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Soils, Science and Community ActioN (SoilSCAN): a citizen science tool to empower community-led land management change in East Africa

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Abstract

Pastoralist communities worldwide face complex challenges regarding food and feed productivity. Primary production systems are under stress, nutritional choices are changing and the relationship between development and agriculture is undergoing profound transformation. Under increasing pressure from climate and land use change, East African agro-pastoral systems are approaching a tipping point in terms of land degradation. There is an urgent need for evidence-led sustainable land management interventions to reverse degradation of natural resources that support food and water security. A key barrier, however, is a lack of high spatial resolution soil health data wherein collecting such information for each individual community is beyond their means. In this context, we tested whether bridging such data gaps could be achieved through a coordinated programme at the boundary between participation and citizen science. Key outputs included a community-led trial of a hand-held soil scanner, which highlighted a range of positive benefits and practical challenges in using this technology in this context, with identification of some potential solutions; and a targeted soil organic matter and nutrient status dataset in a small catchment-based community setting. The results show that if the practical challenges can be resolved, use of portable soil scanner technology has the potential to fill key knowledge gaps and thereby improve resilience to the threat of land degradation through locally responsive farmer and community decision-making.

1. Introduction

1.1. Rationale and aim

Land degradation is a global issue that is occurring in all parts of the world, negatively affecting soil health, biodiversity and ecosystem services that are vital to life on Earth and sustainable well-being. Land degradation negatively impacts more than three billion people, costing the world an estimated loss of more than 10% of the Global Domestic Product per annum (IPBES 2018). Healthy soils are the foundation of sustainable food production, underpinning regional food security. Yet levels of land degradation alongside wider socioeconomic and environmental challenges threaten the productivity of many regional agricultural systems worldwide (Pimentel and Burgess 2013).

Land degradation is increasing in severity and extent in many parts of the world, with more than 20% of all cultivated areas, 30% of forests and 10% of grasslands undergoing degradation (FAO 2008). This calls for urgent and concerted action to avoid worsening land degradation and biodiversity loss in the face of population growth and unprecedented anthropogenic and climate-related change (Cowie *et al* 2018). While the unsustainable management of crop and grazing lands (amplified by limited access to up-to-date data and technologies) is currently the most extensive direct driver of land degradation, climate change has exacerbated the impacts of soil erosion and thus limits options for addressing challenges of land degradation (Blake *et al* 2018, IPBES 2018). Although land degradation issues may be addressed through institutional, policy and governance mechanisms, these mechanisms are often missing accurate and locally accessible soil health data, so may fail to address the ultimate causes of land degradation.

Recent United Nations Convention to Combat Desertification (UNCCD) and FAO Land Degradation Neutrality ambitions have called for action to halt current levels of soil degradation by promoting sustainable soil and land management to lift communities out of poverty and ensure healthy populations (Bot and Benites 2005, Cowie *et al* 2018). Translation of these ambitions for resource-poor East African farming communities, however, poses many challenges (Bouma and Mcbratney 2013). Socio-economic and cultural transitions, driven by population growth, political upheaval, changes in markets, land tenure change, and migration put unprecedented pressure on the natural resources that support food and water security (Wynants *et al* 2019). Primary production systems are under stress, nutritional choices are changing (Chege *et al* 2015) and the relationship between development and agriculture is undergoing profound transformation (Homewood *et al* 2009).

Soil organic carbon (SOC) is of fundamental importance to soil health, exerting important controls on soil functions including moisture retention, aggregate formation and nutrient cycling (Lefèvre *et al* 2018, Stewart *et al* 2020, Taylor *et al* 2021). SOC is, therefore, widely accepted as a key indicator of soil health (Liniger *et al* 2011). Access to up to date and accurate SOC data as a proxy for soil health would support the mission to reduce and reverse soil degradation, but such data is not readily available to the majority of smallholder farmers and pastoralists in these contexts. Establishing the data that can address underlying causes of land degradation provides local and global communities as well as policymakers and practitioners with the information needed to develop appropriate responses.

Whilst farmers possess detailed local environmental knowledge on climate and weather patterns, they often lack in-depth scientific knowledge and capacity to evaluate soil health. Most farmers rely on visual indicators of soil health, such as texture and colour, which provide a rather broad indication of soil condition and are often not effectively utilised in soil management decisions (Eze *et al* 2021). Recent advances in mobile phone application technology aim to improve the use of visual indicators by guiding farmer-led assessments and providing decision support on a site-specific basis (Quandt *et al* 2020). To complement visual assessments, the development of portable instrumentation has enabled high spatial resolution data to be obtained for important soil health parameters, including SOC (Visser *et al* 2020). Near infrared (NIR) spectroscopy has been shown to be an effective tool for measuring SOC in African soils (Recha *et al* 2021), with portable NIR devices capable of providing rapid, *in situ* data to inform soil management decisions (Amasi *et al* 2021). Access to these data would enable smallholder farmers to implement more complex sustainable soil management actions and potentially achieve higher yields alongside protecting their land against soil erosion. Novel agricultural technologies, such as portable soil scanners, provide opportunities to address these soil health challenges in partnership with citizen science participatory approaches (Van Beek *et al* 2018, Visser *et al* 2020). The ability of portable soil scanners to quickly deliver *in-situ* data on multiple soil health indicators allows farmers to measure, report and verify sustainable land management outcomes for wider community and regional benefit (Amasi *et al* 2021).

