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Anne W. Kuria [a,b], Edmundo Barrios [a], Tim Pagella [b], Catherine W. Muthuri [a], Athanase Mukuralinda [c], Fergus L. Sinclair [a,b]

[a] World Agroforestry Centre (ICRAF), UN Avenue, Gigiri, Nairobi, P.O. Box 30677-00100, Nairobi, Kenya
[b] School of Natural Sciences, Bangor University, Bangor, Gwynedd LL57 2DG, UK
[c] World Agroforestry Centre- Rwanda Country Office. C/O NIRDA Research Center, P.O. Box 227, Huye, Rwanda

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Abstract

The growing need to intensify smallholder farming systems to enhance food security for a rapidly growing population in sub-Saharan Africa constitutes a major sustainability challenge. Intensification of agriculture has often resulted in degraded, highly vulnerable, exhausted and unproductive soils. Even though smallholder farming systems are heterogeneous and dynamic, conventional approaches to improving soil management have focused on promoting one or two technologies, informed by coarse-resolution assessments, rather than tailoring technologies to context. This has resulted in technologies that have been promoted not being locally adapted. The research reported here explores the extent to which farmers' indicators of soil quality vary with land degradation status and gender and can be used in selecting locally appropriate land restoration practices. Knowledge was elicited from 150 smallholder farmers across a land degradation gradient in Rwanda through combined use of a systematic knowledge-based systems approach (AKT5), and a participatory knowledge sharing method for indicators of soil quality (InPaC-S). Data were analysed using R software through frequency statistics, 'ggplot'-generated bar plots and Chi-square tests of independence. Farmers described 12 indicators of soil quality with a mean of five per farmer. The four most frequently mentioned were: soil colour (96%), indicator plants (90%), crop vigour (71%) and soil texture (67%). Farmers' knowledge about 10 out of 12 indicators varied with land degradation status (p b .05), and there were other variations according to location of fields along slopes, and gender. Farmers had knowledge of 51 indicator plants and 22 soil macrofaunal species and mentioned seven soil management practices, including: compost manure (83% of farmers), livestock manure (64%) and tree biomass incorporation (54%). There were variations in the practices by degradation status, slope location and gender. These variations revealed the importance of matching management options to ecological context and farmer circumstances to foster adoption. There were relationships between farmers' knowledge of indicators of soil quality and their soil management practices. This research has shown that acquiring farmers' knowledge about soils can help to identify fine-scale contextual differences useful for informing the design of soil management options and it is recom-mended that this is done in future so that appropriate options can be offered to different farmers making them more likely to be adopted.

1. Introduction

Land degradation is a major threat to food security, particularly in the context of a rapidly growing global population living on finite land resources. Approaching 15% of the seven billion people alive today are classified as food insecure (FAO et al., 2017; FSIN, 2018). With the global population projected to hit nine billion by 2050 (Montpellier, 2013), the food insecurity challenge can be expected to become more severe, especially for sub-Sahara Africa, where an estimated quarter of the people are already hungry (Bremner, 2012). Current attempts to meet food and livelihood needs of sub-Saharan smallholder farms have often led to severe soil degradation.

Land degradation has been blamed on various factors including un-sustainable agricultural practices that emphasize use of external inputs while ignoring the natural processes that support soil formation and build agroecosystem resilience. These include nutrient cycling, soil erosion control, carbon sequestration and water regulation (Swift et al., 2004; Verchot et al., 2007). Other drivers include deforestation and land-cover loss (Bewket and Stroosnijder, 2003; Eshetu et al., 2004; Tsegaye et al., 2010), unfavourable government policies, insecurity of tenure, overstocking and free grazing, slash and burn, and lack of adequate soil and water conservation interventions (Eswaran et al., 1997; Sanchez et al., 2003; Tesfahunegn et al., 2011).

In Rwanda, following the 1994/1995 genocide, extensive deforestation took place as a result of population pressure and its associated effects, such as high demand for land for cultivation, settlements, energy, tree products and grazing that collectively led to severe land degradation (Bizoza and Havugimana, 2013; Safari, 2010). Soil quality degradation also occurred due to loss of soil nutrients resulting from continuous cultivation with few or no inputs, and short or no fallow periods because of decreasing size of household land holdings (Byiringiro and Reardon, 1996; Drechsel et al., 2001). Other drivers include cultivation of unsuitable areas such as steep slopes and wetlands (Bizoza and Havugimana, 2013; Nabahungu and Visser, 2013). Coupled with the effects of climate change, such as prolonged drought and flash floods (Westoff, 2013), there has been severe soil loss through erosion and landslides. There is, therefore, an urgent imperative to employ sustain-able intensification strategies to not only increase food productivity and profitability, but also to ensure the ecological resilience of the agroecosystems from which it is produced (Folke et al., 2010; Pretty and Bharucha, 2014). Such an approach can contribute to reconciling achievement of two of the United Nations Sustainable Development Goals (SDGs; United Nations, 2015), to end hunger (SDG 2.3) while protecting the environment (SDG 15.3).

A key challenge limiting sustainable intensification of agriculture is that smallholder farming systems are heterogeneous and dynamic, not only in their biophysical context (including soils) but also in terms of famer circumstances, production objectives and socio-technical conditions (Kmoch et al., 2018; Tittonell et al., 2005; Vanlauwe et al., 2014). Despite this heterogeneity in smallholder farming systems, conventional soil management and land restoration approaches in Rwanda have prescribed a narrow set of soil management options, often informed by coarse-resolution assessments. This has led to variable performance and adoption of these options because they are not tailored to variable farmer context (Habarurema and Steiner, 1997; Verdoodt and Van Ranst, 2006). Acquisition of agroecological knowledge is a potential means to capture contextual heterogeneity but there has been only limited effort to collect or collate knowledge about land degradation and restoration processes in Rwanda (Rushemuka et al., 2014).

Research elsewhere indicates that acquiring farmers' knowledge can provide detailed understanding of fine-scale farm and farmer context (Barrios and Trejo, 2003; Cerdán et al., 2012; Dumont et al., 2014). This often complements global scientific knowledge about managing ecosystem service provision, and can be used in the design of more sustainable and locally adapted agricultural technologies (Jacobi et al., 2017; Tengö et al., 2014). This knowledge is dynamic and evolves with changing circumstances, through observation and experience of farmers and knowledge exchange, representing a practical and direct feedback mechanism useful when responding to system changes (Joshi et al., 2004).

Soil scientists categorize indicators of soil quality as either biological, chemical or physical. Chemical indicators refer to nutrient cycling, water relations and bufering and include: measurements of Ph, salinity, soil organic carbon, total nitrogen (Nael et al., 2004). Biological indicators of soil quality include plant and animal species that play a key role in supporting critical soil functions and hence ecosystem services and include: soil macro and micro fauna and indicator plants (Barrios, 2007). Physical indicators are related to the arrangement of solid particles and pores involved in soil hydraulic flows and include aggregate stability, soil structure, available water capacity, bulk density, infiltration, porosity, slaking, texture and compaction (Schloter et al., 2003). Previous farmers' knowledge studies on soil quality indicators have revealed that they have knowledge of mostly physical or biological indicators. Physical indicators reported by farmers include soil colour, texture, soil tilth, moisture retention; while biological indicators include crop performance, crop yield, indicator plants, soil macrofaunal and the main chemical indicator reported by farmers is soil organic matter (Barbero-Sierra et al., 2018; Ericksen and Ardón, 2003; Mairura et al., 2007).

The majority of scientific studies that have assessed landscape function have failed to incorporate resource users knowledge (Merrill et al., 2013). This leads to the exclusion of farmers, who are the main man-agers of soils and whose observations might be useful to enrich and in-form the use of scientific knowledge. Other studies have focused on only a few pre-selected soil types or only one of the three categories of soil quality indicators (Tesfahunegn et al., 2016; Veum et al., 2014) or have only focused on the fertility aspect of soil quality (Kambiré et al., 2015; Mowo et al., 2006). Most agroecological knowledge studies have focused single landscapes (Carter, 2002; Tesfahunegn, 2016), so that comparative analysis of different landscapes at various levels of land degradation are not available. Studies in Rwanda have mostly fo-cused on the influence of soil quality indicators on decisions about which crops to grow where and have often been confined to single land-scapes (Nabahungu and Visser, 2016; Rushemuka et al., 2014). This has contributed to the promulgation of universal soil restoration interventions across soils, despite the very different constraints they are subject to.

