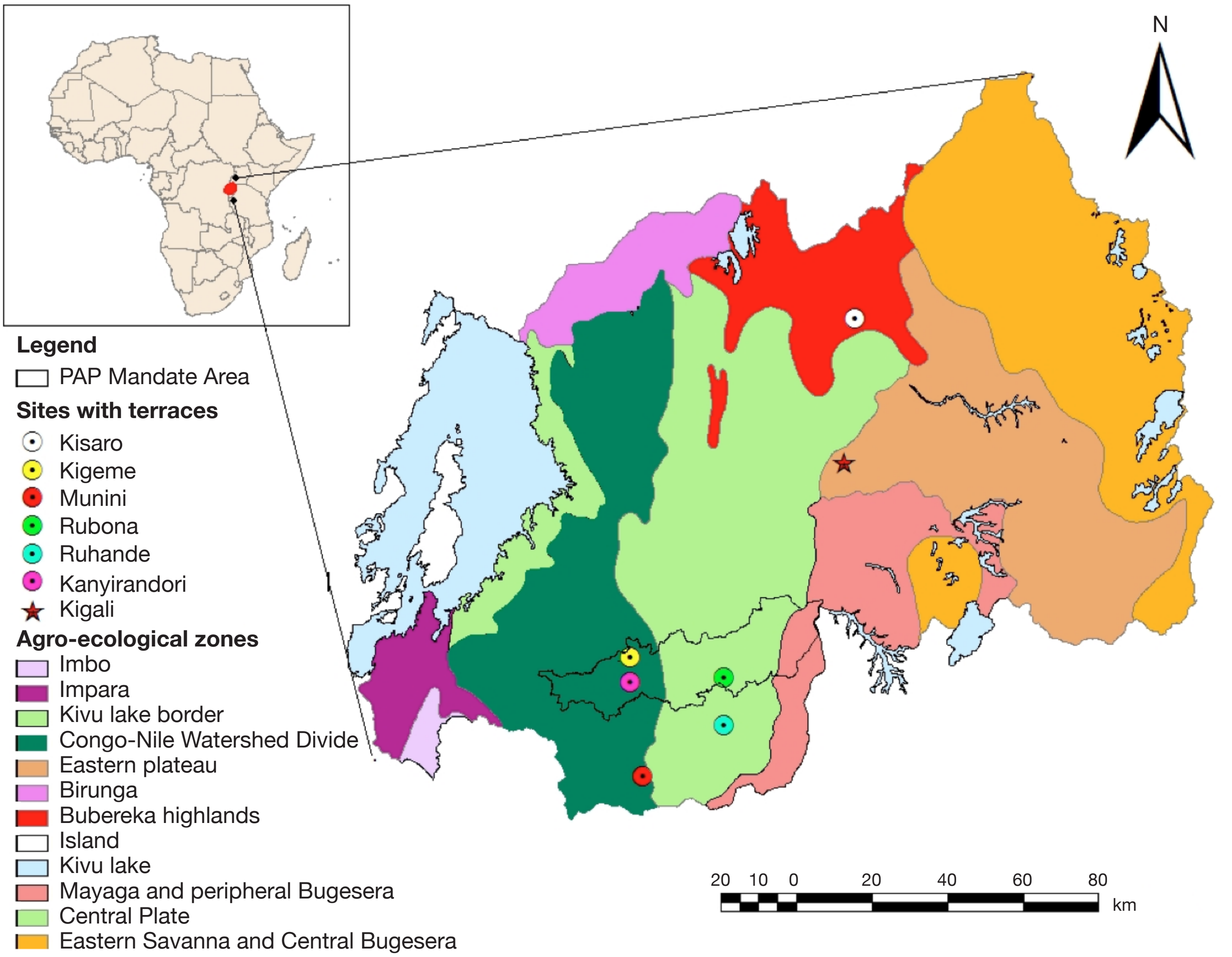

Figure 1. Location of Rwanda within Africa, Rwanda Agro-Ecological Zones and sites cited in the text (adapted from Verdoodt, 2003a and Schörry, 1991) — *Localisation du Rwanda par rapport à l'Afrique, Zones Agro-Écologiques du Rwanda et sites cités dans le texte (d'après Verdoodt, 2003a et Schörry, 1991).*

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: soil survey, soil conservation, and soil fertility management.

