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Comparing Uganda's indigenous soil classification system with World Reference Base and USDA Soil Taxonomy to predict soil productivity

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Abstract

This study examines three soil classification systems - Buganda, World Reference Base, and US Soil Taxonomy - in order to evaluate their relative strengths and feasibility for making linkages between them. Nine field sites and 16 pedons were considered across the soil landscapes of the Buganda catena. Each identified field pedon diagnostic horizons and characteristics were described and their soils analyzed using standard pedological techniques and measurements. To document the indigenous use of the Buganda classification system, interviews and discussions were held with farmer groups and local extension specialists. Using this local expertise, five local soil units were identified. We also identified two landscape toposequences with pedons that classified into six WRB Reference Soil Groups and five US Soil Taxonomic Suborders. While four local soil classes each mismatched with international systems' groups, *Liddugavu* (black) soil corresponded to Phaeozem (WRB) and Udolls (US Soil Taxonomy) and is consistently viewed as the most productive soil due to faster weed growth, diversity of crops it supports and its stable landscape location. Statistical comparisons indicated that the Buganda classes were more homogeneous and effective at separating variability of different soil properties than those of either the WRB Reference Soil Groups or US Soil Taxonomy Suborders. Integrating soil texture, pH and bases information in indigenous system methods could locally complement international classifications and linking the best of both systems would be ideal for the generation of a hybrid system. Our findings show that using the toposequence framework assists in comparing these systems in a way that is useful for scientists and local farmers.

Keywords

Indigenous soils knowledge, Soil classification, Catena, Mollisols, Oxisols, Ferralsols

Disciplines

Agriculture | Community-Based Research | Soil Science

Comments

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Comparing Uganda's indigenous soil classification system with World Reference Base and USDA Soil Taxonomy to predict soil productivity

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A B S T R A C T

This study examines three soil classification systems - Buganda, World Reference Base, and US Soil Taxonomy - in order to evaluate their relative strengths and feasibility for making linkages between them. Nine field sites and 16 pedons were considered across the soil landscapes of the Buganda catena. Each identified field pedon diagnostic horizons and characteristics were described and their soils analyzed using standard pedological techniques and measurements. To document the indigenous use of the Buganda classification system, interviews and discussions were held with farmer groups and local extension specialists. Using this local expertise, five local soil units were identified. We also identified two landscape toposequences with pedons that classified into six WRB Reference Soil Groups and five US Soil Taxonomic Suborders. While four local soil classes each mismatched with international systems' groups, *Liddugavu* (black) soil corresponded to Phaeozem (WRB) and Udolls (US Soil Taxonomy) and is consistently viewed as the most productive soil due to faster weed growth, diversity of crops it supports and its stable landscape location. Statistical comparisons indicated that the Buganda classes were more homogeneous and effective at separating variability of different soil properties than those of either the WRB Reference Soil Groups or US Soil Taxonomy Suborders. Integrating soil texture, pH and bases information in indigenous system methods could locally complement international classifications and linking the best of both systems would be ideal for the generation of a hybrid system. Our findings show that using the toposequence framework assists in comparing these systems in a way that is useful for scientists and local farmers.

1. Introduction

Farmer knowledge of soils and their management play an important role in developing greater sustainability of agricultural systems. In developing countries, few farmers have soil science training, but they usually have a good comprehension of their soils and crops that are better suited to specific locations (Payton et al., 2003; Goettsch et al., 2016; Apanovich and Lenssen, 2018). For farmers to enhance their reflective minds like scientists do, they generate classification systems based on comparable needs and physical soil-landscape realities of their environments. Occasionally, these local classification systems are only understood by a limited number of users. Improved understanding of indigenous and scientific soil classification systems by scientists and farmers, respectively, would likely improve communication between the two groups. Linking indigenous and scientific systems can then serve to facilitate technology transfer from similar soils outside the local area, which have been named differently. Farmers' knowledge of soils is largely ignored in Africa (Rushemuka et al., 2014), and rarely integrated with scientific methodologies for soil classification, a gap that proves particularly important when dealing with problems of land degradation, climate change, food security and limited data.

Farmers differentiate soils by naming them with respect to observed and experienced unique properties. Their experience with local soils enables them to generate village's soil maps (Rushemuka et al., 2014). Farmers' ability to recognize constraints on each soil unit is a guide for practicing precision agriculture. For example, a farmer's soil selection

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may include attention to depth appropriate for potato growing. A deep rooting plant that requires high fertility like spear grass (*Imperata cylindrica*) can be an indicator of such soil conditions. The presence of spear grass positively correlates with soil K concentration and suggests a greater potential for local potato production (Tenywa et al., 2014). Similar relationships have led to the development of local soil theories and concepts (Colfer et al., 1988; Abdulrashid and Yaro, 2014; Kuria et al., 2018; Yageta et al., 2019).

Although many hypotheses suggest that farmers differentiate their soils based primarily on surface characteristics, farmers have been working their soils over generations, digging beneath the surface and aware of properties at different depths (Niemeijer and Mazzucato, 2003; Abdulrashid and Yaro, 2014; Winowiecki et al., 2014). Farmers likely, therefore, consider many properties, including soil depth, productivity, slope, altitude and surface properties (Colfer et al., 1988; Niemeijer and Mazzucato, 2003; Payton et al., 2003; Abdulrashid and Yaro, 2014; Winowiecki et al., 2014). Surface properties used by farmers include among others, soil texture and colour (Yageta et al., 2019) and contribute to evaluating soil productivity in all classification systems. Such properties also apply to subsurface soil to form local soil-related perspectives that are under-utilized in formal science.

Failure to recognize the importance of local soil knowledge utilized by farmers has led to under-exploitation of specific technical management options to increase productivity. Current soil recommendations are based on scientific approaches that do not specifically include farmers' knowledge of soil or the resources at their disposal (Vanlauwe and Giller, 2006; Fairhurst et al., 2012). Similarly, scientific knowledge is hardly understood by farmers, typically resulting in slow or non-adoption (Omotayo and Musa, 1999). Scientists rarely value indigenous soil systems because of the different properties considered and languages used across regions (Saito et al., 2006). However, both systems report the ways humans seek to understand natural patterns and processes, albeit in significantly different ways. Typically, soil scientists are not trained in the methods for accessing knowledge contained in indigenous systems. Indigenous soil classification systems are sometimes claimed to be pedologically non-hierarchical, for which minimal statistical evidence is available (Payton et al., 2003; Barrera-Bassols and Zinck, 2003; Showers, 2006; Barrera-Bassols et al., 2006). Such evidences in all systems likely complement each other and potentially could generate better hybrid knowledge.

