Identification of sustainable land management practices within smallholder agriculture is a challenge. This is partly driven by the challenge of documenting farmers’ perspectives and practices in an integrated manner with site-specific scientific soil assessment. Smartphone applications such as LandPKS provide new approaches to quantify site-specific soil degradation and fertility but are untested with African farm management. We surveyed 578 households in rain-fed maize (Zea mays) production areas of Tanzania using a stratified sampling frame to encompass a wide range of soils and agroecologies. A socio-economic survey and simultaneous sampling in focal plots documented farmer characteristics, perspectives, and management practices, along with soil properties and crop yields. For a subsample of 58 households, we additionally assessed site-specific field status with the LandPKS application. Farmer perceptions of change in soil fertility status were consistent with soil properties, for example, a field perceived to be declining in fertility was also likely to have low SOC (1.8% relative to 2.7% for increasing fertility). LandPKS provided additional novel insights into soil limitations such as identifying poor water infiltration areas consistently associated with farmer use of erosion control practices (water infiltration of 4 mm hr⁻¹ vs 20 all other plots). This charts a way forward to address soil fertility and land degradation challenges through the use of smartphone applications to capture site-specific conditions and farmer concerns as the basis for land management recommendations that are highly relevant and address local conditions.

**Keywords**
- erosion control
- farmer practice
- land management recommendations
- smartphone applications
- soil fertility
bio-physical characteristics, whereas researchers focus on laboratory soil analyses, creating gaps in perceptions. Additionally, researcher recommendations tend to be general in nature and at a coarse resolution, whereas farmer interest is in site-specific and finely targeted advice (Snapp, Blackie, & Donovan, 2003). This has led to calls for improved means to incorporate farmer knowledge into research and extension (Barrios et al., 2006; Norgrove & Hauser, 2016; Oudwater & Martin, 2003). Farmers’ knowledge often involves detailed descriptions of soil types and appropriate management practices by soil or land classification (Oudwater & Martin, 2003). Previous studies have primarily focused on linkages or gaps between farmer and researcher knowledge of soil properties (Oudwater & Martin, 2003). Barrios et al. (2006) identified multiple indicators used by farmers to assess soil quality and erosion, many of which differed from researchers’ indicators due to farmers using multiple site-specific and seasonal indicators versus researchers’ static measurements. Norgrove and Hauser (2016) expanded the findings of Barrios et al. (2006) and sought to inform extension recommendations. These authors noted, however, that their recommendations were not site-specific and had a limited ability to connect local knowledge with extension across farming communities. These studies highlight the limited nature of most indigenous soil knowledge studies and the need for systematic documentation and integration of farmer knowledge.

One area of potential disconnect relates to researchers frequently using a framework that poses questions on soil fertility as a separate category from soil degradation. For example, in Barrios et al. (2006) and in Assefa and Hans-Rudolf (2016), fertility and degradation were separately used to elicit farmer reflections and indicators, and in other studies, soil fertility is considered on its own (Berazneva et al., 2018; Karltn, Lemenih, & Tolera, 2011). Indeed, reviews often focus on just one of these topics and relate this to a set of recommendations, such as soil water conservation practices or integrated soil fertility management (Vanlauwe et al., 2015).

Additionally, agricultural advisors often promote practices based on perceived land degradation and production gaps that do not take into account local perceptions or knowledge, which may differ (Paul & Steinbrecher, 2013). Ramisch (2014) recorded dissonance between scientists and farmers in a community-based project for integrated soil fertility management in western Kenya. He found that addressing differences among groups leads to innovation and improved learning. Bayard and Jolly (2007) provide a theoretical framework that specifically considered farmers’ perceptions of environmental degradation in connection with their attitudes and behavior toward land restoring practices. They positively connected farmer perception of the severity of land degradation with farmer awareness and attitude of the problem, which in turn affected farmer behavior around using land restoration practices. Therefore, for researchers to provide improved agricultural practices, farmers’ current perceptions and practices must first be identified.

To address these gaps, the overall objective of this study was to connect local farmer knowledge around land quality with soil science research and develop relevant recommendations. Specifically, this study addresses two research questions: How do scientific measurements of land fertility and degradation compare to farmer perceptions and use of land management practices? Furthermore, how do Tanzanian farmers’ perceptions of land fertility and soil degradation status influence their practice, for example, land management, to enhance soil fertility and conserve soil and water?

2 | MATERIALS AND METHODS

2.1 | Study sites

This study encompasses agricultural areas in the northern and southern highlands zones of Tanzania (Figure 1). The northern sites (Arusha, Kilimanjaro, and Manyara regions) support a wide range of agricultural systems and have highly variable production potential. The Kilimanjaro region in particular has many agro-ecologies based on varying topography and bimodal rainfall pattern (Table 1). The southern sites (Irvinga, Mbeya, Njombe, and Rukwa regions) are generally at a higher altitude than the northern sites, with the exception of Ruvuma, and on average have greater rainfall and cooler temperatures than the north (Table 1). Across the study sites, there are a wide range of soil types, with areas dominated by Cambisols (Arusha and Manyara), Ferralsols (Kilimanjaro, Mbeya, Njombe, Rukwa, and Ruvuma), Luvisols (Manyara), and Acrisols (Njombe).