3.1. Soil survey

The first soil survey in Rwanda was undertaken by the team of the "*Institut National d'Études Agronomiques au Congo*" (INEAC), beginning in 1955 at Rubona Station (**Figure 1**). After Independence (1962), INEAC activities were continued by the "*Institut des Sciences Agronomiques du Rwanda*" (ISAR), which was integrated in 2012 into the Rwanda Agriculture Board (RAB). By 1963, the major soil types of the country had been described (Van Wambeke, 1963). In the 1980s, almost all soil knowledge acquired by the INEAC-ISAR team was synthesized into a soil association map at a scale of 1:250,000 (Prioul et al., 1981). During the same period, Pietrowicz (1985) undertook a soil survey in the mandate area of the project "*Projet Agro-Pastoral (PAP) Nyabisindu*" (**Figure 1**).

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

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"[1]) 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), erosion control was abandoned and many erosion infrastructures were even deliberately destroyed (Kabiligi, 1985). In 1966, the government of Rwanda revived a national program of soil erosion control. Following this, several compulsory five-year programs (1966-1970; 1977-1981; 1982-1986) were implemented.

In 2005, as the country was recovering from the 1990-1994 civil war and genocide, the erosion control program was re-started with the same approach. Since then, 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 common examples of erosion control infrastructure in Rwanda is in the use of infiltration ditches (*imingoti*) stabilized by grass verges parallel to contour lines (**Figure 2**). In addition to being labor-intensive and lacking positive impacts on crop yields, the method is inefficient in controlling soil erosion on steep slopes. In fact, the ditches do not have any impact on tillage practices (the root cause of human-induced erosion) or on physical soil properties (*e.g.* improvement of water infiltration rate).

Figure 2. Fields on a steep slope with infiltration ditches and grass verges parallel to contour lines for erosion control — *Champs sur forte pente avec fossés d'infiltration et bandes enherbées parallèles aux courbes de niveau pour lutter contre l'érosion.*

Thus, when soils with low organic matter content on steep slopes are cultivated (to ~ 60 cm depth), at the beginning of the rainy season when land is bare, they are exposed to high erosion risk. It is common for the ditches to fill up within a few days (Roose et al., 1993).

Bench terraces. Bench terraces (**Figure 3**) were introduced in Rwanda in 1973 in the mountainous region of Buberuka AEZ at Kisaro hill (**Figure 1**). In this region, terraces have been greatly appreciated as an effective way of controlling soil erosion and maintaining or progressively improving soil fertility. Since 1992, the use of bench terraces has been expanded to the unproductive soils of the topographically similar mountainous region of the Congo-Nile watershed divide AEZ, at Kigeme hill (**Figure 1**). In this region, in contrast, bench terraces have not been adopted, and the terraced terrains have remained unused.

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 ancient and recently constructed terraces have led to a situation where some terraces are used effectively, while others were totally abandoned just after their construction. This has been reported as embarrassing for policy-makers and other non-soil scientists 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). Alternatively, effective terraces would be constructed on very strongly acid and inherently poor soils, but with appropriate input supply (limestone, organic input, fertilizers and improved seeds). Terraces that

[1] MONAGRIS refers to "moniteurs agricoles".

Figure 3. Bench terraces with farmers harvesting Irish potatoes at Munini — *Terrasses radicales avec les cultivateurs récoltant la pomme de terre à Munini.*

become abandoned would be those constructed on very strongly acidic, depleted and unproductive soils without adequate input supply. Indeed, it has been demonstrated that where appropriate inputs are well combined, high yields are obtained (**Figures 4a** and **4c** -1st and last plots) on bench terraces constructed on the otherwise unproductive soils of southern Rwanda (Rushemuka et al., 2011). In this region, zero yields have been obtained when there was low input (**Figures 4b** and **4c**- 2nd and 3rd plots).

