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Local soil quality assessment of north-central Namibia: integrating farmers' and technical knowledge

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Abstract. Soil degradation is a major threat for farmers of semi-arid north-central Namibia. Soil conservation practices can be promoted by the development of soil quality (SQ) evaluation toolboxes that provide ways to evaluate soil degradation. However, such toolboxes must be adapted to local conditions to reach farmers. Based on qualitative (interviews and soil descriptions) and quantitative (laboratory analyses) data, we developed a set of SQ indicators relevant for our study area that integrates farmers' field experiences (FFEs) and technical knowledge. We suggest using participatory mapping to delineate soil units (*Oshikwanyama* soil units, KwSUs) based on FFEs, which highlight mostly soil properties that integrate long-term productivity and soil hydrological characteristics (i.e. *internal SQ*). The actual SQ evaluation of a location depends on the KwSU described and is thereafter assessed by field soil texture (i.e. *chemical fertility potential*) and by soil colour shade (i.e. *SOC status*). This three-level information aims to reveal SQ improvement potential by comparing, for any location, (a) estimated clay content against median clay content (specific to KwSU) and (b) soil organic status against calculated optimal values (depends on clay content). The combination of farmers' and technical assessment cumulates advantages of both systems of knowledge, namely the integrated long-term knowledge of the farmers and a short- and medium-term SQ status assessment. The toolbox is a suggestion for evaluating SQ and aims to help farmers, rural development planners and researchers from all fields of studies understanding SQ issues in north-central Namibia. This suggested SQ toolbox is adapted to a restricted area of north-central Namibia, but similar tools could be developed in most areas where small-scale agriculture prevails.

1 Introduction

Soil degradation is a major cause of marginal agricultural productivity and food insecurity in sub-Saharan Africa (FAO and ITPS, 2015). In north-central Namibia (NCN), increasing land tenure security through the Communal Land Reform Act (Government of the Republic of Namibia, 2002) aims to increase investment in land and improve soil quality (SQ) in communal areas (Adams et al., 1999). The state of environmental and soil degradation remains, however, unclear in the area (Newsham and Thomas, 2011). The selection of SQ indicators adapted to local conditions thus represents an important step towards sustainable soil management practices (Ditzler and Tugel, 2002). We consider that the SQ is a function of soil properties, intended land use, and management possibilities and goals (Andrews et al., 2004). This definition favours a use-dependent approach, which is in line with farmers' and local administration's needs. A bottom-up approach is vital as farmers are the key actors for developing and implementing soil management policy (Mairura et al., 2007).

1.1 Technical soil quality assessment

Many SQ indicators have been developed over the past decades (e.g. Mueller et al., 2010; Wienhold et al., 2004) and the need to adapt SQ indicators to local conditions was acknowledged very early (Granatstein and Bezdicek, 1992; Nicholls et al., 2004). Most of the indicators require measuring physical, chemical, and/or biological soil characteristics that need laboratory measurements, specific technical material, and/or experts' knowledge (Table 1). Therefore, most

SQ indicators cannot be used directly by farmers (Nicholls et al., 2004), which is particularly problematic in low-income regions due to limited availability of laboratory and experts' services (Musinguzi et al., 2015), like in NCN.

Many SQ indicators are based on yield data collected during 2 (e.g. Andrews et al., 2004) or even only 1 year (Hillyer et al., 2006). With such short records, it is impossible to consider how inter-annual climatic variability affects subsistence farmers, who aim to reduce the risk of harvest failure (Graef and Haigis, 2001). Therefore, most SQ indicators developed using yield data collected during periods too short to fully reflect climatic constraints to production are of limited relevance in areas with high inter-annual rainfall variability. Considering the shortcomings of some SQ indicators, it is therefore imperative to develop "cost-effective and user-friendly tools" (Musinguzi et al., 2015) to evaluate SQ based on land users' requirements.

1.2 Farmers' field experiences

Farmers' field experiences (FFEs) include all farmer-based soil fertility assessment techniques (Musinguzi et al., 2015). This terminology is preferred over "indigenous knowledge" or "local knowledge" because it refers to a clearly defined group of land users, all people involved in farming (farm owners, workers, children). FFEs are essential as an entry point for outsiders to understand local land use practices and local soil variability (Mairura et al., 2007; Ramisch, 2004). Many studies incorporate FFEs to select the most appropriate properties to use as SQ indicators (Musinguzi et al., 2015; Nicholls et al., 2004). The resulting local SQ indicators cover broader agronomic properties than technical SQ indicators as they may account for economic issues (Warren, 1991), long-term productivity, or risk management practices (Graef and Haigis, 2001), for example dealing with rainfall variability.

Aside from improving the relevance of SQ indicators, the use of FFEs involves farmers in the evolution of agricultural practices (Ditzler and Tugel, 2002; Mairura et al., 2007; Warren, 1991). However, FFEs can be inaccurate, biased by social context (Gray and Morant, 2003) and resilient against environmental and socio-economic changes (Briggs and Moyo, 2012). Technical knowledge, on the other hand, is valuable for its level of standardisation, which allows for spatial and temporal comparisons and facilitates international communication (Niemeijer and Mazzucato, 2003). Scientists should therefore integrate both knowledge systems to provide tools connecting FFEs and technical knowledge (Lima et al., 2011). Methodologies to select indicators for SQ based on the integration of FFEs with technical knowledge have been developed and discussed, and yielded promising results (Barrios et al., 2006). Most studies concerning integrated soil knowledge showed the parallels between technical and farmers assessment, but only a few developed local SQ toolboxes to fully evaluate the SQ conditions (Table 2).

Farmers' knowledge of environmental factors and SQ in NCN has been already collected and discussed in various studies (Hillyer et al., 2006; Rigourd et al., 1999; Verlinden and Dayot, 2005), but there is still "a lack of understanding [of local land classification system] by scientists or extensionists" (Verlinden and Dayot, 2005). A relatively high number of "indigenous land units" were described based on vegetation, landforms, and/or soils (Hillyer et al., 2006; Verlinden and Dayot, 2005). These studies present an interesting collection of FFEs, but none was developed into locally adapted SQ indicators. Yet, such indicators are essential to allow researchers and farmers to assess SQ at a specific location and time period relevant for agricultural cycles (Barrios et al., 2006). Based on qualitative (semi-structured interviews, soil profile descriptions) and quantitative data (field soil profile descriptions, laboratory measurements), we suggest a set of SQ indicators relevant for our study area that integrate FFEs and technical assessment. Following Barrios and Coutinho (2012) these indicators must (a) be practical and easy to use under field conditions; (b) be easy to interpret; (c) be relatively economical; (d) be sufficiently sensitive to highlight the changes under study; (e) integrate physical, chemical, and biological characteristics and processes; (f) be useful for estimating all relevant soil properties; and (g) give good correlations between plant productivity and soil health. We aim to verify the benefits of using FFEs for soil quality assessment, as the development of SQ estimation tools is vital for SQ management in areas where small-scale family agriculture represents a large proportion of land use.