The northern and southern study areas were chosen based on a stratified spatial sampling frame based on preidentified areas of interest. This included the main maize producing areas in Tanzania with the aim to sample the range of soil types and diverse agro-ecologies within this country (Andrade et al., 2019). While maize is the primary crop grown in all of these areas, a range of cash crops and legumes are also grown, often as an intercrop or in rotation with maize (Mnenwa & Maliti, 2010). Maize yield potentials vary across regions, with maximum maize yields ranging from 11 t ha⁻¹ (Ruvuma and Mbeya) to 6.64 t ha⁻¹ (Manyara and Irvinga) as indicated by field plot survey measurements collected in this study (Table 1).

To examine farmer perceptions of soil fertility and degradation and identify possible connections between perceptions and current farming practices, a mixed methods approach with multiple primary data sources was used. This included a survey carried out in 2017, referred to as Study 1 Survey, and a follow-up survey in 2018 with a subset of Study 1 Survey households, referred to as Study 2 Sub Survey.

2.2 | Study 1. Survey

A survey with a household socio-economic component and focal plot with questions covering farmer practices on the plot, plus soil and plant measurements, was conducted during the main maize harvest
season in 2017. This study 1 survey was conducted by the International Maize and Wheat Improvement Center (CIMMYT) as part of the Taking Maize to Scale in Africa (TAMASA) project. Detail of the spatial sampling framework was previously reported in Andrade et al. (2019). From this sampling procedure, 75 $1 \times 1$ km grid locations were identified as target areas for the survey. Within each of these grids, a list of all households actively farming land in the grid area was collected and 8 of these households were randomly selected to be surveyed. This resulted in a target of 600 households. The household member interviewed for the survey identified a focal maize plot from which detailed plot management information, soil, and plant samples were collected as described below. The focal plot was defined as the plot within the study grid that the household identified as being most important to their maize production. If a household grew maize on multiple plots within the study grid, the focal plot was identified based on economic importance, often determined based on plot size, location, or intensity of production. The focal plot was identified in the project’s first year based on maize production, and the same plot was revisited in 2017 regardless of whether maize was the primary crop that year. If the focal plot was no longer under maize, the plot level questionnaire was carried out and soil samples taken, but no plant samples were taken.

Both the household and focal plot levels of the study 1 survey included structured questionnaires. The household questionnaire covered socio-economic and agricultural topics such as characteristics of the household landholdings, crop production, livestock, assets, income, and household demographics. The focal plot questionnaire consisted of farmer management questions such as crops grown, inputs applied, agronomic practices used, and history of applied practices on the focal plot. All data collection was done in Swahili by a team of 12 trained enumerators and supervised by the lead author along with CIMMYT-TAMASA researchers.

### 2.3 Soil and plant samples

Plant and soil samples were taken at the focal plots following TAMASA protocols for soil sampling and yield crop cuts. In focal plots where maize was mature, crop cuts were taken from three $5 \times 5$ m quadrats within the plot and total maize harvest calculated per hectare.

Soil samples were collected using a combination auger (7 cm diameter) at 0–20 cm depth by stratified random sampling through sampling at three random points in each quadrat with the final sample consisting of 9 composited subsamples per depth. Samples were
Airdried and sieved to 2 mm. All samples were analyzed for soil chemical properties (N, K) and soil organic carbon (SOC) by infrared (IR) spectroscopy (Shepherd & Walsh, 2007). Soil pH was measured in H2O with a 1:2 soil to water ratio. For the topsoil layer (0–20 cm), soil texture was measured in the laboratory from sieved soil using the hydrometer method (Jasrotia, 2008). Active carbon was measured for the 0–20 cm soil layer using the permanganate oxidizable carbon (POXC) method (Weil, Islam, Stine, Gruver, & Samson-liebig, 2003).

### Study 2. Sub Survey

A subset of study 1 farmers was revisited in 2018 to collect additional data for the purpose of understanding in-depth farmer perceptions of land quality and site-specific characterization of land potential. This study 2 sub survey consisted of a semi-structured questionnaire and focal plot assessment with the LandPKS app (Herrick et al., 2013). The subset of study 1 farmers was chosen with the goal of capturing a comprehensive representation of land types and farmer perceptions.

### TABLE 1  Biophysical characteristics of study sites—Northern Zone sites

| Factors                  | North                          | South                          |
|--------------------------|-------------------------------|--------------------------------|
|                         | Arusha (n = 69)               | Iringa (n = 70)                 | Mbeya (n = 73)               |
| Altitude (masl)          | 1,005–1,523                   | 1,288–1,730                    | 1,265–2,063                  |
| Max temperature (°C)     | 32.2–36.6                     | 27.3–35.8                      | 27.0–33.8                    |
| Min temperature (°C)     | 15.3–18.7                     | 14.1–17.6                      | 12.0–17.0                    |
| Annual rainfall (mm)     | 485–762                       | 593–1,042                      | 896–1,296                    |
| Rainfall pattern         | Bimodal + Unimodal            | Unimodal                       | Unimodal                     |
| Climates                 | Tropical savannah, humid subtropical | Humid subtropical, subtropical highland | Humid subtropical, semi-arid |
| Cropping systems         | Banana/coffee/horticulture; | Banana/coffee/horticulture;   | Tea/maize/                   |
|                         | maize/legume; cotton/maize    | maize/legume; cotton/maize     | pyrethrum                    |
| Maize maximum yield (t ha⁻¹)  | 7.63                          | 6.64                           | 10.4                         |
| Households with livestock (%) | 88%                           | 87%                            | 87%                          |