In complex knowledge systems, tailoring information to solve local farmers' demands for everyday living would require finding how soil classifications and data collections can be linked. Barrios et al. (2006) observed that local knowledge can add local relevance and potential sensitivity to complex environmental interactions but has the limitation of farm specificity. Local systems may be specifically designed for major activities that occurred in the area. In contrast, the international systems are natural systems (IUSS Working Group WRB, 2006, 2014; Soil Survey Staff, 2010, 2014) designed to establish hierarchies of classes that permit understanding of the relationships among and between soils and the factors responsible for their character. The Food and Agriculture Organization of the United Nations (UN-FAO) World Reference Base for Soil Resources (WRB) or the United States Department of Agriculture (USDA) US Soil Taxonomy classifications, however, can provide some broad indications of a soil's properties relevant to crop growth (Schaetzl et al., 2012). This is most true if the full classification (e.g., to the family level for US Soil Taxonomy) is known. To improve local relevance and soil survey data, farmers' knowledge of soil characteristics needs to be considered. This is because local farmers' knowledge is rapidly accessed, less costly, highly reproducible, and may offer long term insights into human response to nature (Payton et al., 2003). However, most tiers for indigenous classification are at the highest level, though other levels exist, if rarely used. Hence for consistency, major groupings at the highest or Reference Soil Groups (RSG) and suborder level for local, WRB and US Soil Taxonomy, respectively, are used here.

Identifying strengths and ways to combine scientific and local knowledge using participatory learning would be a breakthrough in utilizing and improving knowledge. Earlier works by Radwanski and Ollier (1959) and Pinheiro and Grashey-Jansen (2016) identified texture, colour, and landscape arrangement of soils along a slope that forms the Buganda catena but neither included local farmers' knowledge of soils. In our attempt to better understand soil as seen by farmers and scientists, there is a need to emphasize commonalities and complementarities of their knowledge and assess contrasts related to biophysiochemical properties. Contributing further to improved precision of knowledge linkage, the integration process may require grouping of soil information on a similar scale related to farm and within farmer field plots across systems (Isabirye et al., 2004). Integration of scientific and local knowledge has been considered in earlier surveys (Payton et al., 2003) but has lacked statistical support for the properties they use (Niemeijer and Mazzucato, 2003; Abdulrashid and Yaro, 2014; Berazneva et al., 2016)

Most attempts at integration of soil classification systems are mere correlation of soil names and their characteristics which are only a first step in understanding the necessary processes and causes of the properties they group. Quantifying the homogeneity of soil properties within a system's groupings and quantifying the effectiveness at separating soil groupings would help all to recognize and use soil heterogeneity in order to target better land use decisions. Quantifying performance of US Soil Taxonomy, WRB and indigenous classification systems, at grouping soil properties key to crop production may aid in identifying and managing constraints and opportunities to improve crop production.

The aims of this study were:

1. Identify how Buganda farmers locally classify soils and what indicators are used in local knowledge;
2. Compare the local, indigenous classification system and its grouping of soils with WRB and US Soil Taxonomy classification systems.
3. Quantify and statistically test the performance of US Soil Taxonomy Suborders, WRB RSG and indigenous classification systems at grouping soil properties known to affect crop production.

2. Materials and methods

2.1. Description of study area

The study was conducted on small farm households in Kabonera sub-county of Masaka district, in the Buganda region of Uganda. This area lies in the vicinity of geographic coordinates 0° 15′ 45.6228″ S and 31° 48′ 49.8708″ E. The soils of the region have been classically described as the Buganda Catena (Radwanski and Ollier, 1959). This landscape is located on the East African Plateau between the West and East African Rifts on an extremely old surface characterized by hills and ridges highly dissected by streams and drainage ways (Harrop, 1970). The geology of the area is reported to be largely undifferentiated acid and hornblende gneisses of the basement complex and the soil is formed in pre-weathered gneiss (Harrop, 1970). Aniku (2001) identified Ferralsols, Nitisols, and Gleysols developed from Precambrian schists and quartzite as common in the area. The climate of the region is tropical wet and dry. The average annual precipitation is 1350 mm with a bimodal distribution (Alou et al., 2014). The rainy seasons are March–May (Season A) and August–November (season B). The drier periods are January–February and June–July. Mean daily temperature varies between 16-27° C with an annual average of about 21° C. Temperature, humidity, and wind patterns display relatively small variability throughout the year. The Uganda Bureau of Statistics, UBOS (2015) estimates the population of the area at 307,900 with a 3% annual growth rate.

2.2. Data collection

Participatory learning from farmers involved identification of the area's local soils using a combination of methods previously applied by Barbero-sierra et al. (2017). Methods included focus group discussions, key informant interviews using local Luganda language fluently spoken by Ugandan team members, field reconnaissance, and soil profile descriptions. Sixteen soil profiles were identified and selected for the study.

A wide range of crop performance and productivity information on local soils was collected through conversation, semi-structured interviews, and observations. Local soil names were collected with description of the attributes of each from group farmers including young, old, male, and female individuals. Each soil profile's local name was confirmed by seven to 10 farmers with experience and knowledge of that soil.

Following local soil type verification and site description across nine villages, locations of each of the 16 profiles were georeferenced using GPS and each separately described (IUSS Working Group WRB, 2006, 2014; Soil Survey Staff, 2014). At least three soil profiles for each local soil class were described and sampled. Among the properties described were soil surface gravel and stoniness estimated as recommended in IUSS Working Group WRB (2006). Where the soil was wet within 200 cm with transitory or permanent internal free water, water table was determined. A water table was considered as the upper surface of saturated conditions that seasonally and sporadically, in response to rainfall events, invades soil profiles and in some areas rises to the soil surface initiating chemically reducing conditions in the soil (Buol et al., 2011). Soil colour was determined using the Munsell soil colour chart (Munsell Color Company, 1954). Core samples for bulk density and bulk samples were collected from each profile horizon for physical and chemical analysis. Soil samples were analyzed at the National Agricultural Research Laboratories (NARO), Kawanda, Uganda.

2.3. Laboratory soil analysis

Bulk soil samples were air dried and gently crushed to pass through a 2 mm sieve. Bulk density was determined using undisturbed cores (Lutz, 1947). Texture was determined by the hydrometer method (Black, 1965). Soil pH was potentiometrically measured in the supernatant solution on a 1:2.5 soil: water suspension (Black, 1965). Organic carbon (OC) was determined by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982). Phosphorus was extracted using the Mehlich 3 solution (Mehlich, 1984) and determined spectrophotometrically (Watanabe and Olsen, 1965). Cation exchange capacity (CEC) and exchangeable bases were extracted by saturating soils with neutral 1 M NH_40Ac (USDA, 1996) and the bases in the resultant solution were measured by atomic absorption spectrophotometry (AAS). Other soil properties such as ECEC, CEC/clay ratio, base saturation, Al saturation, ECEC/ 100 g clay and Mg:Ca were also calculated.

2.4. Statistical analysis

The A horizon for each of the 16 profiles was standardized by averaging each measured soil property to a depth of 15 cm for at least three samples to enable testing each classification system's efficiency and performance using means, variances and fit to the general linear model of each classification system (given below in Eqs. (1) and (2)).

The mean separation technique was applied at the highest local level, RSG, and suborder levels for respective classification systems. These enabled statistically testing sources of variability within and across classification systems. The data were further sorted according to landscape position, altitude and terrain characteristics in order to develop toposequence relationships. There were three replicates of all Buganda soil classes permitting the calculation of variances, but there were not the minimum three soil profiles for some classes of the WRB and US Soil Taxonomy thus the statistical effectiveness of those classes could not be tested and compared in the Genstat 12.1 software.