2 Methods

2.1 Study area

In NCN, the climate is semi-arid subtropical with a rainy season from December to April. Average annual precipitation ranges from 350 to 550 mm with large inter- and intra-annual variability (Mendelsohn et al., 2000). In Ondangwa, the annual rainfall during the period 1959–1973 ranged from 200 to 1039 mm with an average of 495 mm (Verlinden et al., 2006). Crop production failure because of rain quantity and distribution occurs every second year (Keyler, 1995). The area lies over the Owambo sedimentary basin with the upper part constituted of aeolian sands redistributed throughout the Quaternary period (Miller et al., 2010). The region is characterised by the endorheic Cuvelai drainage basin and the north-eastern Kalahari woodlands or Kalahari Sandveld (Fig. 1; Mendelsohn et al., 2000).

Non-commercial agricultural activities are the most important land use in NCN (Mendelsohn et al., 2000). Around 120 000 households farm in the region, mostly cultivating small-scale (1–4 ha) rainfed pearl millet (Pennisetum glaucum; Mendelsohn et al., 2013). Average yields of millet are very low, (220 kg ha^{-1} on average in the Ohangwena region), highly variable from year to year, and from household to

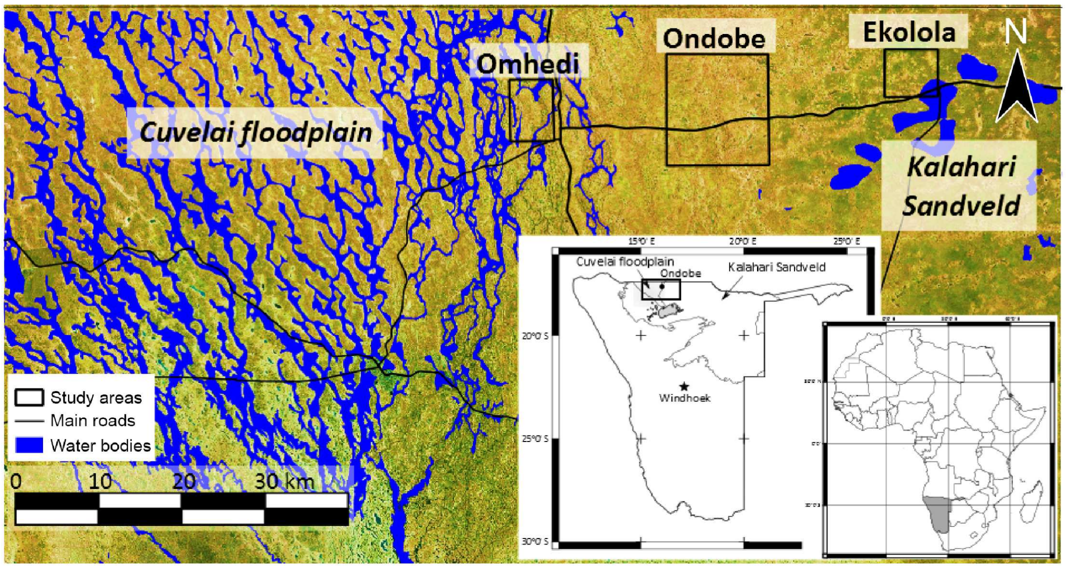


Figure 1. Overview of southern Africa and satellite view (GoogleEarth; with enhanced colour saturation) of north-central Namibia with the Cuvelai floodplain (northwest), the Kalahari Sandveld (northeast) and location of the three study areas (Omhedi, Ondobe, and Ekolola). Vegetation appears in green, bare soil appears in orange, water bodies in blue (Digital Atlas of Namibia).

Table 1. Frequently used soil properties that may be used as field soil quality (SQ) indicators, possible field measurements techniques and challenges for local users (adapted from Wienhold et al., 2004).

	Soil properties	Field measurements	Challenges for local use
Physical	Texture	Texture-by-feel method,	Subjectivity, expert knowledge
		Kruedener test	Specific material
	Depth of topsoil	Observation	Expert knowledge
	Bulk density	Weighing scale	Dry soil required, specific material
	Water infiltration rate	Infiltrometer	Time consuming, specific material
	Water-holding capacity	Estimation from texture	Subjectivity, Specific material (see above)
Chemical	Organic C	Estimation from colour	Approximation, Colour chart
	Total N	Test kit	Specific material
	pH	pH-Hellige, sensors	Specific material
	Electrical conductivity	Probe, sensors	Specific material
	Extractable N, P, K	Test kit	Specific material
Biological	Microbial biomass C and N	Unknown	
	Potentially mineralisable N	Test kit	Specific material
	Soil respiration	Test kit	Specific material

household, due to low soil fertility, low nutrient supply, irregular rainfall, and pests (Central Bureau of Statistics, 2003; Mendelsohn et al., 2000; Rukandema et al., 2009).

Three groups of villages in the Ohangwena region were selected (Omhedi, Ondobe, Ekolola; Fig. 1) based on dialect homogeneity (*Oshikwanyama*) and environmental heterogeneity (vegetation, soils). These villages lie on a west–east climatic, edaphic, and land-use gradient with a mosaic pattern of soil and vegetation (Mendelsohn et al., 2013). The annual rainfall quantity, the proportion of deep sandy soils, and forest cover increase eastwards. The westernmost area (Omhedi) is largely influenced by the active drainage system of the Cuvelai River, which creates a network of water channels (called locally *iishana*) that significantly influenced soil development (fluvial deposits, salinisation). Ondobe is located between the drainage basin in the west and the Kalahari Sandveld in the east. Further east, Ekolola is characterised by the Kalahari Sandveld, which is dominated by deep loose sand deposits (Mendelsohn et al., 2000). All three areas were recently settled by immigrants from Angola, mostly during the 1910s–1920s, but population density increased more dramatically in the westernmost areas due to water accessibility (Kreike, 2004).

Table 2. Selection of studies suggesting series of local soil quality indicators. SOM: soil organic matter; SOC: soil organic carbon.

References	Region	Local soil quality indicators	Toolbox for SQ evaluation
Ditzler and Tugel (2002)	Various climates; USA	Compaction, drainage/infiltration, nutrient-holding capacity, salinity, soil organisms, earthworms, residue decomposition, crop vigour.	Farmers' evaluation; Qualitative and subjective evaluation
Gruver and Weil (2007)	Humid subtropical; Acrisols, Luvisols, Lixisols; USA	SOM, crop performance, soil water availability, erosion history.	Soil C and structure evaluation; No method suggested
Lima et al. (2011)	Humid subtropical; Luvisols, Lixisols; Southern Brazil	Earthworms, soil colour, yield, spontaneous vegetation, SOM, root development, soil friability, rice plant development.	No method suggested
Mairura et al. (2007)	Subtropical highland; Nitosols, Ferralsols; Central Kenya	Crop yield, soil colour, texture and tilth, soil macro fauna, the abundance or diversity of weed species.	No method suggested
Murage et al. (2000)	Subtropical highland; Nitisols; Central Kenya	Crop performance, soil tilth, moisture and colour, presence of weeds and soil invertebrates.	SOM or $KMnO_4$-oxidisable C; Laboratory measurements
Musinguzi et al. (2015)	Tropical savanna; Ferrralsols; Central Uganda		FFE and scientific quantitative rating with SOC.; Laboratory measurement
Nicholls et al. (2004)	Temperate; North California	Structure, compaction, soil depth, status of residues, colour, odour, SOM, water retention, soil cover, erosion, presence of invertebrates, microbiological activity.	Farmers' evaluation; Qualitative and subjective evaluation

2.2 Assessment of farmers' field experiences

From February 2013 to June 2014, 46 farms were visited, in which 87 semi-structured interviews were conducted to collect FFE, mainly in Ondobe (52 interviews held on 22 farms). The farmers who showed during the first interview broad soil and agricultural knowledge and openness to discussion were visited several times. Mostly people above the age of 50 (75 % of interview time) were surveyed because of their availability to talk and the knowledge they wished to share, typically elderly men (49 % of total interview time). Most interviews were held in the house, providing conceptual references, but some were held in the fields or in front of soil pits, providing locational references (Oudwater and Martin, 2003). Questions aimed to generate information on the types of soil that are cultivated and the characteristics that differentiate them. By "*Oshikwanyama* soil units" (KwSU) we refer to the soil units that are distinguished by the farmers by sight, touch, experienced yields, or others (following the definition of Indigenous Land Units suggested by Verlinden and Dayot, 2005).