|                         | Manyara (n = 89)              | Njombe (n = 66)               | Rukwa (n = 45)              |
|--------------------------|-------------------------------|--------------------------------|-----------------------------|
| Altitude (masl)          | 1,352–1,928                   | 1,861–2,086                   | 1,540–1,751                 |
| Max temperature (°C)     | 26.7–36.0                     | 22.7–27.9                     | 30.9–32.9                   |
| Min temperature (°C)     | 15.2–20.5                     | 9.9–12.9                      | 13.3–15.3                   |
| Annual rainfall (mm)     | 615–1,077                     | 1,008–1,354                   | 927–1,041                   |
| Rainfall pattern         | Bimodal                       | Unimodal                      | Unimodal                    |
| Climates                 | Subtropical highland          | Subtropical highland          | Subtropical highland        |
| Cropping systems         | Banana/coffee/horticulture;  | Tea/maize/pyrethrum           | Maize/legume                |
|                         | maize/legume; cotton/maize    |                                | Maize/legume                |
| Maize maximum yield (t ha⁻¹)  | 9.77                          | 8.64                          | 10.4                         |
| Households with livestock (%) | 87%                           | 83%                           | 85%                          |

| Dominant livestock⁵       | Poultry, cattle, goats, sheep | Poultry, cattle, goats, sheep | Poultry, goats, cattle, sheep |

Sources: JAXA ALOS World 3D DSM data set at 30 m resolution (elevation); Wan, Hook, and Hulley (2015) 8-day land surface temperature (2007–2017); Funk et al. (2015) monthly precipitation (2007–2017); Mnenwa and Maliti (2010) cropping systems; Census 2012 livestock (http://www.nbs.go.tz/).

¹Maximum maize yield recorded from crop cuts in study 1 survey.

⁵Listed in order of magnitude.
diversity of farmer soil perceptions and management practices. Households were grouped by practices used on the focal plot identified in study 1. The practices of interest were those that either addressed soil and water conservation through physically changing the land or those used for improving soil fertility as defined by the research team. The sampling grids from study 1 were then used to identify grids containing both households using the practices of interest and those not using practices. This resulted in seven sites in the southern highlands zone totaling 58 households across five districts (Figure 1). Information collected on the household's focal plot included management of the plot, information on farmer decision making around farming practices, and farmer perceptions of presence and causes of erosion and soil quality. Training of enumerators for the questionnaire and use of LandPKS app took place over 2 days and was conducted by the lead author. All data collection was done in Swahili and completed during July 2018.

2.5 | LandPKS smartphone application

The LandPKS (https://landpotential.org) smartphone application was used to gather additional land characterization information of focal plots as part of study 2. LandPKS is an open-source project with the goal of improving sustainable land management through providing tools that capture local user input into a cloud database system (Herrick et al., 2013). Information was collected for each focal plot through the LandInfo module of the LandPKS application on Android-based smartphones and tablets. Information collected included the slope, aspect, elevation, and soil limitations. Soil erosion signs assessed included presence of rills, gullies, and other signs of soil loss based on the Land Degradation Surveillance Framework and recorded on a three-point scale of not present, few, or many (Vågen, Winowiecki, & Tondoh, 2013). Following the LandPKS protocol, the soil profile was assessed to a depth of 70 cm for the 0–10 cm, 10–20 cm, 20–50 cm, and 50–70 cm depth ranges. At each depth, soil texture-by-feel and rock fragment category was recorded. Outputs provided by the app included local climate and plant available water holding capacity setting organic matter at a constant 1% for comparison across sites.

2.6 | Data analyses

2.6.1 | Study 1. Survey

Study 1 survey data were analyzed through data characterization based on principal factor extraction, presented as descriptive means and variation, Kruskal-Wallis test, and means comparisons by Dunn's test using Bonferroni correction for nonparametric data with details provided below. Households missing complete sets of information from the questionnaires and soil analyses were dropped, resulting in 578 studied households. Data from the study 1 questionnaires, study 2 sub survey questionnaire, and LandPKS output were compared to address the main research question of how farmers' perceptions of land fertility and soil type influence land management practices. Land management practices were categorized first from the study 1 survey dataset based on the main practices of interest, specifically those related to soil and water conservation practices and soil fertility. From this total list of practices, minimum/no tillage, grass strips, and drainage ditches were dropped due to low frequencies (n < 10). This final list included ridging, terracing, contour bunds, manure amendment, slash-burn, fallow, fertilizer input, and crop residue incorporation. Fallow practice was defined as any non-cultivation of the plot over the last 10 years for at least one growing season and repeated over multiple years, as recorded in the land use history. Fertilizer input was only considered if it was reported as an input for both the current survey year and the previous year. These eight practices, input as discrete variables consisting of 300 observations, were grouped based on principal factor extraction using an oblique promax rotation (Yong & Pearce, 2013). The analysis identified three factors that explained the majority of variability across the variables and a screeplot confirmed this finding. The first factor was labeled as erosion control as it included terracing and contour bund practices. The second factor was labeled the soil fertility group, as the practices (slash-burn, fallow, and chemical fertilizer application) have been frequently reported as means to improve soil fertility (Norgrove & Hauser, 2016; Vanlauwe et al., 2015). The third factor was labeled the organic amendment group as it included manure application and crop residue incorporation. Ridging was considered as a separate practice group since it was not accounted for in any of the three factors.

