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Understanding farmer knowledge and site factors in relation to soil-borne pests and pathogens to support agroecological intensification of smallholder bean production systems

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Introduction: Pests and diseases limit common bean (*Phaseolus vulgaris*) production in intensifying smallholder farming systems of sub-Saharan Africa. Soil-borne pests and diseases (SPD) are particularly challenging for farmers to distinguish and manage in cropping systems that vary in terms of soils, farmer knowledge, and management factors. Few studies have examined soil drivers of SPD in smallholder systems, integrated with farmers' perceptions and management practices.

Methods: In Kilimanjaro, Tanzania, we assessed farmer knowledge and SPD management for common bean alongside soil type and soil quality. Focus group discussions and field survey findings including farmer observations and soil nutrient balances were integrated with soil analyses of farmers' fields. Multiple correspondence analysis (MCA) and principal component analysis (PCA) assessed relationships among farmer demographics, pests and diseases, soil characteristics, and management practices.

Results and discussion: Surveys revealed that 100% of farmers knew of the bean foliage beetle (*Ootheca bennigseni*) but few recognized the soilborne pest *Ophiomyia* spp. or bean fly despite it being more destructive. About a third of farmers knew of root rot diseases caused by *Pythium* spp. and *Fusarium* spp. Synthetic pesticides were used by 72% of farmers to control pests, while about half that (37%) used pesticidal plants, particularly *Tephrosia vogelii* extracts sprayed on foliage. Regarding SPD, 90% of farmers reported that their management practices were ineffective. Meanwhile, synthetic fertilizers were used by nearly all farmers in beans intercropped with maize (*Zea mays*), whilst very few farmers used manure or compost. Soil available phosphorus was lowbut showed a balance between inputs and outputs regardless of whether fields were owned. Field nitrogen balances were more negative when fields were owned by farmers. An MCA showed that older farmers employed a greater number of pest control practices. The PCA showed that field variability was dominated by soil organic matter, elevation, and soil pH. Higher organic matter levels were also associated with less stunting and wilting of beans observed by farmers. Our results suggest that research and farmer learning about SPD ecology are key gaps, alongside recycling of organic residues to soils. Cost-effective and sustainable practices to manage bean SPDs for smallholders are also needed.

KEYWORDS

pesticidal plant, botanical pesticide, *Fusarium* spp., *Pythium* spp., *Phaseolus vulgaris*

1. Introduction

Smallholder farmers producing common bean (*Phaseolus vulgaris* L.) are constrained by a number of challenges, including diseases, insect pests and poor soil fertility, which can result in severe yield losses in Tanzania (Hillocks et al., 2006; Nassary et al., 2020). Insect pests and diseases are ranked first in causing losses and these can reach 60% in common bean in Tanzania (Ronner and Giller, 2013) and up to 100% crop loss when no control measures are taken (Laizer et al., 2019). Pests and diseases affecting leaves and pods are generally recognized and managed by farmers (Stevenson and Belmain, 2017). However, soilborne pests and diseases (SPD) are often neglected in common bean production due to poor knowledge of causal agents, or the attribution of belowground damage to above-ground pests and diseases (Sekamatte and Okwakol, 2007). Farmers neglect SPD because they are not aware of the feeding habit of soil-borne insects and the damage caused by soil-borne pathogens. Three bean fly species *Ophiomyia phaseoli* (Tryon), *Ophiomyia spencerella* (Greathead) and *Ophiomyia centrosematis* (DeMeijere), and bean foliage beetle (*Ootheca bennigseni*) are the most important insect pests at the germination and seedling stages of common bean (Buruchara et al., 2010). Previously published studies on the larva of bean fly which is referred to as "bean stem maggot" shows that the pest status and management are poorly understood among farmers (Laizer et al., 2019). For example, bean fly and bean foliage beetle larval feeding activity cause above-ground symptoms from nutrient deficiency in common bean plants, affecting root growth and nutrient transport (Schwartz and Pastor-Corrales, 1989). Hence, if neglected, these pests can seriously damage common bean seedlings leading to 33–100% crop loss for bean flies (Karel and Ashimogo, 1991; Abate and Ampofo, 1996) and 18–30% crop losses by bean foliage beetle larvae in the soil in Tanzania (Abate and Ampofo, 1996). Poorly recognized soil-borne fungal diseases in common bean include root rot which can be caused by a variety of fungi including species from the genera of *Rhizoctonia, Pythium, Fusarium, Sclerotium*, and *Macrophomina* (Rusuku et al., 1997; Buruchara et al., 2010). Root rot fungi attack the root or crown region of the stem of the host plant (Sekamatte and Okwakol, 2007) causing damping-off, seed rot at the pre-germination, germination stage or even after germination, restricting water and nutrient uptake (Valenciano et al., 2006) leading to 70% yield loss (Papias et al., 2016; Mwaipopo et al., 2017). Laizer et al. (2019) indicated that farmers rank field insect pests as the major constraint leading to common bean yield loss followed by weeds, whereas crop diseases are least reported.

Huber et al. (2011) reported that plants with optimum nutrient supply grow more vigorously and enable a plant to have a higher capacity to compensate for pathogen infection and insect feeding. Symptoms of nutrient deficiency in plants may be caused by bean fly and bean foliage beetle larval feeding activity (Schwartz and Pastor-Corrales, 1989), which impairs root growth and nutrient transport (Huber et al., 2011) while poor soil fertility can also exacerbate the severity of insect attack (Hillocks et al., 2006). However, the application of excess inorganic N can increase amino acid concentrations which influences the penetration and growth of fungal hypha (Huber et al., 2011) and increased bean fly (O. *spencerella)* infestation (Letourneau, 1994). Bean fly and bean foliage beetle infestation are further aggravated by the presence of soil-borne pathogens such as *Fusarium* spp. and *Pythium* spp. root rots (Buruchara et al., 2010) where the insects take advantage of fungal damage to enter into the plant roots and stem (Schwartz and Pastor-Corrales, 1989).