3.3. Soil fertility management

Soil fertility may be examined either from a classical or conventional perspective or from an integrated agroforestry approach.

Conventional soil fertility management. In the 1970s, a series of pot experiments was undertaken on over 500 soil samples in order to diagnose soil fertility limiting factors (Iyamuremye, 1983). It was noted that the major soil fertility limiting factors were (in order of importance) P, K, N and, in some soils, Ca and Mg. Following these initial experiments, a nine year (1971-1980) soil fertility experiment was undertaken (Rutunga et al., 2006) at Mata in the Munini region (**Figure 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, the Faculty of Agriculture at the National University of Rwanda (NUR) has conducted other soil fertility-related researches (Ndoreyaho, 1985). The project SFI[2]-FAO (1980-1990) carried out an important study on fertilizer use in collaboration with ISAR and NUR (Coursier, 1985). The project undertook simple fertilizer trials countrywide for the most widely grown crops. Pietrowicz et al.[3] (1987) cited by Drechsel et al. (1996) adopted a more "ecological" approach (green manure or farmyard manure plus fertilizer) in the PAP Nyabisindu mandate area.

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):
– fertile soils;
– medium fertility soils;
– infertile soils.

The characteristics and proportion of each of these fertility classes are summarized in **table 1**. Fertile soils are unresponsive to fertilizers. They need manure for fertility maintenance. Medium fertility 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.

The experiments that led to these conclusions were generally undertaken on a trial and error basis, assuming the homogeneity of AEZs. Consequently, it is a challenging task, in the complex soilscape of Rwanda, to replicate experimental results. This is one of the main obstacles to the adoption of soil-related technology recommendations.

Figure 4. Bench terraces on extremely acid and depleted soils of southern Rwanda — *Terrasses radicales sur sols extrêmement acides et fortement lessivés du sud du Rwanda.*

a. Irish potatoes with travertine + manure + fertilizers — *pomme de terre avec travertin + fumier + fertilisants*; **b**. Irish potatoes without any input/control — *pomme de terre sans intrant/témoin*; **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 — *dispositif de quatre parcelles : la première et la dernière correspondent à du travertin + fumier + DAP ; la seconde à du travertin + DAP ; la troisième à du travertin + du fumier.*

[2] SFI: Soil Fertility Initiative.
[3] Pietrowicz P. & Neumann I., 1987. *Fertilisation et amélioration des sols. Étude sur l'application d'engrais vert, de la fumure organique et des engrais minéraux*. Études et Expériences n°11. Nyabisindu, Rwanda : GTZ.

Table 1. Soil fertility classes, their characteristics and their proportion towards arable land in Rwanda — *Classes de fertilité de sols, leurs caractéristiques et leur proportion par rapport aux terres cultivables au Rwanda.*

Fertility classes	**Limitation level**	**pH (water)**	**Al** (meq·100 g^{-1} soil)	**SEB** (%)	**Proportion**
Fertile soils	Low	> 5.5	< 1.5	> 3	27.5
Medium fertility soils	Medium to high	> 5.2 < 5.5	> 1.5 < 3	> 1 < 3	29.6
Infertile soils	Very strong to extremely strong	< 5.2	> 3	> 1	43.2

Al: Exchangeable Aluminum — *Aluminium échangeable*; SEB: Sum of Exchangeable Bases — *Somme des Bases Échangeables*; Sources: Birasa et al., 1990; Rutunga, 1991.