To compare the soil fertility of the focal plots across groups, soil variables (SOC, active carbon, pH, and texture) were used as well as maize yield. These variables were identified as being most important in determining soil fertility and are widely used in soil fertility assessments (Berazneva et al., 2018; Li, Messina, Peter, & Snapp, 2017). Yield, SOC, active carbon, and pH variables were winsorized at the 99th, 90th, and 95th percentiles, respectively, to account for outlier data (Ghosh & Vogt, 2012). Independent samples t-tests were conducted to compare these soil fertility variables against users and non-users of each practice group. Kruskal-Wallis tests for nonparametric data were conducted to compare the effect of soil fertility variables across farmer perceptions of soil fertility status and soil fertility change. In this survey, respondents were instructed to rank the soil fertility status of their field from 1—Not fertile to 4—Very fertile. Soil fertility change was determined by asking "Since this household first began cultivating this plot, do you think the soil has become more fertile or less fertile," with responses on a three point scale of 1—Decreasing, 2—Same, 3—Increasing. Dunn's test with Bonferroni correction (p = .05) was used to make multiple pairwise comparisons to identify significant differences in soil fertility variables across farmer perception groups.

2.6.2 | Study 2. Sub Survey

Study 2 sub survey data are presented as frequencies, means, and standard deviations for comparison of erosion and soil fertility.
perceptions across farmer practice groups. Practice groups compared
in study 2 are the same practices as used in study 1, with the excep-
tion of the erosion control group where reported erosion control prac-
tices also included fanya juu/fanya chini, grass strips, and drainage
ditches. Respondents were asked to rank the level to which erosion
and soil fertility were a problem on their plot along a four-point scale
from 1 (no problem) to 4 (large problem). Observed erosion signs were
also recorded for each focal plot and frequency of occurrence was
compared across practice groups. Output from LandPKS app used for
analysis included soil texture determined by hand texturing, soil water
storage capacity in the surface 20 cm and 1 m of the soil profile and
the surface infiltration rate that is the rate at which water moves into
the soil. Calculations were provided by LandPKS app and based on
Saxton and Rawls (2006). Means and frequencies of LandPKS outputs
were compared across farmer practice groups. All data was analyzed
using STATA 14 statistical software.

3 | RESULTS

3.1 | Study 1. Survey

Households surveyed in study 1 ranged in socioeconomic aspects,
and corresponding focal plots exhibited a range of biophysical charac-
teristics across regions (Table 2). Focal plot size varied across regions,
from averages of 0.73 acres (Njombe) to 4 acres (Manyara). Soils sam-
ped in survey focal plots showed large variation in soil fertility status,
including SOC, N, and pH. Plots from the northern sites of Arusha and
Kilimanjaro tended to have high SOC values (2.1–2.4%) compared
with southern sites (1.3–1.5%), with the exception of the high SOC
average observed at Njombe (3.2%; Table 2). Soil pH in the north was
generally moderately acid (6.1–6.5), with slightly higher acidity in the
South (5.4–6.2), although pH varied within all sites and some focal
plots were alkaline.

3.1.1 | Soil properties and farmer perceptions

No relationship was observed with regard to soil properties and
farmer perceived soil status (Table 3). For example, SOC values did
not vary substantially for soils that farmers perceived as varying from
low (1.72%) to high (1.85%) fertility status. No trends were observed
in terms of maize yields by soil fertility status, with low fertile plots
having 2.39 t ha$^{-1}$ yield and very fertile plots averaging 3.42 t ha$^{-1}$
with large variability within groups. However, differences among soil
properties were found for focal plots when grouped by whether
respondents perceived the plot soil fertility as increasing or decreasing
over time. Plots categorized as increasing in soil fertility had higher
total and active carbon and lower pH compared to all other plots.
Increasing soil fertility plots also had higher clay content than soil fer-
tility plots perceived as decreasing in soil fertility. Farmers also identi-
fied which indicators they use in determining soil fertility, with the
majority (81%) using previous crop yield as well as soil color (40%) and
presence of local plants (40%).

3.1.2 | Soil properties and farmer practices

Farmer management practices were compared to soil fertility mea-
surements to identify if there were measurable soil fertility differ-
cences among users and non-users of practices. Differences were
found between users and non-users of some practice groups, but not
all (Table 4). Focal plots with erosion control practices were not asso-
ciated with altered soil fertility status relative to other plots, although
we note the small sample size of this category. Plots amended with
organic inputs under fertility management practices or ridged all dif-
fered in soil fertility status compared with unamended plots. How-
ever, not all differences were in a positive direction. For example,
plots with soil fertility management practices (fertilizer applied, crop
residue burned, or fallowed) had low SOC and pH, but at the same
time, high maize yields ($p < .10$), compared with other plots (Table 4).

3.2 | Study 2. Sub Survey

3.2.1 | Soil fertility perceptions

Responses from study 2 farmers show an overwhelming concern
among respondents with the soil fertility of their plot (Table 5). Soil
fertility was identified as either a problem or a large problem by all
respondents. Few trends across practice groups emerged, with one
exception being farmers who reported the highest score for soil ferti-
licity challenges, were likely to be using soil fertility and erosion control
practices. Consistent with this, low SOC levels (less than 2%) were
observed for the majority of farmers, across all categories (Table 5).
Farmers also noted the indicators they use for assessing soil fertility,
with the majority using soil color (64%) as well as previous crop yield
(47%) and presence of local plants (22%) in their assessment. Black
soil color was overwhelmingly identified as being associated with fer-
tile soil, whereas red and white colors were associated with infertile
soil by a few farmers.