1.2. Citizen science as a tool to manage land degradation

In this research, we work from the premise that '*citizen science is a rigorous process of scientific discovery, indistinguishable from conventional science apart from the participation of volunteers. When properly designed, carried out, and evaluated, citizen science can provide sound science, efficiently generate high-quality data, and help solve problems*' (Mckinley *et al* 2017, p 15). Our ongoing participatory soil erosion research in northern Tanzania (Kelly *et al* 2020, Blake *et al* 2021, Taylor *et al* 2021) has highlighted an urgent need for accessible technology to assess soil health parameters, to enable communities to design long-term soil erosion repair and rehabilitation plans, alongside sustainably increasing crop yields to maintain precarious livelihoods. Use of a hand-held soil scanner provides a key opportunity to work with one Tanzanian community to test the applicability and utility of the technology in a process of 'collaborative citizen science', as defined by Pocock *et al* (2018). In this respect, our work moves away from traditional scientist-defined 'research needs' towards a more open approach where farmer-citizens begin to define their own farm-specific research needs and have the space to explore opportunities for experimentation and innovation.

Our previous research in northern Tanzania has shown that soil erosion is a civic as well as a practical problem (Wynants *et al* 2019). In rural East Africa, many roads, trackways and community spaces are surfaced with soil. Gully and riverbank erosion can sever roads and undercut bridges, disconnecting villages from access to main roads so hindering trade in both produced goods and consumed products (Blake *et al* 2018). In the rainy season, soil sticks; it cakes hooves, boots, shoes and tyres. The problem is not limited to those engaged in agriculture; it is a challenge for the whole community and from our past research (Kelly *et al* 2020), it is clear that every individual in the community has a stake in finding sustainable solutions. Further, our ongoing social science work has highlighted a critical gap in that local scientific understanding of soil components is needed to effect lasting change.

Although accessible and portable scanning technology can enable farmers in low resource settings to collect data and establish databases that support critical landscape decisions (Burton *et al* 2020), AgroCares found in a recent evaluation of their NIR soil scanner that despite positive experiences of using the device, uptake and engagement was less than expected (Van Beek *et al* 2018). Interviews with Kenyan farmers from a number of diverse co-operatives using the scanners revealed several critical 'non-technical' challenges. These challenges were linked to, among other things: (a) lack of farmer awareness of the importance of soil testing and wider benefit of research that they would deliver into; (b) lack of sufficient data available to Extension Officers and lack of expertise to enable them to provide specific and tailored advice based on scan results; (c) challenges finding and retaining 'champions' or early adopters to actively disseminate experiences and promote the use of agricultural technology as a citizen science tool; (d) a lack of ownership and engagement with technology, perceived as purchased with external donor support; and (e) lack of technical support and ongoing training for maintenance and repair of equipment (Van Beek *et al* 2018).

Our research was co-designed and trialled as a citizen science approach that could overcome these barriers to community-generated soil health data (Pocock *et al* 2018). Using our past experience, we also envisaged wider impacts through embedded citizen learning and development opportunities that these technologies might offer in future to integrate marginalised groups in agro-pastoral communities, such as women farmers and younger generations, into a shared community aspiration for evidence-based sustainable land management (Bonney *et al* 2009, Buytaert *et al* 2014, Mckinley *et al* 2017, Turrini *et al* 2018, Head *et al* 2020). Working in agro-pastoral landscapes of Tanzania, the aim of this study was to explore community-led solutions to soil degradation by developing and trialling citizen science protocols for community diagnosis of soil health using nutrient status, SOC content, cation exchange capacity (CEC), and soil textural class within erosion risk frameworks from prior research (Blake *et al* 2021). Farmers, along with NGO partners, are our citizen scientists and both groups have had critical input into the design and delivery. Using the handheld soil scanner, we tested the potential for using soil scanners as a tool for mapping farm-to-community soil health characteristics, to deliver research that empowers stakeholders to create a sustainable community landscape plan. By using a 'collaborative citizen science' approach (Pocock *et al* 2018), our research also aimed to realise the potential for a shift in power towards the farmer-citizen; generating research needs priorities from inside the farm rather than from outside; and supporting multi-directional knowledge flows with clear legacy benefits for inter and intra- and cross-community learning and research (Chambers *et al* 2021).

2. Methods

2.1. Research context

Our research programme was undertaken in partnership with an agro-pastoralist community in northern Tanzania, where all citizens have a stake in soil erosion challenges in their everyday lives. The village of Emaerete in Monduli District has been a key partner in the Jali Ardhi suite of projects, since its inception, and the project team has a trusted working relationship with the community, District Council and local sustainable land management NGOs (See, for example, Blake *et al* 2018, 2021, Kelly *et al* 2020). The village is also located in a headwater catchment dominated by agricultural lands in the upper areas, and rangeland in the lower areas (Blake *et al* 2021). Achievement of our research aim was structured around three specific objectives; (a) to introduce a farmer-led opportunity to test portable agricultural technology in one specific community context; (b) to provide smallholder farmers with practical 'hands-on' sessions to test the kit; and (c) elicit views on the wider applicability of this type of agricultural technology in low-resource settings.

2.2. Portable soil scanner technology and soil scanning

During this study, soil quality data was obtained in the field using the AgroCares portable soil scanner (Device name: SC_203d, Serial No. 5052G41NA). Guided by the associated mobile phone app, and following manufacturers guidance, the scanner was calibrated by putting it on a yellow cap (once a day) and a white reference cap (after every sample), both supplied with the scanner. For each selected sample

Figure 1. Working with citizen scientists to create new knowledge through new technology. Source: Authors.