A common control method used for the management of SPD is synthetic pesticides (Mahmood et al., 2017). However, their use by smallholder farmers is limited by high cost (Abate et al., 2000), and their misuse results in considerable human and environmental health problems (Stevenson and Belmain, 2017). There is renewed interest in the use of pesticidal plants along with soil health improvement to better manage insect pests and diseases (Belmain et al., 2022). Common bean smallholder farmers in our study area use pesticidal plants for controlling insect pests and diseases, mainly targeting above-ground pests and diseases (Mkindi et al., 2021) as there is little evidence of the use and efficacy of such products on below-ground pests and pathogens (Toepfer et al., 2021). Further, more needs to be known in African smallholder systems on how soil type, soil quality and farmer management of soil health and fertility contribute to SPD, although studies from other areas show some promising findings (Watson et al., 2002; Janvier et al., 2007; Birkhofer et al., 2008; Huber et al., 2011). Therefore, the purpose of this study was to explore the knowledge of and perceptions of damage from SPD, as well as local management strategies, in relation to soil type and soil fertility. We also sought to explore these factors along an elevation gradient of smallholders' bean fields near Mount Kilimanjaro, Tanzania. Furthermore, the study related these knowledge and management aspects, including the use of pesticidal plants, in a smallholder community setting with different livestock herd sizes, field sizes and land ownership parameters.

2. Materials and methods

2.1. Study site

The study was conducted on the slopes of Mount Kilimanjaro along an elevation gradient in smallholder farming communities in Hai District (latitude −3.232 to −3.384 S and longitude 37.238

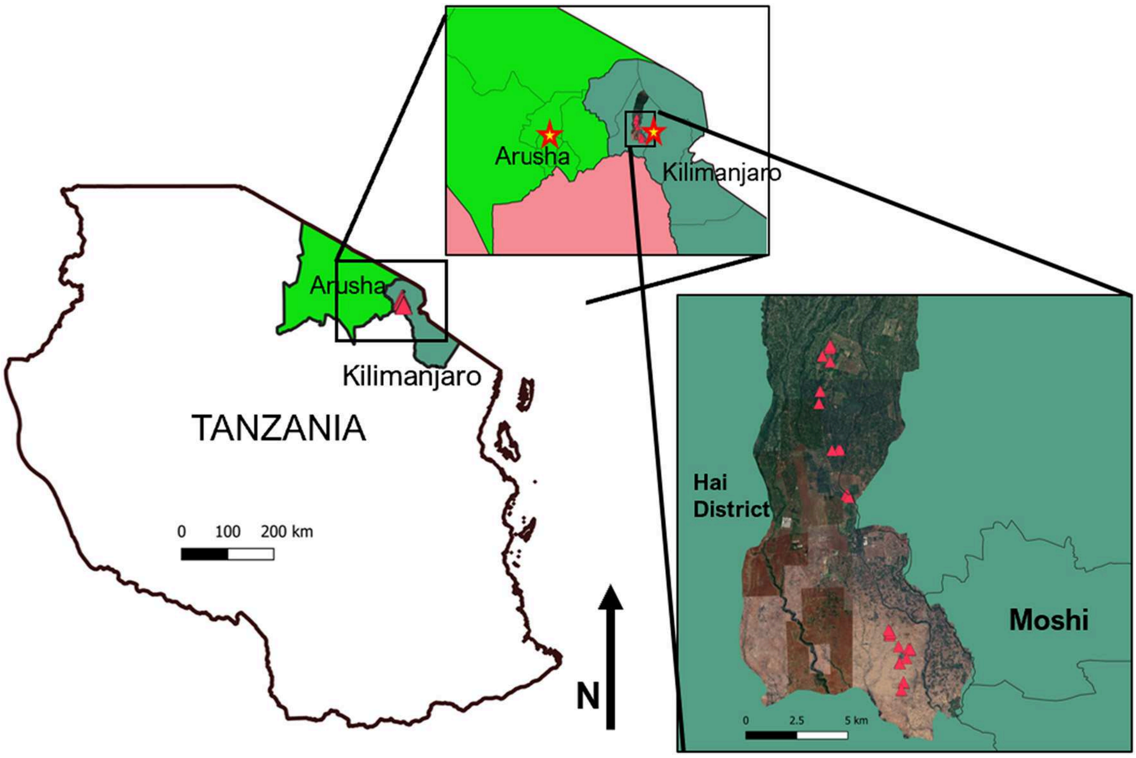

FIGURE 1
Study location indicating farmers' fields in the Hai District of the Kilimanjaro Region of northern Tanzania, where farm-level questionnaire surveys were conducted. Survey fields were arranged along an elevation gradient on the lower slopes of Mt. Kilimanjaro.

to 37.281 E; Figure 1). Permission to carry out the research was granted by the district council and community-based officials, with all farmers involved providing their consent. The study was done under the Farmer Research Network (FRN) project with an official research permit from the Tanzania Commission for Science and Technology (2021-181-NA-2021-061). The annual temperature ranges from 15 to 30°C, with a mean annual rainfall ranging from 500 mm in the lowlands and 2,000 mm in the highlands. Rainfall is bimodal with a long rainfall season from March to June and a short rainfall season from November to December. Altitude ranges from 700 to 1,500 meters above sea level (m.a.s.l) (Lema et al., 2014). Soils in the higher elevations are Acrisols (https://soilgrids.org/) (extracted study area map in Supplementary Figure 1) which have low base cation status, low activity clay on topsoil, and more organic matter (FAO, 2006). Soils in the middle elevations are ferralsols with good physical properties and poor chemical fertility having relatively weak cation retention capacity (Massawe and Mrema, 2017). Soils in the lower elevation are chromic luvisols having high base status and low activity clay on topsoil (FAO, 2006). Farming practices in the area consist of smallholder agriculture where most farmers practice intercropping of maize and beans. Other crops grown include bananas, coffee and leafy vegetables. Common beans are often grown as a monocrop during the short rain season and as an intercrop with maize in the long rain season and have been grown in the region for several decades. Farmers in higher and middle elevations grow common bean on rented land or in small pieces of land around their homestead while most farmers in the lower elevations own larger farm fields.

2.2. Focus groups and interviews with farmers

Farmer's knowledge, attitudes, and practices with regard to bean cropping and particularly SPD were collected in the Narumu Ward of Hai District. Focus group discussions (FGD) with 64 farmers within eight different groups were facilitated with the assistance of village extension officers and research assistants involving farmer representatives nominated by farmers in different areas. Eight participants were selected for each focus group in a purposive way to cover a wide possible range of experience and knowledge in common bean production. Preliminary information on the level of farmer knowledge and their local taxonomy of SPD were collected. Farmers' observations and knowledge of field disease symptoms and insect damage were also recorded. The discussions allowed farmers to share their knowledge and experiences regarding SPD and their management practices including synthetic and pesticidal plants use. General guiding questions were used, and provoking questions were asked when necessary (questions available in online Supplementary material 1). Topics discussed included knowledge on common bean production, SPD, use of pesticidal plants and other practices for controlling pests and diseases, constraints to their control as well as methods observed to be successful by farmers in managing SPD.