3.2.2 | Erosion perceptions

In direct contrast to soil fertility perceptions, most respondents identi-
fied their focal plot as having no or small problems with erosion and
not one respondent reported the highest score for erosion (Table 5).
Based on enumerator plot observations, only 36% of plots were
reported to have signs of erosion present (e.g., rills, gullies, or other
signs of soil loss detailed in Vågen et al., 2013). Fewer farmers in
study 2 (16 out of 58) implemented erosion control measures than soil
fertility management practices (45 out of 58), which was consistent
with farmer perceptions that erosion was not a major problem. At the
same time, about one-third of plots had observable signs of erosion, based on study 2 survey assessment (Table 5).

### 3.2.3 Farmer perspectives on management practices

Farmers in study 2 subset were asked open-ended questions concerning their reasons for using reported practices. For soil fertility management practices, reasons commonly centered around themes of resource conservation and desire to improve soil fertility, although a broad range of reasons were reported (Table 7). Responses showed farmers had multiple objectives when managing their fields, with themes of land management to prevent losses of soil and water, as well as reduce labor and protect crop health and seedling establishment (e.g., prevent bird damage). Reasons for using soil fertility management practices were broad and showed an awareness of interactions such as soil water dynamics and managing for soil moisture retention (Table 7).

### 3.2.4 LandPKS assessment

Output from the LandPKS application was used to compare land characteristics of the subset focal plots across management practice groups (Table 6; Figure 2). The LandPKS app used user input of slope, soil texture by depth, rock fragmentation, and soil limitations to produce estimates of plant available water capacity (AWC) to

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**TABLE 2** Biophysical and socioeconomic characteristics of households and focal plots from study 1 survey (N = 578)

|                | North                      | Southern highlands          |
|----------------|----------------------------|-----------------------------|
|                | Arusha (n = 69)            | Iranga (n = 70)             |
|                | Kilimanjaro (n = 120)      | Mbeya (n = 73)              |
|                | Manyara (n = 89)           | Njombe (n = 66)             |
|                |                            | Rukwa (n = 45)              |
|                |                            | Ruvuma (n = 46)             |
| Maize yield (t ha$^{-1}$) | 3.0 (1.8)                 | 2.1 (1.8)                  |
| Household size$^b$                        | 3.7 (2.0)                 | 3.5 (2.8)                  |
| Age of household head$^b$                     | 2.5 (1.7)                 | 2.5 (2.6)                  |
| Plot size (acre)$^b$                           | 5.6 (2.6)                 | 5.2 (2.6)                  |
| Crops grown on focal plot$^b$                   | 4.9 (1.8)                 | 6.8 (4.2)                  |
| SOC (%)$^c$                                     | 6.4 (2.4)                 | 4.2 (1.9)                  |
| Soil N (%)$^c$                                  | 48 (13)                   | 48 (15)                    |
| K (mg kg$^{-1}$)                                | 57 (11)                   | 51 (14)                    |
| pH$^c$                                         | 2.5 (1.7)                 | 2.5 (2.6)                  |

**Note**: Figures are averages. Values in parentheses standard deviations from the mean.

$^a$Maize yield determined by crop cut from focal plot of survey.

$^b$Data from household questionnaire in study 1 survey.

$^c$Data from focal plot soil samples.

**TABLE 3** Farmer perceptions from household survey and soil fertility properties from 2017 samples (0–20 cm) of focal plots in study 1 survey presented as average and standard deviation (in parenthesis) associated with each farmer perception of soil fertility

| Soil fertility status | SOC (%) | Active carbon Mg kg$^{-1}$ | pH | Maize yield t ha$^{-1}$ | Sand % | Clay % |
|-----------------------|---------|-----------------------------|----|-------------------------|--------|-------|
| Not fertile            | 1.72 (0.84) | 487 (178) | 5.95 (0.55) | 2.39 (2.10) | 54.6 (22.9) | a | 28.2 (13.9) |
| Moderate fertility     | 1.89 (0.95) | 506 (199) | 6.12 (0.56) | 3.18 (2.25) | 42.0 (25.7) | b | 35.4 (16.5) |
| Fertile                | 2.00 (1.0)  | 504 (182) | 6.15 (0.60) | 2.62 (1.97) | 45.2 (23.2) | ab | 34.2 (14.8) |
| Very fertile           | 1.85 (0.89) | 521 (183) | 6.25 (0.55) | 3.42 (1.88) | 61.3 (27.5) | ab | 24.4 (12.8) |

**Soil fertility change**

| Decreasing            | 1.81 (0.90) | 488 (194) | 6.11 (0.57) | 2.83 (2.13) | 47.7 (24.7) | a | 32.3 (15.7) |
| Same                  | 1.83 (0.90) | 504 (182) | 6.14 (0.55) | 3.18 (2.34) | 40.4 (26.9) | ab | 35.6 (16.5) |
| Increasing            | 2.67 (1.2)  | 609 (207) | 5.85 (0.53) | 3.79 (1.99) | 31.9 (21.1) | b | 42.5 (15.3) |