location, a composite sample (10× top 5 cm) was collected with a hand trowel in a bucket following (Amasi *et al* 2021). Stones and vegetation were removed, and the sample was mixed. A subsample was collected in a sample tray (grey, PVC, cylindrical: 10 cm diameter and 5 cm depth), and the scanner was placed firmly on top of the subsample. The AgroCares soil scanner has a central light source (8× Tungsten lamps Bulb, 150 mA, 5 V) that shoots out light throughout the sample in each scan. The reflectance of the light from the container is captured using a Near Infra-Red Spectrometer (Range: 1300–2550 nm MEMS technology (Shepherd and Walsh 2007)), and the electrical conductivity is measured using six probes (alternate bi-polaire EC 1 kHz). After the scan, the subsample is mixed back in the bucket, the scanner is cleaned, and a new subsample is collected from the bucket for analysis. For each sample, five subsamples are analysed to account for variability in the soil due to aggregates. The resulting spectral signature from the five scans and EC measurements are subsequently converted to soil quality parameters using the AgroCares algorithms. These are specifically developed for Tanzanian soils by comparing spectral signatures of scans with standardised laboratory measurements of the same soils (Van Beek 2019). The conversion algorithms are built using machine learning and are constantly updating as more scans are being performed (Van Beek *et al* 2018). However, because these algorithms are the core aspect of the technology, they are subject to intellectual property and are therefore not open access. An accuracy assessment (comparing with standard laboratory analysis) done by AgroCares shows that the classification accuracy of the scanner ranges between 68.4% for total phosphorus (TP) and 80.2% for total organic carbon (TOC). Especially for samples that fall outside the ranges of typical farmland soils, the performance of the scanner decreased rapidly (Sarjant and Tomczyk 2022). However, the soil scanner scanner performs much betterfor determining the relative differences in soil quality in the highly complex Tanzanian setting.

Through the associated app, a rapid assessment of the following soil characteristics is obtained: pH, soil texture class, TOC (g kg^{-1}), total nitrogen (TN; g kg^{-1}), TP (g kg^{-1}), total potassium (TPo; mmol + kg^{-1}), and CEC (mmol + kg^{-1}). This hand-held soil scanner can enable farmers to become citizen scientists empowered to collect data to establish research data bases that support critical landscape decisions (Ewing *et al* 2021). This offers a step change from existing piecemeal, often commercially driven data gathering by external actors (figure 1). Using the AgroCares device employed in this study, results can be seen in real time (via a mobile device app), allowing farmers to test in-field variation and soil health.

2.3. Research process

This research was structured in three stages (an initial workshop; a testing programme; and an evaluation workshop), each tackling a key project objective. All elements were conducted in Swahili. The first stage was an open workshop and round-table discussion event that included community leaders, farmers, Agricultural Extension Officers and District Council land management staff. In total, 17 participants attended the workshop (6 female, 11 male). The workshop discussions were audio recorded and subsequently transcribed and translated into English. The purpose of the workshop was to introduce the soil scanner, explore its potential as a citizen science tool and co-design a community testing programme (Objective 1). To achieve this, the workshop was split into three parts: (a) 'what is a soil scanner?'; (b) 'what do you think of it?'; and (c) 'how should we test it?' (See table 1). In part 1, the operation of the soil scanner was demonstrated, and its potential uses explained in relation to this community context. Participants were invited to try out the scanner to see how it felt and learn how to connect it with its smartphone app. Afterwards, an open discussion was initiated by asking participants what they felt about the scanner; whether they could foresee a use from their own specific perspectives; and whether they felt that there were any practical or gender-based barriers to using it in their community. In the final part of the workshop, participants were asked to suggest where and how could it be tested to explore wider potential uses as well as possible issues (Objective 2). The participants decided to nominate one of the Village Officers

Table 1. Workshop 1 structure: introducing the soil scanner and testing programme.

1. What is a soil scanner?	
Topic to be addressed	Key questions
Explanation of what a soil scanner is	What is soil organic matter (SOM)/what does this machine measure?[a] Why is SOM important to me as a farmer and/or pastoralist? What can I do with the SOM data/other data produced?
Introduce the soil scanner	How does it work? How does the data app work and how does it integrate with the scanner? What do the readings/data mean? What is the data telling us? How do we use this information? What else could we do with this information?
Have a play with the scanner	Try and ensure everyone has a go, especially those who are hanging back/shy/hesitant/nervous of it
2. What do you think of it?	
Topic to be addressed	Key questions
What do you think of it?	Separate views on the scanner and on the app? Is it possible to use the app with the phone you have? How useful is it likely to be to you specifically? What was particularly good about it/what did you like? What was not very good/what did not you like? What would you change about it? Is there anything that would make it easier to use? Was there anything about it that worried or confused you? What about practical issues? Is it heavy/cumbersome to use? What about power and recharging—would you be able to recharge/repower it easily? Does it work with everyone's phone? Any other practical good or bad points?
3. How should we test it?	
Topic to be addressed	Key questions
How would you use it?	Identify what specific uses this community would have for the scanner; how long each user would need it; and how often in a year
How do we test the potential barriers?	Ask them to think about potential barriers, and see if there is a way to test those barriers (i.e. would women farmers feel comfortable enough to use it?)
Who else might be interested in using it?	For future testing (not within this plan), identify other types of users who might be interested in using the scanner (other communities; other types of users, like NGOs, schools, community organisations, the District Council etc)
Who will test it?	Using the information and discussions above, identify the individuals who will be invited to use the scanner and help deliver the testing programme Ask for a volunteer to help co-ordinate the testing process. This person should help identify who can help test the scanner. They also need to help co-ordinate the data collection from the trial: • Natural science data produced by the scanner • Social science data on ease or otherwise of use, any issues, and their views and perspectives on its usefulness

[a] We use TOC in this manuscript because that is what is reported by the scanner. However, Agricultural Extension Officers in the study area already use the concept of SOM and % in their advice to these farmers, so this term was used during the participatory work, hence its use here.

(a community member) to lead the co-ordination of the scanning trial. All those participants who wanted to trial the soil scanner left their contact information with the Village Officer. Moreover, it was also agreed that any community members who were not present at the meeting could contact the Village Officer if they wanted to participate in the trial.

Figure 2. Community soil scanning. Source: Authors.

Once the trial programme and sample locations had been designed and agreed with the community, the research team was guided around the village by the Village Officer. The sample locations were visited on foot and scan measurements were made by farmers, supported by the research team (figure 2). In addition, the team walked most of the trails in the area, so that farmers who were out working on their land could also be approached and asked if they would like to participate, enabling the inclusion of those who had not participated in the original workshop. Farmers chose the scanning locations on the farms themselves which was, depending on the size of their farms, mostly done in two or three areas of differing productivity, either in the same, or in different fields.