A farm-level, individual questionnaire survey was also carried out to capture farmer demographic information as well as their knowledge of bean fly, foliage beetle and root rot disease damage, and management practices including pesticidal plant use practices. A total of 54 common bean farmers were interviewed individually. Some participants in the farm-level questionnaire were also involved in the FGDs but new participants were included who did not have experience in using pesticidal plants to control insect pests and diseases. To provide clear references for the responses and observations of pest incidence in the field, live insects were shown to farmers to see the color and size of insect pests. Also, damaged plants showing feeding or oviposition behavior of bean fly and bean foliage beetle were displayed before starting the interview. Questions for the farm-level individual questionnaire were prepared using Kobo Toolbox (https://kf.kobotoolbox.org/) and data were collected using smartphones with Open Data Kit (ODK) open-source mobile data collection software (https://opendatakit.org/). The questionnaires were pre-tested in a pilot study before being used by the targeted respondents.

2.3. Assessment of soil nutrient and management by farmers

Farmer practices with respect to soil fertility management were collected in individual discussions in farmer fields with the same 54 farmers involved in questionnaires about pest and disease management. Information on livestock keeping, herd sizes, land ownership and soil management was collected as part of a nutrient balance survey. A partial nutrient balance reflecting nutrient inputs, harvests, and estimated nitrogen (N) fixation was adapted from the NUTMON framework and previous nutrient balance assessments in smallholder systems (Smaling and Fresco, 1993; Ampofo et al., 1998; Vanek and Drinkwater, 2013; Nyamasoka-Magonziwa et al., 2020). The nutrient balance information on field size, crop type, harvests, and types and amounts of manure, fertilizer, and other inputs were gathered using a second survey implemented in ODK (see above). Nutrient balance information was collected on 45 farm fields belonging to farmers included in the larger field-level individual questionnaire survey. Field areas were assessed, and partial nutrient balances were obtained as nitrogen (N), phosphorus (P), and potassium (K) in inflows (mineral fertilizer input, compost, manure, and estimated N fixation of beans as equal to harvested N) (Ojiem et al., 2007); minus export flows (harvested grain and nutrients within crop residues when these were exported). Nutrient contents of crops and manures were based on data from similar smallholder systems in the literature and unpublished data from analyses. The frequency of use of organic nutrient sources and the retention of crop residues on fields was also assessed in the survey to characterize the tendency of farmers' management to sustain soil organic carbon.

Composite soil samples were collected from the 45 farm fields in the field-level nutrient balance survey. The samples were collected to evaluate key soil properties that are known to influence plant resilience and the presence of soil-borne pathogens using a tool kit of accessible assessment methods (Nyamasoka-Magonziwa et al., 2020). These measurements included particulate organic matter (POM), permanganate-oxidizable soil carbon (POXC), aggregate stability, soil pH and phosphorus. From each field, five sub-samples were sampled to a depth of 20 cm, collected, mixed, and a sample of 1 kg was taken. Care was taken to not break aggregates during mixing for subsequent aggregate stability analysis. The soil samples were air-dried and sieved through a 2 mm sieve prior to analysis, except for the aggregate stability analysis for which a portion of the sample was carefully broken along natural planes of weakness by hand to pass a 10 mm sieve prior to drying and stability analysis (see below).

Soil pH was measured using a portable pH meter (Test Equipment Depot, Woburn, MA, USA) and particulate organic matter (POM) was determined by gentle wet-sieving of particles between 250 microns and 2 mm, followed by density flotation and decanting of organic matter in clean tap water. Permanganate oxidizable carbon (POXC; adapted from Weil et al., 2003) was measured based on the oxidation of labile soil C by potassium permanganate in a calcium chloride solution (0.015 M $KMnO_4$ and 0.1 M $CaCl_2$). Soil available phosphorus was determined using a modified Olsen method (Olsen et al., 1954) in which Olsen solution (0.5 M $NaHCO_3$, adjusted to pH 8.5 using NaOH) was used to extract reactive P which was then acidified using sodium hydrogen sulfate ($NaHSO_4$) prior to analysis for dissolved phosphate using a reagent pack for the molybdate blue colorimetric method and a low-cost colorimeter (Hanna Instruments, Providence, RI, USA). Aggregate stability was determined using wet sieving methods adapted from Nyamasoka-Magonziwa et al. (2020) and the mean weighted diameter (MWD) of three size classes (2–10, 0.25–2, and 0–0.25 mm diameters) calculated as a single parameter summarizing aggregate stability, with larger MWD representing higher stability. Soil texture was assessed by the USDA feel method (Thien, 1979; Rictchey et al., 2015).

2.4. Data analysis

Discussions with farmers in FGDs and during surveys were recorded and transcribed together with notes taken during the sessions. Transcripts were then coded and analyzed to identify recurrent themes and patterns on farmers' awareness of soil-borne insect pests and diseases, the use of pesticidal plants and other soil management issues. Data about soil nutrient and residue management were analyzed using a principal component analysis (PCA) to understand associations between site and management variables. Regression analysis was used to assess which site, soil, and nutrient management parameters were associated with farmers' perceptions of damage by soil-borne pests and diseases, subject to the insights provided by the PCA on potential confounding of soil, site, and management effects. To examine the relationship between soil factors and SPD damage, a single stunting and wilting disease index was created that was rated 1 when any symptoms of stunting and wilting were observed by farmers (e.g., wilting of seedlings, death of taproot, adventitious root formation, stunting), and 0 when none of these symptoms were observed. Multiple correspondence analysis assessed potential relationships between respondent demographics from the farmer surveys (age, gender and education level) and their responses on soil-borne insect pests and diseases and management practices. All analyses were carried out in XLSTAT statistical package version 2022 (Addinsoft, New York, USA).

3. Results

3.1. Participant demographics, existing knowledge, and practices

Most farmers interviewed were male (>60%) and over 80% were over 30 years old with most farmers (>50%) aged over 50 years (Table 1). Most farmers (>85%) had only completed primary education, and over 60% of respondents reported that farming was their main livelihood activity. From the sample of interviewed farmers, synthetic pesticide was reported to be a major (>72%) control method used by most farmers for whatever insect pest or disease appeared in common bean including SPDs (Figure 2). Less than half (37%) were using pesticidal plants for the management of insects in their field. On cultural management practices, >50% of farmers reported practicing intercropping of common bean and maize, >50% reported practicing timely planting, and <30% practiced crop rotation. Demographic parameters influenced some responses provided where multiple correspondence analysis showed some relationships (Figure 3). For example, the use of synthetic pesticides, intercropping and early planting correlated significantly with farmers of age >60 years whereas crop rotation correlated with farmers with age between 40 and 60 years having primary education and female farmers. Among farmers who reported using pesticidal plants, >35% used *Tephrosia vogelii*, 7% used *Tithonia diversifolia* and >3% used *Lantana camara.* All farmers reported that the parts of pesticidal plants used were leaves, which were extracted in soapy water and sprayed onto crops. These pesticidal plants were reported to work well for a variety of pests and diseases on foliar parts of plants but were not perceived as effective on SPDs.