Even within a single landscape, previous studies have not assessed indicators of soil quality along slopes despite their importance in land degradation. Research on gender and farmers' knowledge has mostly focused on the soil fertility component of soil quality (Christie et al., 2016) and has not assessed whether understanding of soil quality by gender influences soil management practices.

The objective of the present research was to elicit farmers' knowledge about indicators of soil quality and assess whether they varied along a land degradation gradient and in relation to gender. There were two interrelated central hypotheses: 1) that farmers' indicators of soil quality vary with land degradation status and gender, and
2)that farmers knowledge of indicators of soil quality and their gender influence soil management practices.

2. Materials and methods

2.1. Study area

This research was carried out in two districts, Nyabihu and Rubavu, which form part of Gishwati forest, a protected reserve in Western Rwanda, that falls within the sub-humid agro-climatic zone. The area comprises fragmented forest remnants resulting from decades of land degradation and deforestation, with the greatest impact occurring after the 1994/95 genocide due to resettlement of returnees and refu-gees who had high dependence on forest resources (Ordway, 2015). Three landscapes with contrasting levels of land degradation were selected for the research along a degradation gradient. Recovering and re-stored landscapes were located in Kadahenda cell, Karago sector of Nyabihu district, located at 1°37′38.28“S and 29°30’48.24”E within the Eastern Congo-Nile Highland Subsistence Farming Zone, with a mean annual rainfall ranging from 1200 to 1500 mm (REMA, 2010) across an elevation range from 1460 to 3000 m above sea level. The degraded landscape was located in Gikombe cell, Nyakiliba sector of Rubavu dis-trict, located at −1°40′16.68“S and 29°21’37.44”E, with an elevation N2109 m within the North-Western Volcanic Irish Potato Zone (*ibid*) that receives a mean annual rainfall ranging from 900 to 1500 mm. The soil map of Rwanda taken at a scale of 1:50,000 classifies soils in Nyabihu district as Alisols while those in Rubavu district as Andosols using the World Reference Base (Verdoodt and Van Ranst, 2006). The topography of all sites is mountainous and steep sloped with some areas having a slope inclination of over 50%, hence the landscape is susceptible to severe soil erosion (Byiringiro and Reardon, 1996; Kagabo et al., 2013; Roose and Ndayizigiye, 1997)

2.2. Site selection

Using a Paired-Catchment Experimental design, three study sites that we labelled as: degraded, recovering and restored; were selected along a land degradation gradient identified in previous studies (Aynekulu et al., 2014; Bigagaza et al., 2002; Hintjens, 2006; Kuria et al., 2014). Historical timelines show that all three study sites underwent simultaneous tree cover loss during their conversion to agriculture and settlements following the post-genocide period in 1995 but then followed different restoration and recovery trajectories.

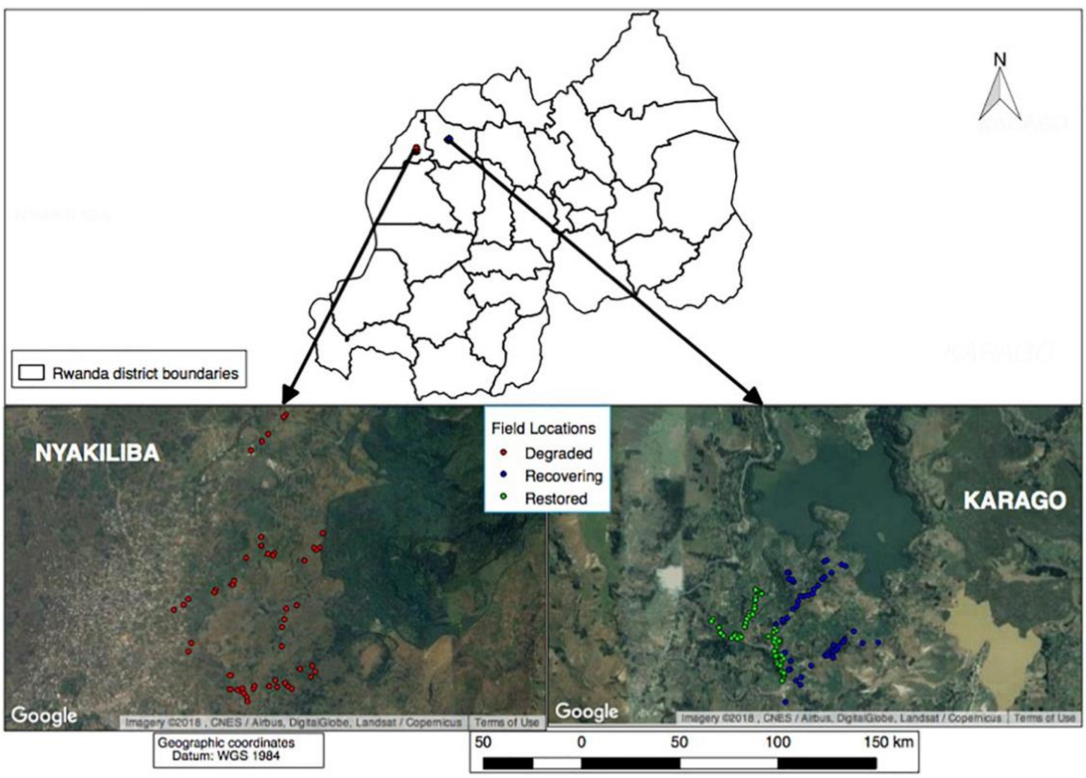

Fig. 1. Map of Rwanda showing location of fields sampled in Nyabihu and Rubavu Districts (n = 150).

The upper part of the degraded landscape is an area adjacent to Gishwati protected forest while the lower part borders Mahoko town. It is characterized by severe soil loss as a result of soil erosion, landslides and siltation as well as frequent flooding in the flat areas found downslope (Fig. 1). The area has not received any soil and water conservation interventions following the post genocide deforestation in 1995. After the government of Rwanda evicted farmers who had encroached Gishwati forest in 2010, soil and water conservation efforts have involved reforestation of the protected forest, but not the adjacent farming landscapes.

The study villages included: Rushubi, Nyabibuye and Nyakibande, Nyakiliba sector in Rubavu district.

The recovering landscape is adjacent to Karago Lake and still experiences significant soil loss through surface run-off and erosion. This area is receiving soil and water conservation interventions led by ICRAF through the Australian Centre for International Agricultural Research (ACIAR) Trees for Food Security Project. The project aims at sustainably improving productivity of farming landscapes, and to recover food and nutritional security through the promotion of suitable agroforestry in-terventions. The study villages included: Karandaryi, Gakoma and Nkomane in Kadahenda cell, Karago sector of Nyabihu district.

In the restored landscape, which is adjacent to Lake Karago and the recovering landscape, soil loss has been controlled as a result of soil and water conservation interventions that were implemented over a decade ago. In 2005/2006, the government of Rwanda through the 'umuganda' community service embarked on soil erosion control as part of the national soil and water conservation programme; whereby bench and progressive terraces were established on steep slopes (Bizoza, 2014) and stabilized through planting of *Alnus acuminata* and *Setaria sphacelata*. The interventions were also intended to protect Lake Karago and Busoro river from siltation including provision to set aside a 50 m strip of adjacent land all around water bodies for planting trees. The study village was Gihira village, Kadahenda cell, Karago sector of Nyabihu district.

2.3. Data collection

This study, which was conducted between August and November 2015, used the Agroecological Knowledge Toolkit (AKT5) and methodological framework (Sinclair and Walker, 1998; Walker and Sinclair, 1998) in combination with the InPaC-S participatory knowledge integration and sharing methodology to study indicators of soil quality (Barrios et al., 2012a). Agroecological (local) knowledge on indicators of soil quality was elicited by use of knowledge-based methods and semi-structured interviews with a stratified sample of willing and knowledgeable informants. The knowledge was then recorded and rep-resented using the AKT5 software (Dixon et al., 2001).

