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Report on the status of land degradation, restoration options and priority SI technologies

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HISTORY OF CHANGES

Version	Date	Description of changes
REV 1	12 February 2024	● Additional information in section 3.1.2 page 15 and in Annex 2, section A 2.2.1 (page 20) has been provided to better explain how farmers were selected and how degraded lands were mapped in Ethiopia. ● Maps on land use and land cover changes (LULCC) and soil erosion prevalence in Tanzania have been added under section 3.3.2 (Figs 12 and 13 in page 20-21). A short discussion of these results was also added. ● Clarifications on the results in Fig 14 (now Fig 16) and Fig 15 (now Fig 17) have been provided with additional literature review (e.g., Wekesah et al 2019; Harman Parks et al 2022) to support the results on gender-based response to the benefits of contour farming and conservation agriculture (section 3.3.3.2 in page 24) ● Section 4.3.3.2 (page 31) has been added to include the research on salt-fluoride affected soils in Tanzania previously reported in deliverable. 2.8. ● Annex 4 has been revised to integrate the LULCC maps (3.3.1 – page 15) and a section on salt-fluoride affected soils (Section D – pg 37)

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EXECUTIVE SUMMARY

Land restoration has become a global agenda in the United Nations' declaration to prevent, halt and reverse the degradation of ecosystems worldwide. Africa countries through the Africa Forest Landscape Restoration Initiative are also responding to this declaration with a target to restore 100 million ha of land by 2030. Integrating landscape restoration with livelihood benefits using Sustainable Intensification (SI) technologies is key to the successful engagement of smallholder farmers in Sub-Saharan Africa (SSA). The EWA-BELT project is well positioned to generate evidence on land recovery options to restore degraded farmland sustainably while benefiting small-scale farmers. In this context Sub-Task 2.2.1 focuses on the recovery of abandoned land to restore sustainable agricultural production. The deliverable 2.6 report provides information on activities conducted by partners in Burkina Faso, Ethiopia, and Tanzania contributing to Sub-Tasks 2.2.1.

1. Introduction

The United Nations' declaration of 2010-2030 as a Decade of Ecosystem restoration, has put land degradation issues into the international development agenda. The declaration aims to prevent, halt and reverse the degradation of ecosystems worldwide. In Africa, the Africa Forest Landscape Restoration Initiative is responding to this global challenge by promoting actions aiming to restore 100 million has of land by 2030. Already over 27 countries have committed to restore 111 million hectares, surpassing the Afr100 restoration target by 11 %. Integrating landscape restoration with livelihood benefits using Sustainable Intensification (SI) technologies is key to the successful engagement of smallholder farmers in Sub-Saharan Africa (SSA). The EWA-BELT project is well positioned to generate evidence on land recovery options to restore degraded farmland sustainably while benefiting small-scale farmers. In this context, Sub-Task 2.2.1 focuses on the recovery of abandoned land to restore sustainable agricultural production through the following two stages:

- Section A: Identification and mapping of abandoned land through reconnaissance surveys aiming to collect and process soil management, cropping systems and socio-economic data (characteristics of agricultural holdings, access to factors of production and the market, etc.).
- Section B: Assessment of soil fertility traits in selected FFRUs with abandoned lands through the determination of different soil chemical parameters according to the WRB (2015) standards and the crop yields assessment.

Deliverable 2.6 provides information on the activities conducted by partners contributing to Sub-Tasks 2.2.1. The report is organized into two major sections, listed above, with details of contributions from each partner. Detailed reports from contributing partners are attached as Annexes 2-4. The abandoned land reconnaissance survey module is attached as Annex 1.

2. Section A: Identification and mapping of abandoned land

2.1. Objectives

Identification and mapping of abandoned/degraded lands in the study area through biophysical and socio-economic data collection and processing.

2.2. Methodology

The identification and mapping of abandoned land were conducted using reconnaissance surveys and satellite image analysis. Both biophysical and socio-economic data were collected and processed to give information on the drivers and extent of land degradation and options for restoring crop production in the identified degraded/abandoned lands.

Biophysical data to identify and map abandoned/degraded in selected FFRUs were collected through analysis of soil maps and satellite images as detailed in Annex 2-4. The following biophysical indicators

of land degradation were collected by partners in the sites listed in Table 1 and shown in Fig 1: land use types, land cover and land use, tree cover, tree density, cropping systems etc.), topography (slope, topographic positions), soil erosion prevalence, and presence of land restoration practices.

Qualitative information, including socio-economic data, was collected mainly using a common survey tool named "ST 2.2.1- Abandoned land reconnaissance survey" that was developed by partners involved in Sub-task 2.2.1, namely UNB, NM-AIST, TARI-Selian, JU, ICRAF, and UNISS. The survey tool was developed between July 2021 and August 2021 by collecting ideas and comments from partners through emails and virtual meetings.

Table 1. Study areas and number of interviews conducted to collect information on degraded/abandoned land in Tanzania, Burkina Faso and Ethiopia

Country	Partners involved	Study areas	Number of interviews
Tanzania	13-NM-AIST, 14-TARI, 17-ICRAF	Monduli and Arusha districts, Northern Tanzania	60 interviews
Burkina Faso	6-UNB and 7-INERA	Béréba, Dohoun, Wakuy, Sara; Bondoukuy, Kari/Kamandéna	79 interviews
Ethiopia	16-JU	Omonada district	80 interviews

Figure 1. Collecting vegetation, soil erosion and land use data (a) and soil samples (b) during the fieldwork to assess land degradation in Arumeru/Monduli District (Photo Credit: J. Kalonga)

The tool included open and closed-ended questionnaires covering the following topics: i) farmers' perception of the status of land degradation; ii) constraints in implementing soil fertility management; iii) characterization of the degradation and fertility status of degraded lands (soil surface characterization (signs of erosion, microtopography, surrounding topography, cartographic unity, soil classification/FAO system, human influence), and; iv) vegetation survey (e.g. floristic inventory, soil cover rate). A total of 219 respondents were interviewed in selected areas in Burkina Faso, Ethiopia, and Tanzania (Table 1; Fig. 2). With technical support from UNISS and OCCAM, the questionnaire was uploaded online using the "KoBotoolbox", making it possible for partners in the field to collect the data using PCs, tablets and smartphones. Data were cleaned and submitted to OCCAM for uploading to a central server. Descriptive analysis of the data was done by partners in collaboration with OCCAM who managed the database.

Figure 2. The interview team paying a courtesy call at the Village office (a) and ICRAF staff administering questionnaire using the smartphone (b) in Arusha, Tanzania. (Photo Credit: J. Sianga)

In Tanzania, a Participatory Trade-off analysis of SI technologies (Annex 4) for land restoration was also used to collect socioeconomic data on land restoration technologies with the potential for integration into sustainable land management in FFRUs (Sub-task 2.2.2). The analysis was based on the perception of farmers with prior exposure to the technologies from previous projects. The participatory trade-off analysis was developed by Winowiecki et al. (2021) based on the SI framework manual by Makumba et al. 2007 and it has been used in previous projects in Tanzania. The methodology involved the collection of perceptions of farmers on the trade-off and synergies of a given technology across the five domains of sustainable intensification namely, Productivity, Income, Human Condition, Land health, and Social. A total of 218 farmers were interviewed using the focused group discussion in Arusha and Monduli Districts (Table 2; Fig 3). A total of 41 groups were formed of which 26 (64%) were male groups and 15 (36%) were female groups.

Table 2. Participants of the trade-off analysis in Arusha and Monduli Districts, Tanzania

Village	District	Male	Female	Total
Likamba	Arusha	31	17	48
Nengungu	Arusha	14	9	23
Olcholvus	Arusha	23	7	30
Emairete	Monduli	21	25	46
Enguiki	Monduli	28	5	33
Mlimani	Monduli	21	17	38
Total		**138**	**80**	**218**

Figure 3. ICRAF staff explaining trade-off analysis methodology to farmers (a), farmers presenting their results on a paper (b and c) and presenting their results to the group (d) during data collection in Engaruki village, Monduli District, Tanzania (Photo Credit J. Sianga).

3. Results

3.1. Ethiopia

3.1.1. Assessment of land degradation and drivers by farmers (Abandoned Survey Results)

Farmers in the survey areas reported more than 5 major types of soils based on soil colour (red, brown, dark, red to brown, and black). Few farmers have also recognized brown to red, white, and red and dark mixed. In each site, the most recognized soil type was red coloured soil with a percentage of 49, 43, 44 and 62% at the sites Doyoya (A), Nada challa (B), Alle (C) and Toli sabbata (D) within the OmoNada district, followed by brown type soil with percent proportion of 25, 36, 21 and 20% respectively at each site (Fig. 4A-D). Farmers in the present study area have a tradition of associating soil variability with different local soil nomenclatures. The naming and classification indicators of most soil types are relatively homogeneous over a large area in the district of OmoNada and beyond in southwest Ethiopia. Unlike the standard procedure (e.g., WRB) that groups the soils of the study area as Nitisols, farmer's soil types are more detailed and very diverse.

Over 60% of farmers in Ethiopia indicated that their fields are degraded (Fig. 5a) to the extent that about 70% % of them have abandoned their lands and moved to other productive areas (Fig 5b). The main causes of land degradation mentioned were unsustainable farming practices, excessive ploughing and deforestation (Fig. 6a). Farmers mentioned several land restoration practices, including good agronomic practices, afforestation, sustainable intensification practices, cover crop and other forms of soil amendments (Fig. 6b).

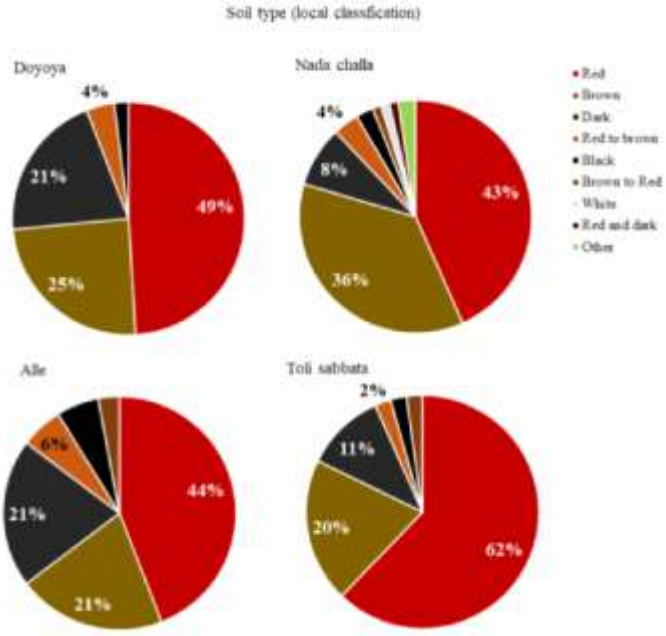

Figure 4. Perception of Farmers on main soil types in FFRUs in Ethiopia

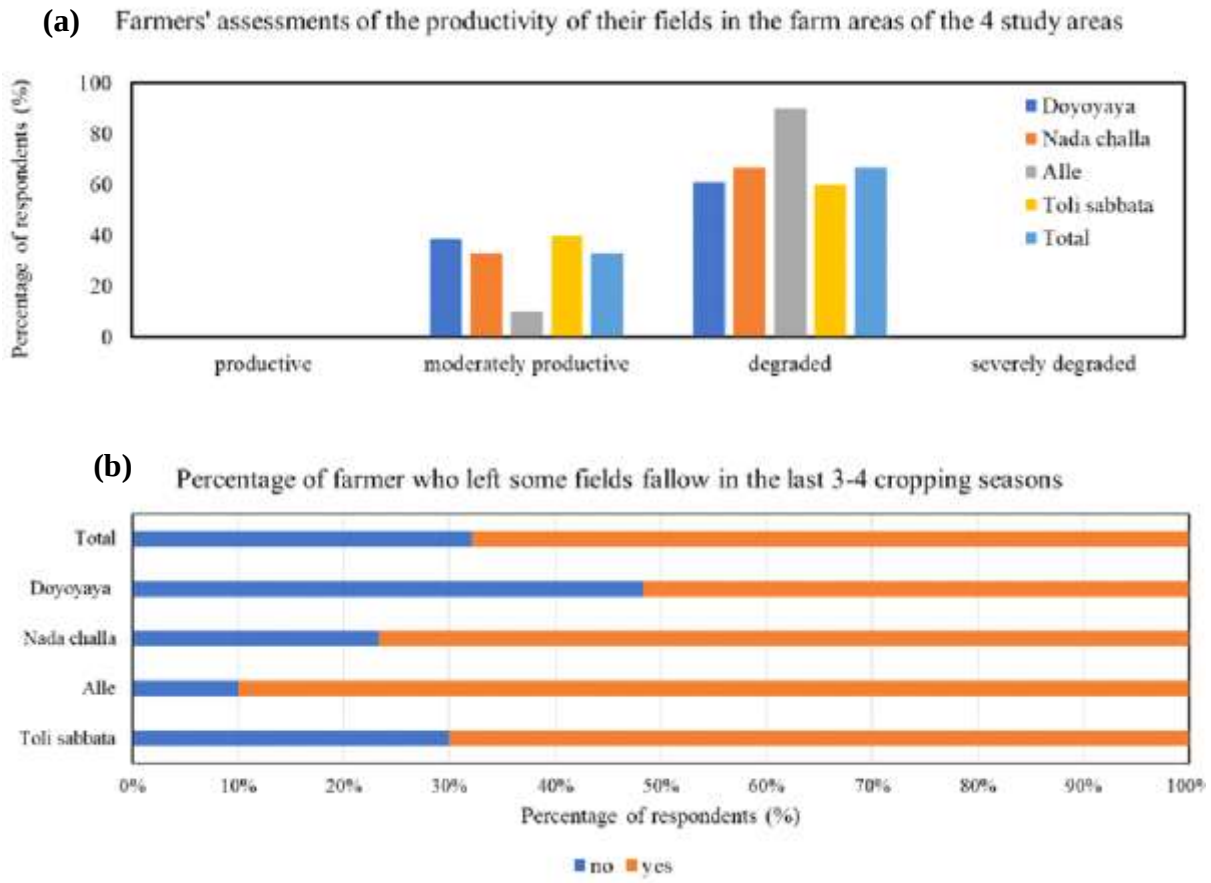

Figure 5. Farmer perception on levels on land degradation (a) and farmers who left some fields fallow in the last 3-4 cropping seasons (b) in Ethiopia.