Most farmers (60%) owned land with a majority of respondents (44%) reported farming on a land size of 0.2 ha. Farmers with larger sizes of land accounted for 40% having a land size between 0.2 and 0.4 ha. Most farmers renting land had land sizes of 0.2 ha (>55%) while almost all (90%) farmers farming on owned family farms had land sizes between 0.2 and 0.4 ha (Table 2). In the study area, fertilizer use bore no relationship to whether farmers permanently own or borrow/rent land for farming and there was no significant relationship between land size and fertilizer use.

Most farmers owned chickens (>60%) and cattle (>50%) while those who owned goats, ducks, pigs and sheep constituted a small

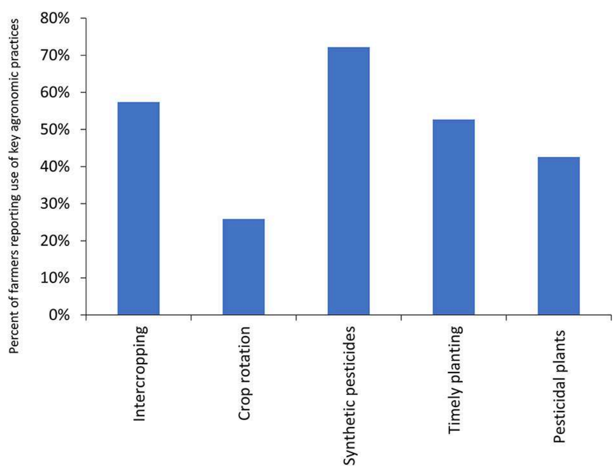

FIGURE 2
Proportion of farmers reporting use of key cultural and plant protection practices for insect pest and disease management in their fields, from a farm-level individual questionnaire in Narumu Ward, Kilimanjaro Region, Tanzania.

TABLE 1 Key demographic information about farmer respondents for 45 farmers with maize and bean fields in Narumu Ward, Kilimanjaro Region, Tanzania.

Variable	Category	All (*n* = 54)	Female	Male
			N (%)	*N* (%)
Age	<30	4	0 (0)	4(12.1)
	30–39	3	2 (9.5)	1 (3.0)
	40–49	12	5 (23.8)	7 (21.2)
	50–59	21	9 (42.9)	12 (36.4)
	≥60	14	5 (23.8)	9 (27.3)
Education level	Primary	47	21 (10)	26 (78.8)
	Secondary	4	0 (0)	4 (12.10)
	Tertiary	1	0 (0)	1 (9.1)
Livelihood activities	Farming	35	14 (66.7)	21 (63.6)
	Farming + herding	11	4 (19.1)	7 (21.2)
	Farming + small business	6	2 (9.5)	4 (11.1)

n, number of respondents; *N*(), percentage of respondents.

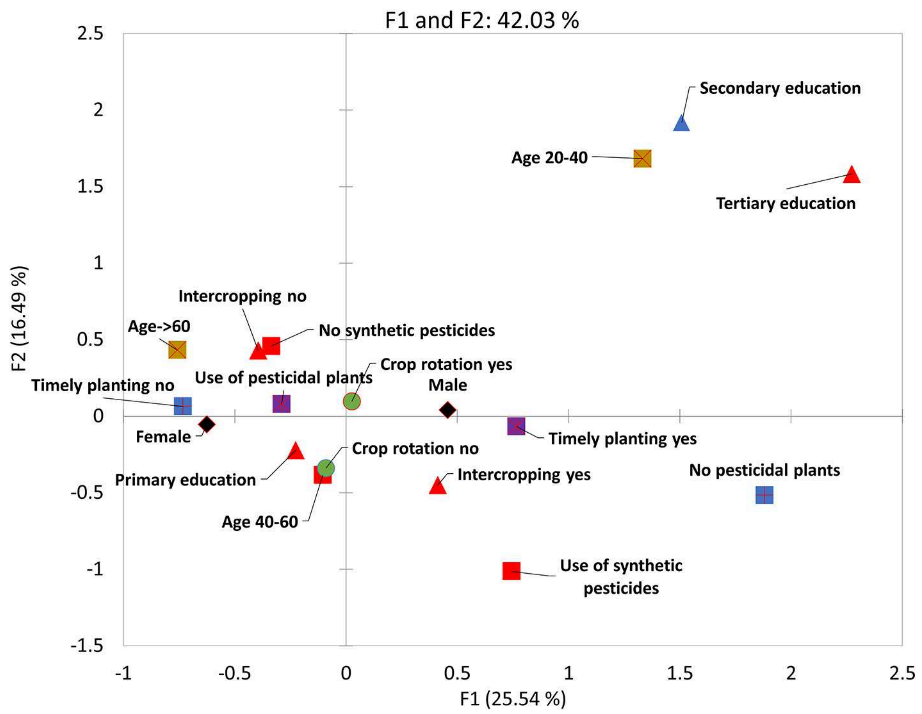

FIGURE 3
Multiple correspondence analysis showing relationships between key demographic information of respondents and their practices related to soil-borne insect pests and disease management practices, in Narumu Ward, Kilimanjaro Region, Tanzania.

TABLE 2 Land ownership and land size of respondents for 45 farmers with maize and bean fields in Narumu Ward, Kilimanjaro Region, Tanzania.

Variable	Categories	Frequencies	%
Land ownership	Does not own (e.g., rents)	18	40.0
	Owns the field	27	60.0
Crop field area (Ha)	0.1–0.19	7	15.6
	0.2	20	44.4
	>0.2	18	40.0

proportion of the respondents. More than half of farmers with cattle had a small number of cattle ranging from 1 to 6 with most farmers owning 1–4 cattle (50%) kept at their homestead surroundings. These zero-grazing practices promoted farmers to collect bean and maize residues from their fields to feed the cattle. Although it was expected that only farmers with livestock would collect crop residue for feeding their animals, all farmers with or without livestock harvested crop residues, whereas farmers with no livestock would sell the residue to farmers with livestock. Cattle manure was the only manure used for managing soil fertility in farms; however, only 3 of 45 maize and bean fields in the survey received manure, and at very low rates, suggesting that recycling of organic nutrient sources to bean and maize fields is very uncommon in these systems. Rather, all but one of the surveyed farmers reported the use of manure on homestead farms or plots near their houses ranging from small vegetable plots to large mixed plots with coffee, banana and beans (Table 3), which were often adjacent to the homestead.