Agroforestry approach. The modern practice and scientific discipline of agroforestry was introduced in Rwanda by the PAP Nyabisindu in 1975 (Neumann et al., 1985). The PAP Nyabisindu was a long-term (1969-1989) integrated project run under the auspices of the German-Rwanda Cooperation Program. In this project, agroforestry was part of a wider concept of EA and was conceived as appropriate means to achieve site-adapted technologies and sustainable land use (Schörry, 1991; Drechsel et al., 1996). The PAP Nyabisindu promoted a system whereby trees and shrubs, livestock and crops were intended to be associated within one farm of ~ 1 ha, known as a "*fermette*". Within this system, trees were primarily considered for their fundamental role in soil fertility improvement under the nutrient recycling hypothesis, but also for collateral multipurpose functions, such as erosion control (hedgerows), fodder, fuel and construction wood and stakes for climbing beans. Livestock was primarily seen as a source of manure and was assumed to be kept in zero grazing and nourished from on-farm produced leguminous and herbaceous fodder. The aim of agroforestery, as promoted by the PAP Nyabisindu, was to anticipate, as far as possible, the inappropriate use of fertilizers (on tropical soils with very low organic matter content and unprotected against erosion) in a land-locked country, where their productivity and sustainability were uncertain (Neumann et al., 1985). Moreover, in the acidic high lands (> 1,800), with high C content (3-16%), fertilizer use efficiency was not guaranteed because correcting pH of such soils requires much more lime due to buffer effect.

By the same token, during the period 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).

Although the concept of EA promoted by the PAP Nyabisindu and many other projects was exciting, the technological packages proposed by these projects ("*fermette*", legume fallows, green manuring) were, surprisingly, not adopted despite their apparent appeal (Schörry, 1991; Drechsel et al., 1996). Instead, farmers selectively chose just some components. The tree component was the most widely adopted. For instance, at the end of the PAP Nyabisindu Project (1990), 80% of farmers had trees on their farms; but only 10% had respected project management prescriptions (biomass pruning and composting or green manuring). Thus, a contrast could be seen between the apparent high adoption of trees and the extremely low rate of farmers adhering accurately to the specified requirements.

The above situation is explained by the fact that trees are mainly accepted for their stated secondary role as sources of fuel wood, timber for construction, and stakes for climbing beans, but less for their effect on soil fertility (Drechsel et al., 1996). The poor acceptability of trees as a soil fertility management factor in Rwanda is attributed to the highly variable and generally minimal effect of green manuring on soil properties and crop yields (Drechsel et al., 1996). This was quite different from the situation reported in other African countries, where the concept of EA was originated. For instance, in Nigeria and in Zimbabwe, the rotation of maize and *Mucuna* green manure was able to maintain maize yields for more than 20 years (Vine, 1953[4]; Rattray et al., 1953[5] both cited by Drechsel et al., 1996). In contrast, in Rwanda, the effect of continuous cropping of maize followed by beans for 8 years was insignificant (Rutunga et al., 1998). It was noted that the sustainable effect of green manure was restricted to rather fertile soils, as the experience of Zimbabwe allowed, on the control plots, continuous maize cropping over 22 years (Drechsel et al., 1996). The Rwandan experience, on the other hand, gave no yield in control plots (Rutunga et al., 1998). Contrary to the experience of Zimbabwe where maize yields obtained after the fallowing season were more than able to compensate the "lost" season, in Rwanda, even in the relatively fertile soils, the residual effect of green manure was of only half a year and was unable to cover the "lost" season (Drechsel et al., 1996). The low

[4] Vine H., 1953. Experiments on the maintenance of soil fertility at Ibadan, Nigeria. *Empire J. Exp. Agric.*, **21**, 65-85.

[5] Rattray A. & Ellis B.S., 1953. Maize and green manuring in southern Rhodesia. *Rhodesia Agric. J.*, **49**, 188-199.

effect of green manure in the relatively fertile soils of Rwanda is attributed to the rapid leaching of N and K or inappropriate foliage incorporation. In the infertile soils, it is explained by the very low nutrient reserves and virtually no nutrient available to recycle in the sub-soil (Drechsel et al., 1996). On the infertile soils, even the combination of green manure with fertilizers was not able to significantly increase crop yields (König, 1992; Roose et al., 1997). The explanation is that while the principal limiting factors of those soils are the basic cation concentrations (Ca^{2+}, Mg^{2+}, K^{+}), it was noted that these elements were unaffected by green manure (Drechsel et al., 1996). Overall, in the complex soilscape of Rwanda, without systematic consideration of different soil types and their level of fertility, green manuring proved to be a risky enterprise with uncertain residual effect, which was entirely inconsistent with farmers' strategy of risk minimization (Drechsel et al., 1996). Therefore, the concept of improving soil fertility with the aid of improved fallow failed (Schörry, 1991; Raquet et al., 1995[6] cited by Drechsel et al., 1996).