Data were checked for normality using Cook's statistics (Payne, 2009) and where non-normality was observed, data were log transformed. Data were analyzed in two ways. Firstly, a one-way ANOVA (no blocking) in the form of a general linear model as described in the Eq. (1) was computed for each of the three classification systems for each soil's compared properties. The F test of the respective classification system at grouping of the soil property was conducted to test the extent to which the classification system accounted for the differences among values of the measured or calculated soil property.

The general linear model for each classification system is represented by the equation below:

$$Y_{ij} = \mu + A_i + \mathcal{E}_{ij} \tag{1}$$

- Where Y_{ij} is the measured or calculated soil property,
- μ is the overall mean of the measured or calculated soil property,
- A_i is a variable representing the various major groupings of the soil property in a given classification system. In indigenous soils, the A_i represented the highest level, the RSG in WRB, and Suborders of the US Soil Taxonomy system.
- and $\mathcal{E}_{ij}$ is the mean error which is the variability of the soil property unexplained by the classification system.

The respective fits of these classification models to the soils data were compared using the following R^2 statistic.

$$R^2\ (\%) = 100 \times (1 - (\mathit{Residual\ Mean\ Square}\ /\mathit{Total\ Mean\ Square})) \tag{2}$$

Where: the “Residual Mean Square” or that remaining after fitting Eq. (1) for each classification system as discussed in Yost and Fox (1981).The model fit of the respective classifications thus represents the extent to which that classification system accounts for or explains the variability in the soil property according to the classes of that system (Yost and Fox, 1981) and was easily tested using the F statistic.

In a second way of testing the extent to which the classification systems grouped the variability in the soil properties, the mean differences among the respective classification system classes, were tested using Fisher's F-protected least significant difference (LSD) at 5% probability level. This provided a quantitative evaluation of the extent to which soil pedons of each classification system classes were similar. Due to the unequal number of soils classified within the different systems and the need to test respective predictions of soil measurements, an unbalanced general linear model regression was calculated (Eq. (2)) for every measured soil variable for each of the three classification systems (Eq. (1)) as discussed in Payne (2009), using Genstat 12.1.

3. Results

3.1. Nomenclature of farmers' soils and their relationship with the scientific classification systems

Five major soils were locally classified by farmers in the Buganda sub region, mainly through the use of epipedon characteristics: i.e., colour, thickness, content of gravel, sand and clay (Tables 1 and 2). These soils also appeared to differ in less defined characteristics related to visual elements, tactile components, and past behavior that key farmers understood.

Scientific evaluations of key properties applied by farmers indicated that the higher sand contents of *Lubumbabumba* and *Lusenyusenyu* separates them from other soils (Table 2). Colour differences separated *Liddugavu* from *Limyufumyufu* with the former soil having greater sand and lower clay concentration than the latter. *Luyinjayinja* soils contain both more stones and gravel than other soils. Farmers appear to

Table 1
Local soil types and their characteristics.

Local soil type	Translation	Description
Liddugavu	Black	Sticks on the hoe, high soil depth, below, is a red soil, relatively higher fertility, weeds grow fast, and all crops can be grown on it.
Limyufumyufu	Reddish	Low productivity, it has *lunnyu* (infertility) conditions, fewer weeds grow on it, sticks on hoe, highly friable, cassava is comparatively bitter on this soil.
Lubumbabumba	Clayey	Hard when dry, retains water for a long time, and sticks on hoes.
Lusenyusenyu	Sandy	Easy to work on even when dry, highly friable, does not stick on hoe, easily absorbs water and loses it fast (high water infiltration).
Luyinjayinja	Gravelly	Productive for groundnuts, coffee, maize does better, not sticky, it is easily affected by dry weather, loses productivity fast.

largely use biophysical parameters to assess each soil, select their main crops, and predict productivity potential (Table 1). Farmers can identify, for example, a soil fertility constraint '*lunnyu*' (infertility) condition in the *Limyufumyufu* soil.

The study also identified two different altitudes with varying soils along the landscape. For a landscape with summits below 1200 m, there were three local soil types with a slight elevation difference between *Liddugavu* and *Limyufumyufu* (Fig. 1). For hilltops above 1200 m, there were six positions for all the five soils located at different topographic positions (Fig. 2). The most productive *Liddugavu* soil was located on the more stable position while the least productive *Limyufumyufu* soil was on the erosive shoulder hillslope position. The *Lusenyusenyu* was located along the footslope and bottom.

The five soil classes in the local system were associated with six WRB RSG and five US Soil Taxonomy suborders (Table 3). All the *Liddugavu* soils were classified as Phaeozems in the WRB. All Phaeozems were classified as Udolls within the US Soil Taxonomy. Other soils of the local system were differently classified in the WRB and US Soil Taxonomy system.

3.2. Partitioning of variability in soil properties within classification systems

Statistical significance for topographical, physical and chemical properties differed across classification systems. The local system resulted in more homogeneity within a group of soils, which was statistically significant among the groups (Tables 4, 5 and 6). Topographically, all systems significantly separated the surface water table. In the local system, the water table was observed only for *Lubumbabumba* and *Lusenyusenyu* (Table 4). Surprisingly, *Lusenyusenyu* had the water table significantly nearer the soil surface than did the *Lubumbabumba*.

Across physical properties, the local system separated three properties while in the WRB RSG and US Soil Taxonomy Suborders, only two properties and none, respectively, were significantly different across soils (Table 5). In textural terms, the *Lubumbabumba* (clayey) and *Lusenyusenyu* (sandy) soils had significantly greater sand and lower clay content than other soils. However, *Lubumbabumba* had significantly greater silt content than *Limyufumyufu* and *Luyinjayinja* (stony) within the local system. There were eleven, two and zero chemical properties tested and found significantly different in local, WRB RSG, and US Soil Taxonomy Suborder systems, respectively, across the measured soil properties (Table 6). Within the indigenous system, the *Liddugavu* soil exhibited significantly greater values of plant nutrients than the other soils. Other nutrients, pH, CEC, ECEC, base saturation and ECEC/100 g clay were significantly greater for *Liddugavu* than other soils. In the WRB RSG, the pH on Phaeozem was higher and exchangeable Al lower than for the Gleysol as expected. The Soil Taxonomy Suborders separated soils for none of the physiochemical properties (Table 6).

3.3. The ability of classification systems at grouping similar soils

There was higher heterogeneity in the data for properties within the RSG of WRB and suborders in US Soil Taxonomy than soil properties within classes resulting from the more homogenous indigenous systems (Table 7). Exceptions were for the most heterogeneous properties of bulk density, OC in the local system, and more homogenous slope, clay, ECEC, Al saturation, base saturation, ECEC/100 g clay and Mg:Ca for the WRB RSG and slope length and Al saturation for the US Soil Taxonomy Suborders (Table 7) than their counterpart classifications. Despite the ability of those classification systems to systematically separate soil properties, there was unexplained variability within some properties of each system (Table 7). These unexplained external variabilities were observed for bulk density and OC in the local classification, slope, silt, CEC/clay, Al saturation, base saturation, and Mg:Ca in WRB RSG and slope length and Al saturation in the US Soil Taxonomy Suborders.

