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Research article

Combining local knowledge and soil science for integrated soil health assessments in conservation agriculture systems

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ABSTRACT

The challenges of soil degradation and climate change have led to the emergence of Conservation Agriculture (CA) as a sustainable alternative to tillage-based agriculture systems. Despite the recognition of positive impacts on soil health, CA adoption in Africa has remained low. Previous soil health studies have mainly focused on 'scientific' measurements, without consideration of local knowledge, which influences how farmers interpret CA impacts and future land management decisions. This study, based in Malawi, aims to 1) combine local knowledge and conventional soil science approaches to develop a contextualised understanding of the impact of CA on soil health; and 2) understand how an integrated approach can contribute to explaining farmer decision-making on land management. Key farmers' indicators of soil health were crop performance, soil consistence, moisture content, erosion, colour, and structure. These local indicators were consistent with conventional soil health indicators. By combining farmers' observations with soil measurements, we observed that CA improved soil structure, moisture (Mwansambo 7.54%–38.15% lower for CP; Lemu 1.57%–47.39% lower for CP) and infiltration (Lemu CAM/CAML 0.15 cms^{-1}, CP 0.09 cms^{-1}; Mwansambo CP/CAM 0.14 cms^{-1}, CAML 0.18 cms^{-1}). In the conventional practice, farmers perceived ridges to redistribute nutrients, which corresponded with recorded higher exchangeable ammonium (Lemu CP 76.0 $mgkg^{-1}$, CAM 49.4 $mgkg^{-1}$, CAML 51.7 $mgkg^{-1}$), nitrate/nitrite values (Mwansambo CP 200.7 $mgkg^{-1}$, CAM 171.9 $mgkg^{-1}$, CAML 103.3 $mgkg^{-1}$). This perception contributes to the popularity of ridges, despite the higher yield measurements under CA (Mwansambo CP 3225 $kgha^{-1}$, CAML 5067 $kgha^{-1}$, CAM 5160 $kgha^{-1}$; Lemu CP 2886 $kgha^{-1}$, CAM 2872 $kgha^{-1}$, CAML 3454 $kgha^{-1}$). The perceived carbon benefits of residues and ridge preference has promoted burying residues in ridges. Integrated approaches contribute to more nuanced and localized perceptions about land management. We propose that the stepwise integrated soil assessment framework developed in this study can be applied more widely in understanding the role of soil health in farmer-decision making, providing a learning process for downscaling technologies and widening the evidence base on sustainable land management practices.

1. Introduction

In response to challenges of climate change and increasing soil degradation, conservation agriculture (CA) is being widely promoted across sub-Saharan Africa (SSA) as a form of climate-smart agriculture. CA is characterized by three key principles of minimum soil disturbance, continuous organic soil cover, and crop diversification through rotation or intercropping (FAO, 2015). Regional studies on CA performance compared to conventional practices have shown improvements in soil water retention (Thierfelder et al., 2015b; Thierfelder and Wall, 2010), infiltration capacity (Ngwira et al., 2012b; Thierfelder et al., 2015b; Thierfelder and Wall, 2010), soil structure (Eze et al., 2020), biological activity (Ngwira et al., 2012b; Thierfelder et al., 2015b), crop yields (Ngwira et al., 2012b) and heat stress resilience (Steward et al., 2018). Therefore, CA systems are being promoted by governments and international organizations citing its potential to improve soil health and to increase or sustain yield in the long-term. However, the CA adoption rate across SSA remains low, for example in Malawi CA covers only 5.6% of the arable land (Kassam et al., 2019).

Various reasons for slow CA adoption have been documented, such

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as lack of sufficient residues or resources (Andersson and D'Souza, 2014; Giller et al., 2009). There has been a lack of local participation in the design of management practices and impact assessment of externally recommended practices. The absence of sufficient 'scientific' data on performance of CA in different climatic areas, farming conditions and on the livelihood benefits experienced makes some researchers question its widespread promotion (e.g. Giller et al., 2009). In particular, examination of the individual impacts of different CA principles on site-specific soil and climatic conditions is required to more holistically understand the benefits of CA. Whereas most studies on soil health have concentrated on 'scientific' measurements, local knowledge can also contribute to this understanding by providing reflection on local processes and outcomes. The importance and value of local knowledge or mixed hybrid knowledge in fields such as soil, and environmental science has been widely published (Mairura et al., 2007; Oppenheimer et al., 2014; Prudat et al., 2018; Raymond et al., 2010). Including this knowledge in the process of analysing the impacts of CA ensures the assessment is embedded in the farming context, thereby contributing to improved understanding of farmers' decision-making and the role of soil health knowledge in land management decisions. This can support the scaling, in particular downscaling, adoption and adaptation of technology land management practice.

On-farm trials represent an opportunity to bridge local and scientific knowledge through a participatory and integrated methodological approach (Hermans et al., 2020a). Baudron et al. (2011) highlighted that evidence for CA benefits is often based on controlled research station studies and working on-farm in collaboration with farming communities opens an avenue for knowledge exchange. A combination of participatory and scientific methods can address the call for CA research to use a systems perspective with an interdisciplinary, integrative and participatory bottom-up approach (Andersson and D'Souza, 2014; Giller et al., 2011; Whitfield et al., 2014). Combining conventional soil health knowledge embedded in scientific literature and local knowledge can contribute to our overall understanding of CA performance and the processes explaining observed outcomes ('why does it work here?').

1.1. Soil health background

The soil improvement narrative of CA raises the need to discuss the meaning of soil quality and soil health, often used interchangeably. Soil quality refers to the capacity of a specific kind of soil to function within ecosystem boundaries to support a particular use such as crop production (Laishram et al., 2012). Conversely, soil health refers more broadly to the capacity of soil to function as a living system to support plant, animal and human life (Laishram et al., 2012). In the context of CA, soil improvement is related to the benefit to human life through increasing food and nutrition security, environmental quality as well as climate change resilience. This conforms most closely with the concept of soil health.

Soil health or soil quality cannot be measured directly, they are concepts for examining functions and relationships between biological, physical and chemical soil parameters important for sustainable agriculture (Karlen et al., 1997). To transfer from a conceptual definition to measurable soil health a minimum dataset (MDS) of measurable soil parameters has been suggested, including biological, physical and chemical soil parameters (Arshad and Coen, 1992; Bünemann et al., 2018; Carter et al., 1997; Govaerts et al., 2006; Gregorich et al., 1994; Laishram et al., 2012; Singer and Ewing, 2000). The most popular MDS of soil health indicators are presented in Table 1. The selection of MDS is guided by those parameters that 1) indicate sensitivity to soil management, 2) can inform land management decisions, and 3) contribute to an understanding of soil system processes; and 4) are readily measurable (Karlen et al., 1997; Laishram et al., 2012; Parisi et al., 2005).

MDS soil parameters have been used for assessing the impact of CA on soil health, in particular in relation to organic matter content and hydraulic dynamics. The improvement of hydraulic dynamics (e.g. infiltration and water holding capacity as defined in the MDS) is one of the most important benefits attributed to CA management in terms of soil health improvement (Thierfelder and Wall, 2009). The CA literature has shown that the conventional ridge and furrow system decreases water retention, especially during dry and hot spells, and increases moisture loss on uncovered soil due to tillage increasing the soil surface area (Thierfelder et al., 2013; Thierfelder and Wall, 2009). CA impacts on soil hydraulic properties are influenced by site specific factors such as soil texture and are more apparent on sandy soils (Steward et al., 2018).