The AKT5 methodology comprises four stages (Walker and Sinclair, 1998). At the scoping stage, research activities carried out included: participatory transect walks to understand the landscape setting, topography, degradation hotspots, soil types, field typologies and the location of different resources. This also helped to inform stratification criteria. Further, key informant interviews were held with the crop, livestock, and natural resource extension officers and the area administration to elicit expert knowledge on the research subject. Six focus group discussions were held with a total of 69 farmers drawn from the three study landscapes. These were conducted using a set of semi-structured questions and a participatory process that aimed to identify, categorize and prioritize farmers' indicators of soil quality associated with high and low quality soils using the InPaC-S methodological guide (Barrios et al., 2012a). This was followed by participatory soil mapping of the three study landscapes. In addition, photography was used to visually capture differences between soil types along the slope and across the slope. Transect walks were also undertaken along and across the slopes to identify the different soil types and to triangulate the information provided by farmers.

The definition stage highlighted knowledge boundaries and stratification parameters. Two farmers in each of the nine locations (e.g. three slope positions – upslope, midslope and downslope, on the three study landscapes – degraded, recovering and restored) were selected at random for in-depth interviews, which aimed at understanding the status and characteristics of soils, as related to indicators of soil quality and soil management practices. The compilation stage involved an iterative pro-cess whereby knowledge elicited from individual farmers guided by the InPaC-S methodological guide (ibid) and recorded systematically using the AKT5 software, were evaluated for consistency and then further explored through repeated visits to the same farmers in order to probe further to get additional information or clarifications where apparent contractions or gaps were revealed. This process was repeated (at least two visits per farmer) until no new information was obtained from further discussion with the respondent.

In the generalization stage key research questions were formulated as a formal questionnaire based on issues deemed pertinent from analysis of the in-depth knowledge obtained during the previous three stages. Pre-testing of the questionnaire was then conducted with 12 farmers (four from each of the three landscapes) and the questionnaire then administered to 150 farmers (50 farmers from each of the three landscapes). To ensure degradation-related heterogeneities were represented in the sample, 50 farmers were drawn from each of the three study landscapes namely degraded, recovering, restored, in a stratified random sample. Within each landscape, stratified randon sampling was further applied to select farmers from various slope locations (up-slope, midslope, downslope) based on transects walks along and across the slopes. The sample comprised 67 women and 83 men. Results presented here were generated at the generalization stage.

Following the identification of native indicator plants as an important biological indicator of soil quality, farmers were requested to help locating specimens of these plants for botanical classification. Indicator plants were collected, dried and stored in a press and mounted following standard botanical sample collection methodology (Eymann et al., 2010). Information collected for each specimen included: photos, plant number, date, Kinyarwanda name, topography, elevation, latitude, longitude, habitat, abundance, and collector's name. Further, farmers were asked to identify if an indicator plant had another Kinyarwanda name/s, which were noted down to avoid registering one species known by more than one name as a separate species. The specimens were then transferred to the National Museums of Kenya for botanical identification.

Following the identification of soil macrofauna (earthworms, milli-pedes, termites, ants and beetles) as important biological indicators of soil quality, and with conflicting results regarding earthworms being named as an indicators of both fertile and infertile soil, a second farmer visit was conducted in order to collect specimens, accompanied with more in-depth farmer interviews. Sampling of macrofauna was under-taken during the rainy season in March 2017; a time when macrofauna are expected to be most active in the top-layer of the soil and thus easily captured. The macrofauna were collected by farmers through hand-picking or excavation where necessary (Pelosi et al., 2009; Smith et al., 2008). Earthworms collected were first placed in 70% ethanol and then preserved in 4% formaldehyde; while the millipedes, termites, ants and beetles were preserved in 70% Ethanol prior to identification by an entomologist.

2.4. Data analysis

Data and knowledge elicited through the first three stages of the AKT process were analysed and interpreted qualitatively using the AKT5 tool (Sinclair and Walker, 1998; Walker and Sinclair, 1998). This involved breaking down knowledge into unitary statements and then representing it using formal grammar and taxonomies where applicable. This is what formed a basis for formulating the questionnaire for collecting quantitative data.

Farmers' responses to formal questions were recorded in Microsoft Excel as whether specific knowledge items were or were not articulated by the farmer. These results was then exported to R statistical software (R Development Core Team, 2013) for further statistical analysis. Frequency statistics (including percentages) were run to show the number of farmers that held knowledge about a specific indicator of soil quality or soil management practice. Data was also represented through bar plots generated using the ‘ggplot’ function. Due to the categorical nature of the variables, where a stratum had a sample size of at least five, a Chi-square Test of Independence was applied for analysis (Gingrich, 2004; Mchugh, 2013). The test was undertaken to determine whether the sample data was consistent with the distribution that had been hypothesized, that is, that there were significant differences in farmers' knowledge about indicators of soil quality along the different levels of degradation, different field locations along a slope and gender. Where sample sizes per strata were less than five, Fisher's Exact Test was applied as it gives an exact accurate and unbiased p-value for small sample sizes (Raymond and Rousset, 1995).

3. Results

3.1. Farmers' soil classification and perceptions about land degradation status

Farmers in all three study landscapes in Gishwati named and de-scribed nine soil types, with Kinyarwanda names being assigned and differentiated according to several dominant characteristics: texture, colour, level of compactness, easiness to plough and productivity potential. Table 1 illustrates the characteristics for each of the nine soil types encountered in Gishwati fields. ‘Inombe’ in Kinyarwanda translates as ‘to stick together or smash’, while ‘urucucu’ means that soil can be transported easily by wind because it contains a lot of dust; while ‘igitakaza’ means a mixture of very fine particles from various sources, while ‘urubuye’ means soil that contains gravel and stone and destroys the hoe; ‘gahuhuma’ means shallow, degraded soil which the hoe or roots do not go through easily, ‘ibeja’ means shallow soil with nutrient deficiency. ‘Urusenyi’ means deep and soft soil with fine sandy particles, while ‘uruchanga’ means large sandy particles. ‘Ubuseseka’ means loose and soft soil where the hoe enters easily.

Farmers described land degradation as gradual loss of fertile soil and clay content to water erosion. All study landscapes had some dominant soils in common, though their location along a slope could differ in some cases (Table 1). Fields in the recovering and restored landscapes shared dominant soil types ‘inombe and urucucu’ on the up-slope and mid-slope locations, but there was additional sand deposition (‘uruchanga’) downslope in the recovering landscape. On the contrary, the degraded landscape had three dominant soil types of differing texture, with de-creasing clay content from upslope downwards from upslope to midlopes, with the fertile top soil being deposited downslope. The up-slope, which is adjacent to Gishwati protected forest mainly had ‘inombe’ or ‘igitakaza’ soils; while the mid-slopes were characterized by ‘urubuye’ or ‘urucucu’ soils of coarse and sandy texture suggesting that soil loss processes were taking place. The downslopes constituted soils with high clay and silt content (‘inombe’ or ‘igitakaza’), probably as a result of deposition of eroded top soil.

Consequently, the type of crops grown by farmers along the land degradation gradient varied and was also influenced by the prevailing soil type including its fertility level. Farmers in the restored and recovering landscapes had a choice of planting a wide variety of major crops on any field location along a slope, including Irish potatoes, maize, beans and carrots due to generally healthy soils. In contrast, farmers in the de-graded landscape were limited to fewer crops, mainly beans, sweet potatoes or Eucalyptus spp. plantations commonly found on midslopes while Irish potatoes and maize were mostly planted downslope taking advantage of deposition of fertile sediments.