Further mean separation through fit of the model analysis showed higher separation values for the local than the WRB RSG and US Soil Taxonomy Suborders (Table 7). The highest goodness-of-fits for the local system were observed with Ca (87%), clay (84%), CEC (84%) and ECEC (84%). The soil OC was associated with the weakest fit for use in the local system. In the WRB RSG, only sand and clay were fit strongly

Table 2
Description of representative pedons and associated main properties for their nomenclature.

Profile	Local soil Name	Munsell colour	Colour code	Surface gravel (%)	Surface stones %	Sand (%)	Clay (%)	Texture
1^{aP1}	*Limyufumyufu*	Dark brown	7.5YR4/3	1	0	56	36	Sandy clay
2^{P2}	*Lubumbabumba*	Very dark grayish brown	10YR3/2	5	0	68	20	Sandy clay loam
3^{P4}	*Luyinjayinja*	Dark reddish brown	5YR3/4	3	0	52	40	Sandy clay
4^{P5}	*Lubumbabumba*	Very dark gray	7.5YR3/1	0	0	70	16	Sandy loam
5^{P6}	*Lusenyusenyu*	Reddish brown	5YR4/3	0	0	74	14	Sandy loam
6^{P8}	*Liddugavu*	Very dark brown	7.5YR2.5/2	0	0	62	27	Sandy clay loam
7^{P9}	*Lubumbabumba*	Black	7.5YR2.5/1	0	0	64	20	Sandy clay loam
8^{P10}	*Liddugavu*	Dark brown	7.5YR3/2	3	0	52	36	Sandy clay
9^{P11}	*Limyufumyufu*	Dark reddish brown	2.5YR3/4	3	0	52	40	Sandy clay
10^{P12}	*Luyinjayinja*	Reddish black	2.5YR2.5/1	5	5	62	30	Sandy clay loam
11^{P13}	*Luyinjayinja*	Dark brown	2.5YR3/2	50	10	50	42	Sandy clay
12^{P14}	*Limyufumyufu*	Dark reddish brown	2.5YR3/4	5	0	48	44	Sandy clay
13^{P15}	*Liddugavu*	Black	7.5YR2.5/1	0	0	58	28	Sandy clay loam
14^{P16}	*Lusenyusenyu*	Very dark brown	5YR3/1	0	0	70	20	Sandy clay loam
15^{P17}	*Lusenyusenyu*	Very dark gray	7.5YR3/1	5	0	70	24	Sandy clay loam
16^{P18}	*Lusenyusenyu*	Very dark brown	7.5YR2.5/2	0	0	58	28	Sandy clay loam

[a] The superscript 'P' and number refer to the pedons numbered in Figs. 1 and 2.

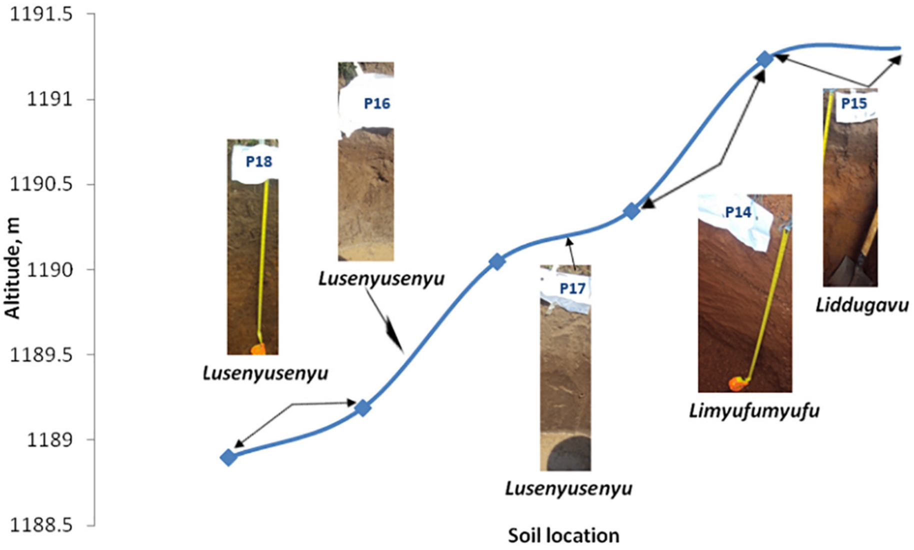

Fig. 1. A graphic depiction of the farmer-recognized soils and their toposequence position in a frequently encountered catena of the Masaka landscape, Uganda.

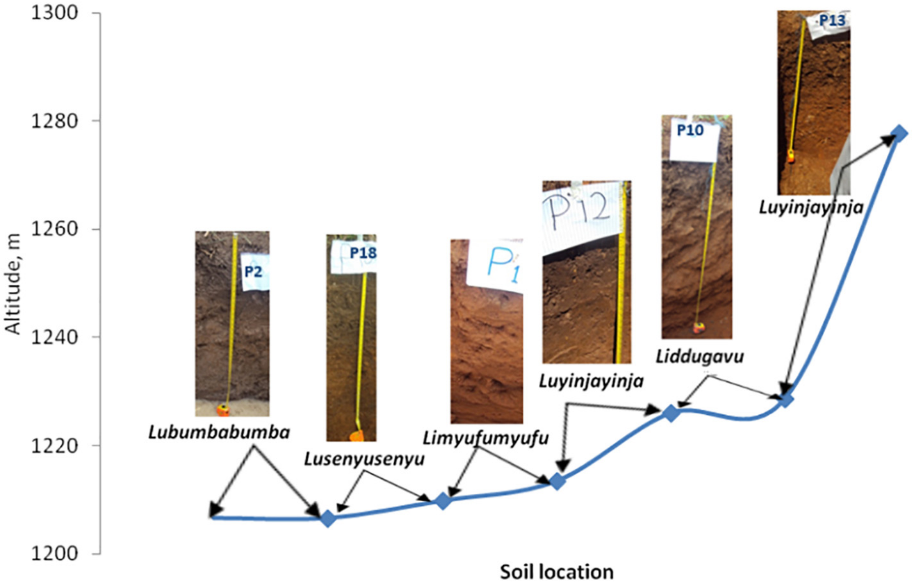

Fig. 2. A graphic depiction of the farmer-recognized soils and their toposequence position in the second most frequently encountered catena of the Masaka landscape, Uganda.

to the model but at a lower percentage than in the local system. In the US Soil Taxonomy Suborders, all regressions were poorly fit for the system.