**Note**: Values with same letters within column not significantly different as determined by Dunn’s test with Bonferroni correction (p = 0.05). Values with no letters not significantly different within column.
### TABLE 4  
Soil fertility properties (0–20 cm) and maize yield of focal plots in study 1 survey, presented as average and standard deviation (in parenthesis) associated with each farmer practice

| Management practices | SOC % | Active carbon Mg kg⁻¹ | pH | Maize yield t ha⁻¹ | Sand % | Clay % |
|-----------------------|-------|------------------------|----|--------------------|--------|--------|
| **Erosion control**   |       |                        |    |                    |        |        |
| Yes (n = 22)          | 1.75 (1.05) | 468 (185)            | 6.08 (0.42) | 2.69 (2.12) | 46.6 (17.6) | 35.5 (9.86) |
| No                    | 1.88 (0.94) | 502 (194)             | 6.10 (0.57) | 2.99 (2.20) | 44.4 (25.6) | 34.0 (16.2) |
| t-test                | ns                | ns                    | ns              | ns                  | ns                  | ns                  |
| **Organic amendment** |       |                        |    |                    |        |        |
| Yes (n = 167)         | 2.19 (1.03) | 538 (201)             | 5.99 (0.55) | 3.06 (2.15) | 41.4 (23.7) | 35.0 (13.8) |
| No                    | 1.74 (0.87) | 485 (188)             | 6.15 (0.57) | 2.94 (2.23) | 45.6 (26.0) | 33.7 (16.9) |
| t-test                | -4.88***       | -2.89***              | 3.19***          | ns              | ns                  | ns                  |
| **Soil fertility practices** |       |                        |    |                    |        |        |
| Yes (n = 135)         | 1.58 (0.82) | 463 (177)             | 6.03 (0.49) | 3.39 (2.70) | 57.9 (17.6) | 27.1 (12.5) |
| No                    | 1.96 (0.96) | 512 (197)             | 6.13 (0.58) | 2.87 (2.02) | 40.9 (26.0) | 35.8 (16.4) |
| t-test                | 4.46***       | 2.72***               | 1.97**          | -1.58*            | -5.53***             | 4.13***             |
| **Ridging**           |       |                        |    |                    |        |        |
| Yes (n = 56)          | 1.65 (0.91) | 441 (180)             | 5.97 (0.52) | 3.15 (2.34) | 60.2 (18.1) | 25.9 (13.6) |
| No                    | 1.90 (0.94) | 507 (194)             | 6.11 (0.57) | 2.96 (2.18) | 42.7 (25.5) | 35.0 (16.1) |
| t-test                | 1.90**       | 2.57***               | 1.91**          | ns              | -4.3***              | 2.66***             |

Note: *p < .10. **p < .05. ***p < .01 ns = not significant.

aTerracing or contour bund practices.
bApplication of manure or crop residues.
cUse of slash-burn, fallow or chemical fertilizer application.
dIncludes open and tied ridges (connected by horizontal and vertical ridges).

### TABLE 5  
Farmer reported erosion and soil fertility status by farmer practice from study 2 sub survey, July 2018. Farmers reported multiple practices on focal plots resulting in overlap across categories (N = 57)

| Management practices | Erosion control (n = 16) | Organic amendments (n = 17) | Soil fertility practices (n = 45) | All respondents (n = 57) |
|-----------------------|--------------------------|----------------------------|----------------------------------|--------------------------|
| Erosion score         |                          |                            |                                  |                          |
| No problem            | 75% (24)                 | 44% (7)                    | 61% (11)                         | 70% (32)                 | 64% (37)                |
| Small problem         | 19% (6)                  | 38% (6)                    | 33% (6)                          | 24% (11)                 | 28% (16)                |
| Problem               | 6% (2)                   | 19% (3)                    | 6% (1)                           | 7% (3)                   | 9% (5)                  |
| Large problem         | 0%                       | 0%                         | 0%                               | 0%                       | 0%                      |
| Plots with erosion present | 28% (9)               | 50% (8)                    | 39% (7)                          | 30% (14)                 | 36% (21)                |
| Slope                 | 1.12 ± 0.49              | 1.10 ± 0.46                | 1.11 ± 0.61                      | 1.12 ± 0.42              | 1.09 ± 0.46             |
| Soil fertility score  |                          |                            |                                  |                          |
| No problem            | 0%                       | 0%                         | 0%                               | 0%                       | 0%                      |
| Small problem         | 0%                       | 0%                         | 0%                               | 0%                       | 0%                      |
| Problem               | 91% (29)                 | 81% (13)                   | 94% (17)                         | 80% (37)                 | 83% (48)                |
| Large problem         | 9% (3)                   | 19% (3)                    | 6% (1)                           | 20% (9)                  | 17% (10)                |
| SOC (%)               | 1.42 ± 0.73              | 1.57 ± 0.74                | 1.59 ± 0.81                      | 1.43 ± 0.66              | 1.41 ± 0.63             |

Note: Erosion control = Fanya juu/fanya chini, grass strips, drainage ditches, or contour bunds practices; Organic amendments = Application of manure or crop residues; Soil fertility practices = Use of slash-burn, fallow or chemical fertilizer application.

aValues in parentheses are counts.
bValues are means followed by standard deviations.
cSource JAXA ALOS World 3D DSM data set at 30 m resolution.
dFrom soil samples.
20 cm and 1 m as well as surface infiltration rates. LandPKS output identified erosion control sites as having poor soil infiltration properties and steep slopes (Table 6). LandPKS identified plots with steeper slopes (categorically recorded) than had previously been identified for the same subset plots in study 1 with slope from remote sensing. 13 out of the 58 plots recorded with LandPKS had...
Farmer reported reasons for use or non-use of erosion control and soil fertility practices. Parentheses indicate frequency of responses of those reporting using practice (or not using practices) from farmers surveyed in study 2 sub survey. Respondents reported multiple reasons and frequency of reason does not directly relate to frequency of practice used