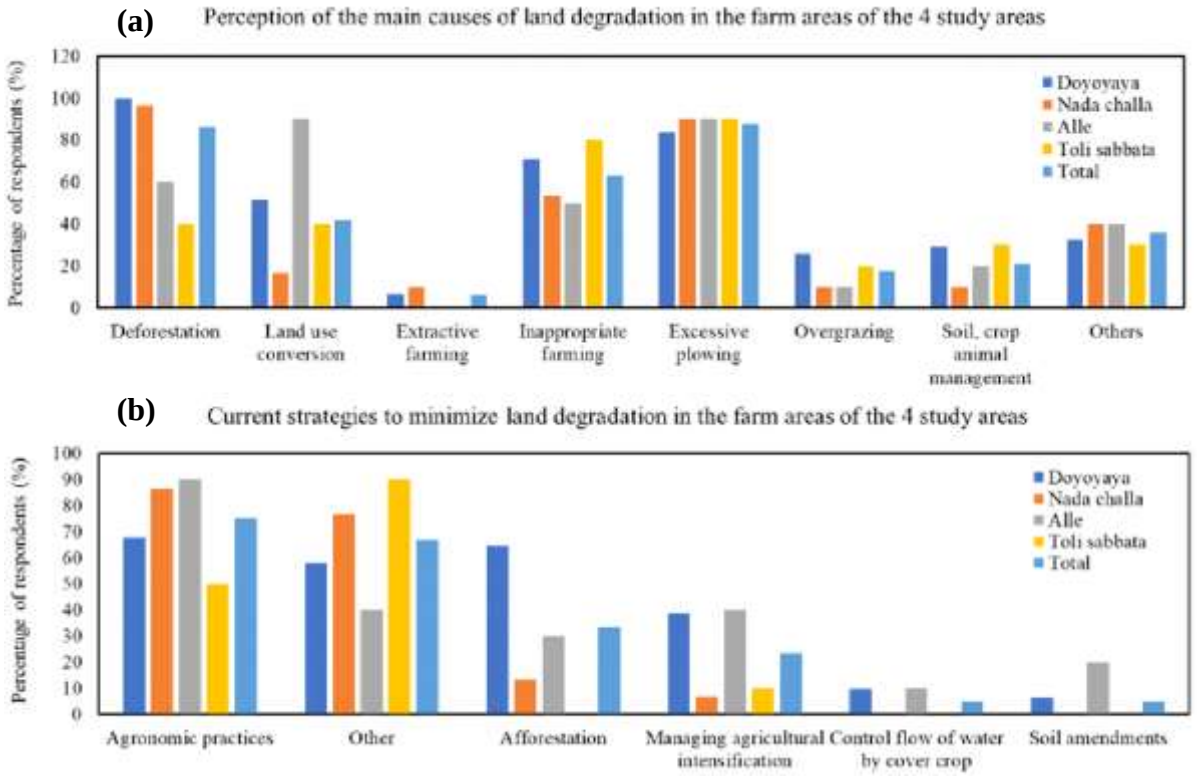

Figure 6. Farmer perception on the main reasons for land degradation (a), and land restoration options (b) in Ethiopia

3.1.2. Mapping degraded/abandoned land in Ethiopia

In the initial mapping of degraded/abandoned land, we used the RandomForest classification method in Google Earth Engine covering a wide area. In this mapping process, the report pertaining to the 9% is the amount of land (in hectares) out of the total landmass that was claimed as degraded. A definition for degraded land is given in Annex 2 (Table A1.1) which did not include degradation in crop lands. Therefore, following purposive selection of sites with degraded lands, farmers were randomly selected for the assessment of knowledge, practices and perceptions towards land degradation. The map of the land use/cover of project districts based on the RandomForest classification in Google Earth Engine is shown in Figure 7. Cropland was the dominant land use, comprising of 53%, 49% and 48% in the Kersa, Omonada, and Tiro-Afeta districts, respectively. Other land use type found in the districts are agroforestry, forest, woodland, water body, build-up (settlements), and degraded areas. Given the focus of this sub-task, the distribution of degraded/abandoned areas in the district is presented separately in Table 3 and Figure 7. Overall, 9.0% of the total area in the three project districts is abandoned/degraded with the largest area found in Tiro-Afeta district (13.5%) and the least area in Kersa district (5.4%). A detailed report of abandoned land identification and mapping can be found in Annex 2.

Table 3. The proportion of Abandoned land in the three-project districts in Ethiopia

District	Total Area of the district (ha)	Degraded land (ha)	Degraded land %
Kersa	10280	558.3	5.4
Omonada	16816	1472.5	8.8
Tiro-Afeta	9077	1224.9	13.5
Total	36174	3255.7	9.0

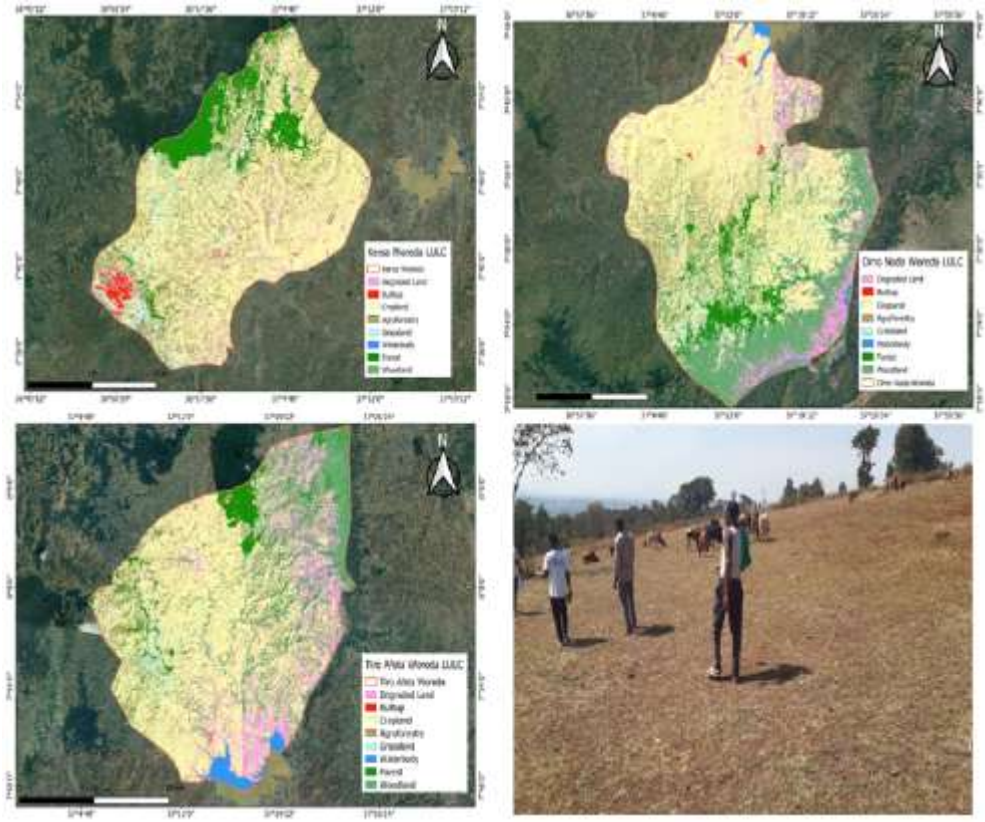

Figure 7. Land cover land use map for project districts (a-c) and degraded farmland in Ethiopia

3.2. Burkina Faso

3.2.1. Abandoned land reconnaissance survey results in Burkina Faso

In the perception of farmers, about 95% of the cultivated land in the study zone was degraded (Fig. 8a). To address this challenge, farmers indicated that they employ a variety of soil fertility management practices, including mineral fertilization (100%), crop rotation (89%), livestock manure (78%) (Fig. 8b). Other practices such as phosphate rock amendments (1%) and crop association (5%) were implemented by very few producers. Fertility management constraints were lack of financial resources (access to mineral fertilizers), low levels of inputs and management (e.g., manure, soil and water conservation practices).

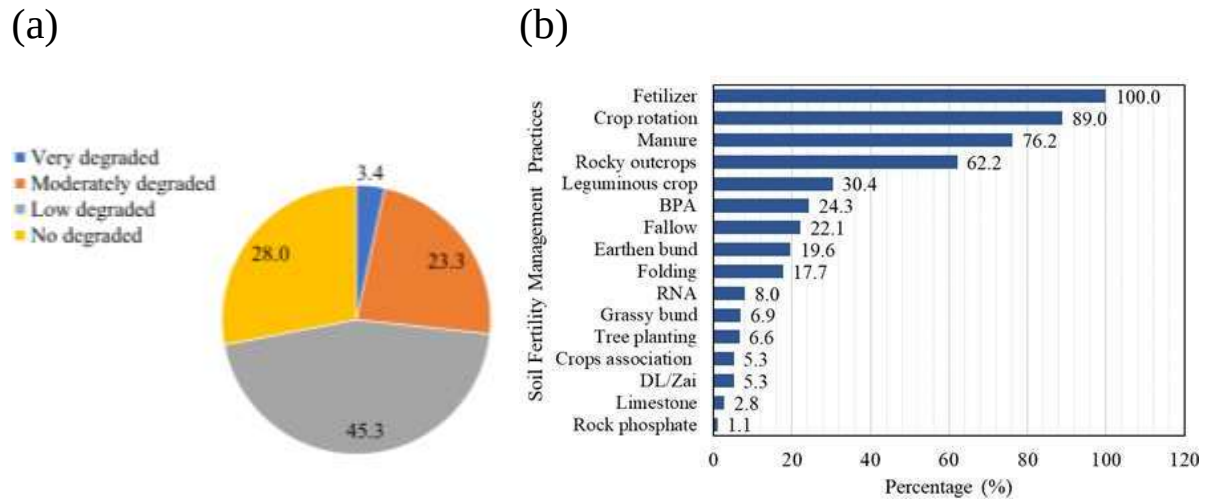

Figure 8. Land degradation severity as perceived by farmers (a) and farmer soil fertility management practices in Burkina Faso (n=79).

3.3. Tanzania

3.3.1. Abandoned land reconnaissance survey results in Tanzania.

Farmers in the FFRUs in Tanzania reported three major types of soils based on soil texture as loamy soils (68%) using different names in the local language (e.g. *tifutifu*, *engulukeni*, *inguluwok*, *losuvuco*, etc.) and clayey (*mfinyanzi*) soils (7%). Other soil types represented the remaining proportion (16%) (Fig. 9). The majority of farmers (> 56%) in Tanzania felt that their farmlands are either moderately productive or productive (38%) and only a few (7%) indicated that their fields are degraded (Fig. 10a). As a result, less than 2% of farmers agreed that they practised fallowing in their farmland in the last 3-4 cropping seasons (Fig. 10b). The main causes of land degradation mentioned were unsustainable farming practices such as excessive ploughing and deforestation (Fig. 11a). Farmers are carrying out

several land restoration practices, including good agronomic practices, afforestation, sustainable intensification practices, cover crop and other forms of soil amendments (Fig. 11b).

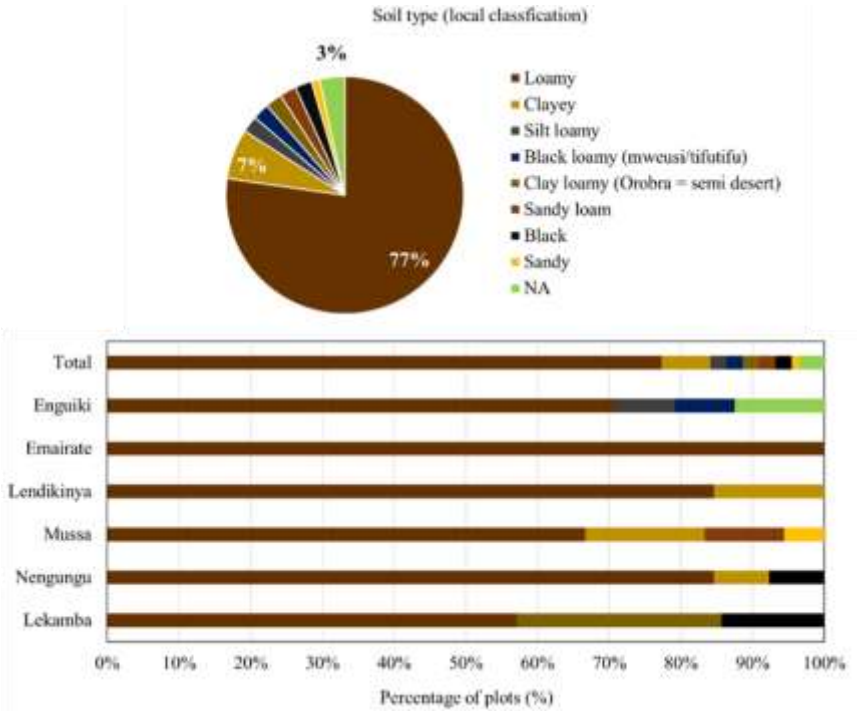

Figure 9. Major soil types based on soil texture and colour identified by farmers in Tanzania

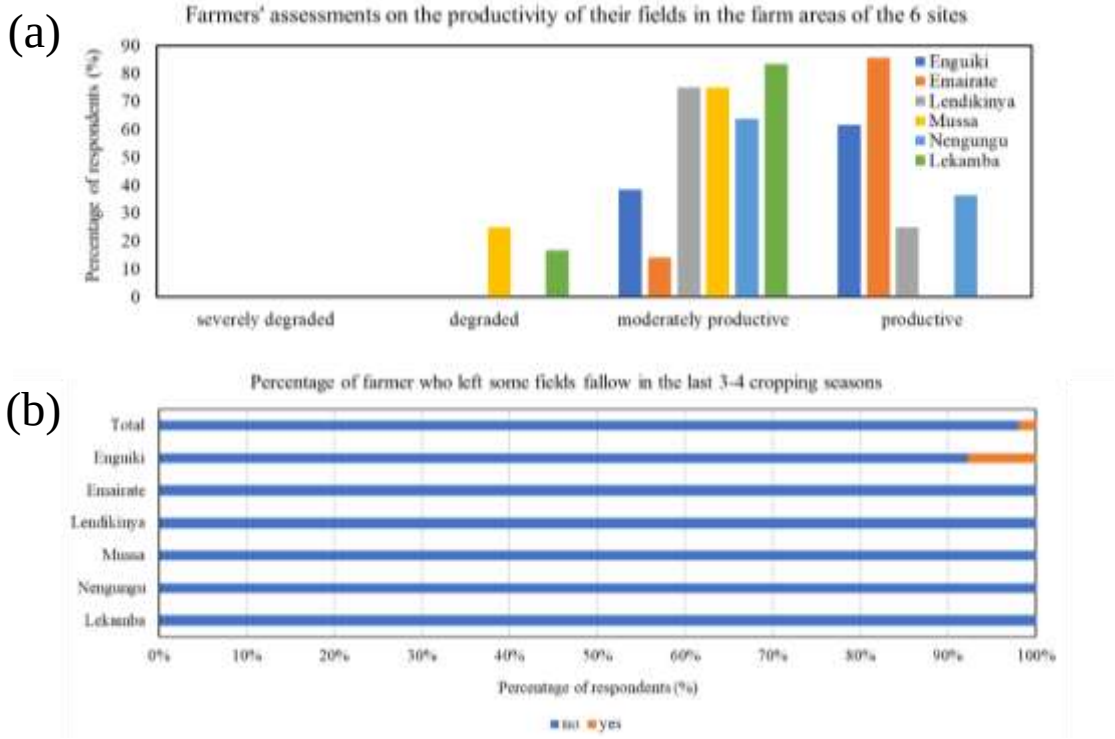

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Figure 10. Farmer perception on levels of land degradation (a), percentage of farmers who practised fallow in the last 3-4 cropping seasons (b) in Tanzania.