Table 1
Minimum data set (MDS) for soil quality and health assessments based on Laishram et al. (2012) (Arshad and Coen, 1992; Carter et al., 1997; Govaerts et al., 2006; Gregorich et al., 1994; Laishram et al., 2012; Singer and Ewing, 2000).

Key soil health parameters	Reason
Organic Matter	Important for soil structure and fertility, and water holding capacity
N forms in soil	Mineralization and immobilization rates, support soil fertility, leaching
Extractable K, N, and P	Potential of nutrients to support plant development
Aggregation	Indicator of soil structure and erosion protection
Texture	Important for soil water and nutrient transfer and retention
Bulk Density	Porosity, adaptation to soil volume
Depth to hardpan	Roots growth potential
pH	Availability of nutrients
Electrical conductivity	Connection to soil structure, infiltration and crop development
Potential pollutants	Potential for plant growth and plant-soil system health
Soil respiration	Indicator for biological activity and organic matter
Infiltration	Indicator for erosion and run off
Water-holding capacity	Sufficient moisture to support plant growth

Various studies on research stations in Zimbabwe, Zambia and Malawi have shown that carbon (C) stocks, the quantity of C per unit area, increased under CA treatments relative to conventional practices (Ligowe et al., 2017; Thierfelder et al., 2012) (0–10 cm, 10–20 cm, 0–30 cm depth). However, results from on-farm trials in Malawi have recorded both insignificant (Cheesman et al., 2016) and significant differences in soil C stocks and concentrations (Mloza-Banda et al, 2014, 2016; Ngwira et al., 2012a). These inconsistencies have also been reported in other locations across Sub-Saharan Africa (Powlson et al., 2016). Another key chemical soil health indicator, is total nitrogen (N). Only a few CA studies have looked at different forms of N (Mloza-Banda et al, 2014, 2016; Ngwira et al., 2012a), and very little has been done in Malawi to examine plant available N. The meta-regression by Steward et al. (2018) showed that CA outperforms conventional treatments when there is high heat stress and low N fertilizer application. Therefore, research on the impact of CA on C stocks and total N concentrations has provided mixed results, depending on site specific temporal and spatial conditions.

In most CA soil health studies only quantitative parameters have been considered and qualitative indicators embedded in farmers' knowledge have received little attention. As an exception, Mairura et al. (2007) used data based on farmers' perceptions in central Kenya and showed that local soil knowledge was beneficial for soil health assessment and that visual soil improvement is central in farmers' assessments. Similarly, a participatory approach to soil quality assessment in Namibia showed that integrating long-term local knowledge and short term technical knowledge can address soil quality assessment limits on temporal scales (Prudat et al., 2018). This suggests that an integrated approach to soil health evaluation, combining local and scientific knowledge, can enrich understanding of the impact of agricultural practices on soil health.

1.2. Aim & research questions

This paper develops and applies an integrated assessment approach, which combines local knowledge with conventional scientific soil measurements to evaluate soil health impacts of CA (Mairura et al., 2007; Prudat et al., 2018) and its role in farmers' decision-making in Malawi. The term local knowledge is used due to its wider conceptual application, meaning all related knowledge about the surroundings and context over time by people in an area (Trogrlić et al., 2019). This study approaches soil health from a farmer's perspective in two case study regions, and uses this to develop and test a set of yield and soil measurements based on a soil health minimum dataset covering soil C, N, infiltration, moisture, structure and bulk density.

The paper addresses two main research questions:

1) What is the contextualised understanding of the impact of CA on soil health at on-farm trial sites in Malawi, based on learning across local knowledge and conventional soil science approaches?
2) In what ways can an integrated knowledge and methods approach contribute to assessing the impact of CA on soil health and understanding related farmer decision-making on land management?

We hypothesize that the combination of local knowledge and conventional soil science provides a broader evidence base for the outcomes of CA and contributes to a better understanding of farmer decision-making around the practice of CA.

We first provide the research design and taken approach including the stepwise integrated soil assessment framework. The results are presented according to the stepwise framework: Section 3.1 Farmers' Soil Health Indicators, Section 3.2 Quantitative Soil Health Indicator Selection, and Section 3.3 Quantitative Soil Health Measurements. The remainder of the paper discusses the soil health indicator measurements (Section 4.1), and the integrated approach for soil health assessment. (Section 4.2).

2. Research design

2.1. Study area and on-farm trial description

The study was carried out at two medium-term CA on-farm trial sites in Malawi: Mwansambo in the central region and Lemu in the southern region (Fig. 1; Table 2).

Each on-farm trial has three main treatments as described and explained previously by Ngwira et al. (2012b) and Thierfelder et al. (2015a). The treatments are as follows:

Table 2
Study sites description.

Site Characteristics	Site	
	Mwansambo	Lemu
On-farm Trials	6	6
Latitude (°)	−13.32	−14.79
Longitude (°)	34.11	35.00
Altitude (masl)	665	735
Soil type	Haplic Lixisols	Chromic Luvisols
Soil Texture	Sandy Clay Loam	Sandy Loam
Rainfall (mm)	1330–1359	605–1226
Year CA started	2005	2007
Farming System	Maize mixed	Maize mixed
Land holding (ha)	0.5	0.4
Population	229,460 (71/km^2)	310,000 (145/km^2)
Distance to Market (km)	30	30
Extension	Total LandCare (TLC)	Machinga ADD (Gov)
Lineage Majority	Patrilineal	Matrilineal