Initial feedback on relative soil quality (compared to regional parameters) was obtained on the smartphone from the AgroCares application. As the management advice provided by the app is not related to any specific socio-economic context, and the aim was to pilot the scanner as a citizen science tool, we provided the farmers with some additional context-specific guidance around the interpretation of the data. Farmers were invited to a follow-up meeting where they would be given more context-specific feedback on soil health. As a reference, a number of scans were also performed on the communal rangelands in the village. Once all scans were completed, the raw data was downloaded from the online portal and then integrated within existing land cover and erosion risk maps (obtained from a drone survey during previous research (Blake *et al* 2021)). The resulting maps provided a spatial representation of soil health in the village. This spatial representation of the data allowed for an easy comparison of soil health within fields and farmsteads. Based on the outcomes of the drone survey (Blake *et al* 2021), the village was also grouped into 5 zones (C-G) based on erosion risk, and land use and topography (figure 4). Zone C was a mixture of farmland and rangeland; Zone E was lowland rangeland; Zones D and F were upland farms; and Zone G were homestead farms. This zonation allowed quantitative comparison of soil health parameters between the different areas of the village using Student's t-tests.

The final stage in the research process was to gain feedback from participants on the practical use of the scanner, and the value and usefulness of data generated (Objective 3). A follow-up workshop was set up, to which all interested participants were invited, including those who had participated in the scanning programme. In total 25 people participated (9 female, 16 male). Printed aerial drone maps of the village were used by the research team to illustrate the spatial pattern of sampling locations and provide context to the results. Farmers whose land was tested were (privately) given the results of the scan data for their farms. The workshop was structured around gaining information about the usefulness of data produced; the potential to scale up the use of portable soil scanners; and, more generally, the value of this type of portable technology to other communities and other agricultural production contexts within Tanzania (table 2 below). Discussions also focussed on governance (equity of access) and economic sustainability of the technology and its

Table 2. Workshop 2 structure: opportunity for feedback on scanner and test programme.

Topic to be addressed	Key questions
Introduction/recap on use and potential value of soil scanner: Recap on what the soil scanner is, how it works, and how the data it generates can be used. *Resources:* Demonstration of scanner use	This will provide another opportunity for people to ask questions about the scanner. It would be helpful to know who got to see the soil scanner in action. Are their people who did not get the chance? Are there people who would be keen to know about the scanner but have not had the opportunity?
Feedback on data collected by soil scanner: Share the information collected about soil health at each of the sample points. *Resources:* *Map* to indicate results at each of the points sampled. For each sample point the map could also show the target levels that community should be aiming for. *SOC information and 'Top tips'* with information about results shown on map and what different figures mean for soil health, plus information for participants about top 5 things they can do to help improve their soils.	How useful is the information generated through the scanning process? Would people use this information to make decisions about soil management? Where else in the area would they like to do soil sampling?
Pros and cons of using soil scanner: Participants thoughts about the value of using the soil scanner. Use table of benefits and disadvantages of scanner as a means to prompt discussion.	If they had the right external support (e.g. smartphone access and other technical support), would they be keen to use the soil scanners in the future? Would using the soil scanners change the way that they engage with the Agricultural extension workers? How might this be beneficial? Could they link information generated from the soil scanners to the existing land use plan for the community? How might this be of benefit to them in that respect?
Looking ahead—practical/technical support to facilitate use of soil scanners: Exploration of needs to support use of the soil scanners in the local community. Suggest possible future scenarios to help think about the possible pathways/processes: e.g. Local NGO raises funds to buy a soil scanner, trains staff to use it, and offer community access or train locally and loan to farmers (for a small charge).	What types of external support and resources would be critical to ensure that they would: • use the scanners; • be able to interpret the data; and • adjust soil management practices based on the evidence generated (e.g. turn the data from the scanner into better decisions about when and where to add fertiliser)?
Wider community involvement	Are there any wider opportunities or benefits as a learning tool for the community, or for local schools?
Wrap up/any other issues to discuss Talk about work being taken forward through other Jali Ardhi activities and other external partners in the community	Is there anything else that people would like to share or ask about this soil scanning project? Is there anything else going on the community that they think might be helpful in tackling soil erosion and soil health? Any other questions for the research team?

potential as an income-generating stream for farmer co-operatives in general.

3. Results and discussion

3.1. Introducing the scanner to the community

Seventeen members of the community (6 female, 11 male) participated in the initial workshop, where the scanner was demonstrated, and its purpose discussed. The discussion was lively, and included many questions around how the scanner worked, how it might help regarding crop selection and soil health. Contrary to the lack of willingness to engage found by Van Beek *et al* (2018), community members were keen to understand more about the technology, and its potential to support management of both private and community-owned land. A selection of these questions is included in Box 1[a] below.

Box 1. Points raised by the community during the scanner introductory workshop.

If I take the scanner to sample at my farm, how can a layman know whether the results are good or bad?

Does the device use its own battery or it needs to be connected to power?

How immediately can a farmer get the report after scanning soil?

We have seen that the results from the device are in English, is there any way that we can set the device to read result in Kiswahili?

The main crops grown in our area are maize, wheat, beans and vegetables. With time the fertility in the soil decreases, so what things can we do to ensure the soil regains its fertility?

You have said that this equipment can help you decide what crops one can grow in his farm. For example, if it tells a crop which is not favourable/relevant in this area say sunflower what can you do?

[a] All images and quotes used in this paper are included with participants' permission.

3.2. Preliminary soil health data

As mentioned in section 2.2, the handheld scanner is a semi-quantitative monitoring tool that provides good representations of relative differences, rather than exact soil chemistry measurements, and the reported results should thus also be interpretated as such.