Although highly variable, the manuring rates on these near plots were much higher than in the maize/bean plots, averaging 14.3 Mg ha^{-1} (standard deviation = 19.4 Mg ha^{-1}) across farms. Over 80% of manure was from farmers' own livestock with few obtaining manure from family or neighbors. Most farmers (>70%) reported that the distance to the farm was the major constraint for using manure on bean and maize fields, particularly where farmers were farming at a distance greater than five kilometers from the homestead. Another constraint reported by farmers was a lack of improved practices for composting manure as an alternative to passive methods in which the manure decomposes for 6–12 months.

3.2. Participant perceptions of soil-borne insect pests and diseases

Focus group discussions indicated that farmers in the study area were aware that insect pests damaged common bean from within the soil (Table 4). The symptoms of crop damage by soil-borne insect pests are observed mainly by uprooting the plants; however, only farmers from one group discussion reported uprooting plants to see if the damage was caused by soil-borne insects. Farmers reported root rot diseases in the field where three groups of farmers knew of such disease as soil-borne, and they reported having seen it in their farms. They perceived the diseases as soil-borne as they could observe field sections of healthy bean seedlings

TABLE 3 Distance from homes, proportion of farmers applying manure, and mean manure application rates of different crop production types of 45 farms in Narumu Ward, Kilimanjaro region, Tanzania.

Production type	Distance from homestead (km, range)	Proportion of farmers with production type (%)	Proportion of farmers with production type applying manure	Mean manure application (Mg ha^{-1}; mean ± std deviation)
Vegetable plot	< 1	18.2	100	23.6 ± 35.6
Banana-bean intercrop	< 1	4.5	100	28.2 ± 13.3
Coffee-bean intercrop	<1	59.1	3.8	0.6 ± 3.1
Coffee-banana-bean intercrop	<1	59.1	96.2	19.2 ± 26.9
Maize-bean outfields	0.5–15	100	6.7	<0.1 ± 0.1

TABLE 4 Summary of 64 farmers' responses during focus group discussions done in Narumu Ward, Kilimanjaro region, Tanzania showing perceptions about key pest insects infesting common bean plants when farmers were shown color images and dead specimens of the insect in comparison to actual scientific descriptions.

Insect pests presented to farmers ($N = 64$)	Farmer perception of the insect	Scientific description of the insect	Associated crop plant symptoms
Adult and larvae of the bean fly, *Ophiomyia phaseoli*	Thought to be larvae of the African black beetle, *Heteronychus arator*, locally named "*Nrokoo*" and thought to eat crop roots. Adults are thought to be another type of fly commonly seen in the field with no potential harm to plants.	Larvae are small and white in color whereas a fully grown larva is 2.5 mm long, yellowish white in color with black rasping hooked mouth parts, yellow-white prothoracic and posterior spiracles. Adults are shiny black with a length of 2.5 mm.	Yellowing of false leaves, stunting, wilting and death of bean plants.
Adult and larvae of the bean foliage beetle. *Ootheca bennigseni*	Larvae are not recognized. Adults are locally named "*Kirombochoo*" and are recognized as a pest damaging leaves.	The larva is elliptical, yellow and translucent. Adults are oval, 6 mm long, and shiny black with orange and dark blue streaks.	Extensive defoliation of young bean plants, wilting, premature senescence and death of plants.

without any symptoms then turning yellow a few weeks after planting. Five groups reported wilting plants, which they thought were caused by soil pests or pathogens. Participants provided with pictures of plants with *Pythium* or *Fusarium* root rot were unable to differentiate between the two pathogens. Many farmers did perceive the link between soil-borne diseases and plants turning yellow, wilting, and dying a few weeks after planting. However, participants' knowledge was limited with some remarking that root nodules on beans that provide N fixation *via* the symbiosis with *Rhizobium* bacteria were a symptom of the disease.

Field surveys showed that farmers reported bean fly and bean foliage beetle to be present in their fields for more than 3 years. Almost all farmers (90%) reported bean foliage beetle adults to be present in their fields with holes on the bean seedling leaves as the main observed symptom of insect damage. Only 6% of farmers reported seeing bean fly adults in their field but >35% of farmers reported wilting and dying of seedlings as the widely observed symptom of damage by the insect. No participant reported the presence of larvae or pupa in the soil nor attributed plant damage to them. Some farmers misdiagnosed bean fly damage, indicated by stunted plants with yellowed leaves, as anthracnose (*Colletotrichum lindemuthianum*), a fungal disease normally triggered by cold weather and high humidity. About 37% of respondents reported having root rot disease in their fields were from higher altitudes with higher humidity. All participants were aware of one key symptom of root rot, which was leaves turning yellow and dropping, followed by plants wilting and dying.

3.3. Soil fertility, soil nutrient balance and principal components analysis of site factors

Soil assessments showed that ∼70% of the fields had active carbon (POXC) in the low and very low ranges (<400 mg kg^{-1}) with the remaining group having a medium amount of POXC with the highest recorded value of <700 mg kg^{-1} (Supplementary Table 1). Almost three-quarters of the soils were either low or very low in available Olsen P (<10 mg P kg^{-1}; Supplementary Table 1) with a median value for Olsen P of 5.3 mg P kg^{-1}. Nevertheless, an analysis of soil nutrient balances on the survey fields showed that most farmers had field P balances not different from zero, regardless of whether fields were farmer-owned or not (Figure 4), due to the widespread use of synthetic fertilizers (over 95% applied fertilizer) that replaced crop exports. Meanwhile, fields owned by farmers, mostly at lower elevations, had negative N balances while those not owned had balances not different from zero on average. Negative N balances on owned fields likely relate to more frequent growing of maize in intercrops with beans on these fields, resulting in high N exports from the cereal crops, whereas on rented fields beans were more often the sole crop with lower N exports due to N fixation and the lack of a non-fixing cereal (Figure 4). On the other hand, the infrequent use of manure and the removal of residue across all the bean and maize fields, described above, is notable because it implies