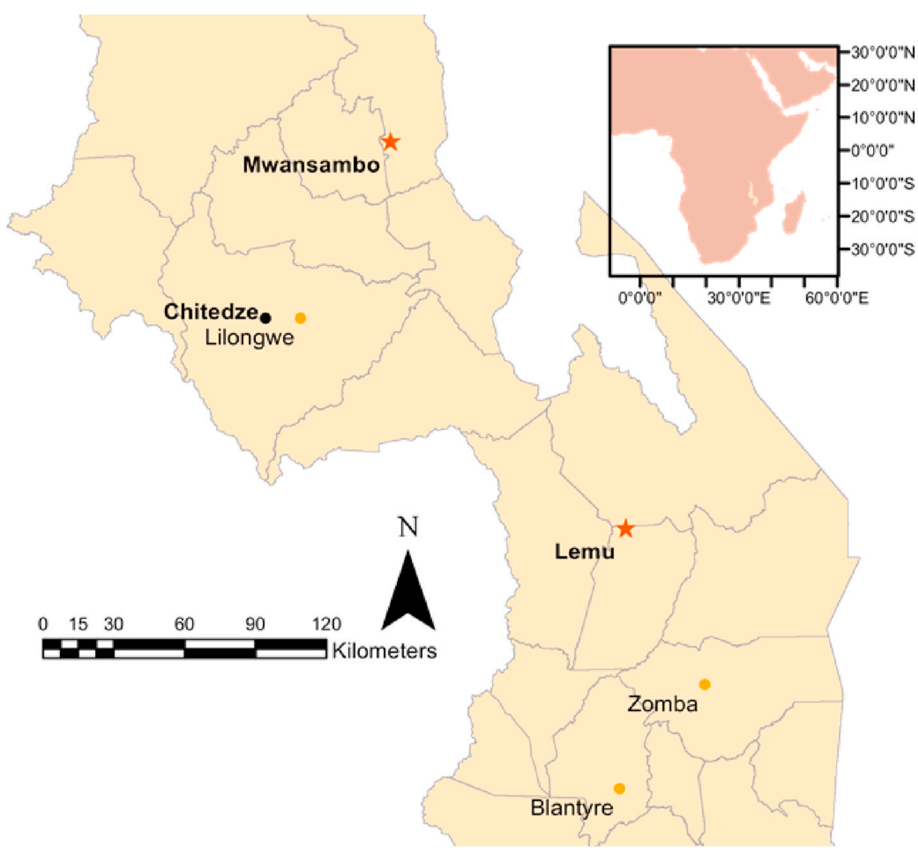

Fig. 1. Map showing the study sites in Malawi: Mwansambo and Lemu.

1) Conventional practice with ridge and furrow system (CP) prepared with a hand hoe in September or October with crop residues removed after harvest.
2) Conservation agriculture with sole maize (CAM). In this treatment there is no tillage and maize is planted with a dibble stick (one hole for seed and one for fertilizer). Residues are retained as surface mulch.
3) Conservation agriculture with maize and legume intercrop (CAML): cowpea (*Vigna unguiculata* L.) in Mwansambo and pigeon pea (*Cajanus Cajan* L.) in Lemu. Crops are planted with a dibble stick and have similar no tillage and crop residue treatment as CAM.

All plots are rotated annually with groundnuts (*Arachis hypogaea* L.) planted on ridges in CP and on the flat in CAM and CAML. Details on trial management can be found in Appendix A.

2.2. Integrated assessment of soil health

The approach taken to evaluate soil health impacts of CA consisted of a sequential process that involved:

(1) discussing CA's impact on soil health with farmers;
(2) identifying soil health indicators used by the farmers and comparing with literature;
(3) taking soil measurements (of indicators) with the help of farmers at the on-farm trials;
(4) discussing the soil measurement results and their connection to farmer observations.

The rationale behind the sequential step wise process is based on previous local soil health assessments applied in SSA (Mairura et al., 2007; Prudat et al., 2018). The four steps were defined and clarified in community meetings during the research design process in order to provide a clear replicable framework, embedded in both social (Newing, 2011) and soil science (Carter and Gregorich, 2007) literature, and able to cover multiple indicators of soil health.

Focus groups and semi-structured interviews were conducted to understand farmers' perspectives on soil health, the agro-ecological system and their decision-making (Newing, 2011). Focus groups were conducted in each community with both trial farmer group (6 farmers) and non-trial farmers (8–10 farmers). A total of 3 focus groups per community were organized. Guiding discussion topics (Appendix B) based on observations or indicators used for assessment of different management practices were provided to explore local soil health knowledge.

The semi-structured interviews followed the focus groups. Interviews enabled in-depth conversations on the indicators used for soil health assessment, and plant and soil outcomes from different management practices. They also supported exploring the diversity in farmers' approaches without the need for group consensus as often required in focus group discussions. The frequency count of indicators and outcomes based on interview results was used to map out the popularity of particular indicators and observations. The semi-structured interviews were conducted with 6 trial farmers in each community and a subsequent snowball methodology, with support from the extension officer, was used to select 12 non trial farmers in Mwansambo and 14 non trial farmers in Lemu. During the interviews, questions about currently used land management practices were asked to clarify the use of CA practices. In total 38 interviews were conducted and the guiding questions can be found in Appendix B.

The selection criteria for participants was based on engagement levels with the CA trials (Hermans et al., 2020b). Trial farmers have most experience with the impact of CA practices, as they directly implement the trials on their land and have direct engagement with the International Maize and Wheat Improvement Center (CIMMYT) and agricultural extension officers. Since the rationale of this study is to gain a broad perspective and understanding on the process and learning across knowledges, the non-trial farmers were selected to represent various age groups and to provide a gender balance in respondents.

Before the interviews and focus groups, written consent was obtained from participants and it was clarified that participation had no influence on any programme involvement and that responses will be anonymised. Ethical consent for this study was obtained from the University of Leeds and Lilongwe University of Agriculture and Natural Resources.

The data was firstly analysed on the frequency of mentioned impacts of CA practices on soil health and the indicators used for this assessment. Using the outcomes and indicators as themes, the qualitative data was explored for each theme to gain an in-depth understanding of the reasoning, observation and assessment (Saldaña, 2015).

2.3. Soil measurements

Based on discussions of soil health, the impact of CA practices and the soil health MDS (Table 1) a set of soil measurements were taken. Soil was sampled and analysed from both sites during February 2019 growing season. Soil measurements covered soil C, total N, nitrate/nitrite, ammonium, infiltration, moisture, structure, bulk density and maize yield. Farmers were involved in the field measurements of soil N, soil infiltration, moisture, soil structure and bulk density to ensure their awareness of measurement techniques and participation in sampling, ahead of two-way discussion of findings.

2.3.1. Soil carbon and nitrogen

Soil samples were collected from all treatment plots at two depths (0–5 cm and 5–10 cm) using an Edelman auger. For each treatment and depth, five soil sub-samples were taken and bulked into a composite sample for analysis. The sub-samples were taken in a Z pattern to get a bulked representation of the plot treatment and enable comparison to the other two treatments (Carter and Gregorich, 2007). From the bulked samples, 3 sub samples of 2 ml of moist soil per field were analysed within 24 h for soil nitrate, nitrite and ammonium using a SKW500 Palintest© soil fertility kit (https://www.palintest.com/products/skw500-complete-soil-kit/). This involved extraction with 1 M ammonium chloride and spectrophotometer reading *in situ* (Carter and Gregorich, 2007). Each final treatment value consisted of $N = 18$ measurements. The remaining bulked samples were air-dried, crushed and passed through a 2 mm sieve, then ball-milled, before total carbon and nitrogen were determined through combustion in an elemental analyser (Elementar Vario Micro Cube) (McGeehan and Naylor, 1988). Each final measurement TC/TN per treatment per depth per community is the mean of 12 sub samples.

2.3.2. Soil infiltration & moisture

Field infiltration measurements were taken with a minidisk tension infiltrometer (METER Group Inc., 2018) with the suction rate set to accommodate for the soil type and texture (Table 2), ranging from −0.5 (compact soil) to −6 cm (sandier soils) following the manufacturer's guide. Ten measurements were taken following a W-pattern in each replicate plot. Infiltration measurements were taken at intervals of 10 s and cumulative infiltration calculated by regressing infiltration measurements with time (Kirkham, 2014). Each final measurement per treatment per community is the mean of 30 measurements. *In situ* soil moisture readings were taken (25 per treatment per field) using a Delta soil moisture probe (https://www.delta-t.co.uk/product/ml3-kit/).