Table 1: Farmers local classification of soils

Local Soil Taxonomy/ Name	Local parameters for classification of soil types								Slope location where mostly found		
	Texture	Colour	Plough easiness	Water Infiltration capacity	Moisture content when dry	Water-holding capacity	Fertility	Erodibility	*Degraded*	*Recovering*	*Restored*
'Inombe'	Very fine and loose	Dark-reddish-brown	Sticky	Very low	High	High	High	High	Up/Down	All	All
'Urucucu'	Moderately fine, dusty when dry	Brown-reddish	Moderate	Moderate	High	Moderate	Moderate	High	Dominant	Dominant	Dominant
'Igitakaza'	fine, loose, light particles	dark-brown	Moderate	Low	High	High	High	High	Up/Down	All	All
'Urubuye'	Stones and gravel	Blackish	Easy	High	Low	Low	Low	Low	Mid/Down	-	-
'Gahuhuma'	mixture of sand and gravel	Brownish - yellow	Difficult	Moderate	Low	Low	Very Low	Low	Down	-	-
'Ibeja'	Sandy-loam	Reddish-brown	Moderate	Moderate	Moderate	Moderate	Low	Very High	Up/Down	-	Mid
'Urusenyi'	Sand and gravel	Blackish	Easy	High	Low	Very Low	Low	Low	Mid	-	-
'Uruchanga'	Sandy	Whitish	Easy	Very high	Low	Very Low	Very Low	Low	Mid	Down	-
'Ubuseseka'	Tiny soft and loose particles	Whitish-yellow	Easy	Moderate	Moderate	Moderate	Low	High	Small	Up/Mid/Dow n	Up/Mid/Down

3.2. Farmer knowledge on indicators of soil quality

Farmers had detailed explanatory knowledge of 12 indicators of soil quality, with each farmer having knowledge of an average of five indicators (mean = 5.1 +/− 0.11). Table 2 illustrates indicators described by farmers to characterize the fertility status of soils on their farms. The indicators were classified as physical (7), biological (4) or chemical (1). Further, the 12 indicators comprised two landscape scale indicators: field location along a slope and slope gradient, while the remaining 10 indicators were manifest at field level.

Farmers' assessment of soil quality was qualitative and based on physical examination. Methods used by farmers to categorize soil as either being of high or low quality included: visual observation (all indicators), and touch involving passing soil through fingers, especially during ploughing, to assess the texture, soil organic matter, moisture content and easiness to plough. In addition, farmers also used indirect methods to assess biological indicators such as crop vigour and the amount of post-harvest crop residue. Indicator plants and soil macrofauna were viewed both in terms of species presence or absence, and frequency of occurrence (abundance).

Table 2: Local diagnostic criteria for describing indicators of soil quality

Local (Kinyarwanda) Name	Scientific Equivalent	Soil Fertility Status		Spatial Scale		Scientific soil properties involved		
		Fertile	Infertile	Field	Landscape	Physical	Biological	Chemical
1. *Ibara ry'ubutaka*	Soil colour	Dark, dark brown, black	Light/ whitish/ yellowish	+	-	+	-	-
2. *Ibyatsi biranga ubutaka*	Indicator plants	Species type and abundance	Species type and abundance	+	-	-	+	-
3. *Imikurire y'ibihingwa*	Crop vigour	Dark green, fast growth, large/tall stem, strong	Yellow & stunted growth, light green, short, weak	+	-	-	+	-
4. *Ubwoko bw'ubutaka*	Soil texture	Fine particles, clay-loam	Coarse, stony, sandy	+	-	+	-	-
5. *Imborera yo' mubutaka*	Soil organic matter	High	Low	+	-	-	-	+
6. *Ibishingwe by' avuye mu myaka*	Amount of post-harvest crop residue	Large, dense biomass	Small, low biomass	+	-	-	+	-
7. *Udusimba two mubutaka*	Soil macrofauna	Species type and abundance	Species type and abundance	+	-	-	+	-
8. *Ubuhaname bw' umusozi*	Slope gradient of a field	Flat/ gentle sloped	Steep sloped	-	+	+	-	-
9. *Aho umuhizi atuye kumusozi*	Location of a field along a slope	Downslope	Upslope/ Midslope	-	+	+	-	-
10. *Ubushobozi by'ubutaka bwo gutambutsa amazi*	Water infiltration rate of soil	High infiltration, no water logging	Low infiltration, water-logging	+	-	+	-	-
11. *Guhingisha isuka byoroshe*	Easiness to plough	Non-sticky	Sticky	+	-	+	-	-
12. *Ubuhehere b'ubutaka*	Moisture content of soil during dry season	Retains moisture in dry season	Dry and retains no moisture during the dry season	+	-	+	-	-

The four indicators of soil quality most commonly used by farmers to characterize soils on their fields were soil colour, soil indicator plants, crop vigour, and soil texture (Fig. 2).

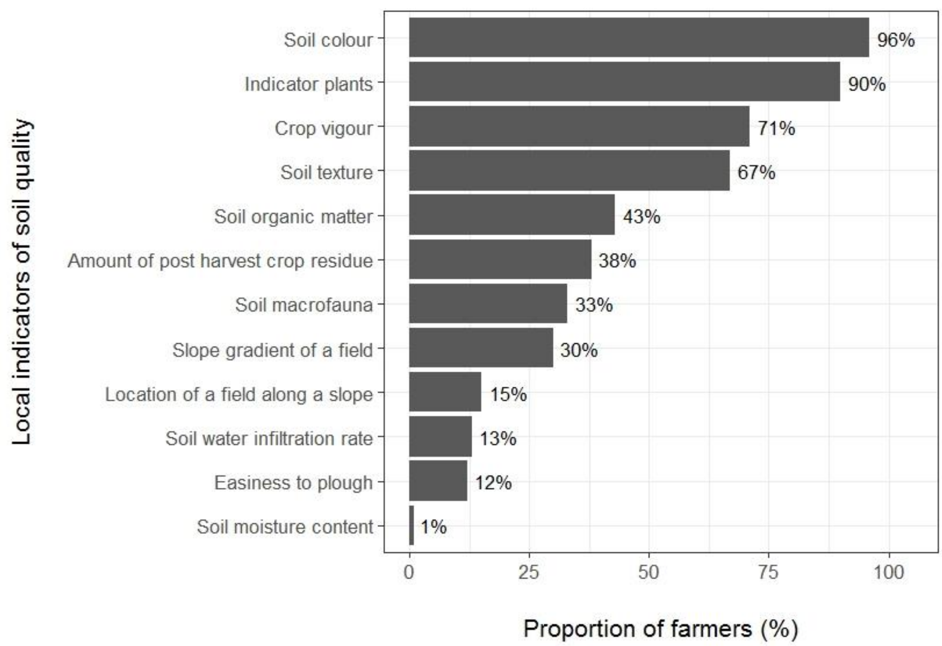

Figure 2: Proportion of farmers mentioning local indicators of soil quality (n=150)

Some indicators of soil quality were consistently used across all landscapes while others were more frequently mentioned in some landscapes than others. Farmers consistently used soil colour and indicator plants as the first and second most frequently mentioned indicator across all landscapes (Fig. 3). Crop vigour, on the other hand, was more frequently mentioned in the restored and recovering compared to the degraded landscape, while soil texture was more prevalent in the degraded and recovering landscapes (p b .05). Soil organic matter and location along the slope were not mentioned by farmers in the de-graded and restored landscapes respectively while the amount of post-harvest residues and soil macrofauna were more frequently mentioned in the recovering and degraded landscapes than the restored landscape (p b .05). Only farmers in the degraded landscape mentioned field location along a slope (downslope, midslope or upslope) as an indicator of soil quality but more farmers in the restored and recovering landscapes mentioned slope gradient than those in the degraded landscape (p b .05). On the contrary, more farmers in the degraded landscape mentioned easiness to plough, significantly different from other landscapes (p b .05). Water infiltration rate was important in the degraded landscape and significantly different from other landscapes (p b .001).

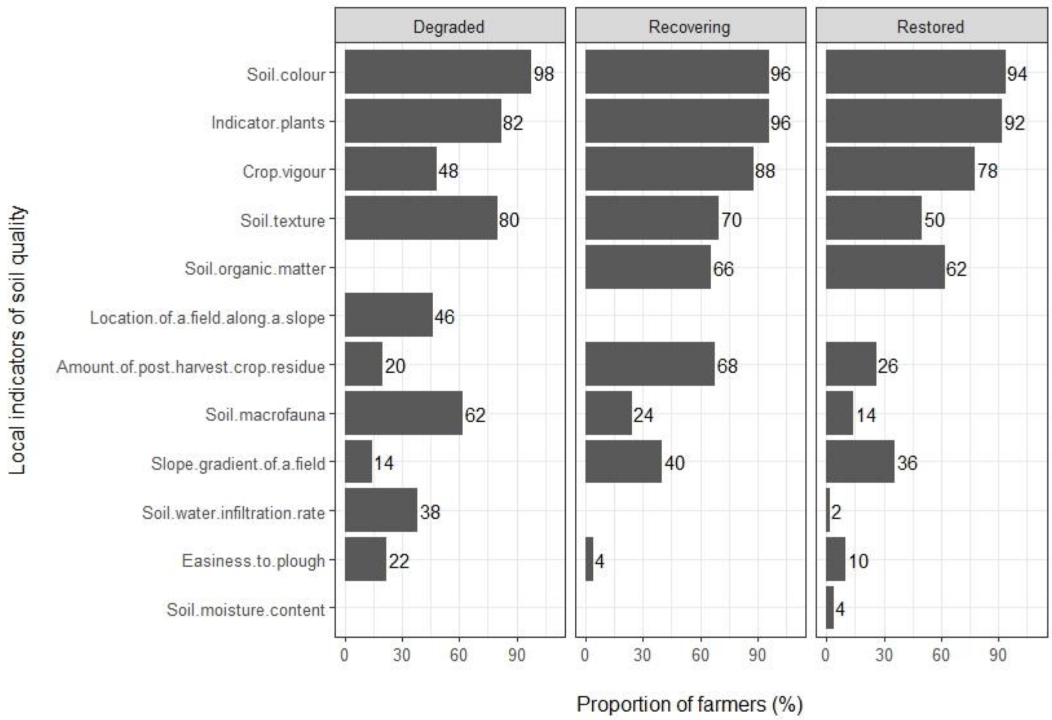

Fig. 3. Proportion of farmers mentioning indicators of soil quality along a land degradation gradient (n = 150; n = 50 per strata).