Figure 5. Kanyirandoli model: agroforestry hedgerows (progressive terraces) on acid soils with high input system (lime + manure + fertilizers) — *Modèle Kanyirandoli : haies vives agroforestières (terrasses progressives) sur sols acides avec système d'intrants intensifs (chaux + fumier + engrais minéral).*

a. general overview of progressive terraces — *vue générale de terrasses progressives*; **b**. Irish potatoes — *pomme de terre*; **c**. wheat — *blé*; **d**. plot after harvesting — *parcelle après récolte*.

With the above experience, it has become clear that in the acid soils of Rwanda, soil fertility constraints cannot be solved with farm-produced inputs only (Drechsel et al., 1996). The recommendation was that the production and availability of farmyard manure and local mineral fertilizers, such as travertine and volcanic ash, should be supported (Drechsel et al., 1996).

In this context, more recently, with agroforestry hedgerows on contour lines, at the Kanyirandoli RAB Research Station, the combination of lime/travertine + manure + fertilizers on extremely acid and inherently poor oxisols has generated spectacular crop yields (**Figure 5**). However, the adoption of the Kanyiradoli model has not yet become widespread. The frequently given explanation is that such an agroforestry system is a knowledge-demanding, labor-intensive and high investment technology (Drechsel et al., 1996). This means that designing an on-site experimental sustainable agroforestry system might be relatively simple compared with the necessary understanding of the contributing factors to ensure its replicability (Rhoades, 1999). Effective adoption depends on factors such as:

– farmers' investment capacity;
– appropriate technology transfer;
– input accessibility;
– crop product market;
– adequate biomass pruning equipment and, perhaps more important;
– farmers' perceived benefits (Coursier, 1985).

The same factors also play a role in the adoption of bench terraces (Bizoza, 2011).

In view of the above, contrary to what some agro-ecology proponents maintain, manuring may not be a cheaper option for soil fertility management (Breman, 2011). Sometimes it is described as a low-input technology since manure is locally available in contrast to external inputs such as inorganic fertilizers (Altieri, 2002). However, the real cost of manuring includes substantial amount of inputs such as labor, skills and management (Drechsel et al., 1996; Altieri, 2002).

[6] Raquet K. & Neumann I.F., 1995. Intensivbrache in der kleinbäueurlichen Landwirtschaft. *In*: Egger K. & Korus U., eds. *Öko-Landbau in den Tropen*. Heidelberg, Deutschland: Müller Verlag, 199-214.

4. DISCUSSION

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 the population has long been exposed to erosion control campaigns, policy-makers have come to perceive soil erosion as the major cause of poor soil fertility in most Rwandan soils. As a consequence, financial resources and extension efforts have been concentrated on erosion. However, despite the different erosion control methods and extension approaches used over the last 80 years, the adoption of erosion control measures has remained very low (Schörry, 1991; Bizoza, 2011). The reason for this might be that, for most Rwandan soils (**Table 1**), underlying the problem of soil erosion is a grave problem of low fertility due to the parent materials. The soils thus require high-levels of investment in soil amendments (Rutunga et al., 2006; Rushemuka et al., 2011). With such soil types, it is not enough to control erosion, as productivity is already very low; they often produce zero yields of cereals and legumes (Rutunga et al., 1998), and only marginal ones of sweet potatoes or cassava (1-3 $t \cdot ha^{-1}$) (Roose et al., 1997). In such conditions, it is wiser to focus on "win-win" solutions: erosion control as part of Integrated Soil Fertility Management (ISFM[7]) with crop yields and farm productivity as indicators (**Figures 4** and **5**). In most cases, the initial investment to convert unproductive soil into productive soil is beyond the financial capacity of farmers (Bizoza et al., 2010; Giller et al., 2011). Thus, the low productivity of a Rwandan farm is primarily due to poor soils, while the main cause of the low level of adoption of proposed ISFM technologies is farmers' lack of resources. However, agronomists, extensionists and farmers lack good understanding of how best to manage available resources (lime, organic input and fertilizers) (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 efficiently use the limited resources.