2.3.3. Soil structure stability index

The soil structural stability index (Pieri, 1992) was estimated based on soil organic carbon, clay and silt contents:

$$Soil\ structural\ stability\ index = \frac{1.72OC(wt.\%)}{(Clay + Silt)(wt.\%)} \times 100 \quad (1)$$

Table 3
Farmers' perception of the impact of CA practices on soil dynamics. n is the frequency in responses and the percentage is based on the number of responses for the group total.

Perception	n	n Trial (%Total 12)	n Non -trial (%Total 26)
Residues			
Residue retention improves soil fertility and adds organic material.	26	10 (83%)	16 (62%)
Residue retention improves retaining soil moisture.	23	6 (50%)	17 (65%)
Flat land only works with residues, because without residues the soil is exposed to the sun, dries, and becomes hard.	10	4 (33%)	6 (23%)
Residue retention attract organisms.	10	2 (17%)	8 (31%)
Many residues and high soil fertility is not good for groundnuts.	9	2 (17%)	7 (27%)
More residues means less weeding, but too little means herbicides are needed.	6	3 (25%)	3 (12%)
If decomposition is not good it does not add to soil fertility and negatively affects growth of the next crop.	6	3 (25%)	3 (12%)
Residues prevent soil erosion.	6	2 (17%)	4 (15%)
Too many residues on flat land will lead to water logging.	6	1 (8%)	5 (19%)
Residues make the ground soft.	5	5 (42%)	0 (0%)
During harvest residues are fresh and good for decomposition. If the residues and soil are dry they are not good anymore and do not decompose well.	4	1 (8%)	3 (12%)
Residues create too much heat.	3	0 (0%)	3 (12%)
Termites help to decompose residues.	2	1 (8%)	1 (4%)
Importing residues risks disease transfer.	1	0 (0%)	1 (4%)
Rotation			
Rotation is good because legume leafs decompose and improve fertility.	10	5 (42%)	5 (19%)
Rotation decreases diseases because diseases do not survive if crops change.	6	2 (17%)	4 (15%)
Rotation is good because crops have specific nutrients and rotating means these can be replenished.	2	0 (0%)	2 (8%)
Ridge making			
No till means the soil is not shaken by the hoes and the soil cannot wash away, so old ridges (banking only) or no till is better.	15	4 (33%)	11 (42%)
Ridges can aerate the soil and make it soft again, so seeds can get nutrients easily.	10	2 (17%)	8 (31%)
Ridges lose moisture quickly.	5	1 (8%)	4 (15%)
Ridge making is good because crop is above water table.	5	0 (0%)	5 (19%)
Ridges or furrows help with conserving water.	5	0 (0%)	5 (19%)
On the flat the water infiltrates, but with ridges the water flows.	4	1 (8%)	3 (12%)
Ridges make water infiltrate quickly in the soil and collect water.	3	0 (0%)	3 (12%)
New ridges will redistribute the soil fertility	2	0 (0%)	2 (8%)
In ridges it takes longer for residues to decompose because there is less moisture.	2	1 (8%)	1 (4%)
On ridges groundnut cannot grow big because it is limited by the ridge sides.	2	0 (0%)	2 (8%)
Ridges help to decompose residues quicker.	1	1 (8%)	0 (0%)

2.3.4. Bulk density

Soil samples for bulk density determination were collected from three points in each treatment plot with a van Eijkelkamp sample ring (5 cm diameter x 5 cm length). The three points were selected around the centre of the field to avoid the border of the field and represent different ridges or maize planting lines. The samples were oven dried for 24 h at 105 °C and a bulk density value calculated:

$$Bulk\ Density\ \left(gcm^{-3}\right) = \frac{Mass\ of\ oven-dry\ soil}{Volume\ of\ soil} \tag{2}$$

Each final measurement per treatment per community is the mean of 18 samples.

2.3.5. Visual Evaluation of Soil Structure (VESS)

The assessment of soil structure for each treatment plot was conducted using the Visual Evaluation of Soil Structure (VESS) chart (Ball et al., 2007). The VESS method uses an illustrated ranking table of soil structure. A structural quality (Sq) score ranging from 1 (good) to 5 (bad) is assigned based on the stability of the aggregates with use of reference photographs (Ball et al., 2007; Mueller et al., 2013).

2.3.6. Yield

The reported maize yield was based on 10 sub-samples of 7.5 m^2 per treatment for 2019, as described in Thierfelder et al. (2013). Weight of biomass and fresh cobs was recorded in field after harvest at physiological maturity. Four weeks after the harvest in end April for Lemu and May for Mwansambo, biomass, shelled grain and dry cobs were weighed and grain moisture was measured. Maize grain yield is based on the conversion of yield data at 12.5% moisture content to $kgha^{-1}$ (Thierfelder et al., 2013).

2.3.7. Statistics

Normally distributed soil nitrogen, carbon, infiltration, bulk density, structural stability and yield data were subject to an analysis of variance (ANOVA) to test for differences between the CP and CA treatments (Fisher, 1992). The Tukey HSD post hoc test was used for mean separation (Tukey, 1949). Non-parametric data were tested using Kruskall-Wallis test and Dunn's test respectively (Dunn, 1961; Kruskal and Wallis, 1952). Statistical analysis was performed in SPSS version 23.0.0.2 (IBM Corp, 2015).

3. Results

3.1. Farmers' soil health indicators

Interviews demonstrated that farmers observe the impacts of CA on soil health in relation to each of the three main CA component practices (Table 3). Practices from the CA package were also used by non-trial farmers, such as rotation, or translated into an adapted practice, such as residue burying in ridges or planting on old ridges (Table 3). Trial farmers also adopted non-CA practices. Therefore, the results are discussed as responses from the total group (Table 3, Appendix Table C.1).

Enhanced additions of crop residues were strongly connected with increasing soil moisture, soil organic matter and higher soil fertility, making the soil 'soft again' through moisture retention and protecting it from the sun ("*Residues keep moisture and without residues the crop is exposed to sunlight on the flat*" Farmer 1). This perception was common amongst trial farmers (Table 3). Some concerns were raised in regard to negative effects on the growth of the next crop: when residues do not decompose well, residues lead to waterlogging in high rainfall seasons, and the attraction of crop pests. Some farmers suggested that the fertility added through residue retention is not good for groundnuts and leads to lower yields.

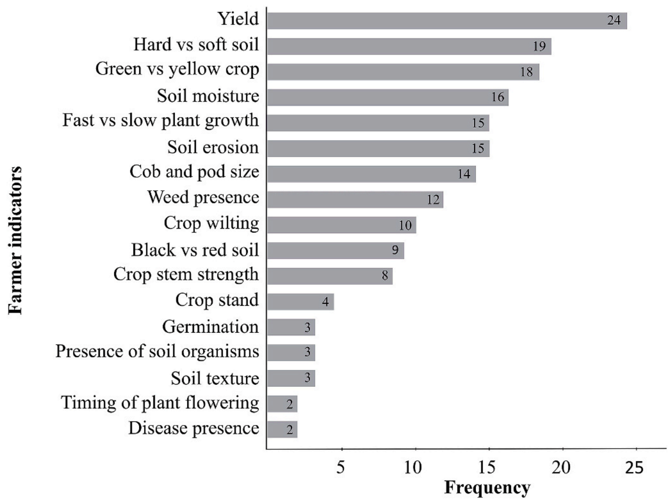

Fig. 2. Frequency table of the indicators used by farmers to assess soil health. The frequency is the number of interviews in which this indicator was explicitly mentioned by farmers. A breakdown of frequency for trial and non-trial farmers can be found in supplementary material Table C.1.