Farmers had knowledge of 28 and 23 indicator plants for high and low-quality soils respectively. Indicator plant species from the Asteraceae family were the most commonly mentioned (seven plant species). Table 3 shows the most important indicator plants as identified and prioritized by farmers. *Crassocephalum montuosum* was the most commonly mentioned indicator plant found in fertile soils in the recovering and restored landscapes. On the other hand, *Galinsoga quadriradiata* and *Commelina benghalensis* were the most commonly mentioned indicators of fertile soils in the degraded landscape. *Bromus unioloides* was the most frequently mentioned indicator of low soil quality across all three landscapes, with the highest number of farmers mentioning it in the degraded landscape. In addition, ‘absence of native plants’ effectively, bare soil, was recognized mainly by farmers in the degraded landscape as indicating extremely poor and infertile soil.

Table 3: The most important indicator plants for high and low quality soils named by farmers along the land degradation gradient.

Local name	**Scientific name**	**Botanical Family**	**Percentage of farmers (%)**			
Local Indicator Plants for Fertile Soil			***Degraded***	***Recovering***	***Restored***	**Average**
Igifuraninda	*Crassocephalum montuosum* (S. Moore) Milne- Redh.	Asteraceae	22	66	60	49
Ibaraza	*Galinsoga quadriradiata* Ruiz & Pav.	Asteraceae	62	34	42	46
Uruteja/ Inteja	*Commelina benghalensis* L.	Commelinaceae	46	18	20	28
Igihwarara/ Ikigembegembe	*Carduus Benedictus* Linn.	Asteraceae	10	14	34	19
Urukarara	*Galium spurium* L. subsp. africanum Verdc.	Rubiaceae	0	8	8	5
Igisura	*Urtica dioica*	Urticaceae	0	4	10	5
Ifurwe	*Dichrocephala integrifolia* (L.f) O.Kuntze	Asteraceae	0	8	2	3
Maguru ingware	*Polygonum nepalense* Meisn.	Polygonaceae	0	4	4	3
Nyiramuko	*Rumex steudelii* A. Rich.	Polygonaceae	2	4	2	3
Local Indicator Plants for Infertile Soil			***Degraded***	***Recovering***	***Restored***	**Average**
Urwiri	*Bromus unioloides* H.B.K	Poaceae	62	38	48	49
Umubobi ntaraza	*Spergula arvensis*	Aizoacea	0	34	36	23
Umucaca	*Cynodon dactylon* L. Pers	Graminae	16	8	10	11
Umuturanyoni	*Conyza bonariensis* (l.) Cronq.	Asteraceae	0	10	4	5
Igihehe	*Botriocline longipes*	Asteraceae	0	8	4	4
Ibirongorero	Unidentified*	*	0	4	6	3
Inyabarasanyi	*Bidens pilosa* L. var. minor (Blume)	Asteraceae	2	6	0	3
Umunigi	Unidentified*	*	0	4	4	3
Absence of native plants	n/a	n/a	18	2	0	7

The table contains the most important indicator plants (those commonly mentioned by farmers)

Farmers had knowledge of 12 and 10 soil macrofauna taxa found in fertile and infertile soils, respectively. Earthworms were the most commonly mentioned macrofauna by farmers, who differentiated them based on colour, size, food type and mobility behaviour. Eight taxa of earthworms from three families were mentioned, with the predominant trophic group being epigeic (7 species) and one endogeic. All earthworm species listed in Table 4 were viewed as an indicator of fertile soil resulting from high soil organic matter content. However, the species *Dichogaster itoliensis* was also recognized as an indicator of infer-tile soils. Farmers described the visible high mobility of *D. itoliensis* when in infertile soil presumably due to lack of soil organic matter to feed on. Conversely, the same earthworm species is not conspicuously mobile and mostly found burrowed in fertile soil with high organic cover, mainly from compost manure and litter. Other macrofauna for fertile soil mentioned were: millipedes, termites, beetles and moth larvae, with their main habitat being soils with either compost or dung added. Ants were mentioned as being an indicator of low quality and infertile soils. The absence of soil macrofauna was also recognized as an important indicator of low quality and infertile soils in the degraded landscape.

Table 4: Soil macrofauna identified by farmers along the land degradation gradient

Local taxonomy	Taxonomic Group					Presence in Landscape		
	Order/Group	Family/ Subfamily	Genera/Species	Functional Group	Soil Found	*Degraded*	*Recovering*	*Restored*
Iminyorogoto	Oligochaeta (Earthworms)	Acanthodrilidae	*Dichogaster (Dt.) itoliensis*	Epigeic	Fertile/Infertile	+	+	-
			Dichogaster (Dt.) saliens	Epigeic	Fertile	+	+	+
			Dichogaster (Dt.) affinis	Epigeic	Fertile	+	+	-
			Dichogaster (Dt.) bolaui	Epigeic	Fertile	+	+	-
			Dichogaster (Dt.) modiglianii	Epigeic	Fertile	+	+	-
		Eudrilidae	*Stuhlamannia spec nov*	Epigeic	Fertile	-	-	+
			Hyperiodrilus africanus	Epigeic	Fertile	-	+	-
		Ocnerodrilidae	*Nematogenia lacuum*	Endogeic	Fertile	+	+	+
Inyongoro	Diplopoda (Millipedes)	Pachybolidae	*Epibolus pulchripes*	Humivore	Fertile	+	-	-
			Trigoniulus sp	Humivore	Fertile	-	-	+
Imiswa	Isoptera (Termites)	Termitinae/Macrotermitinae	*Odontotermes sp*	G II (FWLG)	Fertile	-	-	+
Ikinyomo	Hymenoptera (Ants)	Formicidae/Dorylinae	*Anoma sp*	Humivore	Infertile	+	-	-
Urutozi	Hymenoptera (Ants)	Formicidae/ Ponerinae	*Euponera sp*	Humivore	Infertile	-	-	+
Inanda	Lepidoptera(Moths)	Noctuidae (turnip moth)	*Agrotis segetum*	Humivore	Fertile	-	-	+
Ibihombogoro	Coleoptera (Beetles)	Scarabaeidae	*Phyllophaga sp*	Humivore	Fertile	-	+	+
Ikivumvuri	Coleoptera (Beetles)	Scarabidae/Aphodiinae	*Aphodius ividus ol*	Scavenger/humivore	Fertile	-	-	+

Key: Functional Group for Earthworms based on classification by (Swift and Bignell, 2001); Food type: F-Fungus growers, W-Wood, L-Litter, G- Grass feeders; Functional Group for Ter-mites and Ants based on classification by (Eggleton et al., 2002), Moths and beetles based on classification by (Lavelle et al., 1992).
Key: '+' symbolizes presence; '-' symbolizes absence.

Further, within each landscape, some indicators were consistent across all three slope locations (downslope, midslope, upslope) while others were more frequently mentioned in some slope locations (Fig. 4). In the restored landscape, knowledge of indicator plants and soil colour was consistent across all slope locations, but more midslope farmers mentioned soil texture, crop vigour (p b .001) and amount of post-harvest crop residue (p b .05), than those in other slope locations. On the contrary, a larger proportion of downslope and upslope farmers had knowledge about soil organic matter than midslope farmers (p b .05).