[7] 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 combined with the utilization of improved germplasm (Adesina, 1996 [Factors affecting the adoption of fertilizers by rice farmers in Côte d'Ivoire. *Nutr. Cycling Agroecosys.t*, **46**, 29-39] cited by Sanginga et al., 2009). In hilly country with acid soils, erosion control and liming (travertine and volcanic ash) should be important components of ISFM.

4.2. Industrial *versus* ecological agriculture

The debate regarding IA (IA: predominantly the use of inorganic fertilizers) *versus* EA (EA: largely agroforestry, organic manure and minimal use of inorganic fertilizers) is not new. The IA as proposed by IFAD (2006) is a return to the 1960-1970s when the use of inorganic fertilizer alone was thought to be sufficient to improve and sustain yields (Fairhurst, 2012). The vision of EA proposed by authors such as de Schutter (2010) is also a return to 1980s when organic input use was seen as appropriate option to sustain yields with a minimal role of inorganic fertilizers. In Rwanda, the experience of IA was synthesized for 30 years (1960-1990) (Rutunga, 1991). For more than 20 years, PAP Nyabisindu's main focus was EA, while other projects promoted green manure for almost as long.

The experience of Rwanda shows that rather than seeing IA and EA as opposing concepts, a better way to view them is as convergent concepts. After all, both IA and EA proponents aim to bring about a sustainable "green revolution", which can only be attained through optimal investment in soil amendments (lime and organic input), inorganic fertilizers and germplasm assuming optimum climatic conditions. In this sense, EA and IA have become synonymous with ISFM, as noted by Breman (2011). Today however, the realization is that, in the 21st century, nor the IA nor the EA neither the ISFM has met expectations: since 1960 per capita food production has declined by 20-40% in East, Central and Southern Africa and small-scale farmers remain poorly served by the linear Research and Development (R&D) innovation model and its top-down technology transfer (Keating et al., 2011).

The challenge with ISFM, as with IA and EA, is how to systematically take into account soil variations when designing experiments, evaluating data and extrapolating ISFM recommendations in the complex soilscape of Rwanda. This is normally the role of the soil survey and, in Rwanda, it was the aim of the CPR (*Carte Pédologique du Rwanda*), Rwanda's comprehensive soil survey. However, since the CPR's completion, its results have not been used for this purpose.

4.3. Constraints in using the soil map of Rwanda (CPR)

This study highlights five reasons hampering the use of the Rwanda's soil map in agricultural research for development.

Historical reasons. As with all sectors of life in Rwanda, the CPR and its use did not escape the negative consequences of the 1994 genocide. Almost all personnel involved in soil map's production and use were either killed or driven out, and much information was lost. It took eight years (1994-2002) to rebuild the database and then publish the digitized version. The scant input from Rwandan personnel in the implementation stage meant the loss of valuable experience and understanding of the technology and philosophy underpinning the map. Today, 18 years after the genocide, few Rwandan soil scientists are interested in its use. Moreover, policy-makers are largely unaware of the usefulness of soil maps in agricultural research and development planning. Attempts to build their positive attitude towards the CPR's usefulness had to restart from zero. However, these circumstances are not enough to explain all the difficulties that undermine the use of soil maps in developing countries, such as Rwanda. Indeed, in the region and throughout Africa, examples of the successful use of soil maps for the benefit of small farmer agriculture are few, if they exist at all. In West Africa, Nachtergael (2000) noted the confusion between soil fertility potential identification and land evaluation and the relationship between the two. Muchena et al. (1995) and Lal (1995) discussed the minimal contribution of soil science in East Africa (Kenya, Uganda and Tanzania). Habarurema et al. (1997) and Steiner (1998) have discussed this for Rwanda. Similarly, Burundi's soil suitability maps are little used (Tessens, 1991). The recent IA-EA debate and current state of the art of ISFM (Fairhurst, 2012) demonstrate the slight consideration paid to soil maps in discussions of soil fertility management. Due to this difficulty, the African Soil Information Service (AFSIS) is constrained to experiment with a global integrated soil information service (Shepherd et al., 2010). Thus, beyond the historical reasons, other fundamental causes for the low use of soil maps in Rwanda deserve deeper examination.