A total of 42 soil scans were performed on 23 different farmsteads and the communal land spread over Emaerete village (figure 3(a)). The output from the soil scanner highlighted spatial differences in the soil parameters across the area (see table 3 and S.I. 7 of the supplementary data file, figures 3(b)–(d) for TOC, TP and TN, and supplementary information for boxplot presentation for each parameter). The most distinct finding was that degraded rangelands (zone E) had significantly lower Phosphorus, Nitrogen and Carbon contents (TP, TN, TOC) and significantly higher CEC. In areas used for cropping (zones C, D, F and G), TN and TOC seem to show the same spatial trend, with the highest mean value in zone F, whilst TP had the lowest mean value in zone F. The differences in nutrients between the cropping zones were, however, not significant, except for TN, which was significantly lower in zone D compared to zone F. The TPo was also significantly lower in the degraded rangelands (zone E) compared to zone G, but this difference was less pronounced. The relatively lower nutrient content in rangelands may be the result of fertilizer inputs on croplands, different soil types, the higher rates of soil erosion in the downstream rangelands due to flow accumulation, as discussed in (Blake *et al* 2021) or a combination of these factors. Since the scanner did not pick up a difference in soil texture between rangelands and cultivated soils, the significantly larger CEC values of the degraded rangelands might be related to specific differences in clay mineralogy or soil type. This corresponds with field observations of swelling clay in the rangelands. Overall, the soil scanner outcomes did not show any significant differences in soil quality indicators between zones C, D, F and G, even though there were clear differences in land use, topography, and observed rill erosion.

The scanner did appear able to pick up differences in soil parameters on the plot and farm scale (although this was not independently quality assessed). Most farmers used the scanner to test differences in areas where they had previously identified good and bad productivity, which is evidenced in the high variability in the results at the farm level. For example, two measurements were taken at different ends of the same plot (points 13 and 14 on figure 3). This plot is ploughed along the contour and the points are located on more or less the same contour line. At point 13, the pH, TOC, TN, TP, TPo and CEC were respectively 6.15, 29.4 g kg^{-1}, 2.7 g kg^{-1}, 1.2 g kg^{-1}, 11.0 mmol + kg^{-1} and 286.5 mmol + kg^{-1}. In comparison these values at point 14 were respectively 5.6, 17.5 g kg^{-1}, 1.4 g kg^{-1}, 0.98 g kg^{-1}, 9.7 mmol + kg^{-1}, and 219.7 mmol + kg^{-1}. These large differences in soil parameters on the same small plot show that the soil scanner could potentially provide meaningful information on soil quality at the farm level.

As indicated in the Materials and Methods section, farmers often chose to measure two locations with the biggest difference in productivity. As it stands, however, the small number of data points within fields do not allow any robust assessments of soil quality at the farm level. It should be noted that productivity differences were based on farmers' anecdotal experience and this research has not measured actual crop productivity in these specific locations. Therefore, no direct evaluation of the soil quality parameters for predicting crop productivity was done in this study. In order for future citizen science studies to inform soil quality management on the smallholder farm scale, these should aim to increase the sample resolution. Moreover, they should also perform an independent quality assessment, which should focus on the ability of the scanner to pick up relative differences in the soil quality parameters, as opposed to quantitative prediction of soil chemistry. Nonetheless, this trial has demonstrated the ability for farmers to quickly obtain soil quality information at plot scale using handheld scanner technology. This obtained soil information can be particularly valuable in Tanzanian smallholder farming systems,