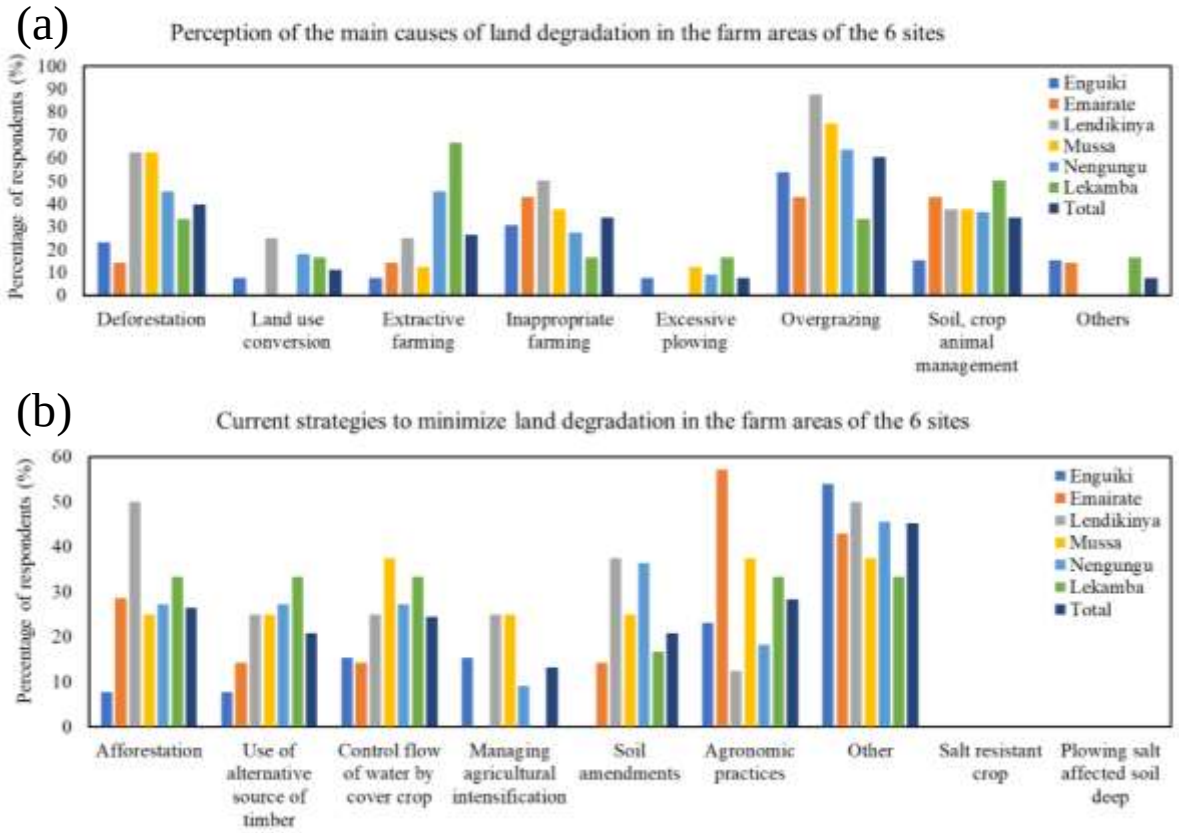

Figure 11. Farmer perception on the main reasons for land degradation (a), and land restoration options (b) in Tanzania.

3.3.2. Land degradation status

Figure 12 shows the maps of land use and land cover change (LULCC) in Emairete and Musa sites. Soil erosion prevalence in these sites is depicted in Fig 13. The maps were generated based on the field data collected as part of the project in each of the sites using remote sensing satellite data and machine learning models to predict changes in croplands, grasslands, tree cover, forest cover, and soil erosion prevalence. The accuracy of these maps is between 85% and 89%. Overall, the LULCC analysis shows an increase in area under cropland in both sites (Fig. 12). In Emairete there appears to be an increase in erosion over the five-year period shown while there appears to be a decrease in erosion in Mussa (Fig. 13). This land degradation trend reflects a comparatively low adoption of soil water conservation (SWC) measures found in Emairete during the field survey as described below.

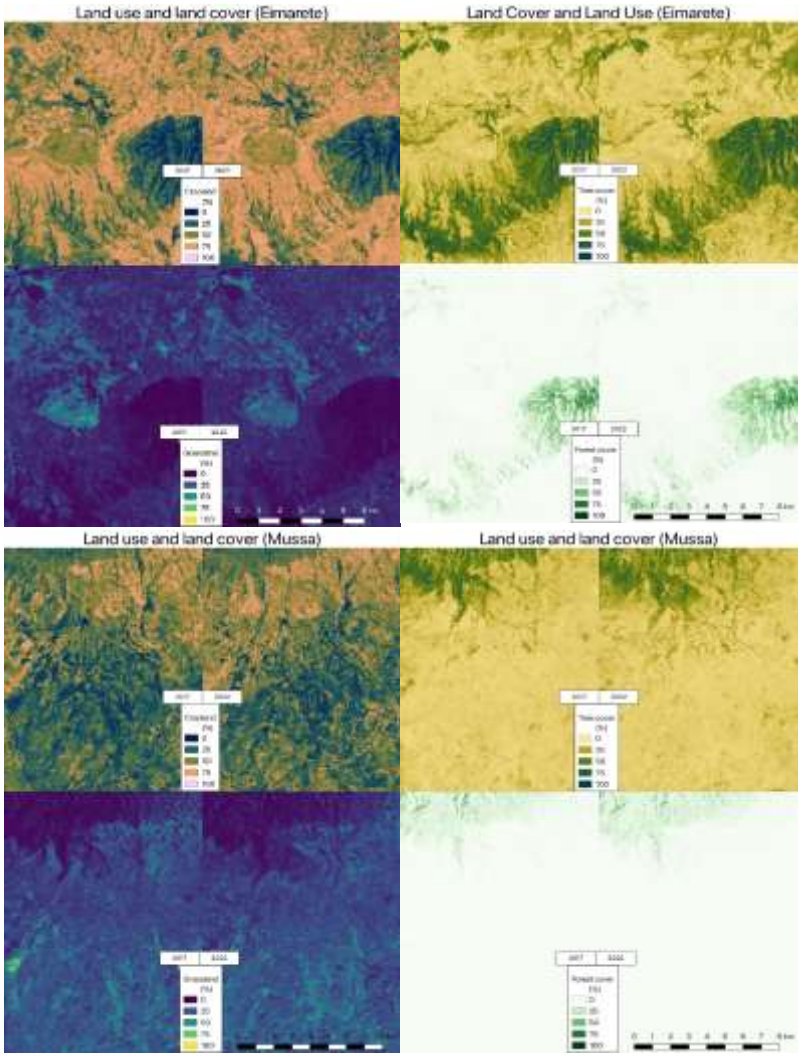

Figure 12. Land use and land cover change analysis for Emairete in Monduli District and Mussa in Arusha District, Tanzania.

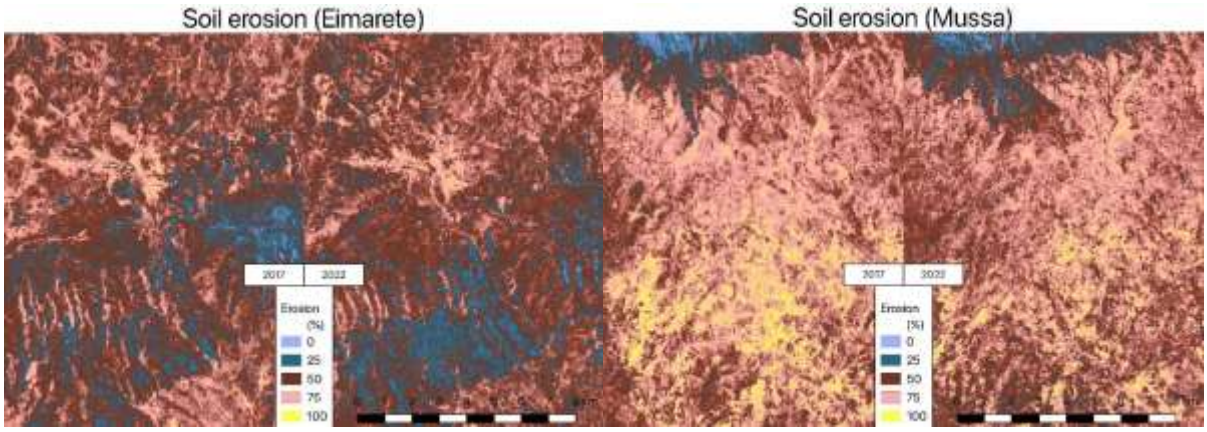

Figure 13. Soil erosion prevalence maps for Emairete in Monduli District and Mussa in Arusha District, Tanzania.

Land degradation was assessed in sampled plots according to the following criteria: i) cultivated or non-cultivated plot; ii) vegetation structure; iii) prevalence of soil erosion and iv) existence of soil water conservation (SWC) measures. In the Emairete site in Monduli district, 27% of the sampled plots were classified as cultivated, while in Musa the percentage of cultivated plots was 50%. Figure 14a and b show the dominant vegetation structure at each site (grassland, cropland and forest in the Emairete site in Monduli District and cropland in Mussa site in Arusha District). Erosion was the most widespread form of land degradation (Figure 14c). Sampled plots that had three or more subplots (75%) with erosion were classified as having severe erosion. In Emairete a lower erosion prevalence (40%) was recorded compared to Mussa (80%).

The SWC measures observed in the two sites were: Stone bunds or *zai pits* (labelled as "structural"), contour tree planting (labelled as "vegetative"), or a combination of both vegetative and structural (labelled as "both") (Figure 14d). In Emairete, there were very few plots with any type of SWC measures being practiced. These results have implications for soil erosion and opportunities to employ sustainable land management options to curb erosion prevalence. A detailed land degradation surveillance report can be found in Annex 4.

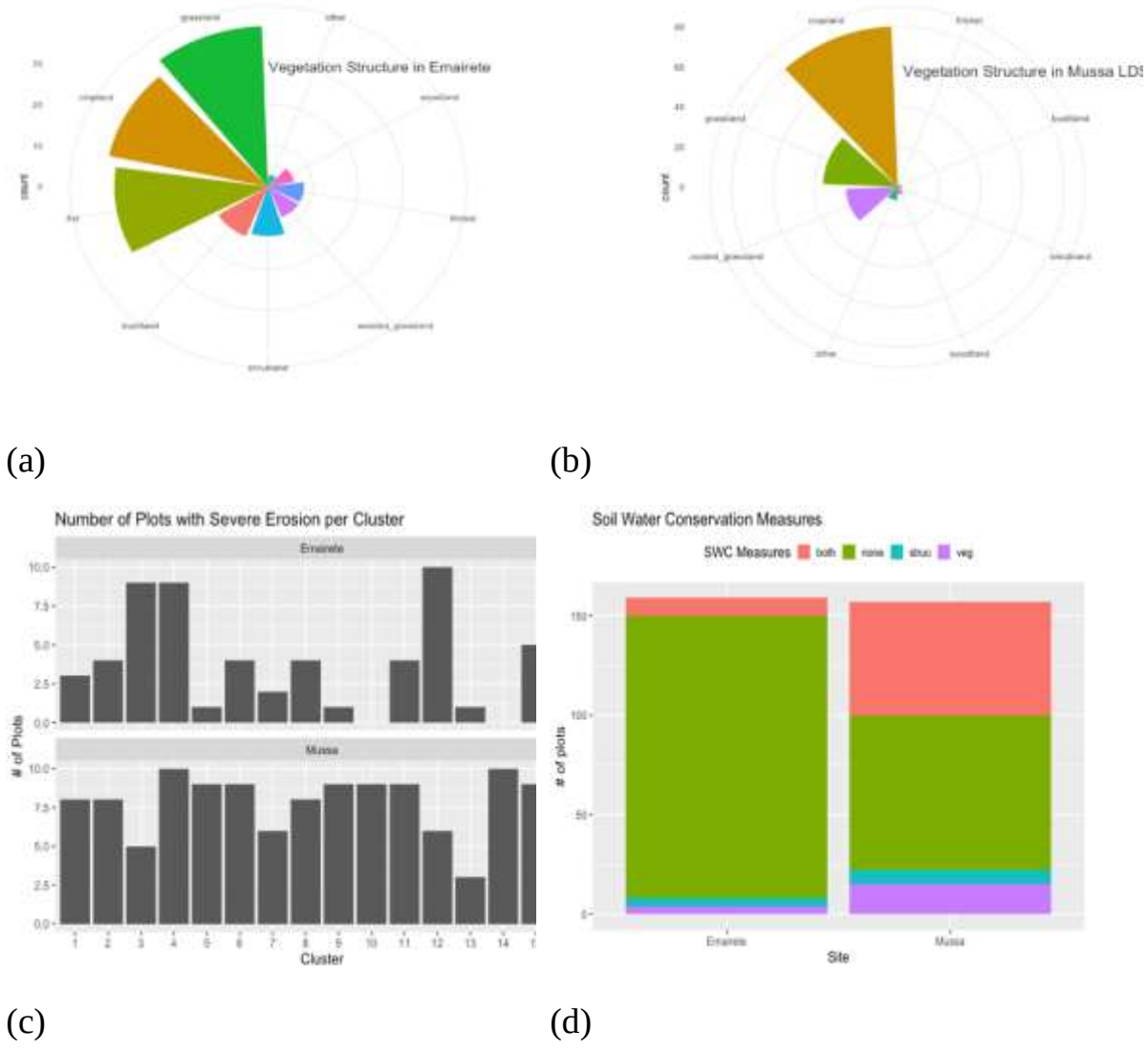

Figure 14. Dominant vegetation structure at each site in Emairete (a) and Mussa (b), soil erosion prevalence in the Emairete (upper) in Monduli District and Mussa (lower) site in Arusha Districts (c), and soil and water conservation measures in Emairete (left) and Mussa (right) sites. (d)

3.3.3. Trade-off analysis of sustainable intensification technologies for land restoration

The reconnaissance survey of degraded and abandoned land revealed several sustainable land management practices with a potential for rehabilitation of degraded land to sustain crop and livestock productivity in FFRUs across project countries (Sections 3.1.1 – 3.3.1). These include good agronomic practices, agroforestry and afforestation, intercropping, soil and water conservation practices such as cover crop, conservation agriculture, contour farming, and in-situ water harvesting (Pit basin, Half-

moons), Zero grazing, and other forms of soil amendments (Figs. 6 and 11). The participatory assessment of trade-off and socio-economic impacts of selected SI land restoration technologies (Annex 4) was conducted to understand their potential for integration into cropping systems in FFRUs as part of Sub-task 2.2.2.

3.3.3.1. Contour farming

Contour farming is the most common land restoration practice identified by farmers (25%) during the abandoned land survey (Annex 4). It was also noted during the trade-off analysis fieldwork in Arusha and Monduli Districts, especially in highland areas where it is used for soil erosion to sustain the production of crops and fodders (Fig. 15). The technology was introduced in the study villages by the project called Soils Conservation and Agroforestry Project Arusha (SCAPA), which started in the late 1990s. Farmers indicated that this technology has larger positive than negative impacts in all five SI domains because of the multiple benefits they have experienced in using this technology for several years. Gender difference in the perception of the benefits contour/bench terrace technology was noted, with men giving an overall score of 3.84 out of 5 and female giving only a positive score of 0.76 for all the domains (Fig. 16). Making contours/bench terraces is a labour-intensive job and this could be the reason the technology was not popular for female farmers. Both male and female emphasize the need for training on good agricultural practices (GAP) in terraces to ensure sustainable increase in crops production.