Table 4
Indicators of good soil health as perceived by farmers.

Indicators of good soil health	
Soft soil	No erosion
High yield	Strong plant
Green crop	Black soil
Fast plant growth	High germination
Large pod and cob	High moisture

Farmers observed that new ridges are often washed away when the wet season starts. Despite the negative perception on soil erosion, ridges are perceived to aerate the soil and making it softer, so seeds can access nutrients easily ("*I make ridges so the soil can be soft again*" Farmer 4). Furthermore, the perceived benefits of no-till are highly dependent on residue quantity because without residues the soil is exposed to the sun and becomes dry and hard.

Rotation or intercropping with legumes was also perceived as useful because of the addition of "*something good*", described by some as "*adding salt*" (i.e. akin to enhancing the flavour of food) to the soil. In particular, the decomposition of legume leaves improves soil fertility and replenishes the soil nutrients ("*Pigeon pea leaves, when they fall they improve soil fertility*" Farmer 7). The collected statements on how CA might affect soil health, demonstrated that farmers perceive the CA practices to lead to a soil or plant outcome. Further discussion on these outcomes enabled us to collate a list of soil and plant indicators used by farmers to assess soil health (Fig. 2, Table 4, Appendix Table C.1).

All indicators are based on visual or touch senses and are mostly described in relative terms, for example yellow or green plant, hard or soft soil, and fast or slow growth. The key indicators used by at least 50% of interviewed farmers were crop yield (63%) and soil consistence (50%) (Appendix Table C.1). In addition to crop yield, the other crop characteristics mentioned by 50% of CA trial farmers was crop colouration whereas the non-trial farmers (50%) emphasised crop vigour.

The indicators can be linked to the understanding of processes listed in Table 3. For example, soft or hard was used to describe the impact of ridges and residues (e.g. "*without residues the soil is exposed to the sun and becomes hard*", "*ridges aerate the soil and make it soft again*"). Moisture was referred to in various statements about ridges and residues, which can keep or lose moisture (e.g. "*residues improve retaining moisture*", "*ridges lose moisture quickly*"). Erosion is also a reoccurring outcome used to indicate the success of an agricultural practice, in particular ridge making and residue retention. Although yield was not explicitly

Table 5
Soil health indicators selected for comparing conservation agriculture with the conventional treatment. The soil health measurements were selected based on literature, whereas the farmer soil health indicators show what farmer look at when comparing fields.

Farmer soil health indicators		Soil health measurements	
Hard vs soft soil - D	SOIL	Total Carbon - C	SOIL
Soil moisture - M		Total Nitrogen - N	
Soil erosion- E		Ammonium - N	
Black vs red soil -C		Nitrate & Nitrite - N	
Presence of soil organisms - B		Infiltration & Moisture – M E	
Soil texture – C		Soil Structure Stability Index – DE	
Yield - C E M D N B	PLANT	Bulk Density - D	
Fast vs slow plant growth – C E M D N B		Visual Evaluation of Soil Structure (VESS) – DE	
Green vs yellow crop - N		Yield – C E M D N B	PLANT
Cob and pod size – C E M D N B			
Crop wilting – C E M D N B			
Crop stem strength- C E M D N B			
Crop stand- C E M D N B			
Timing of plant flowering- C E M D N B			
Germination – C E M D N B			
Weed presence	OTHER		
Disease presence			

B - Soil organisms were excluded from measurements because literature review showed general consensus on CA leading to higher biological activity (Thierfelder et al., 2015b). *D- indicators and measurements related to soil density, M - indicators and measurements related to soil moisture, E - indicators and measurements related to soil erosion (and connected soil structure), C- indicators and measurements related to soil carbon, N - indicators and measurements related to soil nitrogen.*

mentioned as an outcome based on the identified processes in Table 3, it is viewed as an overall proxy of soil health.

3.2. Quantitative soil health indicators selection

Soil properties that correspond with farmers' indicators of soil health and could be measured were total C, total N, available N (as ammonium, nitrite and nitrate), infiltration, moisture, bulk density and soil structure (Table 5). An example of the connection is the green vs yellow plant: according to farmers, a greener plant is perceived as 'good', whereas a yellow plant is perceived as 'bad'. It was largely unknown by the farmers, however, that the yellow colour is caused by a shortage of nutrients, in particular N, which can be quantitatively measured. Further, the colour of the dark soil and high moisture identified by farmers as 'good' provides a connection to the MDS parameter of organic matter (soil C) and water holding capacity, respectively (Gupta et al., 2008). The frequent noting of erosion as an indicator can be translated to measurement of infiltration, which can indicate erosion potential and soil structure (Table 1).

3.3. Quantitative Soil Health Measurements

3.3.1. Total carbon, total nitrogen, and available nitrogen

CAML and CAM systems were not significantly different from the CP system in total soil C, despite 15% and 5% higher total C contents, respectively (Fig. 3, Appendix Table D.1). Total N was higher in the CAM (0.98 gkg $^{-1}$) and CAML (1.19 gkg $^{-1}$) systems than in the CP system (0.90 gkg $^{-1}$) with this being statistically significant only at the 0–5 cm depth ($p < 0.05$) (Fig. 3, Appendix Table D.1). The CP system had a significantly ($p < 0.05$) higher nitrite and nitrate value (200.7 mgkg $^{-1}$) in Mwansambo than the CA systems (CAM 171.9 mgkg $^{-1}$, CAML 103.3 mgkg $^{-1}$) with a difference of 14% and 49%, respectively (Fig. 4, Appendix Table D.1). There were significantly higher values of soil ammonium in the CP systems in Lemu (76.0 mgkg $^{-1}$) than CA systems (CAM 49.4 mgkg $^{-1}$, CAML 51.7 mgkg $^{-1}$) (Fig. 4). Ammonium in the CP treatment was 32–35% higher compared to CA treatments. The ammonium values in Mwansambo were mostly outside the range of the spectrometer and the only detectable values were for some of the CA fields.

The change in soil C concentrations in the on-farm trial plots between 2011, based on Cheesman et al. (2016), and 2019 was not significant (Appendix Table E.1).

3.3.2. Infiltration, moisture and soil structure

Significant impacts of land management on the rate of water infiltration was only observed in Lemu where CAML and CAM had an infiltration rate of 0.15 cms^{-1} and CP 0.09 cms^{-1}, respectively (Fig. 5, Appendix Table F.1). Comparing CP to the CA treatments, moisture readings were between 7.54% and 38.15% lower for CP in Mwansambo and 1.57%–47.39% lower for CP in Lemu.