All the interviews were held in *Oshikwanyama* and audio-recorded. Direct interpretation was performed by, mostly, Ms Martha Shekupe Fillemon (20). The English interpretation was afterwards completely transcribed. Parts of the interviews were transcribed in *Oshikwanyama* and translated into English by non-professional local translators. The interviews were annotated using MaxQDA 11 (VERBI GmbH, 2014) to facilitate the qualitative data analysis. The annotation system included KwSU names (*omutunda*, *omufitu*, *elondo*, *ehenene*, *ehenge*) and "soil quality". The latter annotation was used to select quotes in which a certain location or a specific KwSU was characterised with regard to the suitability for pearl millet cultivation.

Over the total number of informants (46), we calculated the proportion of them who mentioned each KwSU. Afterwards we associated these interviews with specific soil properties, which are finally grouped into five frequently mentioned properties: hardness, soil hydrology, productivity potential, soil colour shade, and soil colour hue.

2.3 Technical knowledge collection

In cultivated fields, 29 soil profiles were described, mostly in Ondobe ($n = 22$), but also in Omhedi ($n = 3$) and Ekolola ($n = 4$). The 29 soil profiles were classified as *omutunda* ($n = 15$), *ehenge* ($n = 4$), *omufitu* ($n = 4$), *elondo* ($n = 3$), or *ehenene* ($n = 3$) by the farmers. For the analysis, we concentrated on *omutunda* given its high agricultural value and its prevalence in the cultivated area.

2.3.1 Field soil profile description and sampling

The *Guidelines for soil description* (FAO, Land and Water Division, 2006) were used for standardised soil profile description. In the context of this study, we only discuss the horizon limits, clod consistence when dry, bulk density, and moist colour down to 40 cm, as they are best suited to the objective of developing an SQ tool that could be used by various land users, who have not the resources and expertise to go through a full soil description. Soil colour was estimated in the field using the Munsell soil colour chart on a moist sample for each horizon. Soil colour provides information about soil formation processes (e.g. leaching, clay alteration) and soil organic carbon content (SOC) (Viscarra Rossel et al., 2006). The consistence when dry was evaluated by crushing a clod of soil between the fingers. This property informs on the amount and type of clay, SOC, and soil particle organisation (FAO, Land and Water Division, 2006).

Two 100 cm^3 sampling rings were collected from each described horizon and homogenised to create a single mixed sample per horizon. Dried samples were weighted to calculate bulk density, sieved (2 mm), and used for further analysis.

2.3.2 Laboratory analyses

Soil texture is the most important soil characteristic with a direct influence on most soil processes and properties (Vos et al., 2016). It was calculated using laser diffraction (Malvern Mastersizer, 2000) that measures volumetric particle size distribution. Prior to measurement, samples were shaken overnight in water and dispersed with 9 J mL^{-1} ultrasonic energy. The particle size class < 20 µm was considered the active mineral fraction (Feng et al., 2013).

SOC plays an important function as adsorbing material and is often used to evaluate SQ (Musinguzi et al., 2015). SOC saturation (C saturation) is defined as "the ratio of the present topsoil total [SOC] level relative to the same soil in its undisturbed [...] state" (Sanchez et al., 2003). Various models have been developed to evaluate the SOC of a C-saturated soil (Six et al., 2002; Zinn et al., 2007), for example based on the proportion of the < 20 µm fraction (Feng et al., 2013). We chose the model of Feng et al. (2013) because it is based on a large review of studies, and developed for soils with predominantly 1 : 1 clay minerals, common in the tropics.

SOC and inorganic carbon contents were determined with a LECO® analyser (RC-612). Soil electrical conductivity was measured in 1 : 5 (soil–water) suspension and pH_{CaCl_2} in a 1 : 5 (soil–0.01 M [$CaCl_2$]).

Cation exchange capacity and base saturation values indicate the cation reservoir of a soil and are important characteristics to evaluate the ability of a soil to sustain plant growth. Neither of these properties were measured in this study because the presence of calcium carbonates (secondary precipitations observed in various soil profiles) and soluble salt (high EC in *ehenene*, mostly NaCl) strongly influences the measurements (Sparks et al., 1996), which makes results very difficult to use for comparison, especially considering the low expected values due to low cation exchanging materials (mostly clay and organic matter). Instead, we used robust and sufficiently accurate methods as a proxy for cation exchange capacity (soil organic carbon and the < 20 µm fraction content) and for base saturation (soil pH) (Blume et al., 2011).

Known to be limiting nutrients in most agricultural land and in particular in sub-Saharan Africa, nitrogen and phosphor availability is most likely significant for plant growth. However, these values were not included in the current study given that it aims at enlightening longer-term soil fertility discussion, while these nutrients are more related to soil short-term fertilisation.

3 Results and discussion

3.1 Oshikwanyama soil units: a homogeneous body of soil knowledge

Like in many areas worldwide (Barrera-Bassols and Zinck, 2003), farmers of NCN classify soil potential (mostly with regards to pearl millet cultivation) using several properties. In cultivated areas, five *Oshikwanyama* soil units (KwSUs) were frequently described: *omutunda*, *ehenge*, *ehenene*, *omufitu*, and *elondo* (Table 3). Knowledge and descriptions of these local soils were largely shared among the interviewed population, and we did not observe differences based on gender, generations, or studied eco-regions. Some criteria used in the FFE were general (e.g. productivity potential), while others were more specific (e.g. soil colour shade and hardness, waterlogging risk; Table 3).

KwSUs' names define specific objects in the landscape. For example, the suffix *-tunda* in *omutunda* means "something on a hill" (TN, 65, Ekolola)[1] and *omufitu* refers to woodlands located close to villages ("a land with many bushes and trees"; KS, 60, Ondobe). These names are instilled in the everyday language, which explains the homogeneity of the soil-related vocabulary among the population and suggests that labelling of places (with KwSUs) changes little over time.

We calculated the proportion of informants mentioning specific characteristics for each KwSU to highlight the most prominent characteristics, per KwSU and based on total number of informants mentioning any of the five KwSUs (Table 3). The most frequently used properties to describe KwSUs were related to soil hardness (63.5 %), productivity potential (57.7 %), soil hydrology (43.8 %), and soil colour shade (38.0 %). The morphological properties (colour shade, consistence when dry) referred mostly to topsoil layers as farmers indicated characteristics that were discussed during transect walks. The consistence when dry, or the concept of hardness, is evaluated under dry conditions, which impacts importantly on the difficulty of ploughing (performed early in the rainy season). As observed by Verlinden and Dayot (2005), the predominance of each characteristic varies depending on the unit described. For example, hardness/softness is a prominent characteristic to describe *omutunda* and *omufitu* (used by 72.2 and 70.8 %), while soil hydrological characteristics were important to describe *ehenge* (68.8 %).