4. Discussion

Looking at the local soil classification and examining how such knowledge could benefit from additional input from more universal systems would contribute to beneficial adaptation of both kinds of systems. Farmers in the Masaka region mainly identify five soils distinguished by visual characteristics (Tables 1 and 2), but are simple generalizations of combined soil properties and their descriptions. Their system uses colour, texture and surface gravels independently to differentiate soils. However, they showed no classification levels, which may be possible if other soil properties are simultaneously included. Upon description of a soil, farmers noted characteristics which clearly separate all soils. These included surface, subsurface, tactile and behavioral characteristics, categorizing red and black as least and most productive soils, respectively (Table 1). Farmers attribute productivity of black soil to high weed intensity, vigor, biomass, diversity of crops it supports (Table 1), less disturbed by soil processes and higher yields (Tenywa et al., 2014). This approach is a reflection of farmers' recognition that nature, ecology and human activity function together to satisfy social and economic needs. Such qualitative productivity assessments are proportional to confirmed quantitative scientific laboratory evaluations (Tables 2, 4, 5 and 6; Goettsch et al., 2016; Apanovich and Lenssen, 2018). Observed properties are partly determined by landscape position (Figs. 1 and 2), which may influence soil processes and management practices affecting soil characteristics (Fungo et al., 2010).

Identification of a *lunnyu* condition on *Limyufumyufu* by farmers has, in many studies, been linked to poor soil fertility (Fungo et al., 2010). A *lunnyu* condition is a fertility constraint embodied with chemical, physical, biological, and fertility considerations (Chenery, 1954). Hence, although farmers do not know the complex scientific language of soil properties, their continued soil use experience enables them to establish multifaceted combinations of those properties to assess and identify

Table 3
Local, WRB, and Soil Taxonomy classifications of the 16 soil profiles of the Masaka region study.

Profile	Local soil Name	WRB	WRB-RSG	US Soil Taxonomy	Suborder
1^{aP1}	*Limyufumyufu*	Eutric Sideralic Cambisol (Clayic, Humic)	Cambisol	Typic Kandiudalf, fine, parasesquic, isohyperthermic	Udalf
2^{P2}	*Lubumbabumba*	Acric Gleyic Umbrisol (Loamic, Ferralic)	Umbrisol	Oxyaquic Humudepts, fine-loamy, mixed, subactive, isohyperthermic	Udepts
3^{P4}	*Luyinjayinja*	Eutric Cambisol (Clayic, Humic, Magnesic)	Cambisol	Humic Eutrudepts, fine, mixed, subactive, isohyperthermic	Udepts
4^{P5}	*Lubumbabumba*	Plinthic Umbric Gleysol (Acric, Loamic, Humic)	Gleysol	Fluvaquentic Endoaquoll, fine-loamy, kaolinitic, isohyperthermic	Aquolls
5^{P6}	*Lusenyusenyu*	Plinthic Umbric Gleysol (Acric, Loamic, Humic)	Gleysol	Dystric Eutrudepts, coarse-loamy, mixed, subactive, isohyperthermic	Udepts
6^{P8}	*Liddugavu*	Cambic Chernic Phaeozem (Loamic, Sideralic)	Phaeozem	Fluventic Hapludolls, fine, mixed, semiactive, isohyperthermic	Udolls
7^{P9}	*Lubumbabumba*	Dystric Plinthic Umbric Gleysol (Acric, Clayic, Humic)	Gleysol	Fluvaquentic Endoaquolls, coarse-loamy over clayey, mixed, subactive, isohyperthermic	Aquolls
8^{P10}	*Liddugavu*	Cambic Phaeozem (Clayic, Sideralic)	Phaeozem	Fluventic Hapludolls, fine, mixed, subactive, isohyperthermic	Udolls
9^{P11}	*Limyufumyufu*	Pisoplinthic Plinthosol (Eutric, Clayic, Humic, Magnesic)	Plinthosol	Humic Eutrudox, clayey-skeletal, parasesquic, isohyperthermic	Udox
10^{P12}	*Luyinjayinja*	Skeletic Lixic Mollic Umbrisol (Loamic, Ferralitic)	Umbrisol	Typic Hapludolls, clayey-skeletal, parasesquic, isohyperthermic	Udolls
11^{P13}	*Luyinjayinja*	Humic Acric Pisoplinthic Ferralsol (Dystric, Clayic)	Ferralsol	Typic Eutrudox, clayey-skeletal, parasesquic, isohyperthermic	Udox
12^{P14}	*Limyufumyufu*	Pisoplinthic Ferritic Ferralsol (Acric,Humic)	Ferralsol	Rhodic Eutrudox, clayey-skeletal, kaolinitic, isohyperthermic	Udox
13^{P15}	*Liddugavu*	Cambic Luvic Phaeozem (Loamic)	Phaeozem	Typic Hapludolls, clayey-skeletal, mixed, semiactive, isohyperthermic	Udolls
14^{P16}	*Lusenyusenyu*	Eutric Plinthic Umbric Gleysol (Acric, Loamic, Humic)	Gleysol	Fluventic Endoaquolls, loamy-skeletal, kaolinitic, isohyperthermic	Aquolls
15^{P17}	*Lusenyusenyu*	Eutric Plinthic Umbric Gleysol (Acric, Loamic, Humic)	Gleysol	Aquic Eutrudox, loamy-skeletal, kaolinitic, isohyperthermic	Udox
16^{P18}	*Lusenyusenyu*	Haplic Phaeozem (Clayic, Ferralic)	Phaeozem	Fluventic Hapludolls, clayey-skeletal, mixed, semiactive, isohyperthermic	Udolls

[a] The superscript ‘P' and number refer to the profile pit photos in Figs. 1 and 2.

Table 4
Statistical analysis results of testing the soil classification systems by comparing the extent to which they accounted for variability in soil properties – the topographical characteristics of soils. Means and standard error of the means for the various classes defined by the classification systems.

Systems and soils	n[a]	Slope (%)	Slope Length (m)	Water table (cm)
Local system				
Liddugavu	3	3.5 ± 0.76	187.0 ± 63.33[b]	0.0[f]
Limyufumyufu	3	6.0 ± 1.00	60.0 ± 17.32	0.0[f]
Lubumbabumba	3	1.3 ± 1.33	187.0 ± 63.33	98.0 ± 11.53
Lusenyusenyu	4	6.9 ± 1.33	92.0 ± 52.97	41.5 ± 24.05
Luyinjayinja	3	4.5 ± 1.89	137.0 ± 57.83	0.0[f]
	n[c] = 16			
F[d] probability value		0.085	0.424	0.003
LSD[e] (0.05)		4.3	174.5	47.7
WRB RSG				
Gleysol	5	4.0 ± 1.92	124.0 ± 51.73	73.0 ± 19.81
Phaeozem	4	4.5 ± 1.14	202.0 ± 47.50	0.0[f]
	n = 9			
F probability value		0.841	0.312	0.014
LSD (0.05)		5.7	170.2	53.1
US Soil Taxonomy Suborders				
Aquolls	3	3.0 ± 3.00	177.0 ± 73.33	93.0 ± 13.53
Udepts	3	2.8 ± 0.73	73.0 ± 13.33	31.0 ± 31.00
Udolls	5	4.4 ± 0.89	174.0 ± 46.54	0.0[f]
Udox	4	6.8 ± 0.95	100.0 ± 51.96	22.0 ± 22.00
	n = 15			
F probability value		0.257	0.438	0.022
LSD (0.05)		4.96	178.9	61