Figure 15. Contour farming in Monduli District, Tanzania (Photo Credit Anthony Kimaro)

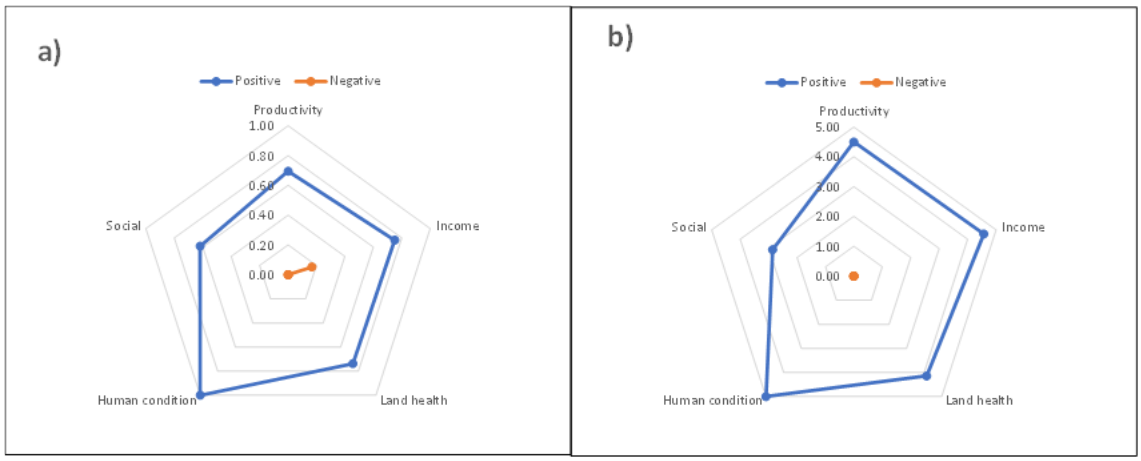

Figure 16. Perception of Female (a) and Male (b) farmers on the impacts of contour farming on SI Domains in Arusha district Tanzania (n = 218).

3.3.3.2. Conservation Agriculture

Conservation Agriculture (CA) is a farming system that can prevent losses of arable land while regenerating degraded lands. It promotes maintenance of a permanent soil cover, minimum soil disturbance, and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production. Both female and male farmers have higher positive scores on the effects of conservation agriculture (CA) on various SI domains (Fig. 17). The positive score for men across the five domains (4.13) averaged slightly higher than the corresponding values (3.89) for female farmers, reflecting gender differences in the perception of the benefits of technologies. Larger difference was in the income domain where females gave a lower score, possibly because this is a part linked to labour inputs. Females provide most of the farm labour and could provide a more precise estimate of the impacts in this domain compared to their male counterpart. These results are in line with the review by Wekesah et al (2019) who also found that CA increased women's incomes, labour involvement (workload), and household food security. Other factors influencing gender-based perception of the benefits of CA technology include differences in access to resources (land, inputs, assets), labour saving equipment (machinery), extension services, credit facilities, and perception on soil properties and productivity (Wekesah et al 2019; Harman Parks et al 2022). The positive score indicates that CA improved both land conditions to support crop production and livelihood strategies in the study areas and thus it has a high potential for wider adoption as a sustainable land management practice.

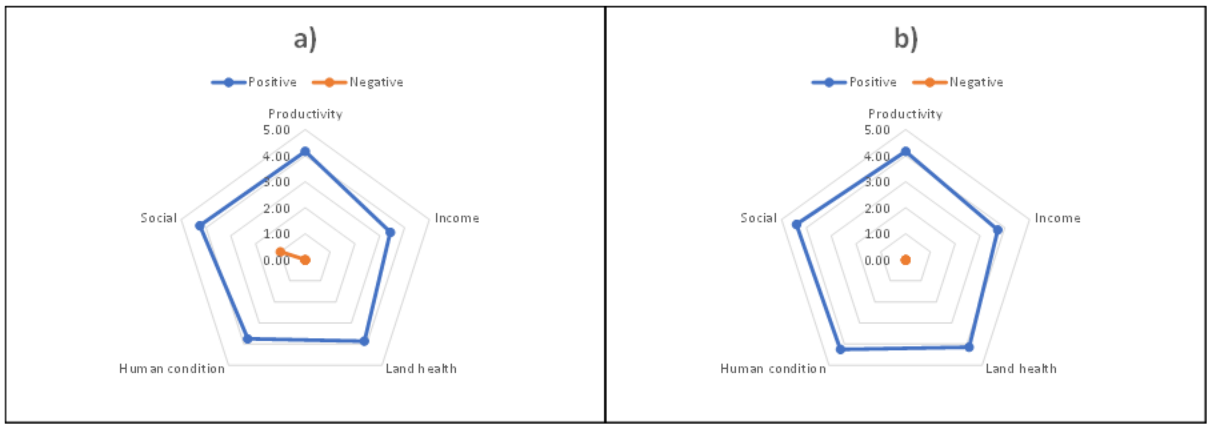

Figure 17. Perception of Female (a) and Male (b) farmers on the effects of Conservation Agriculture on SI domains in Likamba Village, Arusha district Tanzania.

4. Section B: Assessment of soil fertility traits in selected FFRUs

4.1. Introduction and Objectives

Depletion of soil nutrients and soil organic matter are among the major forms of land degradation in agriculture. Soil fertility is highly variable in space and time in agricultural areas and the major constraint for substantial crop production under small-holder farming systems in Sub-Saharan Africa (Bogunovic et al., 2017). As soil properties vary spatially and temporally, understanding their spatial distribution, particularly for degraded croplands is very relevant in agricultural planning for optimizing local land management, and application of nutrients and fertilizers, thereby improving sustainable intensification of production systems. Therefore, the objective of this section is to identify soil types, their physical and chemical properties, and their suitability for implementation at the FFRUs.

4.2. Methodology

Project partners in Burkina Faso, Ethiopia and Tanzania adopted similar methodologies for the collection of soil samples and analysis in the laboratory based on facilities available in each country. Soil fertility assessment work in Burkina Faso was conducted concurrently with soil profit pit descriptions (Fig. 18a). Soil pits were dug to 120 cm depth. The description of the pits followed FAO (1994) guidelines and soil classification according to soil CPCS (1967) and WRB (2006). For each pit, we recorded GPS coordinates and described the environmental conditions around the pit such as vegetation, current land use status, topographic position, slope, moisture conditions, erosion treats, parental material, etc. After the description and classification of soils, samples were collected according to the soil diagnostic horizons and taken to the laboratory for analysis of organic matter (OM), total nitrogen (N), assimilable phosphorus (Pass), total phosphorus (Pt); 5) available potassium (Kav), cations exchange capacity (CEC), Sum of exchangeable bases (S= Ca2+; Mg2+; K+; Na+), Soil pH in water (pH_w) and potassium chloride (pH_{KCl}).

In Tanzania, soil profile pits were also dug in selected areas in FFRUs for the classification of soil types (Fig. 18b). The description of the pits followed FAO (1994) guidelines and soil classification according to soil CPCS (1967) and WRB (2006). Soil samples were also collected by horizons for analysis at the NM-AIST laboratory. Laboratory results of soil nutrients complemented field assessment in classifying soil types in FFRUs. Samples for soil fertility assessment were collected from the 160 plots laid out in each sentinel site for assessing land degradation using the LDSF approach in the FFRUs (Annex 4). The samples were collected using an auger from four sub-plots at 0-20 and 20-50cm, composited by depth and sub-sampled to get a composite sample per plot (Fig. 1b). About 1kg composite sample was collected from each depth, giving a total of 320 samples from 160 plots in each of the two sentinel sites. The soil samples were air-dried, ground, and sieved through a 2-mm sieve in the NM-AIST laboratory. The samples were then packaged in paper bags (300g per sample) for shipping to the ICRAF laboratory in Nairobi for analysis of soil physio-chemical properties (Soil OC, pH_w, Electrical conductivity, Total N, Extractable P, exchangeable bases, Exchangeable acidity etc.), using the MIR spectroscopic method.

Figure 18. Soil profile pit description and collection of soil samples for analysis in Burkina Faso (a) and Tanzania (b) (Photo credit J. Kalonga – b)

In Tanzania, soil profile pits were also dug in selected areas in FFRUs for the classification of soil types (Fig. 18b). The description of the pits followed FAO (1994) guidelines and soil classification according to soil CPCS (1967) and WRB (2006). Soil samples were also collected by horizons for analysis at the NM-AIST laboratory. Laboratory results of soil nutrients complemented field assessment in classifying soil types in FFRUs. Samples for soil fertility assessment were collected from the 160 plots laid out in each sentinel site for assessing land degradation using the LDSF approach in the FFRUs (see Annex 4 for more details). The samples were collected using an auger from four sub-plots at 0-20 and 20-50cm, composited by depth and sub-sampled to get a composite sample per plot (Fig. 1b). About 1kg composite sample was collected from each depth, giving a total of 320 samples from 160 plots in each of the two sentinel sites. The collected soil samples were air-dried, ground, and sieved through a 2-mm sieve at the Laboratory of NM-AIST. The samples were then packaged into paper bags (300g per sample) for shipping to the ICRAF laboratory in Nairobi for analysis of soil physio-chemical properties (Soil OC, pH_w, Electrical conductivity, Total N, Extractable P, exchangeable bases, Exchangeable acidity etc.), using the MIR spectroscopic method.

In Ethiopia, three sites in Omonada (Bioso gombo, Doyo yaya and Nada challa), three sites in Tiro-Afeta (Babo, Kejelo, and Nadi) and one site in Kersa (Bulbul) were selected for soil sampling. A total of 56 soil samples were collected at 0 - 30 cm depth across the entire districts using a random sampling technique in October and November 2021. At each sampling site, three topsoil samples were collected using an auger and mixed to obtain composite soil samples of about 1 kg and each composite sample was labelled in a plastic bag and sent to the soil laboratory of Jimma University College of Agriculture and Veterinary Medicine for analyses. The composite soil samples were air-dried, grounded, sieved to 2 mm size; analysed for pH_w, OC SO soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AvP), cation exchange capacity (CEC), and exchangeable cations (Ca, Mg, K and Na).
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4.3. Results

4.3.1. Burkina Faso

Major soil types found in FFRUs in Burkina Faso are indicated in Table 4. Productivity of these soils is generally low and requires management practices to improve nutrients and soil organic matter levels. Farmers in the FFRUs location also identified the following four SI technologic packages to improve crop production based (Table 4). Details of the soil types and associated management practices in Burkina Faso can be found in Annex 3.

- P1: Evaluation of minimum tillage and recycling of crop residues into compost on productivity and mineral balances in a cotton-cereal system
- P2: Effects of compost and intercropping on sorghum and cowpea productivity and soil properties
- P3: Effects of Fertilization on Sorghum and Maize Productivity in Cotton Farms
- P4: Study of the effectiveness of biochar and co-compost in cotton farms

Table 4. Soil types in FFRUs locations in Burkina Faso.

Experimental site	**Soil types**	**Area**	
		Hectare (ha)	**(%)**
Béréba	Gleyic gleysoil (FLTC)	6832.5	22.52
	Endo plinthic lixisoil (FLIMP)	6539.2	21.56
	epi petric Lixisoil (FLIPP)	1453.6	4.79
In Douhoun	Epipetric plinthosoil (FLIS),	1296.6	1.98
	Gleyic gleysoil (FLTC)	13294.3	20.33
	Endo plinthic Lixisoil (FLIMP)	17331.7	26.51
Kari-Kamandena	Endo plinthic lixisoil (FLIMP),	11024.8	49.84
	Gleyic gleysoil (HPGS),	898	4,06
	Epipetric plinthic and Lixisoil (FLIPP)	7513	33.96
Sara	Epipetric plinthosoil (FLIS and FLIPP),	32871,2	29.01
	Gleyic gleysoil (FLTC),	15737,5	13.89
	Endo plinthic lixisoil (FLIMP),	19531,2	17.24
	Cambisoil (FRM).	1815,7	1.60
	Epipetric plinthosoil (L/r and FLiPP)	36078.0	32.99
Bondokuy	Gleyic gleysoil (HPGS)	12649.2	11.57
	Gleyic gleysoil (FLTC)	6832.5	22.52

Table 5. Technological packages applied in the FFRUs in the different sites

Sites	Technologic packages
Béréba	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P4: Biochar and co-compost amendment of soils in cotton farms systems
Dohoun	P3: Efficient use of mineral fertilizers in order to improve sustainable soil productivity in Sorghum and Maize Productivity in Cotton Farming system P4: Biochar and co-compost amendment of soils in cotton farms systems
Ouakuy	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P4: Biochar and co-compost amendment of soils in cotton farms systems
Sara	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P2: Using compost and intercropping practices for improving sorghum and cowpea productivity and soil properties
Bondokuy	P4: Biochar and co-compost amendment of soils in cotton farms systems P2: Using compost and intercropping practices for improving sorghum and cowpea productivity and soil properties
Kari-Kamandéna	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P3: Efficient use of mineral fertilizers in order to improve sustainable soil productivity in Sorghum and Maize Productivity in Cotton Farming system

4.3.2. Ethiopia

The variability of soil fertility status between sites was assessed using the coefficient of variation (CV) as detailed in (Warrick, 1998). Accordingly, CEC, TN, K and AvP had the highest variability at Kersa and Tiro-Afeta. The variability was moderate for SOC, exchangeable cations such as Ca, and Mg. Although soils in the study area are strongly acidic, pH showed the least variability (CV <5%) across the study areas. The suitability of soils for crop production was determined using the soil fertility status classification developed by EthioSIS (2014) summarized in Table 6. The plant available P (AvP) was generally low (15-30 mg kg^{-1}), organic matter was optimum (3.0-7.0%), TN was low to optimum (0.1-0.3%). The soils CEC was low (9-11 cmol(+) kg-1), while the exchangeable Mg was low (0.3-1.0 cmol(+) kg-1); Ca (<0.2 cmol(+) kg-1) and K (<0.2 cmol(+) kg-1) were very low. The exchangeable Na was below the detection limit and thus omitted from the analyses.

Table 6. Soil chemical properties of degraded crop lands in Southwest Ethiopia

Variable	District	Mean	StDev	CoefVar	Minimum	Maximum	Status
CEC (meq/100g)	Kersa	9.87	3.79	38.34	3.06	12.78	Low
	OmoNada	10.48	2.37	22.58	3.52	15.22	Low
	Tiro-Afeta	11.88	2.88	24.24	5.14	15.34	Low
TN (%)	Kersa	0.21	0.08	36.26	0.16	0.39	Low Medium
	OmoNada	0.17	0.04	22.18	0.12	0.25	Medium
	Tiro-Afeta	0.16	0.03	22.46	0.10	0.24	Medium
K (cmol+/kg)	Kersa	0.10	0.06	56.88	0.02	0.21	Very low
	OmoNada	0.13	0.04	32.12	0.04	0.21	Very low
	Tiro-Afeta	0.08	0.02	29.33	0.04	0.11	Very low
Ca (cmol+/kg)	Kersa	1.24	0.34	27.68	0.47	1.64	Very low
	OmoNada	1.35	0.38	28.57	0.32	2.17	Very low
	Tiro-Afeta	1.16	0.28	24.29	0.68	1.71	Very low
Mg (cmol+/kg	Kersa	0.38	0.10	26.10	0.17	0.48	Low
	OmoNada	0.45	0.08	18.65	0.20	0.63	Low
	Tiro-Afeta	0.43	0.09	19.78	0.32	0.62	Low
pH (H_2O)	Kersa	5.30	0.17	3.15	5.04	5.54	Strongly acidic
	OmoNada	5.49	0.19	3.43	5.10	5.94	Strongly acidic
	Tiro-Afeta	5.35	0.22	4.03	4.98	5.76	Strongly acidic
%OC	Kersa	2.39	0.56	23.38	1.76	3.28	Optimum
	OmoNada	2.59	0.54	20.90	1.44	3.90	Optimum
	Tiro-Afeta	2.55	0.60	23.55	1.56	3.71	Optimum
Avp (ppm)	Kersa	26.35	10.90	41.37	16.77	48.20	Low
	OmoNada	19.13	5.84	30.54	11.83	36.76	Low
	Tiro-Afeta	20.40	9.85	48.29	12.23	51.88	Low

The low pH value of the soils could be due to the leaching of basic cations such as Ca Mg, and K from the surface soil as the area receives high rainfall. The low levels of AvP in most soils of Ethiopia decline by the impacts of P fixation associated with low pH, soil erosion and other losses through cropping practices. The low levels of CEC of the study soils might be due to moderate organic matter content and the high soil acidity whereby, under acidic conditions, Al and H ions may occupy the exchange sites on the clay surfaces. This soil fertility assessment result clearly indicated that the degraded croplands are seriously affected by soil acidity and very low to moderate levels of the essential plant nutrients which are not satisfactory for the growth of most crops. Any agronomic or soil management options that can improve soil pH could increase CEC of soil and subsequently the overall soil fertility status.