Soil structural stability index was significantly greater in the CAML and CAM treatments than the CP treatment when the data for the two communities were combined (Fig. 6, Appendix Table F.1). Bulk density measurements for 0–5 cm and 5–10 cm in both communities did not differ significantly ($p < 0.05$) (Appendix Table F.1).

With the help of soil quality scoring in the VESS exercise, the structure of the soils in the CAML and CAM was judged to be more stable than for CP treatments. Farmers also assessed that CAML and CAM treatments had softer and more easily breakable aggregates than those in CP treatments.

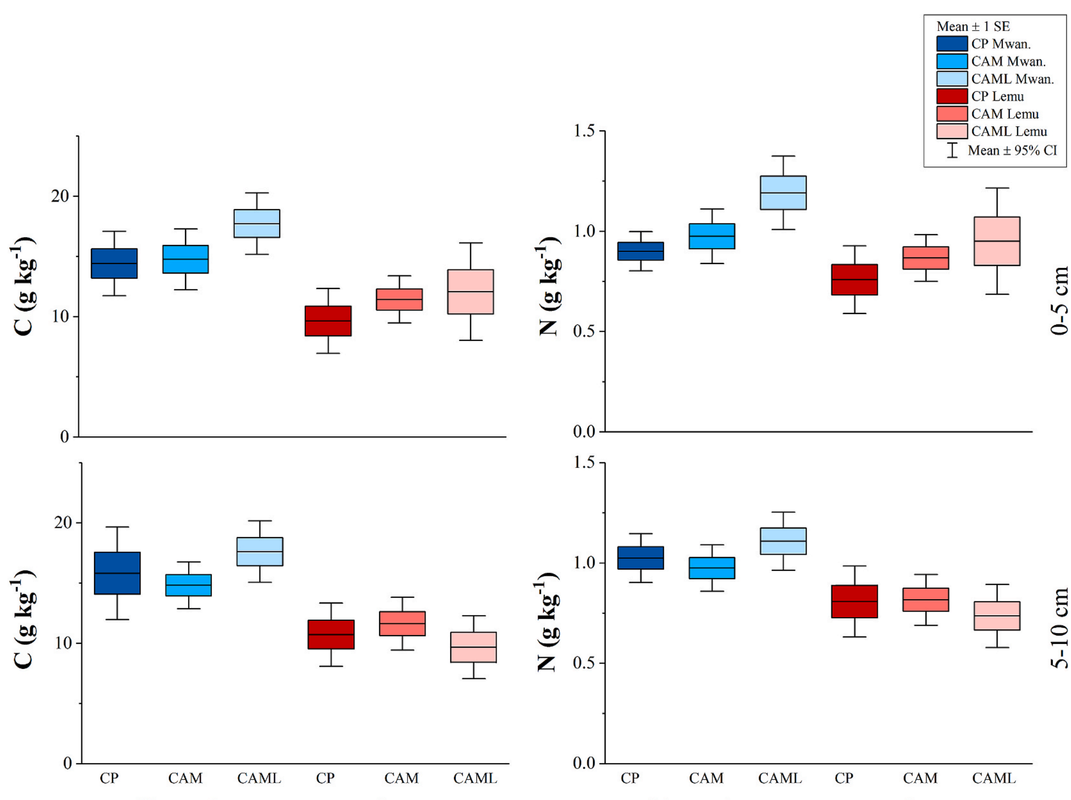

Fig. 3. Total Carbon (C) and Total Nitrogen (N) data for 0–5 cm and 5–10 cm depth showing mean ± 1 standard error (SE) (whiskers show 95% confidence interval (CI)). Lemu data is represented in the red colours and Mwansambo (Mwan.) in the blue colours. Dark red and blue represent measurement from maize in conventional practice (CP), middle colour represent CA with maize only (CAM) and lightest colour represents CA with maize-legume intercropping (CAML). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

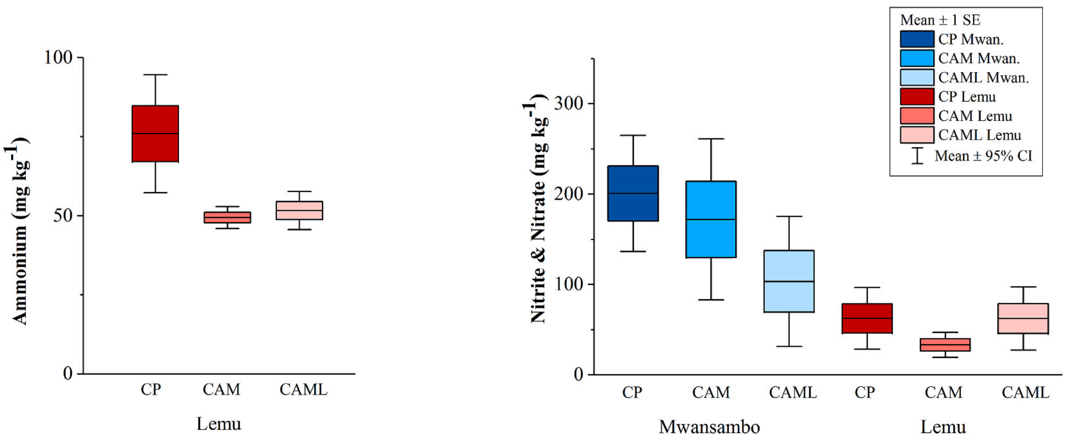

Fig. 4. Ammonium and nitrate/nitrite data for 5–10 cm depth showing mean ± 1 standard error (SE) (whiskers show 95% confidence interval (CI)). Lemu data is represented in the red colours and Mwansambo (Mwan.) in the blue colours. Dark red and blue represent measurement from maize in conventional practice (CP), middle colour represent CA with maize only (CAM) and lightest colour represents CA with maize-legume intercropping (CAML). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

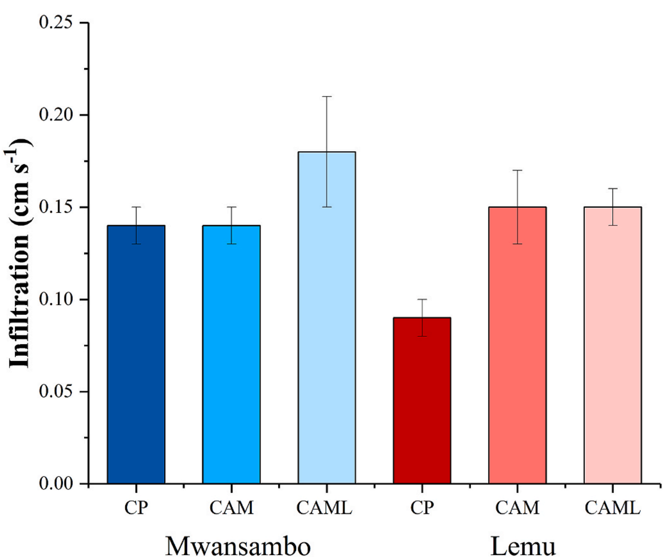

Fig. 5. Infiltration data for Mwansambo (blue) and Lemu (red). Bars shows mean with standard error lines. Dark colour represents conventional treatment (CP), middle colour represents conservation agriculture with maize only (CAM) and lightest colour represents conservation agriculture with legume intercropping (CAML).(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3.3. Yield

Grain yield was significantly higher in the CA systems in Mwansambo, with CP 3225 kgha^{-1}, CAML 5067 kgha^{-1} and CAM 5160 kgha^{-1} ($p < 0.05$) (Appendix Table G.1). For Lemu, there was no significant difference ($p < 0.05$) (Appendix Table G.1), although CAML showed higher grain yields (3454 kgha^{-1}) compared to CP (2886 kgha^{-1}) and CAM (2872 kgha^{-1}).