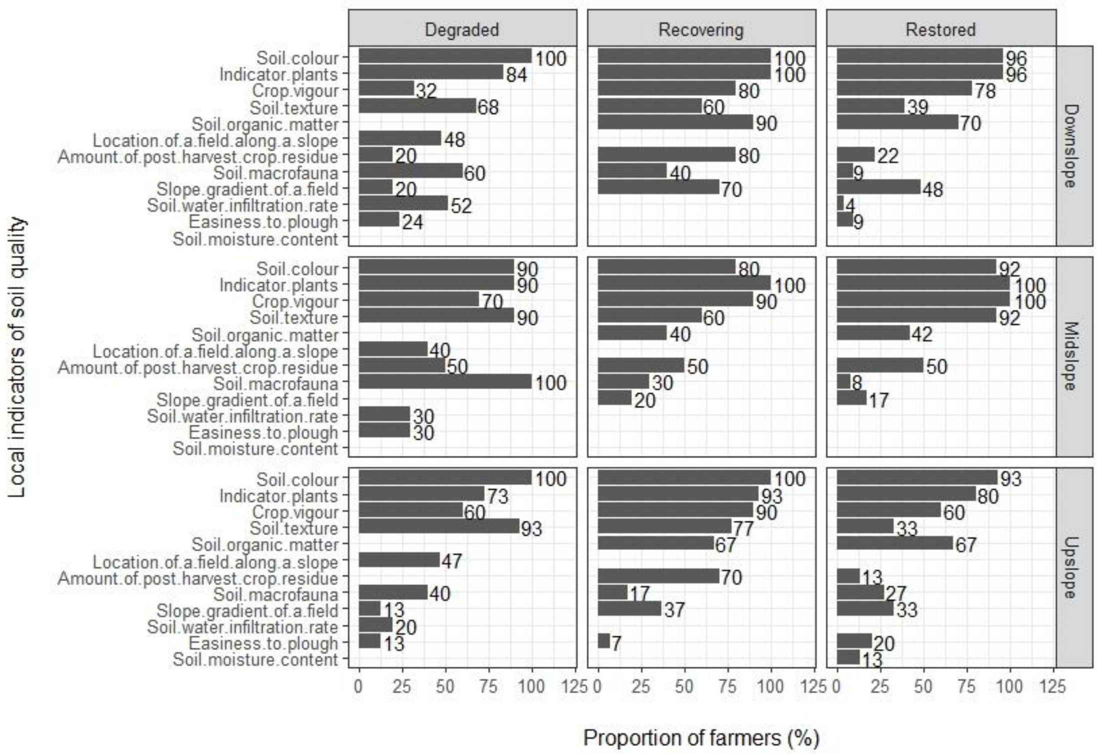

Fig. 4. Indicators of soil quality disaggregated by field location along a slope (n = 150).

In the recovering landscape, 10 indicators were consistent across slope, with only soil organic matter and slope gradient of a field being mentioned more frequently by a majority of downslope farmers, than those from other slope locations (p b .001). In the degraded landscape, 10 indicators were consistently mentioned by all farmers along the slope, with the exception of soil macrofauna and crop vigour, which were mentioned by more midslope farmers, but fewer downslope farmers than upslope farmers (p b .05). More male farmers mentioned crop vigour and soil organic matter than female farmers (p b .05) but there were no other significant differences in knowledge of indicators of soil quality according to gender (Fig. 5).

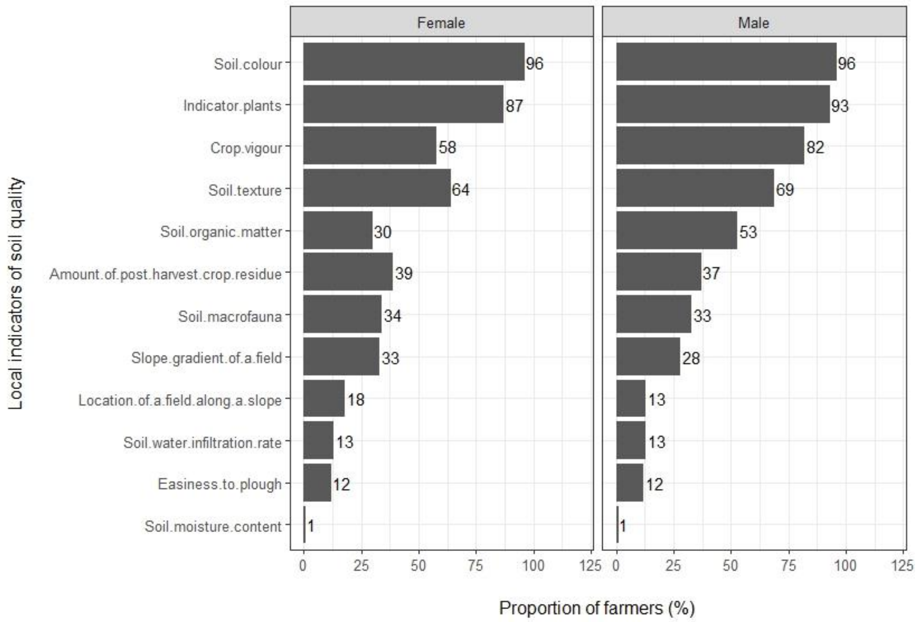

Fig. 5. Indicators of soil quality disaggregated gender (n = 150).

3.3. Predominant soil management practices

The most commonly used soil management practices were: composted manure and livestock manure additions, and tree biomass incorporation mainly from *Alnus acuminata*. Farmers explained that these soil management practices had four main goals namely to in-crease: soil nutrient availability, soil organic matter, and water retention and to decrease soil erodibility rate. Other practices included soil erosion control structures including physical structures namely bench terraces, progressive terraces; and vegetative interventions namely planting of trees and grass strips along contours, often associated with the physical structures.

All seven generic types of soil management practice were employed at the field level, with two (erosion control structures and trees in crop land) also manifesting at landscape scale (Table 5). Indicators of soil quality most influenced by soil management practices were soil colour, soil texture, crop vigour and subsequent yields, size of post-harvest crop residue, soil organic matter and moisture content of soil. Farmers explained that other indicators such as the presence and abundance of indicator plants and soil macrofauna were also influenced through increased nutrients and organic matter content in the soil.

Table 5: Linkages between indicators of soil quality, soil management practices, scale and soil management goals.

Soil Management Practice	Spatial Scale		Soil Management Goal				Local Soil Quality Indicator
	Field level	Landscape scale	Increase soil nutrient availability	Increase soil organic matter	Increase soil structural stability	Increase soil water retention	
Compost manure	✓		✓	✓		✓	1,2,3,5,6,7,12
Livestock manure	✓		✓	✓		✓	1,2,3,5,6,7,12
Tree biomass accumulation	✓		✓	✓		✓	1,2,3,4,5,6,7,12
Soil erosion control structures	✓	✓	✓		✓	✓	1,2,3,4,5,6,10,7,11,12
Chemical Fertilizer	✓		✓				2,3,6,7
Crop residue	✓		✓	✓		✓	1,2,3,5,6,7,12
Trees scattered in cropland	✓	✓	✓	✓	✓	✓	2,5,6,7,12

KEY: 1-Soil colour, 2- Indicator plants, 3- Crop vigour, 4-Soil texture, 5-Soil organic matter, 6- Size of post-harvest crop residue, 7- Soil macrofauna, 8- Slope gradient of land, 9-Field location along a slope, 10-Soil drainage capacity, 11- Easiness to plough the soil, 12-Moisture content of soil

Significantly more female farmers used crop residues than male farmers (p b .001) but significantly more male than female farmers a) incorporated tree biomass, mainly *Alnus acuminata* green manure, retained scattered trees on their farms (an agroforestry practice involving planted and/or regenerated trees retained within landscapes for multiple functions including soil erosion control), c) used livestock manure and d) chemical fertilizers (p b .05) (Fig. 6).