The high frequency of interviews mentioning productivity (57.7 %; Table 3) might have been influenced by the aim of the study and frequent questions concerning productivity by the researchers. Farmers considered unanimously *omutunda* to be the most fertile soil and agreed that pearl millet productivity is strongly limited in *ehenene* (Table 4). Productivity in *elondo*, *ehenge*, and *omufitu* did not reach a consensus. The productivity of these KwSUs may largely depend on factors less dependent on soil (rainfall, fertiliser availability). Notably, *ehenge* is good in poor rainfall years, but poor in good rainfall years (Table 4).

Each KwSU is characterised by a series of indicators. A selection of these indicators is illustrated in Table 4. However, it should be kept in mind that these descriptions are only a summary of the characteristics mentioned by the informants.

The productivity of soils depends not only on internal soil properties and processes (waterlogging risks, landscape position) or climatic conditions, but also on management strategies (e.g. fertiliser application). The effect of management was acknowledged by farmers who explained that KwSUs do not accurately represent the actual SQ (e.g. "*omutunda* is not always fertile, it needs to be dark"). Farmers estimated the actual SQ of a location also based on crop health, soil consistence when dry, soil colour shades ("needs to be dark"), and hardness ("millet likes hard soil"). We discuss the technical significance of these properties below.

Soil hydrological properties were mentioned frequently to describe KwSUs. These properties need to be understood in relation to rainfall variability (Table 4). Productivity of *omutunda* drops during droughts ("pearl millet is burnt"), while it increases in *ehenge* ("*ehenge* is good in a year with lack of rain"). Therefore *ehenge* secures minimum harvest during poor rainfall years, which is essential for farmers relying on yearly food production (Graef and Haigis, 2001). Conversely, *ehenge* undergoes waterlogging during good rainfall years ("[*ehenge*] used to be full of water"), which strongly limits pearl millet growth. These soil hydrological characteristics are difficult to assess during standard field surveys and the integration of these characteristics in KwSU definitions is crucial for SQ evaluation as soil water availability is the most significant limitation in semi-arid regions (McDonagh and Hillyer, 2003).

3.2 Technical analysis of farmers' field experiences

Results from technical analyses are summarised in Table 5, in which the soil characteristics are calculated for the layers

[1] To keep the informants anonymous, we used a code that indicates (1) a two-letter name, (2) the farmer's age, and (3) the study area of the farm.

Table 3. List of farmers' field experience (FFE) characteristics used to describe each KwSU, with the number of informants mentioning each KwSU (n) and the proportion of informants mentioning each characteristic (in relation to n). Values are only indicative as the data collection method was not adapted for quantitative analyses.

KwSUs	Number of informants mentioning the KwSU ($n=46$)	Hardness/ softness (in %)	Soil hydrology (in %)	Productivity potential (in %)	Soil colour shade (in %)	Soil colour hue (in %)
Omutunda	36	72.2	36.1	66.7	33.3	0.0
Omufitu	24	70.8	41.7	66.7	50.0	12.5
Ehenge	32	53.1	68.8	43.8	25.0	6.3
Ehenene	29	62.1	51.7	51.7	41.4	0.0
Elondo	16	56.3	0	62.5	50.0	56.3
Average		63.5	43.8	57.7	38.0	10.2

Table 4. List of the KwSUs identified and the most frequently used farmers' field experiences characteristics. GRY, good rainfall year; PRY, poor rainfall year.

	Soil type attributes and local soil indicator			Suitability for pearl millet
	Soil hydrology	Consistence when dry	Colour shade	
Omutunda	No waterlogging; high water retention; Dries out quickly	Hard	Dark/black	Very good (GRY) to limited (PRY)
Omufitu	No waterlogging; low water retention	Loose	Dark or light	Poor
Elondo	No waterlogging	Intermediate	Intermediate	Good (GRY)
Ehenge	Waterlogging risk; dries out very slowly	Loose	Light/white	Poor (GRY) to good (PRY)
Ehenene	Waterlogging risk; low water retention; dries out quickly	Hard	Light/white	Very poor

5–15 cm and 25–35 cm using an arithmetic mean weighted by the depth of each horizon. All described soils have very low organic carbon (< 5 mg OC g^{-1}) and high sand (> 70 % in the 5–15 cm layer) content. *Omutunda* has a larger proportion of < 20 µm fraction (6.5 to 22.8 % in the layer 5–15 cm) and more SOC (1.4 to 4.4 mg OC g^{-1}) than all other studied KwSUs. Furthermore, slightly alkaline conditions (Table 5) indicate a high base saturation. All these characteristics suggest the higher potential of *omutunda* to provide nutrients, coming from any sources, compared to the other KwSUs. This capacity is hereafter called chemical fertility. A slightly more acid soil solution, a smaller amount of < 20 µm particles, and SOC in *elondo* indicate lower chemical fertility. The proportion of < 20 µm fraction in *ehenene* can be high (up to 16.4 %), but high pH_{water} (up to 10.1; results not shown) restricts plant growth. All *ehenge* and *omufitu* described have a very low proportion of the < 20 µm fraction (< 6.5 %) down to 40 cm. Our laboratory results therefore support the farmers' assessment pointing to the greater chemical fertility potential of *omutunda*.

3.3 International classification: the WRB

Only one diagnostic horizon and a limited number of diagnostic properties or materials could be described following the WRB (IUSS Working Group WRB, 2014). The soil texture is the main characteristic used to describe the Reference Soil Group (RSG). Indeed, soil profiles without layers finer than Loamy sand were categorised as Arenosols (17), and the others as Regosols (11). *Omufitu* and *elondo* are exclusively Arenosols, while the other KwSUs include soils from both RSGs, and *ehenene* and *omutunda* are mainly Regosols (Table 6).

3.4 *Omutunda*: uniform or plural?

FFEs and our technical analyses indicate a large diversity in *omutunda* soils. The diversity is expressed in FFEs, as not all *omutunda* are similar and as their productivity varies ("The soil [*omutunda*] … inside the country [floodplain] breastfeeds on water streams … it is hard not like ours."). Technical analyses support this observation as some measured properties show a large variability, like a large coefficient of variation (proportion of the < 20 µm fraction and TOC) (Table 7) or a broad spectrum of pH_{CaCl_2} around 7 (from 4.7 to 7.7 in the topsoil). Given the high proportion of *omutunda*

Table 5. Chemical and physical characteristics of topsoil (5–15 cm) and subsoil (25–35 cm) layers of the studied soil profiles. Quantitative data are represented by average values and colour hue by the most frequent value.