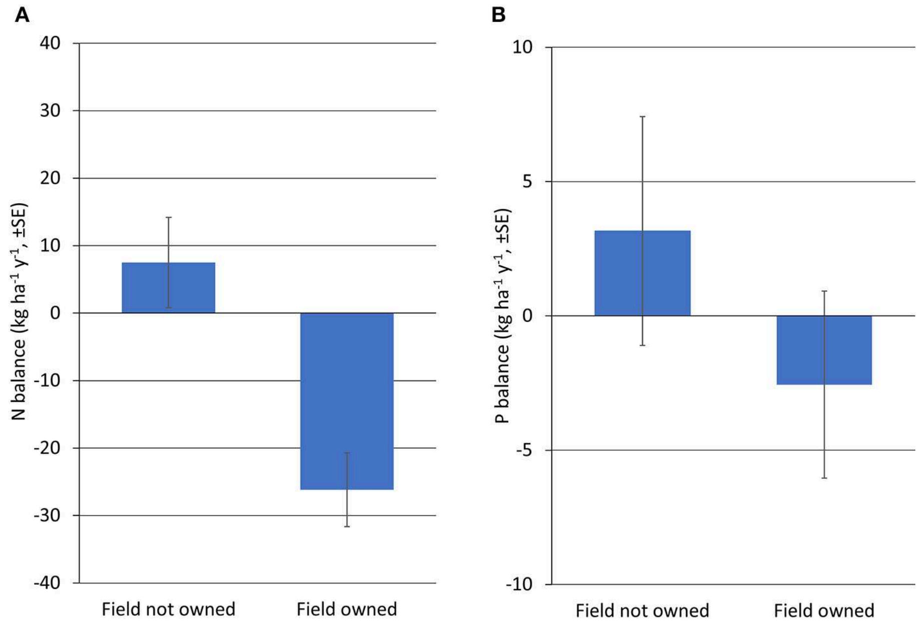

FIGURE 4
Partial nutrient balances, incorporating nutrient inputs in manure and fertilizer, estimated nitrogen fixation, and crop exports in grain and residues, based on surveys regarding 45 farmers' fields in Narumu Ward, Kilimanjaro Region, Tanzania: **(A)** nitrogen balances and **(B)** phosphorus balances, comparing fields that are owned by farmers with those not owned by farmers. Error bars show the standard error of each mean.

that little organic carbon is being returned to any of these fields (Table 3).

A principal component analysis (PCA) of site and management variables for fields (Figure 5) demonstrated a strong first component encompassing just over 30% of variability, combining pH, elevation, total inorganic N inputs, organic matter (POXC) as well as soil available P, and aggregate stability to a lesser extent. Aggregate stability (MWD of aggregates) was also positively correlated to POXC ($r = +0.55$, $p < 0.0001$, $n = 45$). Meanwhile, soil nutrient balances, total P fertilizer additions, and soil clay content were segregated into a second component (Figure 5, PC2). The third axis of variability in PC3 with 81% of the variability was loaded highly only on MWD related to aggregate stability (Supplementary Table 2). The negative association of fertilizer N inputs with elevation likely is another result of the higher frequency of maize-bean intercrops in lower fields with N fertilizer inputs during both surveyed seasons, while the association of total inorganic P inputs with P balances indicates how these inputs may be dominating the P balances across all the surveyed fields.

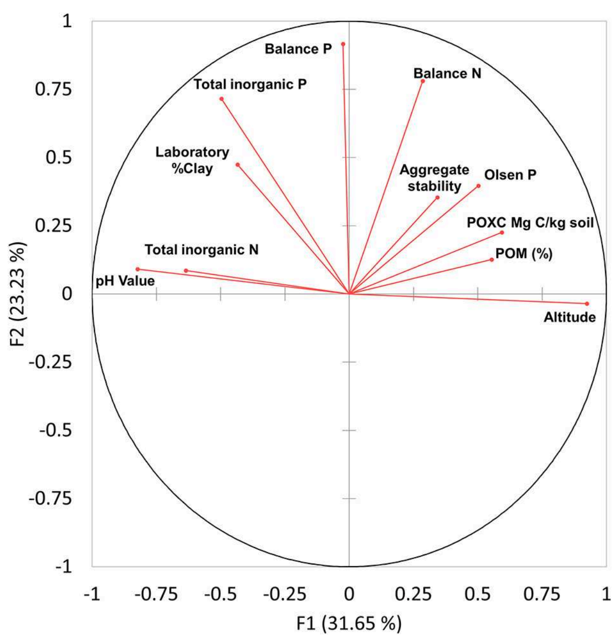

FIGURE 5
Principal component analysis of the key site and soil variables drawn from 45 farm fields for bean cultivation in Narumu Ward, Kilimanjaro Region, Tanzania. Percent variability explained by each principal component (PC) is indicated along the axes.

3.4. Linkages between site and soil factors and crop management with perceptions of soil-borne pests and disease

Logistic regressions testing the association of each of the site and management principal components, with a binary variable testing whether wilting, stunting, or root damage (S/W) was observed at each site, showed that the three principal components were all significantly associated with these farmer observations related to soil pests and diseases (Table 5). Within principal component 1 (PC1), Soil pH, soil active Carbon, and Olsen P were negatively correlated to S/W observations so that for example, fields with higher active C had lower rates of S/W reported by farmers (in

TABLE 5 Logistic regressions assessing the relationship of soil parameters and soil nutrient management predictors, with a synthetic variable summarizing observations of stunting and wilting in beans (farmers observe stunting or wilting vs. do not observe), in Narumu Ward, Kilimanjaro Region, Tanzania.

Predictor	*N*	Significance		Association with observation of stunting/wilting
Principle components				
Principle component one (PC1)	45	0.012	**	Negative
Principle component two (PC2)	45	0.035	*	Negative
Principle component three (PC3)	45	0.011	**	Negative
Individual soil parameters associated with PC 1				
Soil pH	45	0.004	**	Negative
Soil Active Carbon (POXC)	45	0.001	***	Negative
Total Inorganic N inputs in previous 2 years (kg N ha^{-1})	45	0.001	***	Positive
Soil Available P (Olsen P)	45	0.012	*	Negative
Individual soil parameters associated with PC 2				
Total Inorganic P inputs in previous 2 years (kg P ha-^{1})	45	0.403	NS	
2- year running soil P balance (kg P ha^{-1} $y^{-1)}$)	45	0.739	NS	
2- year running soil N balance (kg N ha^{-1} y^{-1})	45	0.363	NS	
Individual soil parameters associated with PC 3				
Soil aggregate stability (MWD)	45	0.003	**	Negative
Soil clay content (%)	45	0.754	NS	

Significance codes: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; NS, not significant.

fields with S/W, POXC levels of 300 ± 23 mg C kg^{-1} compared to 467 ± 41 mg C kg^{-1} in fields without S/W). By contrast, only total inorganic N inputs correlate positively with S/W, while elevation in itself was not significantly related to the S/W synthetic variable. Principal component 2 (PC2) parameters were not significantly related to S/W when tested separately (Table 5), while in PC3, fields with higher levels of aggregation (higher MWD) had lower levels of S/W.