A complex biophysical environment. Due to the complexity of relief and parent materials, Rwanda's biophysical environment has exceptional soil variation 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. Steiner (1998) noted the limitation of identifying a small, well defined and representative recommendation zone in such circumstances. He observed that soils vary between AEZs, as they do within one AEZ. Within one AEZ, soils of different suitability vary from hill to hill (Dressler, 1983). Even on one hill, soils and soil properties 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 compared with upper slopes (Steiner, 1998). This soil fertility gradient along the slope is a common feature in Rwanda (Nizeyimana et al., 1988; Steiner et al., 1994) and in sub-Saharan Africa (Tittonell et al., 2007). The soil fertility gradient is normally well explained by the concepts of catena and toposequence (Okusami, 2006). However, in Rwanda, the forms of slope are complex, so that the slope criterion is rarely 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 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, the conventional research and extension approach becomes less appropriate to develop and transfer ISFM technologies (Steiner, 1998).

Research mode and research institutions. Soil maps are hampered from being the foundation of soil-specific and replicable ISFM technologies by research policy misconceptions and biased funding systems. These in turn lead to research programs oriented towards scientific disciplines or crop or livestock commodities (Raina et al., 2006). For instance, under the RAB and its predecessors, ISAR and INEAC, each crop (*e.g.* maize, rice, sorghum, beans, cassava) constitutes a research program. Similarly, biophysical sciences such as soil science and forestry are subdivided into programs, such as erosion control, soil fertility management and agroforestry. Rigid frameworks, including research agenda, experimental sites, reporting systems, and incentives, govern these autonomous research programs. Such a context prevents soil scientists (pedologists) from partnering with soil fertility experts or crop and animal production specialists. As part of this philosophy, even soil fertility management and erosion control practices are implemented as separate programs, disconnected from the soil resource information contained in the CPR. Today it is clear, however, that no research program is likely to make much progress on its own in the light of the 21st century drivers and needs, and that technical constraints cannot be solved without broad-based institutional innovation (Keating et al., 2011).

It was in this context that in 1982 the International Service for National Agricultural Research (ISNAR) observed that Rwanda's agricultural research and development was entering a crisis phase and strongly recommended reform (ISNAR, 1982). PAP Nyabisindu also recognized the limitation of the conventional agricultural research and development framework when it introduced the concept of "agriculture adapted to the biophysical and socio-economic environments".

More recently, Rwanda's ISAR appropriated the innovative concept of Participatory Integrated Watershed Management from the African Highlands

Initiative (AHI[8]) (German et al., 2006). The AHI model appeared to promise to overcome the problem of the conventional research and its top-down extension approach. However, it has also faced the institutional rigidity of the linear R&D model and experienced the drawbacks of many other development concepts promoted by international research (Rhoades, 1999; Keating et al., 2011). In this planning environment, the soil map finds no place.

Internal limitations of soil maps: complex knowledge. In the current arena of participatory integrated research frameworks (German et al., 2006), and because traditional soil maps (soil-centered approach) are only understood by users who know how surveys are made, soil scientists have realized the challenges of using these maps to work in a trans-disciplinary fashion (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 (Wielemaker et al., 2001).