KwSU	Profile	Area	TOC mg OC g^{-1}		< 20 µm (%)		Sand (%)		pH_{CaCl_2}		EC (µS m^{-1})		Moist colour	
			Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top
Ehenene	Ondobe	EFIDI-01	0.7	0.6	2.3	5.7	96.7	93.5	8	NA	2.1	7.2	2.5Y 7/3	2.5Y 8/3
	Ondobe	NDOB-02	1.6	1.8	10.9	16.3	88.4	82.6	6	NA	1.4	3.9	10YR 4/2	10YR 3/2
	Ondobe	NDOB-18	1.3	0.8	7.5	16.4	90.3	81.4	6.7	7.8	0.7	1.1	2.5Y 5/2	2.5Y 6/2
Ehenge	Ondobe	EFIDI-02	1	0.6	2.8	2.6	97.1	96.9	4.8	5.2	0.1	0.2	10YR 6/3	10YR 6/3
	Ondobe	NDOB-13	1.1	0.9	4.4	5.5	94.1	92.7	4.6	6	0.1	0.2	NA	NA
	Ondobe	NDOB-19	1.5	NA	3.3	5.3	95.2	93.2	4.8	NA	0.1	NA	10YR 4/3	7.5YR 5/4
	Ondobe	OILYA-02	1.1	0.8	4	2.1	95.4	97.5	4.6	4.5	0.1	0.1	10YR 6/3	10YR 8/2
Elondo	Omhedi	OMDI-03	NA	NA	6.5	12	91.2	85.5	6.6	NA	0.5	NA	10YR 3/2	10YR 2.5/2
	Ondobe	ETOPE-01	1.2	1.4	4.7	6.9	94.4	92.2	5	NA	0.1	0.1	7.5YR 4/6	7.5YR 4/6
	Ondobe	OHNG-01	1.8	1.8	7.2	10.2	89.8	86	5.2	4.6	0.2	0.1	7.5YR 4/3	5YR 4/4
Omufitu	Ondobe	NDOB-01	1.5	1.1	4.3	4.7	94.6	94.5	6	NA	0.2	0.2	7.5YR 4/4	5YR 3/4
	Ondobe	NDOB-08	1	1	4.2	3.9	94.7	94.9	5.2	5.2	0.1	0.1	7.5YR 4/4	7.5YR 4/4
	Ondobe	NDOB-20	1.9	NA	2.8	2.9	96.1	97.1	5	NA	0.1	NA	10YR 3/3	7.5YR 4/3
	Ekolola	HNDIB-02	1.3	1.4	2.9	4.4	96.3	94.3	4.8	4.7	0.1	0.1	10YR 4/3	10YR 4/2
Omutunda	Omhedi	OMDI-01	3.2	2.9	22.8	29.8	71.3	65.3	7.7	7.7	1.2	1.5	10YR 4/1	10YR 4/1
	Omhedi	OMDI-02	4.4	2.3	9.2	19.3	86.9	77.5	6	6.4	0.5	0.6	10YR 3/2	10YR 4/1.5
	Ondobe	EFIDI-04	2	1.4	14	12.5	83.1	86	6.8	6.7	0.3	0.2	10YR 5/2	10YR 3/2
	Ondobe	EFIDI-06	1.6	1.7	16	18.5	82.1	79.3	7.4	7.2	0.8	0.6	10YR 3/3	10YR 3/2
	Ondobe	NDOB-03	2.6	1.9	24.8	29.1	72.2	67.6	6.5	7.2	0.5	0.8	7.5YR 4/1	2.5Y 4/1
	Ondobe	NDOB-12	1.6	NA	7.3	14.2	90.9	84	5.1	NA	0.2	NA	10YR 4/1.5	10YR 5/2
	Ondobe	NDOB-14	1.4	1.2	10.6	14.3	86.4	82.5	7.7	7.7	0.9	1	10YR 4.5/2	10YR 4/2
	Ondobe	NDOB-15	2.1	NA	8.2	12.4	90.3	86.6	7.2	NA	0.9	NA	10YR 4/1	10YR 5/2
	Ondobe	NDOB-16	2.9	1.9	8.1	11.5	89.6	85.7	6.8	6.4	0.9	0.4	10YR 4/2	10YR 3.5/2
	Ondobe	NDOB-17	2.6	NA	6.5	6.6	91.3	91.2	7.7	7.7	1	1.1	10YR 3.5/2	10YR 3.5/2
	Ondobe	OILYA-01	5	2.4	19	22.2	77	75	7.2	7.4	1	1.2	10YR 4/1	10YR 4/2
	Ondobe	OILYA-04	2.1	2.2	9.9	21.4	87.4	75.9	6.6	6.3	0.5	0.5	2.5Y 5/2	10YR 4/1
	Ekolola	EKOL-01	1.7	2	7.2	10.4	90.5	86.6	4.7	5.2	0.2	0.2	10YR 4.5/4	10YR 4/3
	Ekolola	HNDIB-01	2.9	NA	7.9	12.2	89.7	85.7	5.5	NA	0.4	NA	10YR 4/2	7.5YR-10YR 4/3
	Ekolola	NGYO-01	1.6	1.6	4.3	10.3	93.9	86.7	5	5	0.2	0.2	10YR 5/2	10YR 4/2

described in Ondobe ($n = 10$) in comparison to the other areas (Omhedi $n = 2$, Ekolola $n = 3$), the statistics presented in Table 7 are skewed towards the characteristics of *omutunda* in Ondobe. This does not jeopardise the substance of these results given the diversity found around Ondobe (transition from the floodplain environment to Kalahari woodlands).

From the FFE perspective, *omutunda* was mostly defined by excluding areas not suitable for pearl millet because (i) it does not experience waterlogging (hypoxic conditions); (ii) it does not have loose sand topsoil (very poor chemical fertility); and (iii) it does not have very shallow hard soil layer (limits water storage capacity and restrict workability). Pearl millet can be cultivated on various soils (Baligar and Fageria, 2007), which contributes to the large variability of soils considered suitable for its cultivation. Temporal variation of SQ was acknowledged in FFEs and various degrees of degradation (e.g. organic and nutrients depletion, salinisation) lead to variability in SQ of *omutunda* at a specific time. Management practices (amount of fertiliser, ploughing) also contribute to adding some variability. There were small differences depending on the area of study and the surrounding environment (Table 5). *Omutunda* described in Ekolola (Kalahari Sandveld environment) has a coarser texture compared to the *omutunda* described in Omhedi and Ondobe (floodplain; Table 5). These differences were expected as FFEs were constructed based on comparative observations (e.g. "harder than") and therefore influenced by the surrounding environment (Birmingham, 2003; Niemeijer and Mazzucato, 2003).

The variability described in the various studied *omutunda* illustrates the need to develop tools for standardisation. This would help to avoid classifying soils that should not be compared directly, but that need to be considered as various entities that show similar features.

3.5 Development of a soil quality evaluation toolbox

3.5.1 Importance of a soil quality evaluation toolbox

We have shown that KwSUs represent locations in the fields with specific soil characteristics and provide information about their potential productivity. This notably includes soil hydraulic characteristics. Clearly, the KwSU knowledge is land use orientated (e.g. suitability for pearl millet, workability), adapted to local conditions (rainfall variability), and represents the local soil productivity potential. Farmers also include crop health, soil consistence when dry, and colour shade to evaluate the SQ of a specific location (Sect. 3.1). We have also shown that each KwSU includes a large variety of soil properties (especially *omutunda*) for which the SQ for pearl millet production differs. To estimate the SQ, it is therefore important to standardise the assessment of the SQ at a specific location and time. This would allow a comparison based on, for example, agricultural or climatic cycles or management techniques. Technical soil characterisation (e.g. soil texture, colour) proved to be suitable for standardising SQ assessment in other locations (Niemeijer and Mazzucato, 2003).

The *World Reference Base for Soil Resources* (IUSS Working Group WRB, 2014) is used to draw the Namibian soil map (Atlas of Namibia Project, 2002). This classification is mainly orientated towards representing "primary pedogenetic process[es]". Therefore, the use of this classification is not relevant for highlighting SQ differences at a small scale in a region with poorly developed soil profiles given the low prevalence of diagnostic properties and horizons.