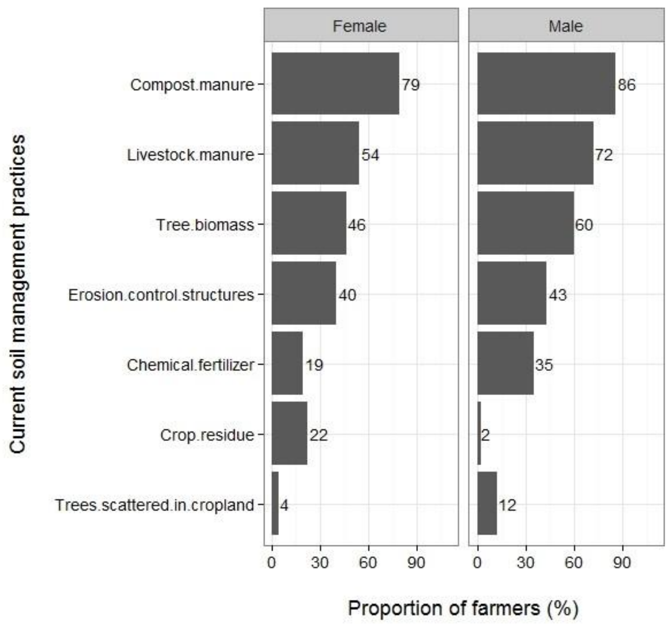

Fig. 6. Priority soil management practices disaggregated by gender.

Despite variations in the level of degradation of the three landscapes, there were no significant differences in the number of farmers that used compost manure, livestock manure and chemical fertilizer among the three landscapes (Fig. 7). Tree biomass was only used by farmers in the recovering and restored landscapes, but not reported in the de-graded landscape. Similarly, soil erosion control structures were more often used by farmers in the recovering and restored landscapes than in the degraded landscape (p b .001).

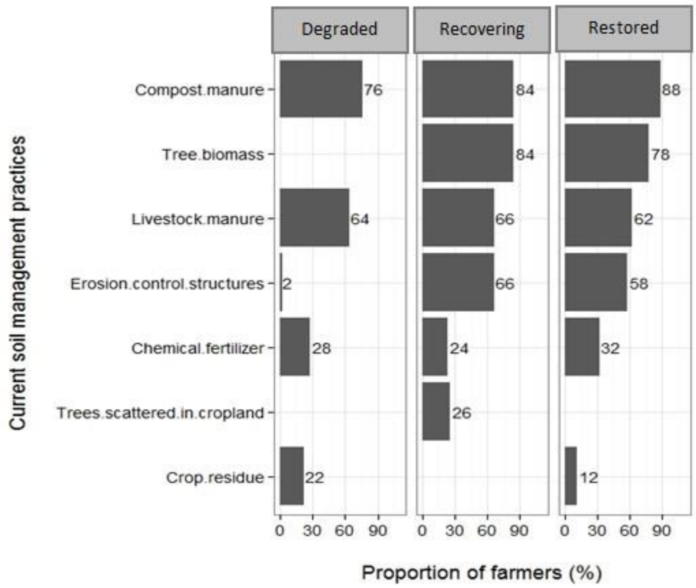

Fig. 7. Priority soil management practices along a land degradation gradient.

In the degraded and recovering landscapes, all seven soil management practices were used across all slope locations but only four of the practices: compost manure, tree biomass, soil erosion control structures and crop residues were used across all slope locations in the restored landscape (Fig. 8). In the restored landscape, livestock manure was mostly used by midslope and downslope farmers than upslope farmers (p b .001).

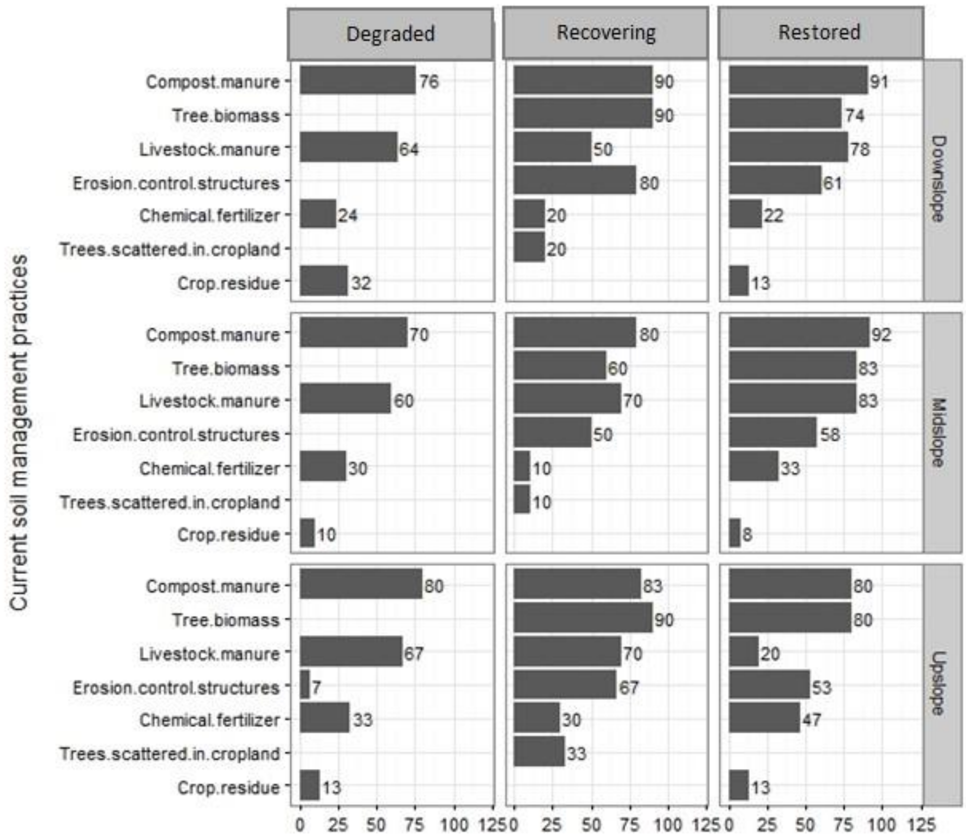

Fig. 8. Priority soil management practices by field location along a slope.

4. Discussion

4.1. Contextual variations in land degradation status

Results from this study demonstrate that soil loss is envisaged by farmers as the most important soil degradation process, and farmers un-derstood that this led to nutrient loss, including the loss of fertile top soil through surface run-off. Farmers from the degraded landscape reported that their soils were mostly rocky and sandy on the midslopes and had high clay deposition downslope, suggesting loss of clay component of the soil, which is also reported by Dlamini et al. (2014). This knowledge is comparable with other studies (Bryan, 2000; Igwe, 2005) that refer to degradation as the dispersion and loss of clay component of soil and eventual soil aggregate instability over time, mainly from water erosion.

Boix-Fayos et al. (2001) further note that loss of the aggregate inorganic and organic cementing agents leads to the destabilisation of soil aggre-gates leading to soil loss. On the contrary, farmers in the recovering and restored landscapes reported stable soils with minimal soil loss or depo-sition, suggesting a more stable soil structure.

Farmers' description of soil quality and classification of high and low quality soils was mainly in relation to physical, biological, chemical and topographic indicators. This knowledge is in line with technical soil clas-sifications (Barbero-Sierra et al., 2016; Gray and Morant, 2003). Of the 12 indicators that farmers identified, those with the highest consistent frequency of mention across the three landscapes namely soil colour, texture, crop vigour, soil macrofauna and indicator plants are robust in-dicators which have been consistently reported by multiple authors (Barrios et al., 2006; Mairura et al., 2007; Winowiecki et al., 2014). Fur-thermore, it is worth noting that farmers did not view indicators of soil quality independent of each other. For example, soil organic matter is recognized as influencing other indicators such as soil colour, presence and abundance of soil macrofauna and indicator plants as reported by Porazinska et al. (2003).