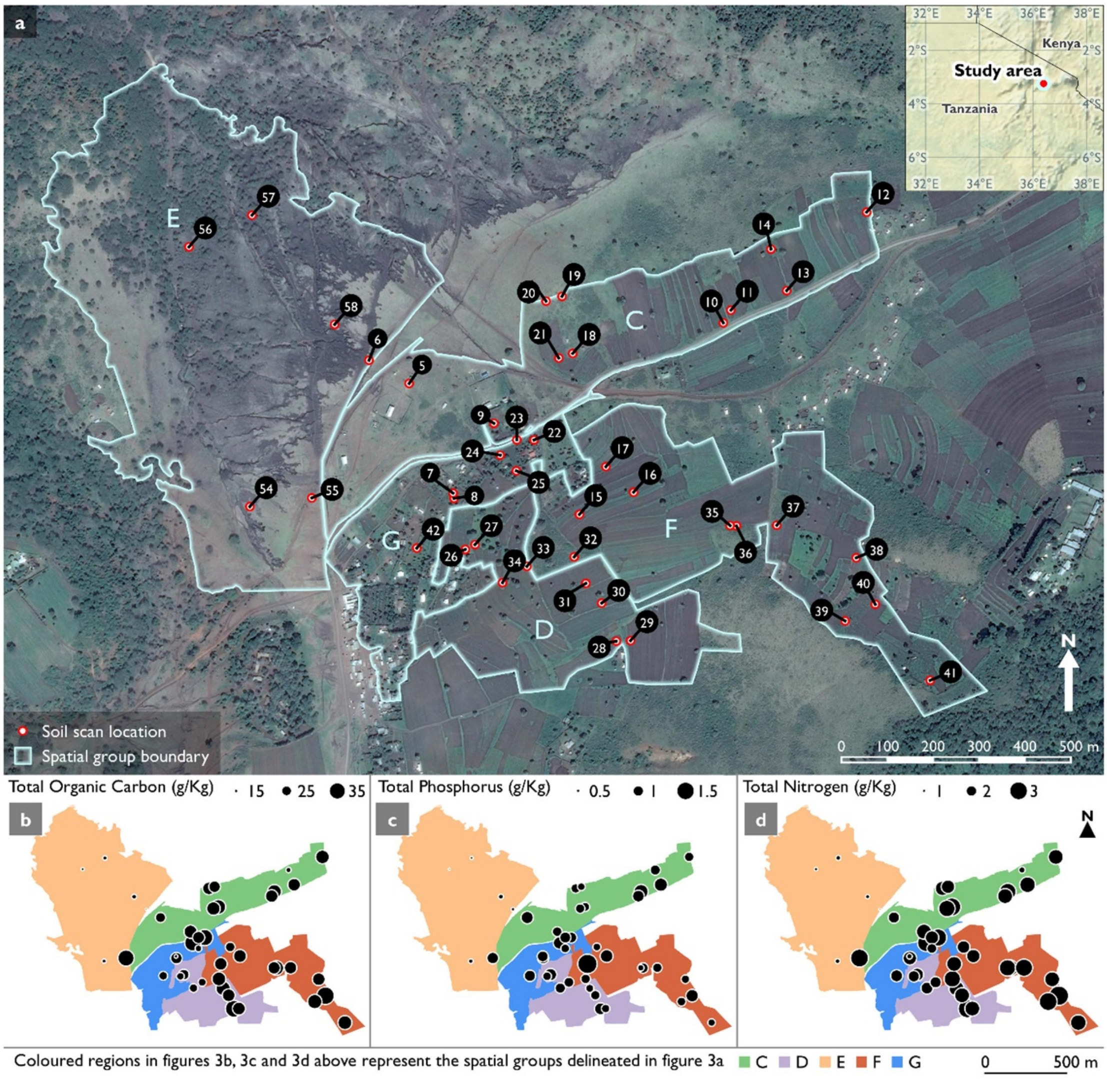

Figure 3. (a) Sample locations for deployment of the scanner within the village zones (see text for details). (b)–(d) are proportional representations of the measured total organic carbon (range: 15–35 g kg^{-1}), total phosphorus (range 0.5–1.5 g kg^{-1}), and total nitrogen (range: 1–3 g kg^{-1}) respectively.

Table 3. Results: summary of scanning results represented as mean ± standard deviation. Significant differences are indicated with superscript letters, wherein different letters indicate significant differences, and letter combinations indicate no significant difference with the overlapping letter. The *p*-values can be found in S.I.7.

Zone	n	Soil texture	pH	TOC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TPo (mmol + kg^{-1})	CEC (mmol + kg^{-1})
C	11	Clay—Clay loam	5.95 ± 0.32^{ab}	28.55 ± 4.13^{a}	2.50 ± 0.43^{ab}	1.01 ± 0.14^{a}	11.49 ± 2.21^{ab}	245.34 ± 40.53^{b}
D	8	Clay—Clay loam	5.66 ± 0.35^{b}	25.76 ± 5.53^{a}	2.26 ± 0.32^{b}	0.91 ± 0.11^{a}	10.12 ± 2.85^{ab}	245.44 ± 54.35^{b}
E	5	Clay—Clay loam	5.57 ± 0.32^{b}	15.04 ± 1.89^{b}	1.06 ± 0.17^{c}	0.51 ± 0.09^{b}	9.64 ± 1.44^{b}	381.80 ± 81.25^{a}
F	11	Clay—Clay loam	6.04 ± 0.38^{a}	30.50 ± 3.05^{a}	2.74 ± 0.26^{a}	0.99 ± 0.25^{a}	11.23 ± 2.31^{ab}	235.23 ± 34.92^{b}
G	7	Clay—Sandy clay loam	5.83 ± 0.28^{ab}	26.31 ± 7.41^{a}	2.29 ± 0.56^{ab}	1.03 ± 0.07^{a}	11.81 ± 1.84^{a}	215.66 ± 38.92^{b}

where there is often a lack of targeted agricultural advice, and high variability in soil characteristics and other environmental factors (Wynants *et al* 2019).

One particular benefit of scanner use identified in this pilot study is the measurement of SOC, as it is widely recognised that SOC is pivotal for soil health, and that this valuable resource has shown decline under intensive agricultural systems in Sub-Saharan Africa (SSA) (Pabst *et al* 2016). SOC underpins a range of functions such as maintaining healthy soil structure and moisture, enhancing CEC, pH buffering, and provision of nutrient pools and microbial diversity (Obalum *et al* 2017). It follows, then, that loss of SOC can lead to physical, chemical and biological degradation. As such, building and maintaining healthy SOC pools is acknowledged in the UNCCD as essential for underpinning soil ecosystem services and achieving global Sustainable Development Goals (SDGs) (FAO 2017). Given that SOC can be impacted by land use, and the importance of site specific factors upon SOC formation and storage (Swanepoel *et al* 2018), our study shows that targeted measurements of SOC can be used to inform local-scale land use planning and complement wider measurements of soil health such as aggregate stability and infiltration capacity (Taylor *et al* 2021). At the international level, the project delivers into the UN Food and Agricultural Organisation (FAO) World Soils Charter '*to manage land for long-term advantage rather than for short-term expediency*' (FAO 2015). Aside from providing the essential data on soil health to inform land use, this research has shown that agritech can also provide a shared learning opportunity, raising awareness of the importance of maintaining and enhancing SOC and helping to foster intrinsic motivation to implement sustainable solutions (Head *et al* 2020).

3.3. Community evaluation: data utility and practical challenges

Follow-up qualitative data collection included a workshop with 25 participants (9 female, 16 male), including members of the Village Committee (community leaders); those who had been at the introductory workshop; those whose land was scanned; and those who had not been able to participate in the scanning process but had wanted to. The majority of participants, therefore, had some knowledge of the soil scanner, although for some, this was familiarity with how it looked and what it could do, rather than how it worked. Out of those present, four participants discussed how they had used data from scans of their land during the testing programme, to improve soil health and adapt farming practice. Those who had not participated in the testing programme showed significant interest in learning more about the scanner, and how to improve soil health on their own land. The findings from these discussions are set out below.