[a] Number of pedons in a given classification system.
[b] Standard Error of a mean for a given soil within a classification system.
[c] Total number of pedons in a given classification system.
[d] F probability value for the F-test of extent the classification model fit the data.
[e] Fisher's F-protected Least Significant Difference for comparing class means for the classification system.
[f] Unsaturated and a confined aquifer with water table far below the land surface.

potential productivity. Consequently, they observe bitter cassava frequently produced from *Limyufumyufu* soils, a condition associated with poor fertility and acidic soils of which *lunnyu* is a part (Fungo et al., 2010; Alou et al., 2014; Tables 1 and 6). The acidifying conditions are likely to be accelerated by erosion processes influenced by landscape position of the soil (Figs. 1 and 2; Table 6) and management practices involved with crops cultivated on each soil (see Fungo et al., 2010). Landscape soil position was not reported but can be considered as part of the farmers' criteria of soil identification since they knew all soils locations. Such toposequences (Figs. 1 and 2) analogous to Buganda catena explains the two forms of soil arrangement based on similar properties used by Radwanski and Ollier (1959). However, the altitude of a given landscape's crest would be the most useful indicator differentiating the two forms of toposequences (Figs. 1 and 2). Conversely, the terrain system does not include local nomenclature amidst farmers' lack of insight regarding differences within soil toposequences. The soil-landscape relationship is strong across the local Buganda catena, as it is in WRB and US Soil Taxonomy, capable of allowing local farmers and far away soil scientists to communicate with one another. Many argue that language and thought are necessarily hierarchical and categorical to allow us to make sense of the continuous reality with which we are confronted. Therefore, knowing ways that farmers combine properties may allow identification of the hierarchical nature of the local classification system necessary for that knowledge to be incorporated into the international systems. For example, farmers have limited knowledge at separating effects due to some properties like high water holding capacity resulting from clay and OM content ratios or type. Besides insufficient knowledge on physical and chemical properties, farmers are poor at seeing biological properties, mainly soil microorganisms (Table 1), which are important to upgrading their own systems. Farmers are thus skilled but with limited understanding of underlying processes, hence the need to combine possible insights from their system with more formal ‘scientific ones’.

In a comparison of classification systems, the nearest association to local *Liddugavu* was Phaeozem in the WRB and Udolls in US Soil Taxonomy systems, despite the differences in great groups or principal qualifiers and lower levels (Table 3). Thus, soil information and management recommendations from other regions in the world on Phaeozem and Udolls may be transferred to *Liddugavu* soils. Likely, each place has its own understanding of soil that can fine-tune and modify the standardized version to make them more useful locally. One simple effective example of the value and utility of international classification systems is of Udolls mapped in the USDA Soil Taxonomy site (soils.usda.gov) that provide better understanding of local-scale soil variability and increasing interpretation for agricultural purposes (Eswaran et al., 2012).

The Soil Survey in the US classifies soils beyond the suborder level to include the great group, subgroup, family (Table 3) and series level. The

Table 5
Statistical analysis results of testing and comparing the soil classification systems by comparing the extent they accounted for variability in soil properties – physical properties of soils. Means and standard error of the means for the various classes defined by the classification systems.

Systems and soils	n[a]	ρ_b[b]	Sand	Clay	Silt
		(g cm^{-3})		Perc (%)	
Local system					
Liddugavu	3	1.2 ± 0.07	57.3 ± 2.9	30.3 ± 2.9	12.3 ± 0.9
Limyufumyufu	3	1.3 ± 0.05	49.9 ± 0.9	42.2 ± 0.9	8.4 ± 0.6
Lubumbabumba	3	1.6 ± 0.34	67.5 ± 1.6	18.8 ± 1.4	13.8 ± 0.9
Lusenyusenyu	4	1.3 ± 0.07	68.0 ± 3.5	21.5 ± 2.9	10.5 ± 1.7
Luyinjayinja	3	1.2 ± 0.21	56.5 ± 2.9	35.5 ± 2.9	8.0 ± 0.0
	n[c] = 16				
F probability value[d]		0.481	0.003	0.001	0.025
LSD[e] $_{(0.05)}$		0.6	8.9	8.1	3.7
WRB RSG					
Gleysol	5	1.5 ± 0.20	69.7 ± 1.5	18.9 ± 1.8	11.5 ± 1.63
Phaeozem	4	1.2 ± 0.06	57.5 ± 2.1	29.8 ± 2.1	12.8 ± 0.8
	n = 9				
F probability value		0.225	0.002	0.005	0.531
LSD $_{(0.05)}$		0.5	5.9	6.4	4.6
US Soil Taxonomy Suborders					
Aquolls	3	1.6 ± 0.33	68.1 ± 1.9	18.8 ± 1.4	13.1 ± 1.6
Udepts	3	1.3 ± 0.10	64.7 ± 6.8	24.7 ± 7.9	10.7 ± 1.3
Udolls	5	1.3 ± 0.06	58.4 ± 1.8	29.8 ± 1.6	11.8 ± 1.1
Udox	4	1.2 ± 0.13	56.2 ± 4.9	36.3 ± 4.4	7.9 ± 0.7
	n = 15				
F probability value		0.274	0.195	0.067	0.053
LSD $_{(0.05)}$		0.5	13.6	14	4.1

[a] Number of pedons in a given classification system.
[b] Standard Error of a class mean for a given soil property within a classification system.
[c] Total number of pedons in a given classification system.
[d] F probability value for the F-test of the classification model fit to the data.
[e] Fisher's F-protected Least Significant Difference for comparing class means for the classification system.

WRB system does not include the series level information even at supplementary level. With these levels included, several properties are addressed similar to the local systems. The local classification even at the highest level would be considered more of a series level with more detail than the WRB-RSG and US Soil Taxonomy suborders. This partly explains the somewhat poor performance of the international systems. The series level can include landscape positions, a refined temperature and soil moisture environment, and textures. Although not included in this study, creating soil map units and descriptions may well have shown a high level of agreement with the local system.

Inadequate local nomenclature correspondences to the WRB and US Soil Taxonomy system for the remaining soils is indicative of differences in quantification scales among the parameters used, purpose and experience (Tables 1 and 3). This shows the many differences and potentially useful information possible, had farmers used more than one parameter to name a soil as observed for their descriptions (Table 1). Similarly, Isabirye et al. (2004) and Pinheiro and Grashey-Jansen (2016) identified greater precision in soil classes with coarser map scale. Hence, amidst limited data, the toposequence approach might be combined with correspondence analysis to calculate empirical cumulative distribution functions of the nearest neighbor distance (Hughes et al., 2018) for both international and indigenous systems in soil mapping. Such would be critical if mere names are important for providing sufficient insight into local perspectives on sustainable land use and management.