4. Discussion

4.1. Soil health indicators

4.1.1. Carbon & nitrogen

The impacts of CA practices on soil C remains contested with different sites producing contrasting results, in particular between controlled research stations and farmer managed on farm trials. In our study, farmers observed that crop residue retention makes soils dark, soft, increase soil texture diversity and improves plant performance, which suggests that the practice of residue retention improves soil fertility and soil organic matter. The associated measurement of total C showed that C contents in the CA systems was not statistically significant due to high variance.

The quantity and quality of residues significantly impacts their decomposition rate and plays an important role in controlling soil C contents (Luo et al., 2016). Additionally, rainfall during the dry season can speed up decomposition by microbes. Farmers mentioned that ridge making increases nutrient release and distributes soil fertility. This combination of positive attributes of mulching and ridge making has led to farmers incorporating residues in ridges. The aeration of soil during tilling incorporates residues and air in the soil, where there are many decomposing micro-organisms (Bot and Benites, 2005; Walters et al., 1992). The practice of incorporating residues and oxygen in ridges speeds up the short term decomposition and decreases long term accumulation of organic matter in the soil (Bot and Benites, 2005; Walters et al., 1992).

The role of legumes in intercropping or rotation systems was received positive evaluations by farmers. They observed that legume rotation or intercropping improves soil fertility through replenishing nutrients so the next crop growth is 'good'. They indicated that the crop colour being increasingly green as opposed to yellow showed this improvement, which can be connected to improved nitrogen levels (Snowball and Robson, 1991). In previous studies, total N was higher in CA treatments compared to conventional practices after 2 and 5 years (Mloza-Banda et al, 2014, 2016).

The results of our study show that only the CA treatments with legume intercrop significantly increased total soil N contents, which was confirmed by farmers' observations on the impact of crop diversification. This is expected as legumes are known to fix atmospheric N and Myaka et al. (2006) had reported that maize-pigeon pea intercrop can contribute up to 60 kg N ha^{-1}. The high quality of legume residues may reduce the C:N ratios of CAML thereby preventing temporary N immobilization by the soil microbial community (Adu-Gyamfi et al., 2007). The forms of inorganic N species available to crops were significantly higher in the CP than the CA systems. According to the farmers, the practices of ridge-making aerates the soil and redistributes soil nutrients. The higher available N levels in CP support this farmer perception. However, the overall yield results show higher grain yields in CA systems.

4.1.2. Infiltration, moisture & structure

This study showed that after 10–12 years of CA, there was significant

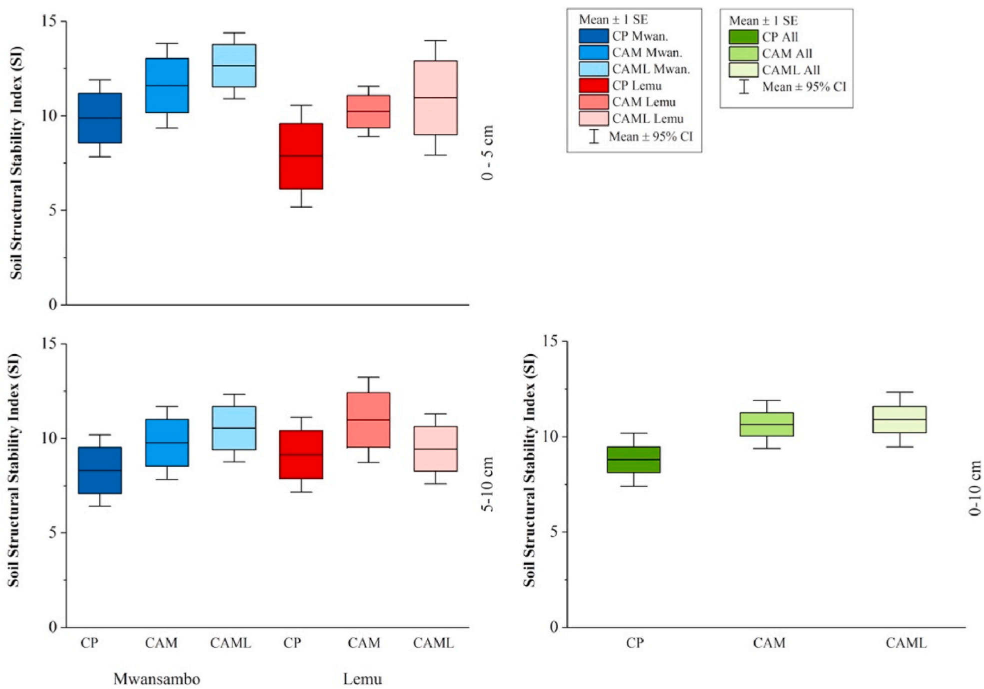

Fig. 6. Soil structural stability index for Lemu (red) and Mwansambo (blue). Dark colour represents conventional treatment (CP), middle colour represents conservation agriculture with maize only (CAM) and lightest colour represents conservation agriculture with legume intercropping (CAML). Green colour shows the results for the data of the two communities combined. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

improvement in moisture and infiltration, particularly at Lemu with sandy soils. The impact of ridge-making on infiltration received both negative and positive observations. Our soils data did not show a difference in bulk density and demonstrated higher infiltration and yield under CA. This suggests that there may be discrepancies between farmer observations and soil measurements on the outcomes of ridge-making. Previous studies have shown that besides residue retention and higher associated biological activity leading to higher infiltration and that no-till practices also lead to changes in pore size distribution which improves infiltration (Bescansa et al., 2006; Thierfelder and Wall, 2009).

Farmers' observations based on the soil structure exercise showed that soils under CA are softer, better structured, stable and have more easily breakable aggregates compared to CP. Farmers also commented that soil erosion decreased due to residue protection and the soil not being disturbed with a hoe. Marginal improvements in soil structural stability index have been reported in previous studies of Malawian on-farm trials after 4–5 years of CA practice (Mloza-Banda et al, 2014, 2016). Improvement in soil structural stability index was found after 10–12 years of CA at on-farm trials, which support the farmer observations and yield outcomes.

4.2. Integrated approach for soil health assessment

In this paper we have presented a stepwise framework for the integrated field assessment of soil health in CA systems, enabling the integration of local and scientific knowledge sources. These steps involved (1) discussing CA's impact on soil health with farmers; (2) identifying farmer soil health indicators and comparing these with literature, (3) taking soil measurements of the indicators with the help of farmers at the on-farm trials; (4) discussing the soil measurements results and their connection to farmer observations. It is important to reiterate these steps in a learning process and assume an equal importance of both knowledges. This process can be applied across contexts to support a more comprehensive and robust understanding of dynamic and complex agricultural systems, including assumptions and ambiguities (Mairura et al., 2007; Prudat et al., 2018; Raymond et al., 2010). Our findings show that there is value in the broader application and institutionalisation of such integrated learning and assessment processes, to enable technology adaptation to context and understand the role of soil health within farmer decision making. Whilst caution is required against taking context-specific findings from individual applications of such assessments and generalizing or scaling those findings across space and time, our insights do show that the process of integrated the approach is valuable and can be used in other contexts.