To solve this communication problem, Wielemaker et al. (2001) proposed a multi-hierarchical land system approach. In this model, 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 University of Liege - Gembloux Agro-Bio Tech. With this concept, Bock (1994) stressed the need to identify soil fertility potential and its link with topsoil fertility evaluation by means of representative composite soil samples. In agriculture, the multi-hierarchical land system approach is very important because each landscape unit has its own specific soil and related level of productivity (Steiner, 1998). There is clearly additional work to do if the CPR is to be used in a more participatory and multidisciplinary manner. For instance, it should be circumscribed in the large national biophysical spatial organization/natural regions and its legend presented in relation to the landscape context, in line with the multi-hierarchical Land Information System (LandIS). 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 fertility management. For soil fertility management, it is important to establish regional soil references on soils that allow to link data on soil types (morphological, physical and chemical characteristics) to the state of the cultivated lands (by means of sub-surface composite soil samples) and to the obtained crop yields considering the soil map, the base of the field understanding and the framework for data archiving finally.

Reliance on soil taxonomy and the neglect of farmers' soil knowledge. Soil taxonomy is the language of the CPR (Birasa et al., 1990). This, for famers and many other potential users of the CPR, presents an additional communication constraint. In the meantime, farmers have maintained their soil knowledge system with an immensely practical soil nomenclature (Habarurema et al., 1997). Since it would be unrealistic to expect non-soil scientists to master soil taxonomy (Thomasson, 1981), Steiner (1998) recommended that Rwandan scientists build ISFM technologies on the synergy between farmers' soil knowledge systems and soil taxonomy. He recommended using farmers' soil nomenclature to transfer ISFM technologies to analogous soil types. In this context, soil scientists must be prepared to understand both technical (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 environment meaning and cultural context, rather than in a narrow linguistic sense (Thomasson, 1981). Farmers should be full partners in research and extension processes.

5. CONCLUSIONS

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

Our findings show that much time and funds have been lost as a consequence of poor consideration of soil resource information in agricultural research and extension planning and implementation during the last 50 years. This study shows clearly that the current controversy around IA, EA and ISFM is a misleading debate, largely because it is conducted with little consideration of the biophysical environmental context. More specifically, it overlooks the existence of soil types of varying suitability and the need to develop site-adapted and soil-specific technologies. Given this, in Rwanda, the CPR emerges as an important planning document that can augment understanding of the complex Rwandan biophysical environment and assist informed decision-making for its sound management. However, due to its inaccessibility to many potential users, the CPR, completed in 1990, has remained unused from the 1994 genocide to date.

[8] 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).

In the field of ISFM, the challenge ahead is how to use this soil map to implement soil-specific ISFM technologies in Rwanda where:
– soil scientists are expected to use the CPR with its soil taxonomy language and collaborate with crop scientists and fertility experts with little background in soil science (pedology);
– agriculture is practiced by smallholder farmers with their own soil knowledge system;
– ISFM technologies are expected to be transferred by extensionists with insufficient understanding of both soil knowledge systems.

This study proposes three complementary alternatives:
– to improve access to the CPR by completing its legend with land unit terms;
– to build ISFM technologies based on the synergy between technical and farmers' soil knowledge;
– to use farmers' land unit terms and soil nomenclature for technology transfer.

In turn, this will require two important changes in the conduct of agricultural research and extension:
– the research modes and institutions will need to change from the current top-down extension approach to more participatory and integrated approaches;
– the gap between technical and farmers' soil knowledge will need to be bridged to improve communication between scientists and farmers.

For this, Rwandan soil scientists will need to master both soil taxonomy and the farmers' soil nomenclature so that they can serve as interpreters between scientists from other disciplines and farmers. Finally, soil scientists will require more training in the use of Geographic Information Systems (GIS), so that they are able to use the digitized version / "soft copy" of the CPR and increase their familiarity with the biophysical environment. All of these, including the construction of a multi-hierarchical Land Information System (LandIS) will help to bring about much needed soil-specific ISFM recommendations in Rwanda and expedite their adoption by farmers.

List of abbreviations

AEZ: Agro-Ecological Zone
CPR: *Carte Pédagogique du Rwanda*
DAP: Diammonium phosphate (*Phosphate de diammonium*)
EA: Ecological Agriculture
IA: Industrial Agriculture
ISFM: Integrated Soil Fertility Management
PAP: *Projet Agro-Pastoral*

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