4.3.3. Tanzania

4.3.3.1. Soil fertility status in Emairete and Musa sites

Soil chemical properties and nutrient contents in soils are essential in determining the nutrient availability to plants. The topsoil pH in Monduli (6.2) and Arusha (7.1) is slightly acidic and neutral (Table 7), which is within the optimum range for crop production according to Landon et al (2014). This is because pH values in this range are not expected to limit solubility and hence the availability of soil nutrients to plants and to cause plant root injury (Amur et al 2017). Soil OC in the Emairet soils in Monduli was close to the optimum level (>0.2%) for crop production while it was very low in Musa site in Arusha. Organic carbon contents in these soils are affected by low vegetation and tree cover due to extensive grazing as noted by low levels in the surveyed plots (Fig. 12). Nitrogen and extractable phosphorus levels in the soils in both sites are very low to support optimum crop production. The deficient levels (<15 mg P/kg) in these soils are due to the presence of exchangeable Aluminium and Iron which fix phosphorus into recalcitrant fractions in the soil. Soil exchangeable Ca and K were low while the levels of exchangeable magnesium were high in both sites. Soil pH and SOM are the major determinants of micronutrient availability in crops. Except for Boron, the levels of micronutrients (Fe and Cu) were sufficient in the soils. While most of the elements measured were in the optimum range, the soils in both sites have low levels of critical elements for sustainable crop production, especially nitrogen, Phosphorus, Potassium and Calcium, and low levels of organic carbon. Thus, overall soil fertility for the sites is very low and farmers will require to implement soil nutrient amendment practices to sustain crop production in addition to mitigating high land soil erosion and low vegetation cover noted in the field (Fig. 14).

4.3.3.2. Land recovery experiment on salt-fluoride affected soils in Tanzania.

Rationale and objective of the trial

Research on the identification of potential soil amendments for salt-fluoride is led by NM-AIST in Tanzania. The intent of this trial was to check if the seaweed which are abundant in the coastal environment can be utilized in fluoride contaminated zones as an organic fertilizer while locking-off the bioavailable fluoride in the soil. Therefore, the objective of the study was to investigate the remediation efficiency of soils contaminated by fluoride using a Fermentation Product of Seaweed (*Eucheuma cottonii*).

Table 7. Soil physio-chemical properties in Arusha (Musa) and Monduli (Emairete) Districts, Tanzania

Parameter	Site		Status	
	Arusha	Monduli	Arusha	Monduli
Soil pH (1:2)	7.09	6.58	Optimum	Optimum
Electrical conductivity (uS/cm)	102.47	113.96	Optimum	Optimum
Organic carbon (%)	1.24	1.88	Low	Optimum
Total N (%)	0.11	0.13	Low	Low
Extractable Phosphorus (mg/kg)	10.26	14.45	low	Low
Exchangeable calcium (mg/kg)	3575	3115	Low	Low
Potassium concentration (mg/kg)	244.94	173.88	Low	Low
Exchangeable magnesium (mg/kg)	591.48	536.23	High	High
Exchangeable manganese (mg/kg)	142.24	114.88	Optimum	Optimum
Iron concentration (mg/kg)	109.64	136.29	Optimum	Optimum
Copper concentration (mg/kg)	2.54	2.28	Optimum	Optimum
Sulphur (mg/kg)	13.23	15.12	Optimum	Optimum
Boron concentration (mg/kg)	0.57	0.58	Low	Low
Exchangeable aluminium (mg/kg)	940.13	940.46	Optimum	Optimum
Exchangeable Acidity (meq/100g)	0.330	0.336	Optimum	Optimum
Exchangeable sodium (mg/kg)	64.73	49.69	Optimum	Optimum
Phosphorus Sorption Index (PSI)	131.55	131.60	Optimum	Optimum
Cation Exchange Capacity (meq/100g)	29.28	27.58	Optimum	Optimum
Clay (%)	57.85	49.02	N/A	N/A
Silt (%)	23.70	28.87	N/A	N/A
Sand (%)	18.45	22.11	N/A	N/A
Textural Class	Clay	Clay	N/A	N/A

Description of the technology

Bio-adsorption is one of the most important techniques for the removal of environmental contaminants. It has advantages of abundance, cost-effectiveness, eco-friendly, and efficiency. Seaweed is amongst the biomasses fitted for their use as bio-adsorbents. The seaweed improves important soil properties such as soil organic matter (SOM), pH, microbial diversity, and nutrient composition and is therefore used as a natural fertilizer worldwide. Seaweed also contains polysaccharides, proteins, and sulphate which act as the binding sites for ions present in the soil solution. The polysaccharides undergo other chemical transformations which additionally alter their chemical interaction with the soil elements. Because of these properties, seaweed has been successfully investigated and used for remediation of soils contaminated with heavy metals, however, not yet been investigated for anionic species particularly, fluoride in the soil. This study, therefore, examines the efficiency of fermented seaweed (*Eucheuma cottonii*) in reducing the amount of bioavailable fluoride in the soil while monitoring its impact on the soil's physical, chemical, and microbial properties.

Methodology

Study Area

The soil used for this study was collected at Ngarenanyuki which is one of the 17 wards of Meru district, Arusha, Tanzania (Figure 19). It is part of the East Africa Rift Valley surrounding Mount Meru which is an active Volcano. Ngarenanyuki ward has five villages (Uwiro, Olkung'wado, Ngabobo, Kisimiri chini and Kisimiri juu). The annual mean temperature is between 20 ± 2 and 29 ± 2 °C. The study area has an Afro-Alpine semi-arid climate characterized by a wet and dry season. The major wet season begins from June through September and accounts for approximately 70 % of the annual rainfall while another wet season which is minor accounts for the remaining 30 % of annual rainfall from mid-February through mid-May and the mean annual rainfall is estimated to be 535 mm.

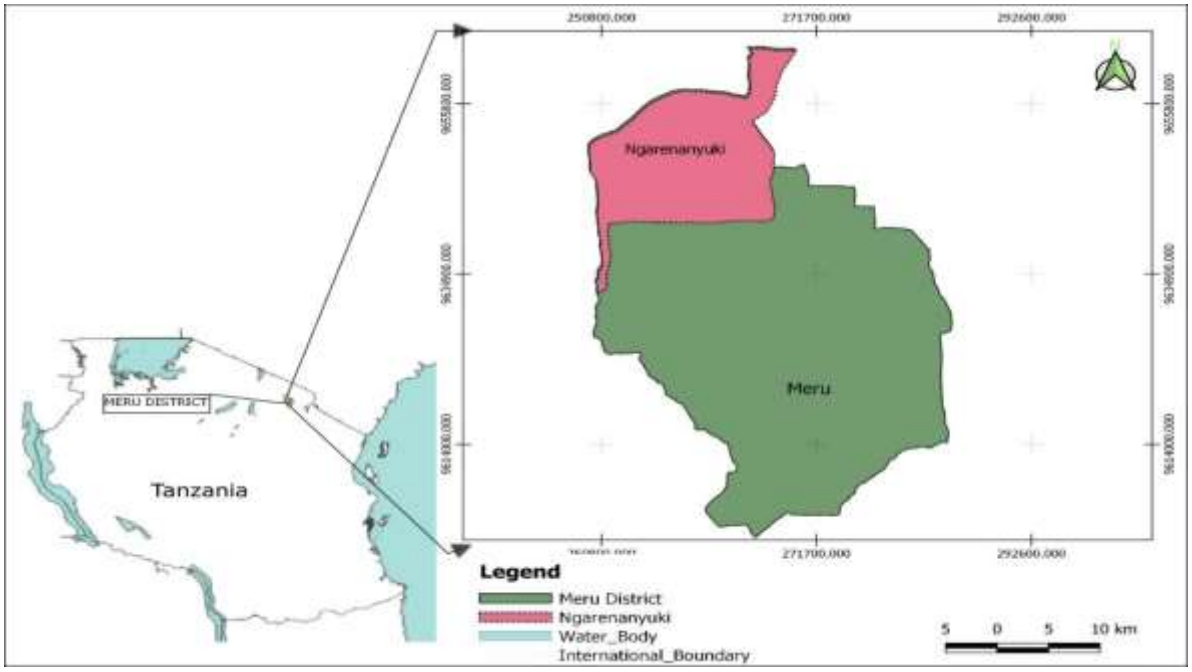

Figure 19. Location of the study area.

The main source of food and income in this area is small-scale farming whereby people are involved in the cultivation of food and cash crops some of which includes, tomatoes, cabbage, potatoes, onions, maize, and beans. The volcanic activities in this area have led to the accumulation of volcanic material containing fluoride at the topsoil, surface water, and groundwater and have attracted the majority of fluoride research activities.

Soil sampling and analysis

The composite soil samples were collected from agricultural fields located along the slopes of Mount Meru, Arusha, Tanzania, (3˚10'35" S 36˚51'35" E) at a vertical profile of 0-20 cm. The composite

samples were packed in plastic bags and brought to the laboratory. The samples were further air-dried and sieved to pass through a 2 mm sieve to remove debris and plant materials and then stored in containers that were cleaned with nitric acids before analysis.

Seaweed sampling and preparation

The seaweed used was *Eucheuma cottonii* collected from the Tanga region, Tanzania. The seaweed samples were brought to the laboratory where it was cleaned thoroughly with distilled water, sun-dried, then powdered using an electric grinder. Afterward, the 500 g of the seaweed powder was transferred to a container where it was mixed with the inoculum (anaerobic sludge from the septic tank), distilled water, and 100 ml molasses. The molasses contains high quantities of sucrose and fructose which is an easily available food source for the anaerobic biomass. Subsequently, 4 ml of iodoform was added to prevent the methanogenesis process from taking place, thereby encouraging acidogenesis and acetogenesis processes (Plácido & Zhang, 2018). After mixing, the container was closed to stimulate the fermentation process. The container was kept in a shaker (110 rpm) at 37 ℃, free from light until the seaweed was entirely soft (5 weeks). The fermented seaweeds were oven-dried at 50 ℃ to obtain a hard solid which again milled into a fine powder.

Experimental set-up

The soil samples (1 kg) were packed into the experimental pots and then mixed thoroughly with either 1.25, 3, or 5 % (*w/w*) of the fermented seaweed powder (FSW) equivalent to the control samples labelled 0 %. Thereafter, the soil was humified to 70 - 75 % saturation and incubated in a shaded area, at room temperature (24 ± 3 ℃). The first soil sample was collected within 24 h of inoculation, and the fluoride fractions, as well as pH, were measured and quantified. The incubation process continued for 4 months while sampling and analysis were conducted every 30 days. The monitored parameters were pH, soil organic matter (SOM), cation exchange capacity (CEC), electrical conductivity (EC), fluoride fractions (water-soluble (Ws-F), Exchangeable-fluoride (Ex-F), fluoride-bound to iron/manganese (Fe/Mn-F), organic matter bound-fluoride (Or-F), and residual-fluoride (Res-F)), phosphorus (P), nitrogen (N) and the exchangeable bases (calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}). Each treatment was replicated three times, and the experiment was conducted in a completely randomized design.

Laboratory analysis

The hydrometer method was used to measure the soil particle size distribution. The content of SOM was calculated using the loss-on-ignition (LOI) method. An electrical conductivity meter and pH meter were used to measure the electric conductivity (EC) and pH. The cation exchange capacity (CEC) was measured using the barium chloride-triethanolamine method (pH 8.2). The water absorption capacity was measured by the centrifugation method (Jumaidin, Sapuan, Jawaid, Ishak, & Sahari, 2017). The specific surface area of the soil was determined using the ethylene glycol monoethyl ether (EGME)

method according to procedures by Yeliz and Abidin (Yukselen & Kaya, 2006). The exchangeable bases were quantified using the atomic absorption spectrophotometer (AAS) and the X-ray fluorescence (XRF) was used to analyze the total elemental composition. Total fluoride was determined according to McQuaker and Gurney's (1977) procedure (McQuaker & Gurney, 1977). Sequential extraction of fluoride was conducted as per our previous study (Moirana, Mkunda, Perez, Machunda, & Mtei, 2021). In short, 2.5 g of soil sample was placed into a 50 mL centrifuge tube and various species of fluoride were extracted by adding 25 ml of the extracting solutions as shown in
Table 8.

Table 8. Extraction processes of various fluoride fractions in the soil

Fluoride specie	**Extraction process**
Water-soluble fluoride (Ws-F)	distilled water
	Shake for 30 min at 60°C
Exchangeable fluoride (Ex-F)	1 mol L^{-1} $MgCl_2$
	Shake for 1 h at 25°C
Fe/Mn bound fluoride (Fe/Mn-F)	0.04 mol L^{-1} NH_4.HCl
	Shake for 1 h at 60°C
Organic matter-bound fluoride (Or-F)	Step 1: 3 ml of 0.02 mol L^{-1} HNO_3 + 10 ml 30% H_2O_2
	Step 2: 12 ml of 3.2 mol L^{-1} NH_4 acetate
	Shake for 30 min at 25 °C
Residual fluoride (Res-F)	Tot-F minus the above for species of fluoride

Gas chromatography (GC) was used to analyze the amount of volatile fatty acids (VFAs) present in the fermentative sap using the flame ionization detector (FID). For analysis, the samples were collected from the fermented sap and then centrifuged at 1,500 rpm for 10 minutes to obtain a clear liquid. The liquid was acidified to pH 1.8 with formic acid. Due to analytical limitations, the VFAs results were given as the total volatile fatty acids (TVFAs) expressed as g acetic acid/l (gAc/l). The C: N ratio of the seaweed was measured using the CHNS analyzer and the rest of the analyses were carried out as the soil samples. All the chemicals used were of analytical grade and distilled water was used throughout.

Results

Soil physico-chemical analysis before and after fermented seaweed (FSW) amendment

The FSW amendment revealed a positive influence on the soil properties as presented in Table 9. The amount of water absorption capacity, clay content, SOM, CEC, and exchangeable bases increased after the amendments whereas the soil pH of each treatment decreased. The impact of FSW on the soil quality was directly related to the amendment dosage such that the higher the dosage the higher its impact on the soil quality parameters.