4. Discussion

4.1. Farmers' knowledge and management of soil-borne insect pests and diseases

The surveys and focus group discussions with farmers suggested that most do not uproot seedlings or investigate roots in other ways when SPD are suspected. This is partly because farmers are not fully aware of how to assess and confirm their presence but also because it is considered a destructive method that could reduce crop yield. Farmer knowledge about bean fly and foliage beetle life cycles was largely absent with little understanding of how to observe plant damage caused by their larval stages in the soil. Damage symptoms of these pests can be similar to those arising from root rot diseases (Abate and Ampofo, 1996), where farmers made general descriptions of the yellowing of plants, stunting, wilting and death. Our results are consistent with other research that reported farmers are often confused by damage caused by bean fly and root rot disease (Buruchara et al., 2010). Holes on bean leaves were commonly reported symptoms of adult bean foliage beetle damage; however, farmers generally did not know the larval stage was a soil pest, as has been observed in other studies (Abate et al., 2000). Further confusion was evidenced by farmers who wrongly attributed bean fly larval damage to the fungal disease anthracnose (*Colletotrichum lindemuthianum*). This may indicate the inability of farmers to recognize the minute adult bean fly as a pest and then rather describe wilting and dying caused by bean fly infestation as a disease (Letourneau, 1994). Our surveys with farmers highlight that plant damage symptoms from different soil-borne pests and pathogens, such as wilting and stunting, are difficult to distinguish by farmers.

This lack of awareness about SPD has clear implications for farmers' abilities to take appropriate management actions. The first line of defense for most farmers is to use cultural practices such as early synchronous planting, using a varietal mixture of seed and intercropping (Abate and Ampofo, 1996). Such practices are considered affordable and are part of local customs, as indicated by the large number of practices in use by the oldest farmers in the MCA (Figure 3). Farmers in the area grow local bean varieties with seeds obtained from their previous harvest. The choice of varieties is based on productivity and adaptability to environmental conditions such as temperature and rainfall. This finding is consistent with research in Uganda that indicated varietal adaptability to farm conditions was one of the keys to farmer preferences for seed varieties (Bruno et al., 2018). Intercropping is commonly used in a variety of cropping systems to reduce pest incidence such as the bean foliage beetle (Farrow et al., 2011; Srinivasan, 2014). However, intercropping of beans with maize was reported to be ineffective in reducing bean fly incidence (Abate and Ampofo, 1996). Some surveys suggest that farmers do not perceive intercropping to be a pest management strategy as they report a prevalence of insect damage despite the use of the method (Laizer et al., 2019), and the observation may be quite correct in that intercropping over many adjacent farm fields supplies pests and pathogens with a constant supply of host bean plants. By contrast, crop rotation is a common cultural practice known to be effective in managing root rot and soil-borne insect pest in common bean (Mohamed and Teri, 1989). Unfortunately, in the study area, very few farmers practiced crop rotation, and among those who did, they were not doing it appropriately as 2–3 years rotation with non-host crops as recommended (Buruchara et al., 2010).

A commonly reported approach used by farmers in the study area for preventing losses from SPDs is the use of synthetic pesticides. Prior studies have noted this to be a common practice in different regions (Mwanauta et al., 2015; Stevenson et al., 2017; Andersson and Isgren, 2021). Insecticide seed treatments and foliar sprays have been recommended for bean fly and foliage beetle (Mwanauta et al., 2015), whilst fungicides and fumigants have been recommended for the control of root rots (Mahmood et al., 2017). Despite the often high cost of synthetics, many farmers use them as they fear the loss of their livelihoods and ability to feed their families. The economics of using relatively safer synthetic products is often restricted by a farmer's perceived limited capacity and autonomy to reduce pesticide use as well as what is considered "normal" practice (Bakker et al., 2021; Deguine et al., 2021). Use of synthetics is exacerbated at the smallholder level as many smallholders are unaware of alternative agro-ecological approaches (Anjarwalla et al., 2016), nor are they often aware of the hazards of synthetic use to their health (Nicolopoulou-Stamati et al., 2016; Andersson and Isgren, 2021) and the environment (Suganda et al., 2020). Farmer use of pesticidal plants has been undermined through commercial advertising and systematic promotion of synthetics over several decades by businesses and governments (Isman, 2008; Lykogianni et al., 2021). Desneux et al. (2007) advocate studying the sub-lethal effects of synthetic pesticides on natural enemies to be sure of their safe use in order to optimize IPM programs involving the use of both natural enemies and pesticides against pests. Further, Belmain et al. (2022) suggest the elimination of synthetic pesticides in order to support these natural processes and food sovereignty. Mkindi et al. (2021) recommend pesticidal plants as one alternative to synthetic pesticides. One-third of farmers in the study area reported using pesticidal plants such as *T. vogelii* and *Tithonia diversifolia*. Extracts of *T. vogelii* have been reported to have broad pesticidal properties which make them effective against most foliar and soil pests (Mkenda et al., 2014; Stevenson et al., 2017). Its use can also increase plant resilience and growth by acting as a foliar fertilizer (Mkindi et al., 2020). Other pesticidal plant species such as neem (*Azadirachta indica*) have been shown to be effective against soil-borne insects (Abate and Ampofo, 1996; Buruchara et al., 2010) where Karel and Rweyemamu (1984) reported *A. indica* to be effective in controlling bean fly in common bean.

4.2. Soil management practices and soil nutrient balance

While the cultural practices and crop protection approaches discussed above have relatively direct and short-term impacts on arthropod pests, soil fertility and organic matter management that we explored in this study are important agroecological aspects of smallholder intensification, with effects on pests and diseases at a variety of different timescales and through a complex set of mechanisms (Altieri et al., 2012; Krey et al., 2020; Belmain et al., 2022; Han et al., 2022). In this light, it is interesting that farmers observed less stunting and wilting in bean crops in fields that differed in terms of organic carbon, soil aggregation, soil available P, and recent applications of inorganic N fertilizer. These results for smallholder management contexts are consistent with more controlled experimental and observational studies suggesting for example that organic management can have positive impacts on plant defense (Krey et al., 2020), or *via* more diverse soil biological communities that can suppress pests such as pythium root rot (Larkin, 2015). It has been observed that soils with higher amounts of organic matter content have more water-stable aggregates (Gachene, 2018), and this was also the case in our study. Stable aggregates provide a habitat for a larger and more diverse microbial population which can create competitive and/or antagonistic environments between microorganisms resulting in disease suppression (Leon et al., 2006; Kevan and Shipp, 2011; Larkin, 2015). Meanwhile, the contrast between inorganic N application and soil available P in their opposite associations with stunting and wilting observations is also consistent with previous research showing that soil fertility influences the outcomes of SPDs. Soil-borne insect pests such as bean fly (*Ophiomyia* spp.) and soil-borne diseases such as root rot from *Pythium* spp. and *Fusarium* spp. are reduced in intensity when crops are grown in fertile soils and crops are less vulnerable, with phosphorus sufficiency being a key aspect (Hillocks et al., 2006; Buruchara et al., 2010; Huber et al., 2011; Samago et al., 2018). Letourneau (1994) also reported phosphorus deficiency resulted in an increase in population densities of all species of bean fly; however, increased total N increased the population of *O. spencerella*. The observation that high levels of available N predispose crops to pest damage is thought to be more generally true (Han et al., 2022).