While some indicators were consistent across all landscapes and slope locations within each landscape, others such as soil organic matter and location of a field along a slope were more important in some land-scapes than in others. For example, although Andosols are normally characterized by high humus content (Matsuyama et al., 2012), farmers in the degraded landscape where these soils were found, reported that they were of low quality. This can be attributed to various factors such as farmers not incorporating organic matter such as green biomass or controlling soil and humus loss through surface run-off. This suggests specific soil characteristics brought about by different levels of land deg-radation, and may in fact provide more accurate representation of the current biophysical and socio-economic context. This is consistent with farmers' knowledge being informed by their context as noted in other research (Dawoe et al., 2012; Engel-Di Mauro, 2003; Pauli et al., 2016). Agroecological knowledge is dynamic and evolves in response to changing context, through observation and experience, providing a feedback from system changes to knowledge and practice (Joshi et al., 2004). As seen in the present research this may include observation of changes in soil at landscape scales over long time horizons (Habarurema and Steiner, 1997; Pulido and Bocco, 2003). Bocco and Winklerprins (2016) argue that people in a similar con-text are dealing with both common and unique pressures resulting in understanding of historical changes in soils and land quality (Ryder, 2003) and complex interconnected concepts about soil processes (Niemeijer and Mazzucato, 2003; Warren et al., 2003). These findings underpin the need to incorporate farmers knowledge (Barrera-Bassols and Zinck, 2003; Barrios and Trejo, 2003) which often complements sci-entific knowledge, in helping to understand the heterogeneity in soil conditions of an intervention area before designing and prescribing soil management interventions (Coe et al., 2014; Nyssen et al., 2009).

4.2. Bio-indicators for the degree of soil degradation

Farmers' knowledge of biological indicators of soil quality namely soil macrofauna, indicator plants, crop vigour and amount of post-harvest crop residue suggest an immediate feedback with regards to the prevailing soil fertility and productivity level of land. Studies have reported that macrofauna are a reliable approach to detecting agroecological changes associated with human activities, including ex-treme habitat disturbance (Andersen et al., 2002; Luke et al., 2014). The absence of indicator plants and macrofauna (in the degraded landscape) signified extremely infertile soils, as mentioned by other authors (Grime et al., 2014). This suggests that biological indicators are a reliable indicator of the extent and degree of land degradation because bare soils signify the absence of essential soil nutrients that support growth.

Farmers had an in-depth and detailed knowledge about how earth-worm types, abundance and behaviour (burrowing and mobility) assisted them in differentiating between fertile and infertile soils. The unusual mobility of D. itoliensis on extremely infertile soils noted by farmers has not been reported in any literature and suggests a direct soil quality feedback. Given that D. itoliensis is an epigeic earthworm species with horizontal mobility that inhabits the soil litter layer, their conspicuous mobility can be interpreted as particular sensitivity of this species to low organic matter content typical of infertile soils, which encourages their mobility on the soil surface in search of food. This new finding derived from farmers' knowledge, should be further explored to explore how the mobility of some earthworms might be used as a sensitive indicator in soil quality monitoring systems (Barrios et al., 2012b).

4.3. Knowledge of soil quality influences crop diversity

Farmers' knowledge of soil taxonomy and understanding of indica-tors of soil quality and attributes influenced their perceptions and con-sequent decision-making processes regarding which crops were suitable to be planted on a piece of land. These findings are similar to those reported by other authors (Rushemuka et al., 2014; Saito et al., 2006; Winowiecki et al., 2014). This can be explained by agricultural productivity being the farmers' primary interest in soils (Ericksen and Ardón, 2003). However, this scenario also suggests a farmer practice that may potentially become a key impediment to current efforts to in-crease food production and restore soils whereby over time, some farmers are adapting to perceptions of decreasing soil fertility and grad-ual soil loss by matching and allocating crops based on the soil nutrient requirement through assessing the status of soil fertility based on the in-dicators (Gray and Morant, 2003; Osbahr and Allan, 2003), instead of investing in building long-term ecological resilience of the soils, such as through agroforestry and soil and water conservation and restoration interventions. This, in turn, will lead to decreased crop and nutritional diversity because fewer crops are being cultivated as land becomes de-graded. Other studies have reported negative adaptation practices such as full abandonment of marginal land once degradation sets in, thus leading to less food production and food insecurity (Benayas et al., 2007; Geta et al., 2013).

4.4. Linkages between agroecological knowledge and practice

The results suggest that farmers' knowledge of soil quality influ-enced some of their soil management practices. For example, farmers in the restored and recovering landscapes had in depth understanding of the transformation of leaf litter into soil organic matter (Grossman, 2003); while on the contrary, there were no farmers in the degraded landscape that mentioned soil organic matter and consequently none of them incorporated tree biomass into the soil. Also, farmers in the re-covering and restored landscapes had knowledge of the high erodility rate of Alisols which they noted was made worse by the steep slopes and high rainfall intensity, hence they understood the value of implementing soil erosion control measures such as thorugh bench and progressive terraces, which were promoted by the Government of Rwanda as from 2007. This is consistent with other studies that have re-ported land management practices being determined by knowledge and perceptions of the soil while other research has shown that farmers may be constrained by social and economic factors in how they apply their knowledge in practice (Barrios and Trejo, 2003; Gobin et al., 2000). Clearly, agroecological knowledge acts on many other actors that determine what soil management practices farmers adopt, includ-ing situations were practices such as terracing may be imposed. Struc-tured stakeholder engagement to acertain what agricultural practices suit different farmers and contexts often identify overarching enabling conditions in respect of markets and policies that are important in de-termining what can be adopted by farmers (Dumont et al., 2017).

Farmers soil management practices varied along the land degrada-tion gradient. Similar observations have been made elsewhere of differ-ent knowledge held by farmers in heterogeneous land conditions and agro-ecologies (Kumwenda et al., 1996). Furthermore, studies in Rwanda indicate that soil management practices depend on farmer's perception of site-specific land characteristics such as: plot position along the slope and land potential based on other inherent constraints such as soil fertility status, soil texture, water availability and crop dis-eases (Habarurema and Steiner, 1997; Nabahungu and Visser, 2013).

Tittonell et al. (2005) further observed that planting of crops in fields perceived as having low soil quality took place later on during the cropping season and with more sparse crop spacing and less intense soil management compared to fields perceived to be of high fertility level. Moreover, in Rwanda, for severely degraded soil, farmers plant Eu-calyptus sp. woodlots on highly degraded and unproductive land for wood products and income (Ndayambaje and Mohren, 2011). Other au-thors highlight the complexity of other factors such as age and cultural interests (Birmingham, 2003) and land shortage and land fragmenta-tion (Corbeels et al., 2000) as influencing farmers' choice of soil man-agement practices, which eventually leads to farmers abandoning soil fertility management practices such as fallowing, manuring, terracing, and using crop residues. This indicates that soil management interven-tions are more likely to be adopted where they embrace the holistic na-ture of farmers management objectives (Adhikari and Hartemink, 2016; Sinclair, 2017) and take account of farmers' knowledge and understand-ing of soils, which will influence their soil management practices.

4.5. Gendered soil knowledge and management

Gender had a significant influence on two out of 12 indicators of soil quality (crop vigour and soil organic matter) and five out of seven soil management practices employed by farmers in Gishwati. These differ-ences are consistent with gender division of labour, since distinctive roles and tasks that men and women play in the society during the cropping cycle (Dah-Gbeto and Villamor, 2016; Oudwater and Martin, 2003) and are likely to expose them to different periods of the cropping cycle where some indicators are more evident or important than others. Crossland et al. (2018), reported different spatial assessment of where degradation was occurring in landscapes among men and women in Ethiopia attributed largely to their access and control over different land areas. Other factors that may influence knowledge and manage-ment practice are gender- differentiated land-use decisions, land use strategies, preferences and motivations (Christie et al., 2016; Villamor et al., 2014a). Other literature (Villamor et al., 2014b) further indicates that men and women's risk taking and access to innovation for land-use decision making may be different. These findings underpin the need for soil management and land restoration options to take gender into consideration when designing soil management interventions.

5. Conclusions

Results from this research show that some locally defined indicators of soil quality are used consistently across landscapes regardless of their degradation status, while others were more important in the more de-graded contexts, highlighting specific soil constraints brought about by different levels of land degradation. Farmers' knowledge of indicators of soil quality influenced their soil management practices, indicating the importance of their utility, alongside other enabling factors, in tailoring soil management and land restoration interventions to contexts. Gender had a significant influence on farmers' knowledge of some indicators of soil quality and soil management practices suggesting that soil and land restoration interventions that recognize gender-sensitive entry points are likely to be more effective than gender-blind approaches. Overall the research shows how combining agroecological and scientific knowledge about soils can help to identify fine-scale contextual differences that could be used to inform the design of soil management options so that they are more appropriate and diverse and hence more likely to be adopted.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:https://doi.org/10.1016/j.geodrs.2018.e00199. These data include the Google map of the most important areas de-scribed in this article.

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