We will first show the meanings of the soil characteristics used by the farmers to evaluate SQ and link these with soil technical analyses. Based on these links, we will suggest ways to use this knowledge and to standardise the SQ assessment.

3.5.2 Important characteristics for field soil quality evaluation

Soils with a high proportion of $< 20\,\mu m$ particles are harder in dry conditions than soils with coarser texture (Welch's F $(3, 55.3) = 28.46$, p-value < 0.01; Table 2), results that are supported by specific studies (Harper and Gilkes, 2004; Rawls and Pachepsky, 2002). These fine-textured soils have a larger area of active surfaces, which plays an important role in fixing SOC and nutrients (Feng et al., 2013). Through talking about hardness, farmers indirectly refer to the proportion of fine soil particles (Osbahr and Allan, 2003). It therefore indicates a major property contributing to fertility. The proportion of $< 20\,\mu m$ fraction content in soils was increased through homestead shifting (clay-brick remains) or mining of riverbeds (Kreike, 2013). Sand content ($> 63\,\mu m$) can be used to estimate the proportion of $< 20\,\mu m$ fraction given the good correlation between the proportion of these two classes (p-value < 0.01, $R^2 = 0.98$). We refer to it as the *potential chemical fertility* because it requires appropriate fertilisation to fully achieve maximum yields.

Soil colour shade is correlated with the SOC of soils (Spearman's rank correlation rho $(-6.68, 108) = -0.54$, p-value < 0.01; Table 2). FFEs acknowledge the importance of "soil darkness" to estimate SQ. SOC is used as an index of SQ in many studies because of sensitivity to management practices (Barrios and Trejo, 2003; Lima et al., 2011; Musinguzi et al., 2015; Osbahr and Allan, 2003). Sanchez et al. (2003) used the concept of C saturation to evaluate the soil fertility capability, in which a C saturation above 80 % indicated good soil conditions. For various textural classes, SOC of undisturbed soils was calculated using Feng et al. (2013), and the colour shade value related to it was estimated using Blume et al. (2011, p. 51) (Table 8).

Table 6. Soil classification using World Reference Base for Soil Resources (IUSS Working Group WRB, 2014) and soil quality evaluation using the suggested toolbox.

KwSU	Profile	WRB (2014)	SQ evaluation
Ehenene	EFIDI-01	Hypereutric Sodic Protosalic Protoargic Arenosol (Alcalic Aridic)	Ehenene poor −
	NDOB-02	Hypereutric Sodic Protosalic Regosol (Epigeoabruptic Arenic Epiprotocalcic Aridic)	Ehenene very poor +
	NDOB-18	Hypereutric Sodic Regosol (Geoabruptic Arenic Aridic)	Ehenene poor 0
Ehenge	EFIDI-02	Eutric Sodic Protoargic Arenosol (Aric Aridic)	Ehenge poor 0
	NDOB-13	Eutric Sodic Protoargic Arenosol (Aridic)	Ehenge poor +
	NDOB-19	Dystric Sodic Rubic Protoargic Arenosol (Aridic)	Ehenge poor +
	OILYA-02	Eutric Sodic Protoargic Arenosol (Stagnic Aridic)	Ehenge poor 0
Elondo	OMDI-03	Eutric Protic Arenosol (Ochric)	Elondo degraded +
	ETOPE-01	Eutric Sodic Rubic Sideralic Arenosol (Alumic Aridic)	Elondo degraded 0
	OHNG-01	Dystric Chromic Sideralic Arenosol (Alumic Aridic)	Elondo good 0
Omufitu	NDOB-01	Eutric Chromic Sideralic Arenosol (Aric Aridic)	*Omufitu* poor 0
	NDOB-20	Eutric Rubic Arenosol (Alumic Aridic) Eutric Rubic Arenosol (Alumic Aridic)	*Omufitu* poor 0
	HNDIB-02	Dystric Protic Arenosol (Alumic Aric Aridic)	*Omufitu* poor 0
	OMDI-01	Petric Calcisol (Loamic Hypocalcic Ochric)	*Omutunda* very good 0
Omutunda	OMDI-02	Eutric Protic Regosol (Loamic Aric Ochric)	*Omutunda* good +
	EFIDI-04	Hypereutric Protic Regosol (Arenic Aric)	*Omutunda* good −
	EFIDI-06	Hypereutric Regosol (Epigeoabruptic Arenic Aridic)	*Omutunda* good +
	NDOB-03	Hypereutric Regosol (Epigeoabruptic Loamic Ochric)	*Omutunda* very good 0
	NDOB-14	Calcaric Regosol (Loamic Ochric)	*Omutunda* good 0
	NDOB-15	Hypereutric Sodic Protosalic Protoargic Arenosol (Aridic)	*Omutunda* degraded 0
	NDOB-16	Eutric Protic Regosols (Alumic Ochric)	*Omutunda* good 0
	NDOB-17	Hypereutric Protic Arenosol (Aric Ochric)	*Omutunda* degraded +
	OILYA-01	Hypereutric Regosol (Loamic Aric Protocalcic Ochric)	*Omutunda* very good 0
	OILYA-04	Hypereutric Regosol (Epigeoabruptic Arenic Ochric)	*Omutunda* good −
	EKOL-01	Eutric Protic Arenosol (Alumic Aridic)	*Omutunda* degraded 0
	HNDIB-01	Eutric Rubic Epiprotoargic Arenosol (Alumic Ochric)	*Omutunda* good 0
	NGYO-01	Eutric Protoargic Arenosol (Alumic Aridic)	*Omutunda* degraded 0

Table 7. Summary of the chemical and physical characteristics of topsoil (5–15 cm) and subsoil (25–35 cm) layers of the studied *omutunda* soil profiles. CV: coefficient of variation.

		n	Min.	Median	Mean	Max.	CV
TOC ($mg\,g^{-1}$)	Top	15	0.14	0.21	0.25	0.54	0.42
	Sub	11	0.12	0.19	0.2	0.29	0.25
$< 20\,\mu m$ (%)	Top	15	4.3	9.0	12.0	28.0	0.53
	Sub	15	6.6	14.2	16.3	29.8	0.42
Sand (%)	Top	15	71.3	87.4	85.5	93.9	0.08
	Sub	15	65.3	84.0	81.0	91.2	0.09
pH_{CaCl_2}	Top	15	4.7	6.6	6.5	7.7	0.11
	Sub	15	5	6.8	6.7	7.7	0.05
Moist colour value	Top	15	3	4	4.1	5	0.15
	Sub	14	3	4	3.93	5	0.14