Table 9. The influence of fermented seaweed (FSW) amendment on selected soil properties at the end of the experimental phase (120th day)

		Soil	Soil + FSW (120th day)			
		Initial %	**0 %**	**1.25 %**	**3 %**	**5 %**
Soil Texture (%)	**Sand**	68 ± 1	67 ± 1	65 ± 3	62 ± 3	55 ± 5
	Silt	21 ± 4	20 ± 1	21 ± 6	21 ± 3	22 ± 3
	Clay	11 ± 2	13 ± 2	14 ± 2	17 ± 4	23 ± 6
Water absorption (gH_2O/g soil)		0.02 ± 0.1	0.02 ± 0.1	0.06 ± 0.1	0.17 ± 0.1	0.23 ± 0.1
pH		9.3 ± 0.0	8.9 ± 0.3	7.8 ± 0.1	7.4 ± 0.1	7.0 ± 0.0
CEC (meq/100g)		32.8 ± 0.9	30.5 ± 0.5	34.5 ± 1.7	35.3 ± 1.7	37 ± 1.3
Phosphate (PO_4^{3-}) (mg kg^{-1})		17.2 ± 0.4	15.8 ± 2	12.5 ± 0.4	14.0 ± 0.9	16.4 ± 0.8
Echangeable Bases (mg kg^{-1})						
	Na^+	8.48 ± 1.7	6.09 ± 1.9	12.8 ± 0.2	13.4 ± 3.3	14.3 ± 1.3
	Ca^{2+}	4.63 ± 0.3	4.66 ± 2.1	5.1 ± 0.5	4.7 ± 0.6	5.8 ± 0.9
	Mg^{2+}	2.03 ± 0.7	1.57 ± 0.6	2.5 ± 0.3	2.9 ± 0.4	3.2 ± 1.6
	K^+	7.37 ± 1.8	7.68 ± 2.3	10.5 ± 0.8	11.6 ± 3.5	13 ± 2.8
Electrical conductivity (EC) (µs cm^{-1})		453.9± 2.3	451 ± 1.6	444 ± 1.3	443 ± 0.4	440 ± 2
Soil organic matter (SOM) (%)		2.5 ± 0.1	2.6 ± 0.4	3.5 ± 0.6	4.2 ± 0.3	5.4 ± 0.3

The impact of FSW on pH of the soil

The influence of the amendments on the pH of the soil is presented in Figure 20. The initial pH of the soil was 9.3 ± 0.0. There was no statistically significant change in pH of the control samples throughout the experiment except for the 60th day when pH dropped to 8.9 ± 0.3 and remained fairly constant thereafter. In the first 24 h, pH dropped from 9.3 ± 0.0 to 9.1 ± 0.2, 9.0 ± 0.1 and 8.4 ± 0.0 following, 1.25, 3 and 5 % amendment dosages, respectively. The pH continued to drop from 9.3 ± 0.0 to 7.8 ± 0.1, 7.4 ± 0.1 and 7.0 ± 0.0 correspondingly, by the 120th day. The pH drop indicates that the process responsible for its behaviour was progressing slowly and attained stability on the 60th day. There was a significant pH difference ($p<0.05$) between the treatments and the control. Even though the pH amongst treatments was significantly different, the 3 and 5 % amendments were not statistically different ($p>0.05$) throughout the experiment.

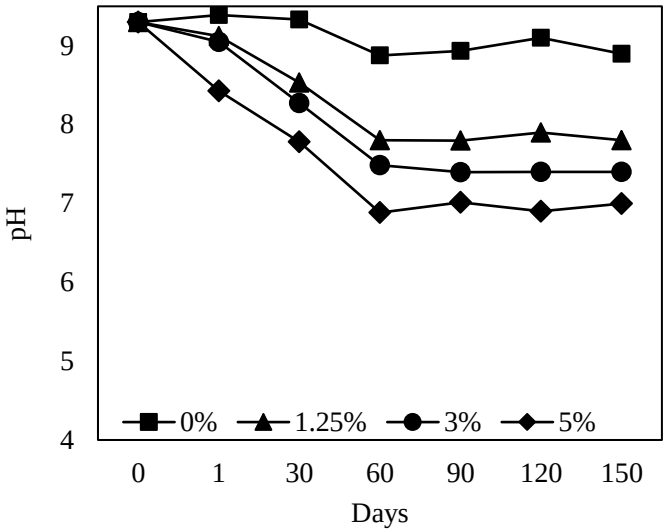

Figure 20. The impact of fermented seaweed amendment (FSW) on the pH pf the soil.

The impact of FSW amendment on the behaviour of fluoride fractions in the soil

The four fractions of fluoride were monitored throughout the experiment and the results are presented in Figure 21. The amendments decreased the amount of water soluble-fluoride (Ws-F) from 81. 7 ± 3.1 mg/kg to 42.7 ± 2.4, 33.7 ± 1.2, 19.6 ± 0.9, and 12 ± 1.3 mg/kg following 0, 1.25, 3 and 5 %, dosages, respectively. The 5 % amendment could reduce the amount of Ws-F below the recommended level of 16.4 mg/kg (Rizzu et al., 2020). Unlike Ws-F, the amount of exchangeable-fluoride (Ex-F) and fluoride-bound to iron and manganese (Fe/Mn-F) increased following the FSW amendment. The Ex-F increased from 5.5 ± 0.1 mg/kg to 14.8 ± 0.7, 19.1 ± 2, 20.3 ± 0.8 and 21 ± 1.6 mg/kg subsequent to 0, 1.25, 3 and 5 %, amendments. The Fe/Mn-F increased from 8.7 ± 0.1 mg/kg to 16.3 ± 3.5, 24.4 ± 2, 24.8 ± 2.1, and 25.7 ± 1 succeeding 0, 1.25, 3, and 5 % amendment which is the lesser bioavailable form compared to the abovementioned two. There was no observed impact of the amendments on the amount of fluoride-bound to organic matter (Or-F).

There was a significant difference ($p < 0.05$) in the amount of Ws-F observed between 0, 1.25, and 3 % to that of 5 % amendment within the first 24 h of the incubation. The amendment dosage was inversely proportional to the amount of Ws-F in the soil such that, as the dosage increased, the amount of Ws-F in the soil decreased. Within 30-day incubation, the amount of Ws-F was significantly different ($p < 0.05$) between the treatments and the control (0 %). The significant difference between 1.25 and 3 % to the 5 % amendment was also noticed but the two (1.25 and 3 %) were not significantly different ($p > 0.05$) up until the 60th day. From the 60th day to the 120th day, there was a significant difference in the amount of Ws-F among all treatments.

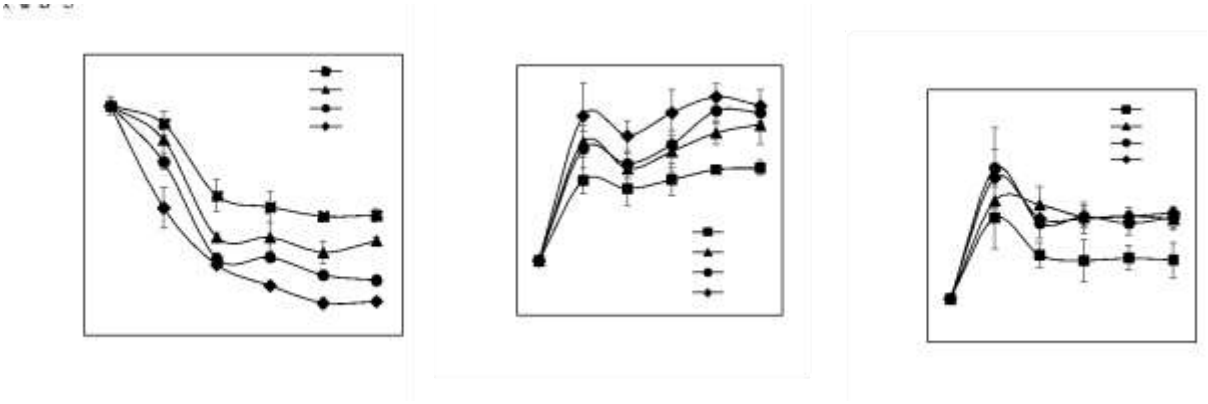

Figure 21. The Impact of Fermented Seaweed (FSW) Amendment on Fluoride Fractions of the Soil (a) Water Soluble-Fluoride (Ws-F), (b) Exchangeable-fluoride (Ex-F), (c) Fluoride-Bound to Iron/Manganese (Fe/Mn-F)

Further information regarding this study were published in an open source and can be found through this link: https://www.hindawi.com/journals/aess/2022/6967031/

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ANNEXES

Annex I: Abandoned land reconnaissance survey module

Annex II: Land Recovery Report for Ethiopia

Annex III: Land Recovery Report for Burkina Faso

Annex IV: Land Recovery Report for Tanzania

Annex I:

Abandoned land reconnaissance survey module

ST 2.2.1 - Abandoned land reconnaissance survey

General Information

Text to read: *Hello, my name is ----------. I work for ----------. We collect data that the EWABELT project and other stakeholders will use for research and decision support planning purposes. I am visiting you to collect data on your farm. The information you provide will be treated confidentially. It will only be used for statistical purposes and will be put together with responses from other farmers for use in the formulation of programmes and policies to promote more productive and sustainable agriculture. This interview should take approximately one hour. We appreciate your participation in answering these questions. If you have any questions regarding this survey, you are welcome to telephone the number indicated on the visiting card of EWABELT project that I leave for you here. I express my gratitude for your participation in this survey in advance*
For the enumerator: if you work for more than one organization in a single FFRU please be sure to select all of them
Select the organization(s) for which you work □ UNIVERSITE NAZI BONI □ INSTITUT DE L'ENVIRONNEMENT ET DE RECHERCHES AGRICOLES □ THE NELSON MANDELA AFRICAN INSTITUTE OF SCIENCE AND TECHNOLOGY □ TANZANIA AGRICULTURAL RESEARCH INSTITUTE □ JIMMA UNIVERSITY □ INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY
Your Enumerator Code is made of a first part that stands for the organization(s) for which you work and a numeric part that indicates your Personal Code. The Personal Code is a 4 digits number (e.g. 0001).
Please insert only the numerical part of your Personal Enumerator Code (e.g. 0001, 0002, etc.):
Your Enumerator ID is:
Select the country where the holding is located □ Burkina Faso □ Ethiopia □ Tanzania

Select the district/study area where the holding is located: □ A □ B □ C □ D □ E □ F □ G □ H
The Holding Identification Number is made of a first part that stands for the country, the organization(s) and the FFRU and a numeric part that indicates the Farmer Code. The Farmer Code is a 4 digits number (e.g. 0001)
Please insert only the numerical part of the Farmer Code (e.g. 0001, 0002, etc.):
The Holding Identification Number is:

Section I: Identification of the soil plot

Q1. Record your current location latitude (x.y °) ---------- longitude (x.y °) ---------- altitude (m) ---------- accuracy (m) ----------
Q2. Region ----------
Q3. District ----------
Q4. Altitude ----------
Q5. Number of soil plots ----------

Section II: Description of the plot environment

Q6. Description of the plot environment (I)	**1) Local classification (soil type):**	**2) WRB classification** ***World Reference Base for Soil Resources***	**3) Physiographic location of the plot**	**4) Surrounding topography**	**4.1) If you selected other in 4), please specify**	**5) Micro-Topography (e.g. small modification on soil surface: plow ridges, ditches left by erosion, soil protection devices etc.)**	**6) Slope**
Plot 1			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope
Plot 2			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope

Plot 3			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope
Plot 4			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope
Plot 5			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope
Plot 6			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope

Plot 7			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope
Plot 8			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope
Plot 9			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope
Plot 10			□ Low slope □ Average slope □ Top of slope	□ Flat □ Moderate □ Flat □ Other			□ Low slope □ Medium slope □ Steep slope

Section II.I: Description of the plot environment

Q7. Description of the plot environment (II)	1) Land use	1.2) If you selected other in 1), please specify	2) Please describe the vegetation of the plot	3) Please describe the cultivation/ land-use history of the plot	4) Parental material (rock)	5) Drainage
Plot 1	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good
Plot 2	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good

Plot 3	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good
Plot 4	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good
Plot 5	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good

Plot 6	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good
Plot 7	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good
Plot 8	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good

Plot 9	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good
Plot 10	□ Cropped land □ Fallow land □ Forestry land □ Crop trees land □ Grazing □ Other				□ Reached □ Not reached	□ Bad □ Medium □ Good

Q8. Description of the plot environment (III)	6) Water state	7) Water table	8) Gravel elements on soil surface	9) Erosion	10) Salinity	11) Human influences
Plot 1	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	
Plot 2	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	
Plot 3	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	
Plot 4	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	

Plot 5	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	
Plot 6	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	
Plot 7	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	
Plot 8	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	

Plot 9	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	
Plot 10	□ Wet □ Dry	□ Reached □ Not reached			□ Reached □ Not reached	

Section III.I: Land Degradation

Q9. Are the causes of land degradation in your farm natural or anthropogenic?

- □ Natural
- □ Anthropogenic

Q10. What are the main causes of land degradation in your farm area?

- □ Deforestation
- □ Land use conversion
- □ Extractive farming
- □ Inappropriate farming
- □ Excessive plowing
- □ Overgrazing
- □ Soil, crop animal management
- □ Others

Q10.1 If other, please specify:

Q11. What are the main processes or mechanism of degradation?

- □ Erosion
- □ Salinization
- □ Nutrients depletion
- □ Acidification
- □ Species extinction
- □ Other

Q11.1 If other, please specify:

Q12. What are the main factors/agent/drivers of land degradation?

- □ Climate
- □ Physiography
- □ Land forms
- □ Socio economic, ethnic/ cultural settings
- □ Other

Q12.1 If other, please specify:

Q13. What are the current strategies to minimize land degradation?

- □ Afforestation
- □ Use of alternative source of timber
- □ Control flow of water by cover crop
- □ Managing agricultural intensification
- □ Salt resistant crop
- □ Plowing salt affected soil deep
- □ Soil amendments
- □ Agronomic practices
- □ Other

Q13.1 If other, please specify:

Section IV: Indicators of productive/degraded cropland

» Indicators of a productive cropland

Q14. What are the indicators of a productive cropland?

Q14.A) Based on the presence of dominant weed species (broad-leaved, grassy, or sedge species, etc.):

Q14.B) Based on soil attributes (e.g. soil physical attributes such as color, texture, moisture retention, macro-faunal activity, and workability; ii. Topsoil characteristics such as thickness/plow depth, subject to erosion, etc.):

Q14.C) Based on crop/weed performance (e.g. the level weed species diversity and vigor, yield of major crops per unit area, crop response to the addition of fertilizers, etc.):

» Indicators of a degraded (least productive) cropland

Q15. What are the indicators of a degraded (least productive) cropland?

Q15.A) Based on the presence of dominant weed species (broad-leaved, grassy, or sedge species, etc.):

Q15.B) Based on soil attributes (e.g. soil physical attributes such as color, texture, moisture retention, macro-faunal activity, and workability; ii. Topsoil characteristics such as thickness/plow depth, subject to erosion, etc.):

Q15.C) Based on crop/weed performance (e.g. the level weed species diversity and vigor, yield of major crops per unit area, crop response to the addition of fertilizers, etc.):

Q16. Based on the indicators, in how many productivity classes would you classify your fields? (Productive, moderately productive, degraded, severely degraded). Or, any classification that farmers usually adopt can be registered.