Comparisons of statistical significance for the separation of means of soil biophysical properties suggest that the local system resulted in groupings of soils that were relatively homogeneous within each group. These were also significantly different among the groups, indicating an effective grouping of soils, particularly when considered for crop production (Tables 4, 5 and 6). The Buganda system has been developed and refined through generations of reflective use of the soils and landscapes by the people who live there hence its strength in the area. Also, knowing its performance outside the region of study would be fruitful. Commonly used WRB-RSG and US Soil Taxonomy suborders could be strengthened by including indigenous knowledge for improved practical application at a local level. An important limitation of the current study is that both international systems typically provide far greater detail in information than was possible in this study. The evaluation could be improved using a larger sample size that would permit comparison of the international system with the local system at a much more detailed level of classification at family or series level.

In the local and RSG-level WRB systems, topographical and physical properties were significantly separated for all the soils (Tables 4 and 5). Such properties influence soil hydrology, formation and chemical properties, which are considered in the WRB and US Soil Taxonomy (Schoeneberger et al., 2012; IUSS, 2014). However, the local system may combine many of the properties into soil descriptions mainly as water retention, infiltration, fertility and *lunnyu* condition (Yageta et al., 2019; Tables 1, 4 and 5). Thus, there was a clear partition for *Limyufumyufu* and *Liddugavu* as separated by clay and for *Lubumbabumba* and *Lusenyusenyu* as separated by texture (sand) from *Luyinjayinja* soil (Table 4) with exceedingly more gravels and stoniness (Table 2). However, there was no strong statistical distinction between *Lubumbabumba* and *Lusenyusenyu*, which are also not ascertained by measured chemical properties. Clay quality influence was also weak (Table 6) necessitating determination of clay type and influence of external factors (Table 7). Similarly, proportions of OC pools, clay type and content ratios may be important in influencing cohesion forces of low altitude soils. Nevertheless, combinations of topographical and physical properties (Fig. 1, Tables 4 and 5) influence oxidation and reduction processes, which determine many chemical properties such as OC (Table 6; Buol et al., 2011). Because OC and bulk density in the local system can be strongly influenced externally by anthropogenic activities, systematic inaccuracies in the WRB RSG and US Soil Taxonomy suborders may include both natural and human-induced properties (Table 7). However, all the resulting unexplained variations affect crop productivity. Yost and Fox (1983) used a similar statistical approach to compare effectiveness of four classification systems in arriving at grouping of soils as evaluated by the greater uniformity within the resulting classification. Greater uniformity within each resulting grouping suggests a more effective grouping of the soils.

Thus, although all systems can separate soils, the Buganda system was consistently more homogenous and effective than the WRB RSG or US Soil Taxonomy Suborders at the local level. The local system also has divisions whose significant relations of landscape, texture, pH and bases could complement international classifications. Combining information for those properties in each system would enable the generation of a hybrid system that utilizes both broad scientific and local soil knowledge. A perhaps more feasible alternative would be to ascertain the international classification of the local soils to identify the analogs and potential sources of improved knowledge and management. It would however be important to establish detailed soils and land evaluation of each classification and mapping unit before merging knowledge across classification systems.

Table 6
Statistical analysis results of testing and comparing the soil classification systems by comparing the extent they accounted for variability in soil properties – soil chemical and several calculated properties.

Systems and soils	n[a]	pH	OC	P	Ca	Mg	K	Exc.Al	CEC
		(1:2.5H_2O)	g kg^{-1}	mg kg^{-1}	'-----------------cmol kg^{-1} soil------------------'				
Local system									
Liddugavu	3	6.1 ± 0.52[b]	24 ± 4.6	65.6 ± 24.3	16.8 ± 1.5	9.7 ± 0.68	1.6 ± 0.53	0.1 ± 0.13	29.3 ± 2.4
Limyufumyufu	3	4.6 ± 0.18	24 ± 2.1	5.8 ± 5.6	5.8 ± 1.7	2.5 ± 1.2	0.3 ± 0.26	0.7 ± 0.09	9.0 ± 3.0
Lubumbabumba	3	4.7 ± 0.07	17 ± 4.4	1.4 ± 0.70	4.9 ± 1.3	2.3 ± 1.8	0.1 ± 0.07	0.7 ± 0.06	7.9 ± 3.3
Lusenyusenyu	4	4.5 ± 0.17	21 ± 2.8	4.6 ± 1.6	4.3 ± 1.2	2.5 ± 1.5	0.1 ± 0.02	0.8 ± 0.13	7.4 ± 2.8
Luyinjayinja	3	4.9 ± 0.57	24 ± 0.3	0.1 ± 0.06	2.4 ± 0.55	0.0 ± 0.03	0.0 ± 0.00	0.6 ± 0.30	2.8 ± 0.63
	n[c] = 16								
F probability value[d]		0.04	0.549	0.005	0.001	0.003	0.004	0.095	0.001
$LSD_{(0.05)}$[e]		1.1	10	33.2	4.2	4.1	0.8	0.5	8.6
WRB RSG									
Gleysol	5	4.6 ± 0.14	20 ± 2.7	4.0 ± 1.3	5.3 ± 0.96	3.3 ± 1.2	0.1 ± 0.04	0.8 ± 0.10	9.4 ± 2.3
Phaeozem	4	5.8 ± 0.52	24 ± 3.3	50.0 ± 23.5	13.1 ± 3.8	7.3 ± 2.5	1.2 ± 0.55	0.3 ± 0.15	22.6 ± 6.9
	n = 9								
F probability value		0.039	0.3	0.065	0.061	0.166	0.054	0.024	0.087
$LSD_{(0.05)}$		1.1	1.0	48.9	8.4	6.1	1.1	0.423	15.7
US Soil Taxonomy Suborders									
Aquolls	3	4.8 ± 0.09	21 ± 4.0	4.1 ± 2.04	6.0 ± 1.2	4.3 ± 1.7	0.1 ± 0.06	0.6 ± 0.09	11.2 ± 3.1
Udepts	3	5.0 ± 0.53	16 ± 3.6	0.8 ± 0.75	2.6 ± 0.47	0.2 ± 0.08	0.0 ± 0.01	0.6 ± 0.31	3.2 ± 0.57
Udolls	5	5.5 ± 0.49	24 ± 2.5	39.7 ± 20.7	11.2 ± 3.5	5.9 ± 2.4	1.0 ± 0.49	0.4 ± 0.16	18.9 ± 6.6
Udox	4	4.4 ± 0.08	24 ± 1.4	1.8 ± 1.6	4.3 ± 1.3	1.8 ± 1.0	0.1 ± 0.02	0.9 ± 0.04	6.6 ± 2.4
	n = 15								
F probability value		0.218	0.265	0.173	0.134	0.19	0.148	0.197	0.155
$LSD_{(0.05)}$		1.4	1.0	50.4	9.1	6.5	1.2	0.6	17.0