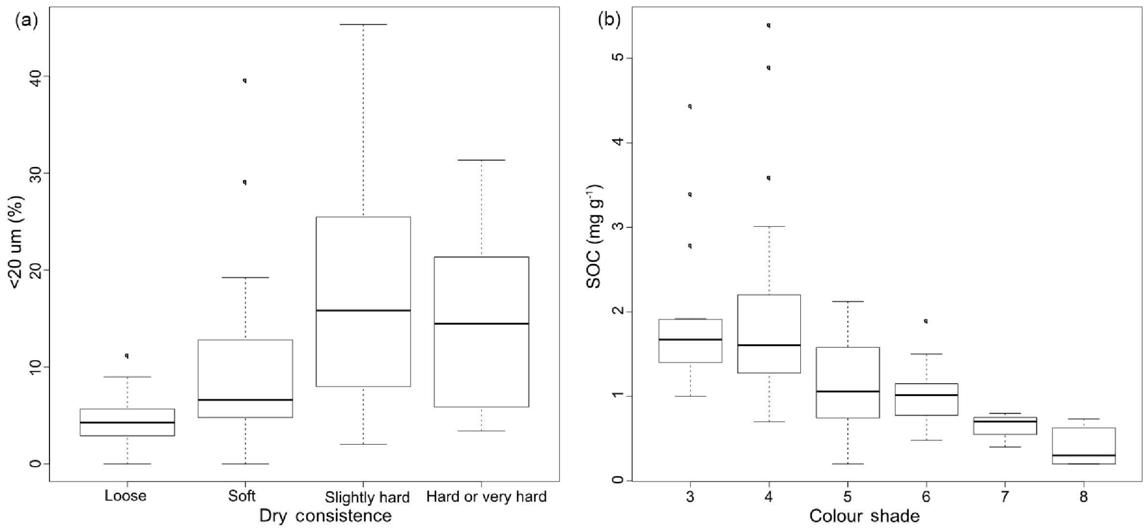


Figure 2. Box plot showing the relation between **(a)** fine particle (< 20 µm) content and soil consistence when dry and **(b)** soil organic content (SOC) and moist colour shade (Munsell colour value).

Table 8. Calculated soil organic carbon content (SOC) of 80 %-C-saturated soil for various sand contents using Feng et al. (2013) and the estimated colour shade value (Blume et al., 2011, p. 51).

Sand content (%)	Saturated SOC (mg C g^{-1})	Optimal colour shade values
80	6.8	3.5
85	5.5	3.5–4
90	4.2	3.5–4
95	3.0	4–4.5

3.5.3 The soil quality evaluation toolbox

Based on the link between FFE and soil technical properties, a toolbox for evaluating the SQ based on indicators adapted to the Western Ohangwena region was developed. With this toolbox, the SQ is assessed in two steps (Table 9): (1) field participatory mapping of KwSUs, and (2) technical SQ evaluation at specific locations using soil colour shade and sand content.

With KwSUs, farmers classify soils with comparable internal properties and suitability for pearl millet production (Table 4). The distribution of KwSUs in the fields is known by most household members. With participatory mapping, the farm can therefore be divided into KwSUs (*omutunda*, *ehenge*, *ehenene*, *elondo*, and *omufitu*), which represent internal soil properties.

Subsequently, soils are divided into three textural categories: < 80, 80–90, and > 90 % sand (Table 9) representing textural limits discussed in various classifications (e.g. IUSS Working Group WRB, 2014). The classes can be estimated in the field using the texture-by-feel method (Vos et al., 2016) or the Kruedener test adapted for sandy soils (Fabry and Lutz, 1950; Nostitz, 1934). The three classes represent the transition from "good" (or "improved") to "very poor" (or "degraded") *chemical fertility potential*. Most *elondo* are fine sandy soils, in which coarse texture (> 90 %) would indicate ongoing or past degradation (e.g. overland flows, eluviation) because *elondo* is described as a fertile soil. Conversely, the proportions of sand are very high in *ehenge* and *omufitu* (Table 5) and < 90 % sand indicates that major soil improvements had been undertaken (e.g. former homestead location). Given that *omufitu* are defined by their high sand content, *omufitu* will never present < 90 % sand without human activity. Plant growth in *ehenene* is limited by the high soil pH and high runoff intensity (Rigourd et al., 1999) and the soil texture is not relevant for SQ evaluation for this specific KwSU.

Theoretical colour shade value of C-saturated soils vary from 3.5 for fine soils (< 80 % sand) to 4.5 for very coarse soils (> 95 % sand; Table 8) (Blume et al., 2011, p. 51). The three levels indicate fertilisation status. *Positive* means sufficient organic inputs and *negative* means largely missing inputs. Munsell colour charts are a standardised tool commonly used to evaluate bulk soil colours. Few issues are related to the use of Munsell in this context. First, the charts are relatively expensive, but affordable for regional agricultural offices, and are available for researchers from most soil science research groups. Second, the colour evaluation is somehow subjective and in the context of NCN mostly only small differences in soil colour could be observed. Therefore, we suggest creating a collection of soil samples representing the regional soils and compare based on those standards.

To align the evaluation closer to FFE, we suggest adapting the colour value scale for *ehenge* and *ehenene* (optimal colour value +1) because these soils are lighter than the other

Table 9. Schematic representation of the suggested SQ toolbox. It integrates local soil quality indicators (LSQI) and technical soil quality indicators (TSQI) to create a semi-quantitative evaluation. Hierarchical SQ evaluation. The evaluation starts with LSQI and classifies location into *Oshikwanyama* soil units (KwSU); afterwards technical assessment is used to determine chemical fertility potential (sand) and the soil organic carbon (SOC) status (colour).

$$\underbrace{\text{Step 1: LSQI, Participatory mapping of KwSUs} \;+\; \text{Step 2: TSQI, Sand content \& colour shade}}_{\text{Semi-quantitative SQ evaluation}}$$

KwSU	Particularities	Sand content	Qualifier	Colour value	Qualifier
Omutunda	Problematic during drought	> 90 %	Degraded	less than 4	+
				4 to 5	0
				more than5	–
		80–90 %	Good	3 or less	+
				> 3 to < 5	0
				5 or more	–
		< 80 %	Very good	less than 3	+
				3 to 4	0
				more than 4	–
Elondo		> 90	Degraded	less than 4	+
				4 to 5	0
				more than 5	–
		< 90 %	Good	3 or less	+
				> 3 to < 5	0
				4 or more	–
Omufitu		>90 %	Poor	3 or less	+
				> 3 to < 5	0
				5 or more	–
		< 90 %	Improved		
Ehenene		> 90 %	Very poor	less than 5	+
				5 to 6	0
				more than 6	–
		< 90 %	Very poor	4 or less	+
				> 4 to < 6	0
				6 or more	–
Ehenge	Good during droughts	> 90 %	Poor	less than 5	+
				5 to 6	0
				more than 6	–
		< 90 %	Improved		

KwSUs ("in *ehenge* the soil will look white", KS, 60, Ondobe) and cannot reach low colour values.

3.5.4 Outcome of toolbox application

The developed toolbox is and remains a suggestion for evaluating SQ and for prioritising SQ improvement practices. The resulting SQ assessment gives a number of values, which bring more information about improvement potential than a single value (Ditzler and Tugel, 2002). The various locations are classified in a three-level system (*KwSU*, *chemical fertility potential*, *SOC status*). KwSUs represent *internal soil properties* that usually cannot be modified in the short term. Sand content indicates the *chemical fertility potential* of the soil, which can be improved only with medium-term (decade) management practices (homestead relocation, erosion reduction). Colour shade indicates the *SOC status* and can be modified in the short term, by agricultural techniques (e.g. manuring, conservation tillage). For each characteristic, the soil can be classified into 2–5 categories, a number that can be easily handled for mapping purposes. The overall number of possible classes (29 classes) would be, however, too high to be used to create meaningful maps. The objective of the current work was to help farmers evaluate the improvement potentials of their soils, which is achieved by using the set of indicators.