| Practices             | Reasons                                                                 |
|-----------------------|-------------------------------------------------------------------------|
|                       | **Erosion control**                                                      |
| Contour bunds         | Reduce soil erosion (7)                                                  |
| Fanya Juu/Fanya Chini | Water conservation (1), prevent runoff (1)                              |
| Grass strips          | Reduce soil erosion (3), improve soil fertility (2), water conservation (1) |
| Drainage ditches      | Control water flow (4), reduce soil erosion (1)                         |
| No erosion control practice | Flat plot (12), no erosion signs (1), fallow plot (1), unaware of practices (1) |
| Ridges (open and closed) | Soil moisture conservation (13), reduce soil erosion (10), support plant structure (6), avoid bird damage (4), ease of planting (1) |
|                       | **Soil fertility**                                                       |
| Manure/compost application | Increase soil fertility (14), increase crop yield (2), improve soil water holding capacity (1) |
| Slash-burn            | Clean plot (14), reduce labor (4), improve soil fertility (3)           |
| Fallow                | Low fertility (1)                                                       |
| Incorporate residue   | Improve soil fertility (2), improve soil water holding capacity (1)      |
| Apply chemical fertilizer | Increase yield (24), improve soil fertility (7), provide crop nutrients (2) |
| No soil fertility practice | Used crop residue (2), Couldn’t afford (2), prevented by weather (1), no reason (1) |

4 | DISCUSSION

4.1 | Farmer perceptions of agricultural land

Farmer perceptions documented in this study align well with many soil fertility and land degradation measures, but not with all. Majority of farmers reported perceptions of low soil fertility, which is reflected in overall low regional averages in SOC levels and other fertility properties (Table 2). This was observed in both the initial study 1 plots and in the follow up study 2 plots. SOC ranged from 1.0 to 2.2%, which is similar to previously reported values found across Tanzania (Bhargava, Vagen, & Gassner, 2018) and is on the low end of SOC content needed for effective fertilizer use based on the literature. Some studies have found fertilizer response from soils as low as 1–1.5% SOC, while other studies suggest a higher threshold of 2.7% SOC is needed for effective fertilizer use (Ichami, Shepherd, Sila, Stoorvogel, & Hoffland, 2019; Kihara et al., 2016; Marenya & Barrett, 2009). Soil nitrogen was similarly low across regions, with a range of 0.03–0.07%, well below the 0.2% threshold used in Berazneva et al. (2018), which also measured soil fertility of agricultural land in Tanzania. Average pH values across sites were not highly acidic (>5.0), suggesting soil acidity did not appear to be a factor exacerbating low soil fertility in the study sites, which has been a limiting factor in other Tanzanian regions (Kimaro, Timmer, Chamshama, Ngaga, & Kimaro, 2009).

A key finding here is the importance of soil fertility change perceptions. In contrast, farmer perception of current soil fertility status is not related to soil fertility variables in this study. This suggests farmers ability to detect soil fertility change over time may be a reliable indicator. Previous studies assessing farmer perceptions of soil fertility in East Africa were unable to find differences between soil fertility status groups (Berazneva et al., 2018; Kelly & Anderson, 2016). In an in-depth study in Southeast Asia focused on a smaller geographical area, Bruun et al. (2017) compared multiple soil quality measurements to farmer perceptions of soil fertility status and found pH and active carbon to have the greatest differences between groups, whereas SOC did not differ. In large household surveys such as the World Bank Living Standards Measurement Study (LSMS), soil fertility is documented based on questions about current status but we know no large-scale surveys that consider farmer perceptions of trends in soil fertility status over time. Karlton et al. (2011) asked farmers in Ethiopia about soil fertility change over time with a modest sample size, and most farmers (92%) reported declining soil fertility. In our study, a range of perceptions was found, where the majority of respondents (65%) reported decreasing soil fertility, and a small but substantial group (7%) reported increasing fertility. Soil properties from fields perceived as increasing in fertility were associated with high SOC and active carbon relative to fields perceived as decreasing in fertility (Table 3; p < .05). The sampling frame in our study purposefully included a wide variability in land types, allowing the capture of farmer perceptions for different soils and environmental contexts. This contributed to the successful differentiation observed in this study.

A range of farmer perceptions were documented along with LandPKS characterization of highly local site information. This provides unique fine resolution data, compared to the coarse soil property data from world databases which is often at a 250-m scale resolution, followed by down-scaling to a specific site (Hengel et al., 2015). Through this protocol, Kelly and Anderson (2016) compared farmer perceptions of field soil fertility status with predicted soil fertility properties and found the two to not be related. Extraction of soil
parameters at a coarse scale is a common approach used by researchers (Berazneva et al., 2018; Bhargava et al., 2018; Nijbroek & Andelman, 2015). However, our use of direct soil measurements at field sites and corresponding farmer perception information contributed to identifying a connection between scientific measurements and farmer perceptions. This expands upon a previous framework connecting farmer perceptions to behavior addressing land degradation (Bayard & Jolly, 2007).

4.2 | Farmer management and soil status

Farmers in our study often had multiple objectives for using practices. This was seen with users of organic amendment practices who had elevated SOC, but not high maize yields, which corresponded with farmers reporting prioritizing increasing soil fertility levels over maximizing yield. Bhargava et al. (2018) evaluated fields in Tanzania for SOC across various farmer practices and did not find a relationship between use of organic amendments and SOC. The authors attribute this to the low frequency of organic amendment use. Berazneva et al. (2018) that compared Tanzanian and Kenyan farmer perceptions of soil fertility to farming practices also found that application of organic amendments did not vary with soil quality perceptions. In contrast, study 1 findings reported here showed that most farmers who perceived their plot as increasing in soil fertility applied organic amendments. Berazneva et al. (2018) and (Bhargava et al., 2018) both used a general household survey, the LSMS, to identify farmer practices, whereas our detailed survey included focal plot monitoring and was able to pick up practices that were not widely reported in the LSMS, and thus find significant relationships between soil quality and practices.