- □ productive
- □ moderately productive
- □ degraded
- □ severely degraded

Q17. In the past 3-4 crop seasons, have you fallowed any of your fields?

- □ Yes
- □ No

Q17.1. If yes, why?

Q18. In your view, what soil fertility management practices can farmers employ to rehabilitate degraded croplands?

Annex II:
Land Recovery Report for Ethiopia

EWA-BELT PROJECT

Report on the Status of Degraded Crop Lands and Soil Fertility Traits - Ethiopia

Degraded lands in OmoNada District, Southwest Ethiopia
Photo by Melkamu Mamuye

July 2022
Jimma, Ethiopia

Contents

Section A:

A-1: Identification and mapping of Abandoned/ Degraded Cop Lands

1. Introduction

In Ethiopia the majority of the population are directly supported by the agricultural economy. However, the productivity of that economy is being seriously eroded by unsustainable land management practices posing problem on agricultural production Kidane (2008), and the agricultural sector is still characterised by subsistence nature and low productivity (CSA 2013).

Ethiopia experiences several types of land degradation including water and wind erosion; salinization and acidification; and other physical and biological soil degradations (Gebreselassie et al., 2016). According to the Global Mechanism (2007) it is estimated that over 85 % of the land in Ethiopia is moderately to very severely degraded. The key problems that challenge land productivity in the highlands of Ethiopia are soil erosion, with its associated loss of fertility and rooting depth, water resource degradation and loss of biodiversity (Eyasu 2003).

In the study area variations in soil type, topography, and land cover, etc. lead to different sensitivity to land degradation (Keddi Lencha & Moges, 2016). In addition, detailed information of the degraded land is scanty for southwestern parts of the country which is characterized as and needs to be collected for designing site-specific management interventions and sustainable and management practices. Hence, the study was carried out to delineate land use/cover of the project districts and to map degraded/abandoned lands

using high resolution satellite data, since remotely sensed imageries are primary data sources for land use classification and high spatial resolution images are important to enable more accurate analysis and identification of land cover types (Shao et al., 2020).

1.1. Objective

The objective of this study was to map land use land cover map of the districts and identify and map degraded lands in EWA-BELT project areas.

2. Methodology

2.1. Description of Study location

The study was conducted in Omo-Nada, Kersa, and Tiro-Afeta and districts; in the Jimma zone of Oromia Regional State, Ethiopia (Figure A1.1). The districts are characterized as mixed crop–livestock farming systems, in which cereals, coffee, pepper, and livestock are mainly part of the farming system. Details of the districts are described below:

2.1.1. Omo Nada

Omo Nada district lies at 7°17'to 7°49'N 37°00' to 37°28'E. It is located at about 71 kms from the zonal capital town, Jimma. It is bordered by Dedo in the west, Sokoru in the North, Kersa in the South, and Tiro Afata in the east. The rainfall of the area is bimodal, with unpredictable short rains from March to April and the main season ranging from June to September. The minimum and maximum annual rainfall range from 1066 to 1200mm with a mean annual temperature ranging from 18 to 25° C (SLMP, 2009). The area is characterized by gentle, flat, and undulating topography with an altitude ranging from 1650 – 2200 m.a.s.l.

2.1.2. Kersa

Kersa district is bordered on the south by Dedo, on the southwest by Seka Chekorsa, on the west by Mana, on the north by Limmu Kosa, on the northeast by Tiro Afeta, and on the southeast by Omo Nada districts. The altitude of this district ranges from 1740 to 2660

meters above sea level; The district is characterized by a tropical highland climate with heavy rainfall, warm temperatures, and long wet period. The mean annual rainfall ranges between 1200-2500 mm with a mean annual temperature of 20- 25 °C. Yebu town is the administrative centre for the district.

2.1.3. Tiro Afeta

Tiro Afeta is bordered on the south by Omo Nada, on the west by Kersa, on the north by Limmu Kosa, and on the east by Sokoru. The administrative centre of the district is Dimtu. The altitude of this District ranges from 1640 to 2800 meters above sea level.

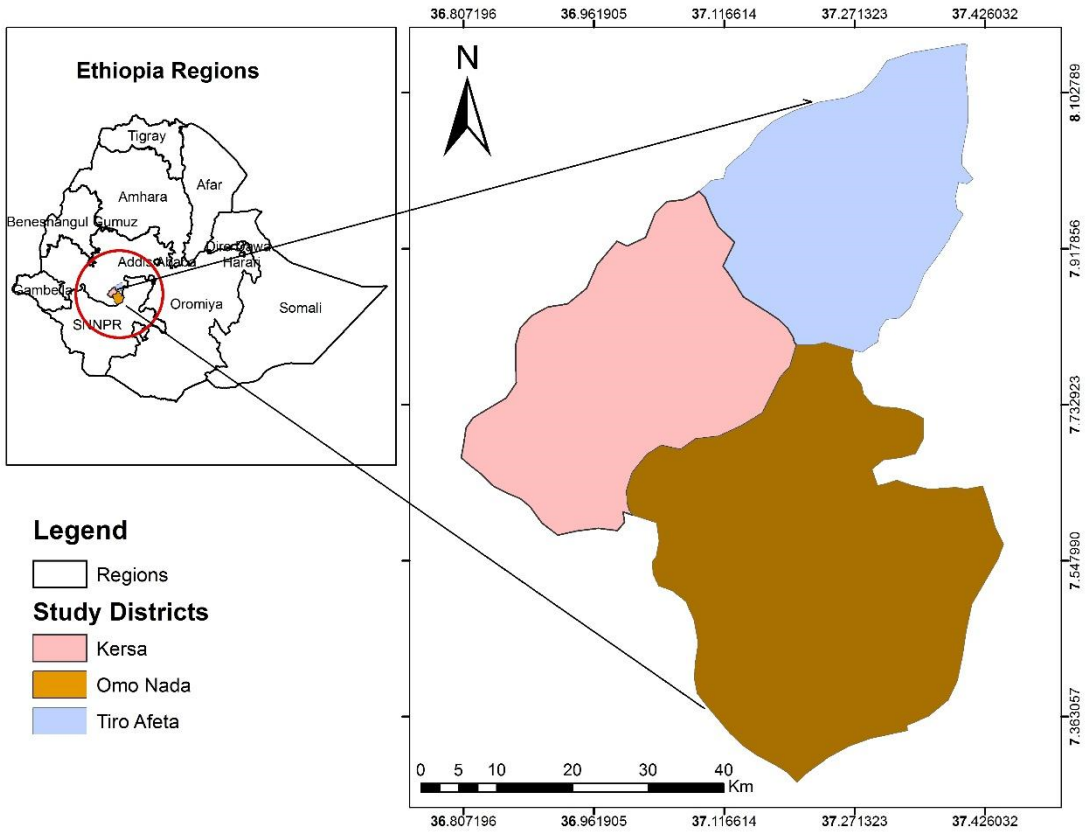


Figure A1.1. Map of the study area

2.2. Data collection and types of data

Premilitary surveys of selected abandoned/ degraded lands in the area were conducted in Omo Nada, Kersa and Tiro Afeta districts using prior knowledge of the farmers and agricultural extension agents of specific districts. Ground truth points (lat/lon) using GPS were collected that were used during classification. The Multi-Spectral (MSI) Sentinel-2 TOA images were used for the classification and mapping of the land cover types.

2.2.1. Basic description of Sentinel 2

The multispectral Sentinel-2A Images were collected by the Sentinel-2 satellite which is a wide-swath, high-resolution, multi-spectral imaging mission, supporting land monitoring research. The radiometric resolution of Sentinel-2 is 12-bit. This gives a potential range of brightness levels from 0 - 4 095. The satellites in the -2 constellation will provide a revisit time of five days at the equator in cloud-free conditions. A Sentinel -2 image having 10 metre spatial resolution was used in this analysis.

2.3. Nomenclatures of Land cover Classes

Before collecting ancillary data, the classification nomenclature derived from (Anderson et al., 1976) and (FAO, 1998) land cover classifications for remote sensing were used and modified based on detailed physiographical knowledge of the researcher about the study area. The land use/cover of the area was categorized into 8 major land cover classes namely, built-up area, degraded land, Agroforestry, woodland, cropland, waterbody, grasslands, and forestland.

Table A1.1. Nomenclature of land cover classes

Classes	Descriptions
Built up area	Area with permanent concentration of man-made structures, residential, commercial services, utilities, infrastructures; buildings, roads, institutions, and rural clustered homestead buildings.

Degraded land	Barren Land is land of limited ability to support life and in which less than one-third of the area has vegetation or other cover. In general, it is an area of thin soil, sand, or rocks. Vegetation, if present, is more widely spaced and scrubby than that in the shrub and Brush category
Agroforestry	Home garden agroforestry, semi-forest coffee ecosystem, which is characterized by significant disturbance of the original natural stand by commercial utilization and other human activities.
Crop land	defined broadly as land used primarily for production of food and areas of land prepared for growing agricultural crops. The category includes areas currently under crop, and land under preparation. For rain fed and irrigated cultivation, including fallow plots, cultivated land mixed with some bushes like scattered chat plantations in the farmland
Water body	Include all kind of wetlands situated on the shallow margins and rivers and other water body (including an area covered by watercourses, rivers, artificial ponds), Lakes, stream, rivers, wetlands
Grass lands	All areas covered with natural grass and small shrubs dominated by grass including grazing lands. where the potential natural vegetation is predominantly grasses, grasslike plants, forbs, or shrubs and
Woodland	land covered with woody vegetation, open canopy, and sparsely distributed vegetation structures,
Forest	Forest Lands have a tree-crown areal density (crown closure percentage) of 10 percent or more, are stocked with trees capable of producing timber or other wood products and exert an influence on the climate or water regime. It refers to the ground cover provided by higher plants and any other specific botanical or geographic characteristics of closed canopy including natural forest and a range of plantation forest types with one common feature and dominated by, *Eucalyptus spp, Gravilia robusta, Cupressus lusitanica,* etc plantations.

2.4. Land use land cover classification methodology

The land degradation mapping was carried out on google earth engine (GEE). The respective district shapefiles were uploaded to the GEE automation system and each district was filtered for respective mapping. Sentinel-2 TOA reflectance data were used to retrieve the required information using JavaScript. The maskS2clouds function was then applied over the yearly image collections to mask clouds using the Sentinel-2 QA band by setting both flags to zero, indicating clear conditions. The image collections were then composited and clipped into the area of interest (the merged Districts shape file) as median image.

A Random Forest machine learning algorithm was applied over the median images as a supervised classification system. The images were classified into eight land uses and landcover classes ('Degraded', 'Builtup', 'Cropland', 'Agroforestry', 'Grass', 'Water', 'Forest'

and 'Woodland'). Training samples collected from the field coupled with feature collections over the sentinel-2 TOA images were merged as feature collections. The training samples were then separated into training and validation fractions using the RandomForest algorithm in the GEE code editor. 75% of the training samples were used to train the algorithm for landuse and landcover classification while 25% of the samples were used to validate the classified image. Then feature collections with spectral signatures of the bands from the sentinel-2 composite images were created and the RandomForest trees and variable importance was also tested to apply the classifier and generate classified image.

2.5. Accuracy assessment

Validation datasets were used to assess classification accuracy applying error matrix and kappa coefficient computation (Lillesand, Kiefer, & Chipman, 2014). Finally, the pre-classified imagery was used for accuracy assessment. The confusion matrix for each clipped land use and landcover of the districts was derived using the confusion Matrix and test Accuracy function codes. The Kappa statistics (total accuracy – random accuracy) / (1- random accuracy) was also estimated using the confusion Matrix kappa function. The confusion matrix and overall accuracy were finally exported as a CSV using the Export code in GEE.

The percentage of user accuracy was calculated as total correctly classified training samples divided by the individual landcover type row totals. The producer accuracy was estimated by percentage dividing the correctly classified samples by their respective column totals.

3. Results

3.1. Kersa District landcover and use

The map of the land cover/use based on the RandomForest classification is depicted below. The degraded area in Kersa district covers 3.2% of the landscape (Figure A1.3) with an area of 55.8ha, 53% (5470.28ha) of the district is covered by crop land (Table A1.2). The

accuracy assessment result of the classification for this district revealed that the overall accuracy of 95% (Table A1.7).

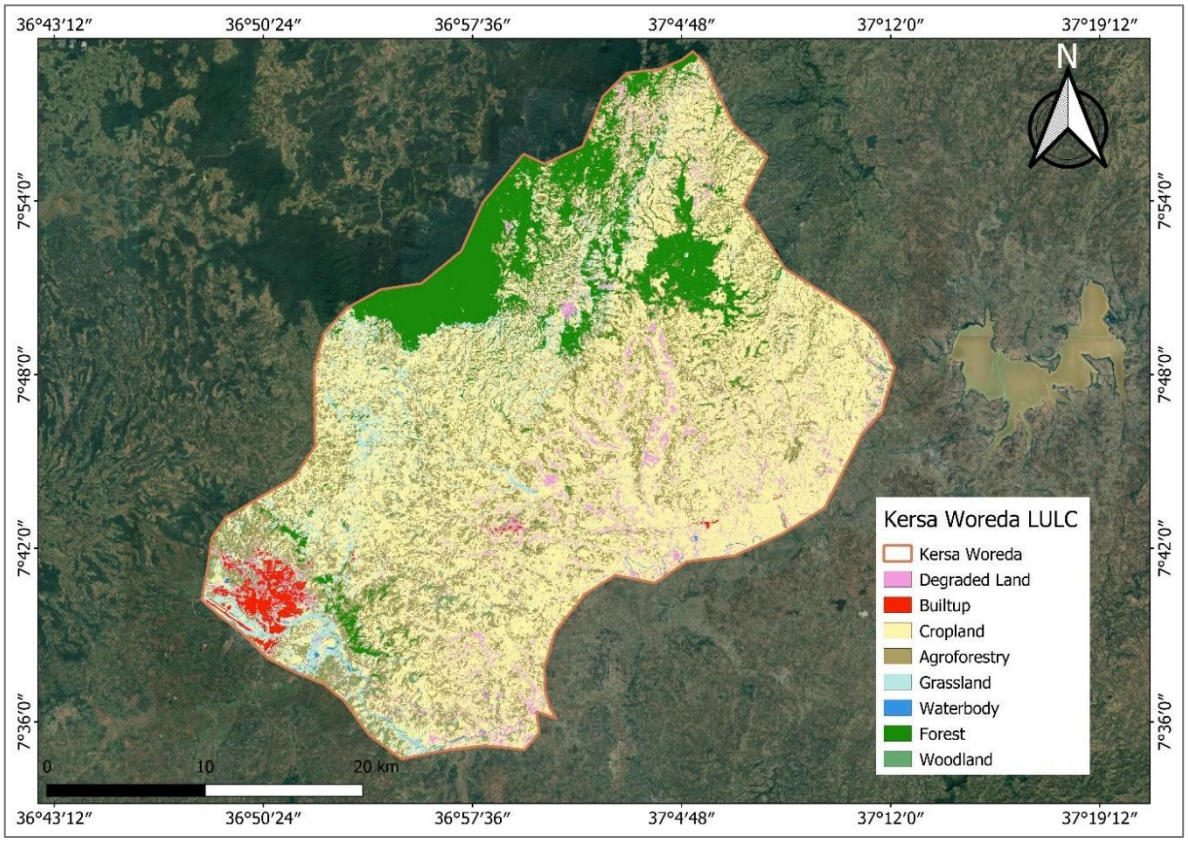
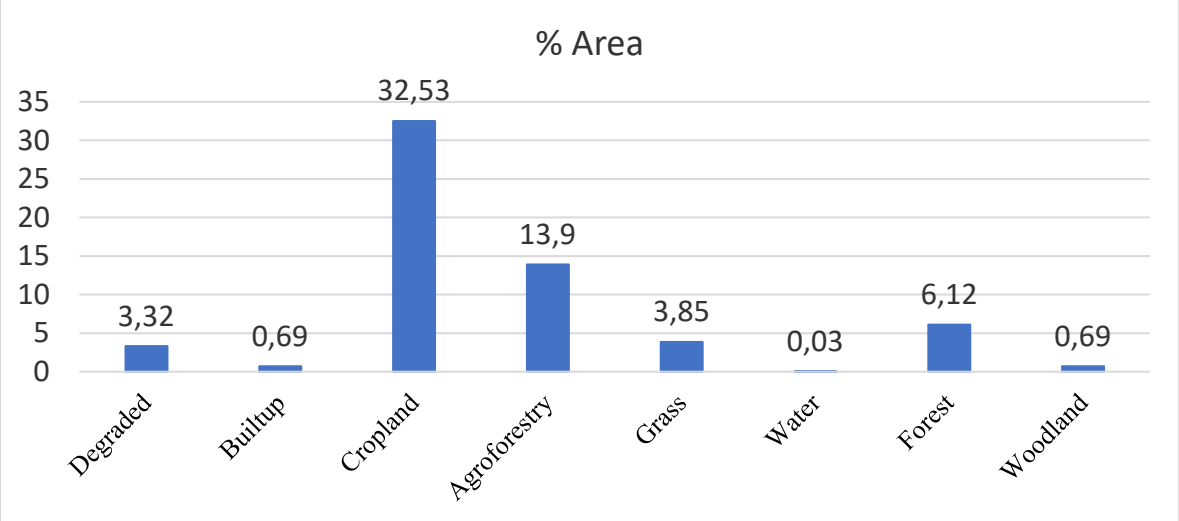