Soil health is one component in the complex decision-making process of agricultural practice adoption (Andersson and D'Souza, 2014). Other socio-economic factors such as labour, resources and social acceptability and dynamics also play an important role within this multifaceted decision-making (Hermans et al., 2020b). CA is however, promoted for its potential to improve soil health and to increase or sustain yield in the long-term. It is important to understand if farmers experience this improvement, or how they view other related benefits in terms of household labour demands.

The enrichment in knowledge on soil health through the integrated approach has shown that certain locally-used indicators are consistent with conventional soil health indicators used in the scientific literature. The process showed that defining soil health from a farmer perspective provided a broader set of soil health indicators, that were subject to defining a 'good' or 'bad' field (e.g. plant and disease indicators). There is particular value in understanding the link between processes and outcomes as described in soil literature and in relation to farmers' observations, which enables the comparison between local knowledge and scientific indices. The improvement of the connection to farmers' experience can subsequently enhance adaptation and uptake of CA and sustainable land management practices.

The integrated approach also improved the understanding of farmers' land management decision-making, and the role of soil health knowledge in this process. The local experience of process and outcomes has resulted in the inclusion of residues in the conventional practice of ridge making. This adaptation challenges the comparison of soil C in conventional and CA systems. Whereas our measurements and farmer indicators show a structural improvement under CA practices such as minimum tillage, the integrated knowledge and methods process reveals mixed observations and understanding on the impact of ridge-making on the soil. CA's positive impact on soil erosion was clear, but simultaneously there is an association of ridges positively affecting soil fertility and aeration. These outcomes are dependent on field context, for example, hillsides are more susceptible to erosion than flat land. The trade-off has led to farmers' adoption of planting on old ridges or banking after the rains, in which case the soil is still mixed, aerated and softened, but erosion is reduced and the soil does not become hard. The integration, comparison and exploration of local and scientific knowledge has enriched our understanding of CA's impact on soil health and farmer evaluation, and soil health prioritization. Both the local and scientific forms of knowledge add to the overall understanding of CA performance and the drivers or processes explaining the outcome ('why does it work here?').

The process of learning across local and scientific knowledge does have limitations. One main concern is that not all local indicators and scientific soil health literature map onto one another. Some of the local indicators do not capture the long-term dynamics or soil health sensitivity. The decision, for example, to incorporate residues into the ridges because of the knowledge on residue benefits does not consider the potentially long-term degrading effect on soil C due to faster decomposition. The indicators used by farmers cover a wider set of parameters including various proxy indicators (e.g. yield, crop strength, cob/pod size, growth speed), but they do not reveal specific processes. The translation of indicators to measurements also creates challenges due to the different set of words in the local language for describing soil dynamics (e.g. 'adding salt'), which can influence the interpretation of recorded responses.

Some measurements, such as C and N require analysis in a laboratory and need to be taken out of the community context. This makes it important to include iterative cycles of assessment, interpretation and discussion without assuming one knowledge is more important than another, as part of mixed methods or participatory monitoring approaches. Two-way feedback with farmers is still frequently missing, but is important to cross check outcomes and consequent decision-making. There are various forms of participatory research and on-farm trials, such as mother-baby trial systems (Biggs, 1989; Snapp and Silim, 2002) or Participatory Action Research (PAR) (Ernesto Méndez et al., 2017). In this study, the on-farm trial design was controlled by researchers, and farmers maintained the trial with assistance and instruction from the extension officer. Farmers participated in sampling on trials and knowledge exchange through the interpretation of soil measurements, whilst the trial set-up has provided the internal validity and robustness needed in agronomic soil research. This addresses some of the concerns about a trade-off between scientific rigour and participation due to the integration of local and scientific knowledge (Reed, 2008). However, this also limits the level of participation, but provides a starting point for further development and discussion.

Previous work conducted in these communities has focused on knowledge transfer which creates a mix of 'old' and 'new' knowledge dependent on information and knowledge access of the farmers. Combining different knowledges requires the researcher's own assumptions to be recognized and addressed in regard to gender differences in knowledge, assumptions in ranking knowledge, the framing of 'scientific objectivity', the presence of a single 'coherent' or individual knowledge, and networks of knowledge (Baker et al., 2019; Ramisch, 2012). The trial farmers have more extensive agricultural experience with CA practices, and information access compared to other farmers. Through involvement of non-trial farmers this was balanced, but this could lead to respondents' bias in terms of explaining the processes and outcomes. The improved understanding of farmer decision-making based on the perception of the outcomes of CA can enhance more widespread CA adoption and local adaptations.

5. Conclusion

In this study an integrated mixed methods and knowledge assessment approach was developed and implemented to evaluate soil health impacts of Conservation Agriculture (CA). A stepwise framework enabling the learning across local and scientific knowledge sources is presented: (1) discussing soil health impact with farmers; (2) identifying and comparing farmer and literature soil health indicators, (3) taking soil measurements (of indicators) with the help of farmers; (4) discussing soil measurements results and farmer observations. The learning across knowledges requires iteration of the various steps to avoid knowledge ranking and to reflect on assumptions.

The translation of farmer-derived indicators to soil measurements showed that some indicators link directly to key conventional soil health indicators such as soil C, N, structure, soil moisture and infiltration. Soil health measurements and farmer observation showed that CA mainly leads to significant improvement in infiltration, soil structure and yield. In the conventional practice, higher exchangeable ammonium, nitrate/nitrite values were recorded, which corresponded with farmers perception of ridges redistributing nutrients. The combination of farmer observation and soil measurements highlights some discrepancies, notably in relation to ridge-making. The perceived benefits of residues (e.g. in terms of C) and ridges as redistribution nutrients has led to the popular practice of burying residues in ridges. Such discrepancies can identify the reasons why farmers make certain contextualised land management decisions such as continuing making laborious ridges.

The development and implementation of an integrated approach to understand CA's impact on soil health is valuable in providing a wider evidence base and contextualizing soil health data. Whereas the aim is not to generalize or upscale local knowledge in itself, the learning process can be generalized to facilitate technology downscaling (e.g. CA adaptation and adoption) into a local context and to understand the role of soil health within farmer decision-making. The co-generation of knowledge on soil health has the potential to increase the knowledge engagement, ownership and trust relations , thereby enhancing the adaptation of CA and sustainable land management to local context.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112192.

Credit author statement

Conceptualization: TH, AD, SW, CP, CT; Methodology: TH, AD, CL, SW, SE, CT; Formal analysis: TH, SW, SE; Investigation: TH, SE; Resources: TH, AD, CT; Writing – original draft: TH; Writing – review & editing: AD, CL, SW, SE, CT; Visualization: TH

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