Fields with soil fertility management practices had low levels of SOC, relative to fields with organic amendments (Table 4, \( p < .01 \)). However, a trend toward high maize yields was observed with this soil fertility group, which was not found with other practices \( (p < .10) \). It should be noted that soil fertility management practices in this Tanzania-based study involved mostly slash and burn, or fallow, with limited use of chemical fertilizer. Previous studies on the effects of burning on SOC support the observation that these fields had low SOC levels, although the magnitude of this effect can vary with soil texture (Bird, Veenendaal, Moyo, Lloyd, & Frost, 2000). Fallow practices may be associated with high crop yields, but studies measuring effects on SOC show minimal change, with changes relative to the inherent soil fertility level (Mertz, 2002; Bruun, Mertz, & Elberling, 2006; Hepp, de Neergaard, & Bruun, 2018). Additionally, farmers’ reasons for conducting soil fertility management practices in study 2 included concern about crop yields and interest in conserving labor (Table 7).

4.3 | Land management and LandPKS

An important observation from this study is a disconnect between farmer perceptions of site characteristics and the need for land husbandry and extension recommendations for soil conserving practices. Extension advice often considers the slope of the site, yet farmers did not implement erosion control measures preferentially to sloped land in our study, nor in a previous study by Tenge, DE Graaff, and Hella (2004). Based on remote sensing data, the slope at the focal plot site was not different for plots with or without erosion control measures as both were around 1%. This is well within favorable land conditions for cultivation (Li et al., 2017). Slope recorded through LandPKS indicated slightly steeper land, with 7 out of the 16 plots with erosion control categorized as moderate to hilly slope (associated with 6–30% slope).

There was no evidence to support that farmers preferentially practice erosion control on steep slope sites. There was evidence for farmer consideration of other site characteristics, such as the site property of water infiltration rates (Table 6). Erosion control measures were often implemented at sites with reduced infiltration rates, often due to the presence of a clay layer at specific soil depths. Indeed, surface infiltration rate as predicted by LandPKS appeared to be a good indicator of farmer utilization of erosion control practices. In Ethiopia, Assefa and Hans-Rudolf (2016) surveyed farmers on indicators they use to assess soil erosion. Farmers noted indicators of soil erosion such as low soil depth and soil workability, which could relate to compaction layers and high clay content. Results from LandPKS in our study show how local knowledge of erosion control practices can be systematically documented to empirically assess soil erosion and relate local observations, such as soil texture and slope, with scientific assessments (eg. AWC, surface infiltration rate) to identify site specific practices. While the concept of assessing soil conditions at different depths on farmer fields is not new, most notably described in Dalglish, Foale, and McCown (2009) with farmers in Australia, the execution of this process in the form of a free, open access smartphone application is novel. Our study provides the first evidence of an accessible way forward that links local and scientific knowledge on smallholder farms and documents site-specific information for enhanced relevance.

4.4 | Farmer objectives concerning land management and soil fertility

Although, in the literature, soil fertility and land management practices are often considered in isolation (Ellis-Jones and Tengberg, 2000; Barrios et al., 2006; Assefa & Hans-Rudolf, 2016), farmers often considered these practices as part of a continuum of overlapping categories. This has implications for extension recommendations, as advice will be ineffective if it disregards farmer strategies that involve multiple practices and cumulative effects on soil. Furthermore, our study highlights that farmers often consider soil fertility and degradation issues together and use practices that are able to address both simultaneously (Table 7). Previous research has found that researchers often focus on the biophysical benefits of practices, whereas farmers report multiple objectives covering biophysical and socioeconomic considerations (Ramisch, 2014). Assefa and Hans-Rudolf (2016) recorded local
knowledge and also found that soil erosion and fertility loss were considered by farmers as connected. Similarly, we found that farmer concerns about soil fertility were interrelated with concerns about soil water dynamics and erosion.

The findings in this study are consistent with the need to identify sustainable agriculture practices that consider both physical soil and fertility management. Current extension services in Tanzania may be ineffective in this regard and could be strengthened through recognition of the interaction between these issues. Nibbroek and Andelman (2015) evaluated extension services in Tanzania and found that only 5% of farmers considered extension services they received as above average, but when farmers did receive good agricultural services there was a measurable increase in maize yield. This is suggestive that increasing access to good agricultural extension, such as through mobile platforms, can positively impact livelihoods. Our results show that to be effective, a smartphone-based approach may need to incorporate farmers’ multiple objectives and address soil fertility and land degradation issues together.

5 | CONCLUSIONS

This study provides evidence that characterization of sites and farmer perceptions through a smartphone application can improve understanding of soil status, at both the surface and deeper depths. This provides a scientific basis for unique, and highly local, insights into soil water drainage and water holding properties. This study shows the value in identifying underlying land conditions, and farmer goals and perceptions, as a basis for locally appropriate advice such as how to target scarce inorganic and organic amendments. This approach utilizes the LandPKS app not as a substitute for an advisor but as a resource that can catalyze engagement between extension agents and farmers for improved soil management advice.

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CONFLICT OF INTEREST

The authors report no conflict of interest.

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