The toolbox output provides three-value estimates that need to be interpreted based on local soil knowledge and socio-economic context. For example, a soil can be characterised by "*ehenge* poor+" (Table 6), which means that (1) the location undergoes waterlogging and is valuable during poor rainfall years (*ehenge*), (2) the *chemical fertility potential* is low (*poor*), and (3) it is well enriched with organic materials (+). Investment to improve SQ at this location could then focus on waterlogging risk reduction or clay enrichment, because strategies concerning SOC are already adapted to the location and ameliorating SOC status would barely improve SQ and productivity. The test represents a way to estimate current soil status and is therefore relevant to survey SQ in NCN. The soils described during this study present a large diversity of SQ based on the developed SQ toolbox (Table 6). Half the described *omutunda* (7/15) would need more organic inputs and five are considered degraded. These results highlight the threat that exists for each location and indicate the measures to prioritise for SQ improvements. There is a lack of data to support the occurrence of soil degradation or improvement. However, these processes were perceived by some farmers and explained during the interviews. Because of the lack of long-term productivity data, it cannot be used to estimate the productivity potential of a location. However, it would be relevant to guide, for example, the systematic collection of yield data.

4 Conclusions

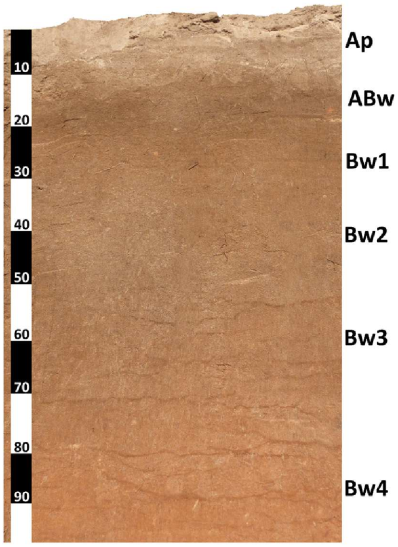
We have developed a locally adapted method for SQ evaluation. Using the toolbox with farmers in NCN showed that it is practical, affordable, precise and relatively easy to interpret. The suggested toolbox combines participatory soil mapping with sand content and colour shade assessment. The toolbox fulfils the following conditions: (i) it is practical and easy to use under field conditions; (ii) it is relatively precise and easy to interpret; (iii) it is relatively economical; (iv) it is sufficiently sensitive to reflect the impact of soil use and management; (v) it integrates physical, chemical, and biological characteristics and processes; and (vi) it is useful for estimating soil properties or functions that are difficult to measure.

The combination of farmers'and technical assessment cumulates advantages of both systems of knowledge – specifically, the integration of long-term knowledge of the farmers (i.e. long-term productivity) and a short- (colour) and medium-term (sand fraction) SQ status assessment, sensitive to land management practices. The toolbox can be used jointly by farmers and researchers from all fields of studies.

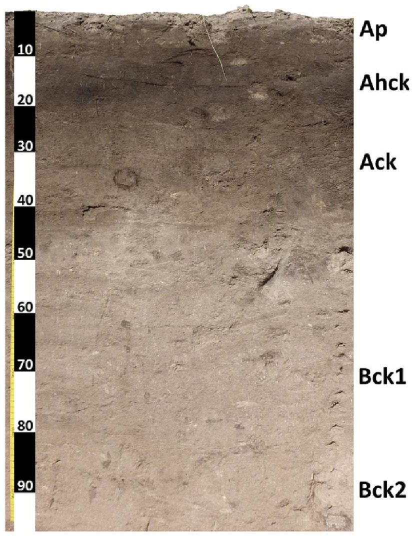
The toolbox represents a step towards better SQ evaluation in NCN. While it is adapted to a restricted area, similar approaches can be used to develop SQ tools for areas where small-scale family agriculture represents a large proportion of land use. The results strongly support the use of FFEs as an entry point to SQ assessment at the regional level, especially in semi-arid regions with high climatic variability and limited resources for SQ assessment.

Data availability. The data that support the findings of this study are available by request from the corresponding author (Brice Prudat). The data are not yet publicly available because they are being utilized in other current studies.

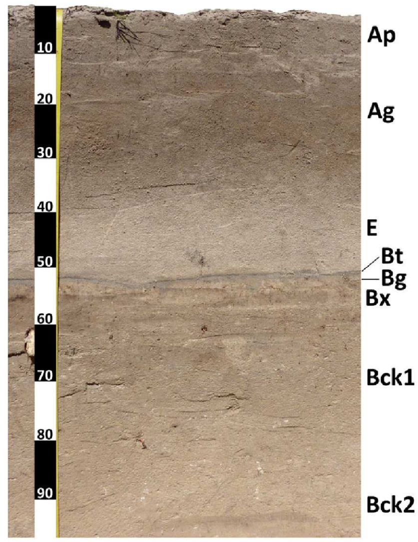
Appendix A: Soil profile descriptions



Eutric Chromic Sideralic Arenosol (Aric Aridic) / *Omufitu*
Location: Ondobe (17°30′41.44″ S, 16°03′04.03″ E); flat elevated area.
Profile description: Diffuse horizons limits; homogeneously sandy (> 90 % sand); slightly reddish 7.5YR 3/4 (Ap) to strongly reddish 5YR 4/8 (Bw4); humus content low (1.5 mg OC g^{-1} in Ap); soft consistence and not compacted; slightly acid (pH_{water} of 5 to 5.5).



Hypereutric Regosol (Loamic Aric Protocalcic Ochric) / *Omutunda*
Location: Oilyateko (17°31′20.46″ S, 16°04′40.79″ E); low level area.
Profile description: Diffuse horizons limits; loamy sand with increasing silt fraction in depth (16 % to 26 %); colour value increases with depth (10YR 3/1 to 10YR 6/2); pH and salinity increase with depth (pH_{water} from 7.7 to 8.4, electrical conductivity from 0.5 to 1 mS cm^{-1}); Ap horizon depleted in humus (3 mg OC g^{-1}) compared to the Ahck horizon (5 mg OC g^{-1}); low bulk density in Bck2 horizon (1.4 g cm^{-3}); secondary carbonates concretions from 8 cm (Ahck) and carbonated (total inorganic carbon up to 6 mg IC g^{-1}).



Eutric Sodic Protoargic Arenosol (Aric Aridic) / *Ehenge*
Location: Efidi (17°30′57.73″ S, 16°07′13.47″ E); elevated level area.
Profile description: Sandy; light to very light in colour with abrupt horizon limits between E and Bt horizons. E horizon (eluvial) is a pure sand layer (100% sand), very light (10YR 8/2) and slightly acid (pH_{water}= 6); Bt horizon (illuvial) is light (10YR 5/2), sandy (90.5% sand) and alkaline (pH_{water}= 8). Mottles in Ag and Bg horizons indicate frequent waterlogging conditions. Bg horizon is underlayed by 5-cm of compact and very hard when dry layer (Bx, bulk density = 1.74 g cm^{-3}). Bck1 and Bck2 horizons are sandy, very light (2.5Y 8/3), strongly alkaline (pH_{water} = 9.6), moderately salty (2.7 mS cm^{-1}), with secondary carbonate concretions.

Figure A1. Soil profiles illustrating three of the most common KwSUs found in the area. Soil descriptions follow the *Guidelines for soil description* (FAO, Land and Water Division, 2006) and soil names of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2014).

Author contributions. BP, LB and NJK designed the research. BP collected and interpreted the data. BP prepared the PAPER with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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