In linking soil properties and management to stunting/wilting, our study is exploratory rather than definitive since this is an observational study that does not completely control for location, e.g., with paired plots of differing fertility and soil organic matter (SOM) status at a number of different locations. However, given the potential, and plausible links between organic matter, soil fertility, and reduced incidence of soil-borne pests and disease, the existing management of farmers raise concerns regarding sustainable intensification of bean cropping in these systems. For example, although farmers clearly used fertilizers to maintain the productivity of their maize/bean intercrops, few farmers used manure or compost in bean production fields as they lacked manure or materials for composting, and tended to use such materials in fields closer to home, often at high rates (>10 Mg ha^{-1}), which suggests the possibility of allocating some of these organic inputs to more remote maize and bean fields. The preference for enriching home fields vs. far fields in smallholder systems, and not applying fertilizer or other inputs onto beans in years where these are grown as a sole crop, has been documented in other systems (Masvaya et al., 2010; Saimon et al., 2017). In addition, although fields were in general balanced for P inputs vs. exports, available P was low across all sites and may be limiting to bean production. We note here that even though a few soil sites had strongly acidic soils which has been thought to lower the efficiency of the Olsen P extraction we used, a number of studies have shown that Olsen P performs reasonably well in acidic soils and was thus well-suited to our study which covered a wide range of soil pH from neutral to acidic (Farina and Channon, 1979; Fixen and Grove, 1990). Growing common bean with insufficient P can be detrimental to grain yield and degrade soil fertility (Araújo et al., 2000; Samago et al., 2018; Meya et al., 2020) as P contributes to effective N fixation (Hernández et al., 2009) and resistance to SPDs as discussed above (Huber et al., 2011). One important observation from our study is that regardless of whether farmers owned or did not own fields, they prioritized soil health and fertility improvement less than they did crop productivity. Other studies have argued that neglecting soils is especially prevalent for farmers who do not have long-term farm tenure and are less committed to investment in soil improvement (Williams, 1999). Conversely, land ownership can potentially lead to management practices that increase SOM affecting soil health (Mganga et al., 2016). However, in our study, few farmers were using manure irrespective of owning the field or not, likely due to transport costs, lack of skills in manure processing and composting, and relatively few cattle in the area. They were however applying more fertilizer to owned plots in order to plant maize every season, even if the balances in these plots were negative on average, due to high levels of N export by maize.

Crop residue removal can also contribute to the loss of SOM (Mganga et al., 2016) which could have beneficial effects on the management of some pests and diseases (Leon et al., 2006; Janvier et al., 2007). Farmers in the area generally use crop residue as livestock feed, and according to our survey, even farmers without livestock sold residue to those with animals. Beyond distance to fields and knowledge of manure management, our results likely do not capture all the factors that determine farmers' use of manure and crop residues, such as labor constraints and the monetary gain from selling residues; part of increasing the recycling of organic materials to soils would be to better understand and address these factors with evidence regarding soil health benefits of recycling residues (Adimassu et al., 2016; Mponela et al., 2016). Crop harvests, residue removal and lack of any organic inputs through animal manure or green mulches suggest that soil structure and organic matter content have likely been degraded in the majority of farmer fields in the area over decades of using such farming practices (Rurangwa et al., 2018), resulting in the low levels of active C observed in this study in many fields. Reversing these trends will likely require investment in better understanding residue use decisions and raising awareness of farmers and training that aims at restoring soil health such as maintaining agricultural residues, application of organic fertilizers, crop rotation, nutrient and carbon recycling (Bunning and Jiménez, 2003; Martinez-Salgado et al., 2010). Though challenging for many farmers, these practices can augment the soil's organic carbon pool, a key indicator of soil quality linked to soil aggregation, available water holding capacity and reduced erodibility of soil (Lal, 2006). Increased SOM will support an increased abundance of microorganisms that are necessary to sustain many soil functions such as the decomposition of organic matter (Janvier et al., 2007), maintenance of soil structure (Puget et al., 2000) and suppression of above and below-ground pests, parasites and diseases (Leon et al., 2006; Janvier et al., 2007; Altieri et al., 2012).

5. Conclusions

A main conclusion from this study with relevance to other African smallholder communities undergoing the intensification of farming is that farmers' awareness of SPDs in the study area is low, which has directly facilitated the prevalence of these biotic production constraints. Therefore, knowledge of these pests and diseases, including their relation to soil factors, should be promoted to motivate changes toward agroecological management of soil pests and pathogens. Further research also needs to explore specific soil mechanisms that are relevant or achievable in smallholder contexts, that may deter or encourage particular pests and pathogens, which are not sufficiently explored in this characterization study. In addition, learning approaches for farmers should be tailored to their needs by considering farmers' current practices, including cultural and soil management, and also aligning with the FAO's elements of agroecological farming for pest and disease management (Belmain et al., 2022) This could involve increased use of pesticidal plants, particularly species such as *T. vogelii* that have been shown to control a wide variety of pests, increase crop plant resilience and help to improve the soil where it is growing due to its deep roots and nitrogen-fixing properties (Belmain et al., 2022). Use of manure, compost, green mulching, short fallows, and other organic inputs need to be facilitated through dialogue with farmers to develop socially and economically sustainable practices alongside them, whilst also improving soils to maintain productivity and also reduce chronic soil-borne pest and disease problems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Tanzania Commission for Science and Technology (2021-181-NA-2021-061). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

ZN, AM, PS, SB, SV, and PN contributed to the conceptualization of the study. ZN, AM, PS, SV, and SB structured the methodology. ZN, AM, and SV wrote the first draft of the manuscript. SV and AM cleaned and managed data. ZN, AM, SV, and SB performed the statistical analysis. AM, SV, PN, and SB mobilized resources for publication.

AM, SV, PN, PS, and SB reviewed and edited the manuscript. All authors have contributed to manuscript revision, read, and agreed to the published version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1094739/full#supplementary-material

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