3.3.1. Data uptake and use

Workshop participants noted that in most communities in this region, farming techniques and crop selection are dependent on external advice on the use of improved seed varieties and fertilizers provided by District Agricultural Extension workers, or by commercial companies. There is currently little farm- or community-specific tailored technical advice available to determine crop choice based on soil type, profile, or nutrient status, other than general advice on the use of inorganic fertilisers and contour ploughing, for example. Most participants felt that they had had good knowledge of local markets and the potential economic viability of crops, but little knowledge about maintaining soil health through sustainable land use methods, or how to plan longer term approaches to improving soil health.

The workshop discussions showed that combined nutrient and SOC data obtained by the scanner can provide an important basis to guide local land use decisions, particularly with regard to crop type and integrated soil fertility management strategies (Mustaphi *et al* 2019). Maintaining and building SOC not only requires mechanisms to reduce soil loss by, for example, implementing cross contour planting, but also requires the addition of quality organic matter (OM) to the land (Gram *et al* 2020). The latter is particularly challenging in SSA, with biomass often used for livestock fodder at the expense of return to the soil (Duncan *et al* 2016). The type of OM applied to the soil greatly influences SOC fractions, broadly termed active and passive SOC fractions, with the former playing an important role in nutrient cycling (Palm *et al* 2001). Application of crop residues with low nitrogen and higher lignin and phenol content is less likely to build active SOC pools and improve yields when applied in isolation, instead, improving yields is likely to require the addition of quality OM (from legume cover crops for example), which can be readily decomposed to contribute to more rapid nutrient cycling (Palm *et al* 2001, Gram *et al* 2020). In this regard use of the scanner can not only identify areas where SOC is generally depleted but the combined nutrient and SOC information can help Extension Service Officers tailor their advice to develop strategies which foster the application of a range of SOM types for the benefit of soil health and associated yields. The soil scanner can thus provide farmers and practitioners with a tool to adapt their management to address farm and plot-level micro-environmental differences.

In this regard, several participants noted that they had increased crop yields by combining the knowledge generated by the scanning process on their land, with technical advice provided by local agricultural advisory services, to improve their crop selection and soil management techniques (figures 4 and 5). For instance, one farmer pointed out:

> The information from the soil scanner has helped me to understand that the use of industrial fertilizers per se isn't the only solution to better soil management and optimal yield rather than to know what type of crops to farm and what technique to use - for me that was through crop rotation, mulching and the use of farmyard manure.

Another maize and barley farmer pointed to his increased yields (figure 5):

> During past seasons I used to get 4–5 bags of maize per acre using improved varieties of seeds and intensive use of

Figure 4. Changes in practice (mulching and crop rotation with maize and beans) resulting from scanner soil quality data linked to available technical advice. Source: Authors.

Figure 5. Use of farmyard manure and intercropping (beans and maize rotated with barley after every two seasons). Source: Authors.

> fertilizers, but after scanning I […] use farmyard manure and intercropping between maize and beans to increase soil nitrogen and agriculture productivity. Now I am getting 7–9 bags of maize in the same piece of land. However, for barley, this is my first season to rotate farms with maize and beans and by the look of it – I will get high produce.

Evidence provided by these farmers was of particular interest to community members who were not able to participate in the initial workshop. Learning by demonstrating has been shown to be a particularly important and effective tool to encourage farmers to adopt locally tailored SLM techniques (Pretty 1995, Turrini *et al* 2018), so this community-led testing process has provided a key mechanism to show how portable technology can bring wider benefits in enhancing awareness of the importance of soil health for improved yields (Head *et al* 2020). Furthermore, participants highlighted the need for more scanning in other areas of the community, including private and communal land, to provide a comprehensive profile of local soil type and health status in order to update and improve the community's Land Management Plan, and address existing severe soil erosion and land degradation challenges (Kelly *et al* 2020, Blake *et al* 2021).

3.3.2. Technological challenges and opportunities

Citizen science hinges on the right balance between scientific quality and ease of access and use to ensure citizen uptake; and access to data for supporting better land management. In this context, the final

Table 4. Benefits and weaknesses associated with using the scanner and app as identified by researchers and participants.

Benefits	Weaknesses
Light and easy to transport	Requirement of smartphone and good internet connection (connectivity can be poor in this area and few have smartphones)
Scanner battery lasts about 30–35 scans which is usually enough to provide a good level of detail in key areas	Battery needs to be charged for about 10 h, which requires access to power. Phone battery is also drained quickly.
App is relatively easy to use (if there is a good internet connection).	'Easy' for scientists and people with technological experience, not necessarily as easy for resource-poor farmers.
Immediate report by the app, which can be used to give tailored feedback to the farmer	Reports are 'arbitrary' giving a relative soil status against a Tanzanian standard. However, given the highly variable soil system, it would be more valuable to compare with localised standards.
App can work offline (this requires the app to connect to the internet first, where there is good signal, before switching off internet connection)	Report also gives guidance about field preparation (manuring, liming etc) and suitable crops, which can be misinterpreted and/or inappropriate. Suggested plot treatments or crop types may not be feasible due to other factors such as climate and economy.
Farmers are happy to share their phone numbers, which makes it easy to communicate afterwards.	As noted above, many farmers do not have a smartphone, nor internet connection.
Reports can be shared with farmers through informal social media platforms, or can be printed and handed out. Results can also be disseminated at meetings.	
By connecting to a smartphone gps, the app can accurately link the coordinates.	When working offline, no immediate feedback can be given to the farmer.
Soil measurements can also be done off-site, in a place with good internet connection. App gives option to manually enter coordinates or press on a map.	This would require the farmers/scientists either to note down the coordinates of their sampling locations, or to be able to pinpoint it accurately on a satellite map.
'Raw data' can be easily accessed through the soil portal. This information is valuable for scientific purposes.	Available soil data are calculated using algorithms based on the relationships between the IR reflections and wet chemistry performed by Agrocares on selected samples. However, these algorithms are part of their intellectual property and are thus not open access, which makes it impossible for an independent evaluation of the quality.
Data on soil health can be mapped by linking to coordinates	Soil data are in 'Total Nitrogen', 'Total carbon', etc. These are not always useful indicators for available nutrients and soil health.
Farmers can guide measurements in the field. For example to test high productivity areas against low productivity ones.	In-field measurements require farmers to be present and willing to share information on productivity.
An informed community can also guide the measurements at the local scale (comparing different areas of the village/different soil types)	As it stands, the scanner is only partly a citizen science tool. External agents are still required to support measurements and interpret results.