Systems and soils	N	Silt:Clay	Base Sat. %	ECEC soil cmol kg^{-1} soil	Al sat. %	CEC/clay	ECEC 100 g $clay^{-1}$ (cmol kg^{-1} clay)
Local system							
Liddugavu	3	0.4 ± 0.05	79.4 ± 0.28	28.3 ± 2.3	0.5 ± 0.54	117.7 ± 8.3	0.94 ± 0.06
Limyufumyufu	3	0.2 ± 0.00	55.2 ± 9.6	9.1 ± 2.8	12.3 ± 5.9	33.0 ± 8.4	0.22 ± 0.07
Lubumbabumba	3	0.7 ± 0.08	53.5 ± 8.6	8.0 ± 3.1	11.3 ± 3.6	68.5 ± 26.3	0.46 ± 0.22
Lusenyusenyu	4	0.5 ± 0.13	50.4 ± 9.9	7.6 ± 2.6	15.9 ± 5.9	57.9 ± 14.3	0.37 ± 0.12
Luyinjayinja	3	0.2 ± 0.02	32.2 ± 5.8	3.1 ± 0.73	17.7 ± 9.9	22.1 ± 3.1	0.09 ± 0.03
	n = 16						
F probability value		0.004	0.031	0.001	0.373	0.008	0.006
$LSD_{(0.05)}$		0.3	26.4	8.1	19.5	47	0.39
WRB RSG							
Gleysol	5	0.6 ± 0.12	57.9 ± 6.9	9.5 ± 2.1	12.0 ± 4.6	75.0 ± 14.2	0.51 ± 0.12
Phaeozem	4	0.4 ± 0.04	67.1 ± 12.3	21.9 ± 6.6	6.1 ± 5.6	95.0 ± 23.9	0.73 ± 0.22
	n = 9						
F probability value		0.175	0.507	0.087	0.437	0.482	0.373
$LSD_{(0.05)}$		0.3	31.2	14.8	17	62.5	0.55
US Soil Taxonomy Suborders							
Aquolls	3	0.7 ± 0.11	62.3 ± 7.4	11.0 ± 2.8	7.6 ± 3.7	87.5 ± 21.5	0.61 ± 0.18
Udepts	3	0.6 ± 0.19	34.5 ± 5.4	3.4 ± 0.74	14.7 ± 8.1	36.5 ± 8.9	0.18 ± 0.07
Udolls	5	0.4 ± 0.05	62.4 ± 10.6	18.4 ± 6.2	8.5 ± 4.9	81.2 ± 22.8	0.61 ± 0.20
Udox	4	0.2 ± 0.02	49.4 ± 9.8	7.0 ± 2.3	18.6 ± 2.3	33.4 ± 10.4	0.22 ± 0.09
	n = 15						
F probability value		0.019	0.231	0.153	0.527	0.145	0.169
$LSD_{(0.05)}$		0.3	33.9	16.1	20.9	66.2	0.58

[a] Number of pedons in a given classification system.
[b] Standard Error of a class mean for a given soil property within a classification system.
[c] Total number of pedons in a given classification system.
[d] F probability value for the F-test of the classification model fit to the data.
[e] Fisher's F-protected Least Significant Difference for comparing class means for the classification system.

5. Conclusion

Indigenous Buganda farmers classify five major soil classes using knowledge continuously developed locally through long term on-farm soil and crop management observations of polypedons behaviors. Productive and poor soil fertility indicators were colour and texture, and texture and stoniness, respectively, both of which influence management practices. These indicators evaluations corresponded with scientific fertility assessment. Using a combination of polypedon characteristics, key farmers identify *lunnyu* chemical constraint on some non productive *Limyufumyufu* (reddish) upland landscape soils. Arrangement of soils forms two types of toposequences differentiated by altitude at 1200 m. Local soils were associated with six WRB-RSGs and five US Soil Taxonomy suborders. Soil association confirmed information and management recommendations on Phaeozem and Udolls as appropriate for *Liddugavu* soils. The lack of analogous correspondence between other local and international systems' classes suggest the possible availability of differences in quantification scales among the parameters used, purpose, social, economic needs and experience. The indigenous system resulted in greater strength at separating

Table 7

A comparison of classification systems to account for variability in soil properties. The RMSE is the residual mean square error after fitting the respective classification model depicted in Eq. (1) representing the local, WRB RSG, and US Soil Taxonomy Suborders.[a] A lower RMSE value indicates that the classification system accounted for more of the variability in soil properties than the other systems, consequently leaving a small term $\mathcal{E}_{ij}$ of the model (see footnote[a]). A higher R^2 indicates that the classification system accounted for a greater portion of the soil property variability than a lower R^2 value.

Soil properties and slope character	Local		WRB RSG		US Soil Taxonomy Suborders	
	RMSE	R^2 (%)	RMSE	R^2 (%)	RMSE	R^2 (%)
Bulk density	0.0975[b]	25.0	0.1154	20.0	0.0926*	29.0
Sand	24.33	75.0	13.98*	77.0	57.26	34.0
Clay	20.35	84.0	16.34*	70.0	60.54	47.0
Silt	4.288*	61.0	8.576[b]	6.0	5.196	49.0
Ph	0.3748*	57.0	0.5085	48.0	0.5914	32.0
CEC	23.07*	84.0	98.47	36.0	89.57	37.0
Exchangeable Al	0.08188	49.0	0.07113*	54.0	0.1057	34.0
Ca	5.349*	87.0	27.68	41.0	25.34	39.0
Mg	5.099*	75.0	14.89	25.0	13.19	34.0
K	0.1922*	73.0	0.52	43.0	0.4356	37.0
OC	0.3284[b]	23.0	0.3986	15.0	0.2992*	29.0
CEC/clay	683.1*	69.0	1550[b]	7.0	1358	38.0
ECEC	20.2*	84.0	87.19	36.0	79.77	37.0
Al saturation	117.7	30.0	114.3[b]	9.0	135.4[b]	18.0
Base saturation	215.5*	59.0	386.3	7.0	355.9	31.0
ECEC/100 g Clay	0.0474*	71.0	0.1214[b]	11.0	0.1036	36.0
P	342.2*	72.0	952.3	41.0	785.3	35.0
Mg:Ca	0.0897	34.0	0.111[b]	2.0	0.0870*	36.0
Water table	703.4*	74.0	1122	60.0	1152	57.0
Slope gradient	5.714[b]	50.0	12.79[b]	1.0	7.602	30.0
Slope length	9425*	28.0	11,514	15.0	9914[b]	21.0

[a] The classification system with the lowest RMSE for each property is marked with an asterisk (*) indicating that classification system accounted for the most variability in soil properties of the three systems resulting in the lowest RMSE. Each classification is represented using the general model (Eq. (1)).

[b] Soil property affected by external factors as observed by ANOVA greater values for Root Sum of Squares (RSS) than RMSE.

variances of different soil properties and was more homogenous and effective compared to the high-level use of international classification systems. With more detail (eg at series levels), the international systems would be similar to local classification and would provide more information for crop productivity recommendation refinement. Using analytical methods provided by the international systems, linking the best of both indigenous and international systems would likely be ideal options to explore similarities and differences related to soil properties and their management in other parts of the world. Relating soil properties along the toposequence with these classification systems would facilitate the possible integration of knowledge among these systems to bridge the communication gap between farmers and researchers.

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