objective for this citizen science research included the opportunity for the community and research team to reflect on the testing programme and provide feedback and recommendations on the wider utility of the scanner and technology. Although many participants recognised the value of having soil health data available to them in real time, and at the field-scale, they raised a number of key challenges. The reflections from community members and the research team are summarised in table 4 below.

In considering the challenges, participants also identified some potential solutions, highlighting how the technology could be integrated with existing expertise available through the District Council and local agricultural and producer networks. For example, although the majority of farmers in the community do not have access to smartphones, some community members do. Participants therefore recommended that selected representatives, such as the Village Committee and local Agricultural Extension Officers could be trained in how to use, read and interpret data from the soil scanner. This would also provide an opportunity for rippling out of wider training, including creating new opportunities for links with local schools and education programmes, creating a network of soil health expertise at the village level (Bezner Kerr *et al* 2019). As a first step, a short course was organised in the local university, where a number of scientists were trained in the use and interpretation of the soil scanner (beyond the scope of this paper) to enable them to continue to use the scanner and train other practitioners. Box 2, below, highlights some specific local recommendations made by participants to increase the utility of the scanner and data produced.

Box 2. Community recommendations to improve the utility of the scanner and associated technology.

It was pointed out that the previous scanning was done in small areas and dispersed households, so the next scanning plan needs to be over a larger area to benefit the whole community.

Re-doing the scanning activity is needed because of the following reasons; first, the soil scanning for those who did not participate in the previous scanning. Second, scanning to a wider area, before and after farming seasons and lastly, the next soil scanning activity should involve all people from the district agriculture department, village leadership to individual households (Boma) for it to have a clear understanding throughout the village.

The village is in dire need of the soil scanner owing to the fact that the land, climate and crops to be cultivated are very varied although found in the same village.

During farming seasons i.e. from November to June, the soil scanner should be placed at the village offices so whoever is in need of the service, it should be readily available.

The use and functionality of the soil scanner should be coached to selected groups so it can be in use even when experts are not around.

During the workshop, it was proposed that the village leadership together with the District Council would select five people, the agriculture extension officer included, to be taught how to use, read and interpret the results of the soil scanner to help them be conversant with the technology. The whole village should know all appointed personnel.

4. Conclusions

Pastoralist communities worldwide face complex challenges regarding food and feed productivity, compounded by climate variation and multi-scalar socio-economic processes (FAO 2015, IPBES 2018). There is an urgent need for diverse evidence-led sustainable land management interventions to reverse degradation of the natural resources that support food and water security (Borrelli *et al* 2017). A key barrier, however, is a lack of high spatial resolution context-specific soil health data, and a lack of knowledge of the importance of soil health for sustainable food and fibre production in this context (Eze *et al* 2021). New soil scanning technology offers rapid assessment of soil health to inform land management decisions (Nocita *et al* 2015) and is a step change from existing piecemeal data gathering by external actors. Using the NIR and visible wavelengths with algorithms developed from machine learning, soil characteristics such as carbon content, pH, nitrogen and soil texture can be determined (Shepherd and Walsh 2007). These tools offer potential new opportunities to underpin local contextual knowledge with scientific data, generating opportunities for citizen science programmes, but a number of challenges exist (Van Beek *et al* 2018).

The results of this pilot study show that in our study communities, there is significant interest in using this technology to support better micro-scale management of plots, and willingness to use the data produced alongside additional guidance from Extension Services, to adopt sustainable land management practices. The workshop evidence also shows that as a citizen science tool, the soil scanner has the potential to support better understanding of soil health status at the farm level. During workshops and scanner trial, we witnessed the development of locally embedded scientific interests and skills, fostering stronger community ownership and engagement in this type of action research. Concurring with Van Beek *et al* (2018), we also found that there remain significant challenges, however, in making this type of technology available in remote communities with patchy or non-existent internet connections. Analysing and interpreting the resulting data also requires input from external expertise, and care needs to be taken to ensure that all resulting advice is appropriately tailored to local climatic conditions, as well as relevant in terms of availability and accessibility of markets for specified crops (Krishnan *et al* 2020).

At a higher spatial level, the data generated during the trial also contributes to soil process and hydrological understanding of Tanzanian landscapes which supports better effective management solutions to regional soil erosion and land degradation challenges. Open-access sharing of these types of data also has the potential to create more robust and better-informed citizen-led soil science programmes, as well as identifying local data gaps (Head *et al* 2020). Further this type of citizen science engagement can expand the utility and applicability of existing techniques and data sets beyond the reach of conventional research (Pocock *et al* 2018).

Author contributions

Conceptualization; Kelly, Wynants, Munishi and Blake; writing—original draft preparation, Kelly, Wynants, Munishi; writing—review and editing, Wynants, Munishi, Blake, Mtei, Mkilema, Ndakidemi, Patrick, Nasseri; funding acquisition, Blake, Kelly, Wynants, Ndakidemi, Munishi, Mtei. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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The authors have confirmed that any identifiable participants in this study have given their consent for publication.

Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Ethical statement

This research has been conducted with full disclosure and permissions from the University of Plymouth Faculty of Science and Engineering Ethics Committee. Consent to participate was collected from all participants.

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