Figure A1.2. Land cover and Land use map of Kersa district

Area cover statistics

Table A1.2. land use land cover area coverage of Kersa district

LULC classes	Area(ha)	% Area
Degraded land	558.30	5.430685
Built up	116.50	1.133243
Crop land	5470.28	53.2107
Agroforestry	2337.68	22.73913
Grass land	647.15	6.294948
Water body	4.21	0.040986
Forest land	1029.59	10.01506
Woodland	116.71	1.135251
Total	10280.41	100



The degraded land distribution map of Kersa District is shown below (Figure A1.3).

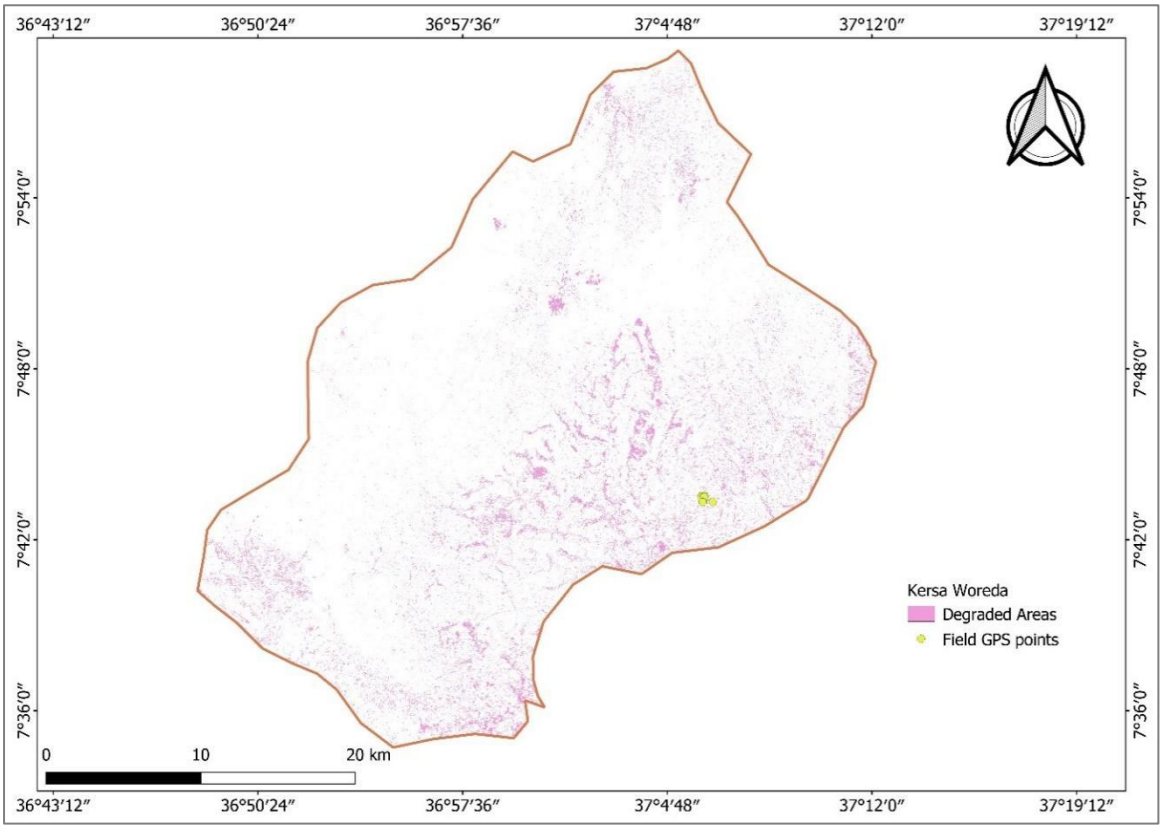


Figure A1.3. Degraded land distribution map of Kersa District.

3.2. Omo Nada district LULC

Omo nada has a total area of 16816.28ha and the majority of the area (49.27%) is covered by crop land and woodland (19.59%). The percent area coverage for degraded land (Figure A1.5) is 8.76 which is 1472.5 ha while the remaining land cover types of agroforestry, grassland, forest land, waterbody and built-up accounts 1640.5ha, 10002.2ha, 943.9ha, 142.5ha and 34.7ha respectively (Table A1.3) which is classified with overall accuracy of 90.2% (Table A1.6).

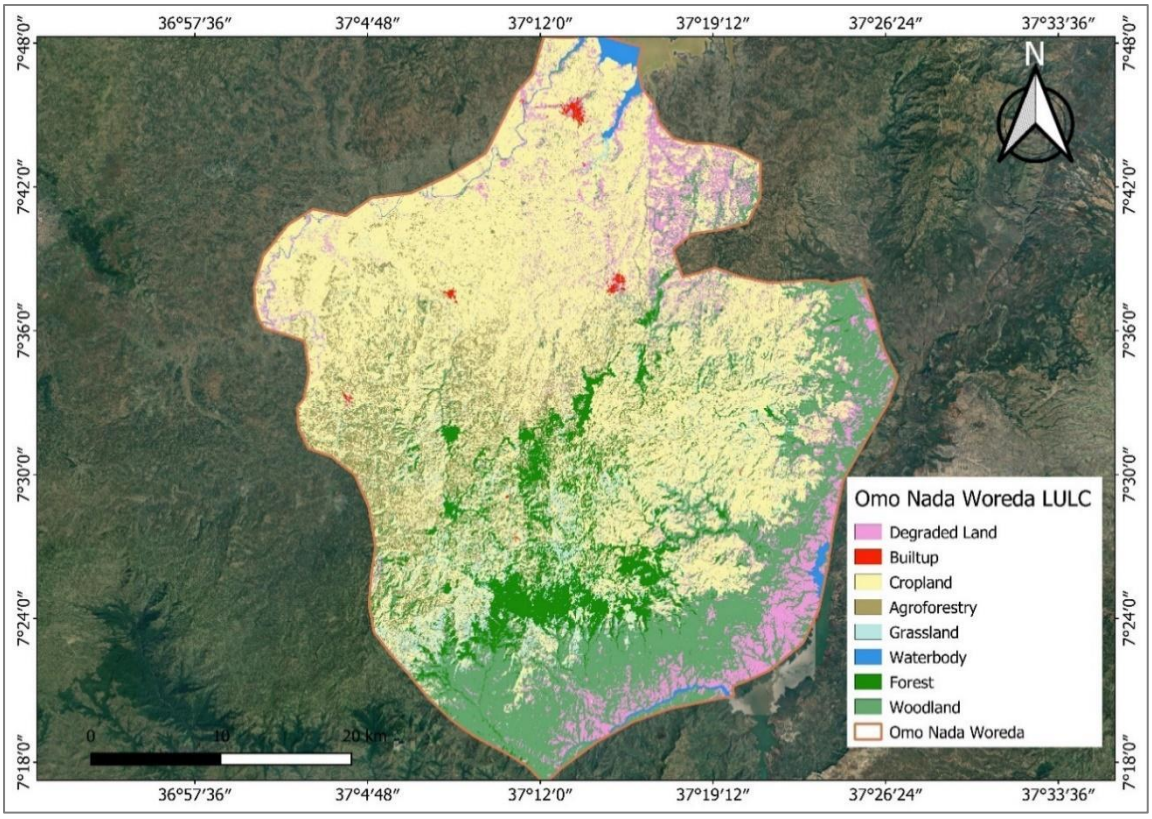


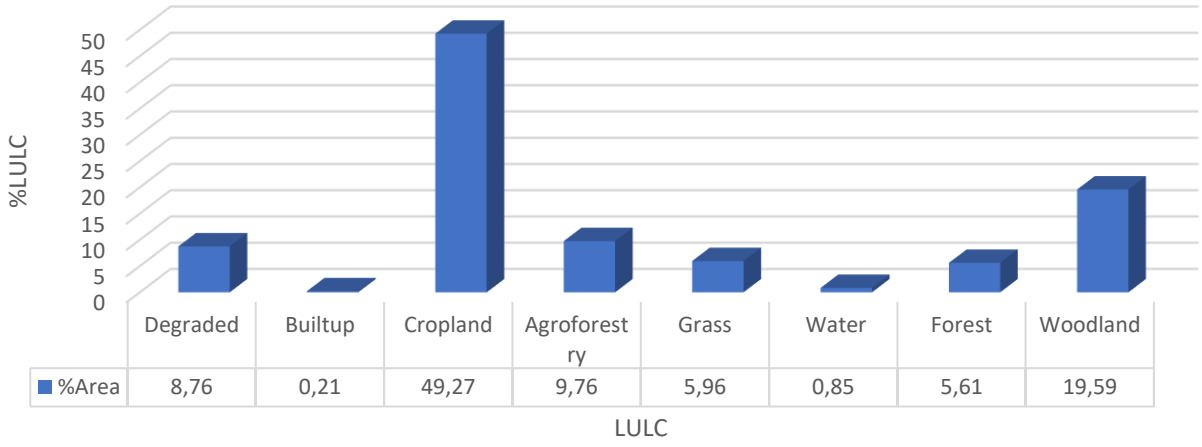
Figure A1.4. Land cover land use map of Omo Nada District

Area cover statistics

Table A1.3. Land use land cover area coverage of Omo nada district

LULC classes	Area (ha)	% Area
Degraded land	1472.5	8.76

Built up	34.7	0.21
Crop land	8285.3	49.27
Agroforestry	1640.5	9.76
Grass land	1002.2	5.96
Water body	142.5	0.85
Forest land	943.9	5.61
Woodland	3294.7	19.59
Total	16816.28548	



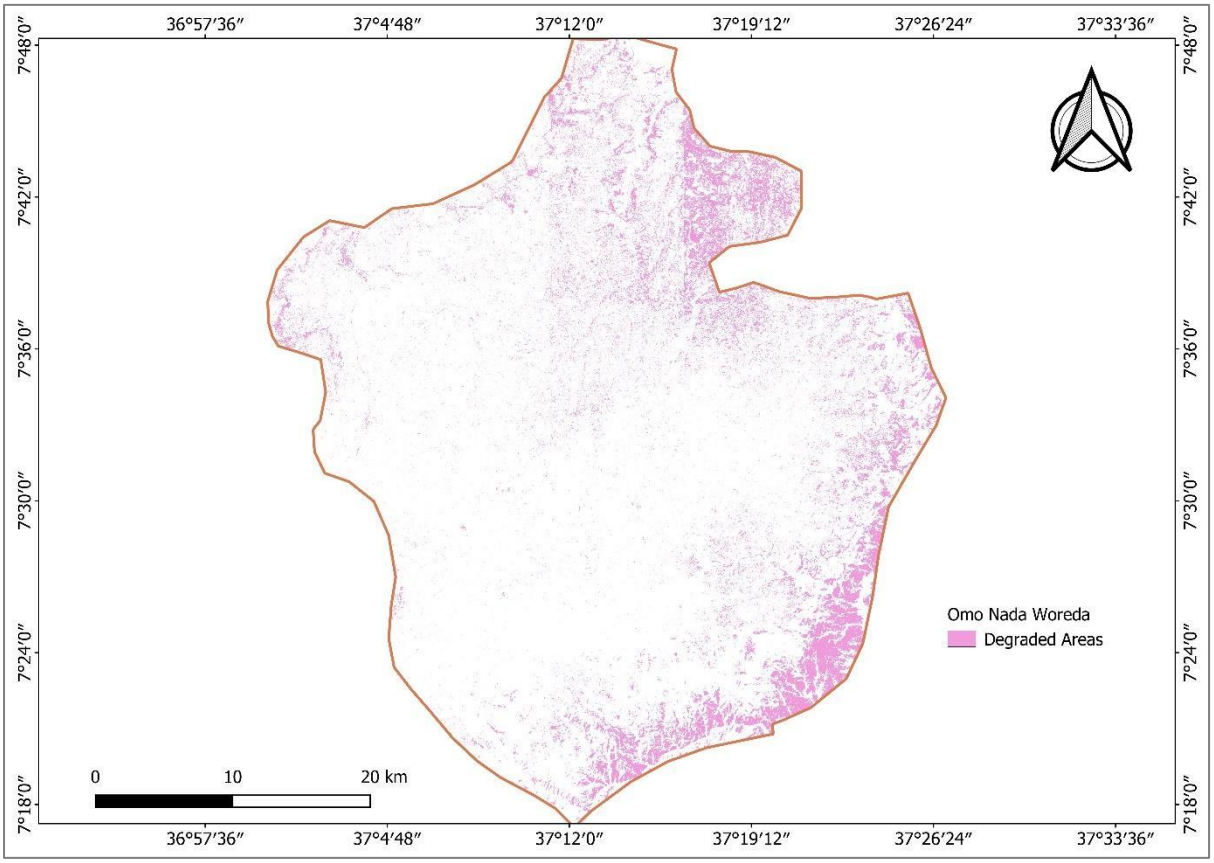


Figure A1.5. Degraded area distribution map of Omo Nada District

3.3. Tiro Afeta district LULC

The map of the land use/cover of Tiro Afeta district based on the RandomForest classification in Google Earth Engine, which is classified with overall accuracy of 91.39% (Table A1.8) is depicted below. Tiro afeta has a total area of 9076.9ha and majority of the area (48.05%) is covered by crop land and woodland (21.74%). The percent area coverage for degraded land (Figure A1.6) is 13.9% which is 1224.9ha. The area coverage of the land use and land cover of Tiro Afeta district showed cropland as the major land use and built-up as the list land use type in the area (Table A1.4).

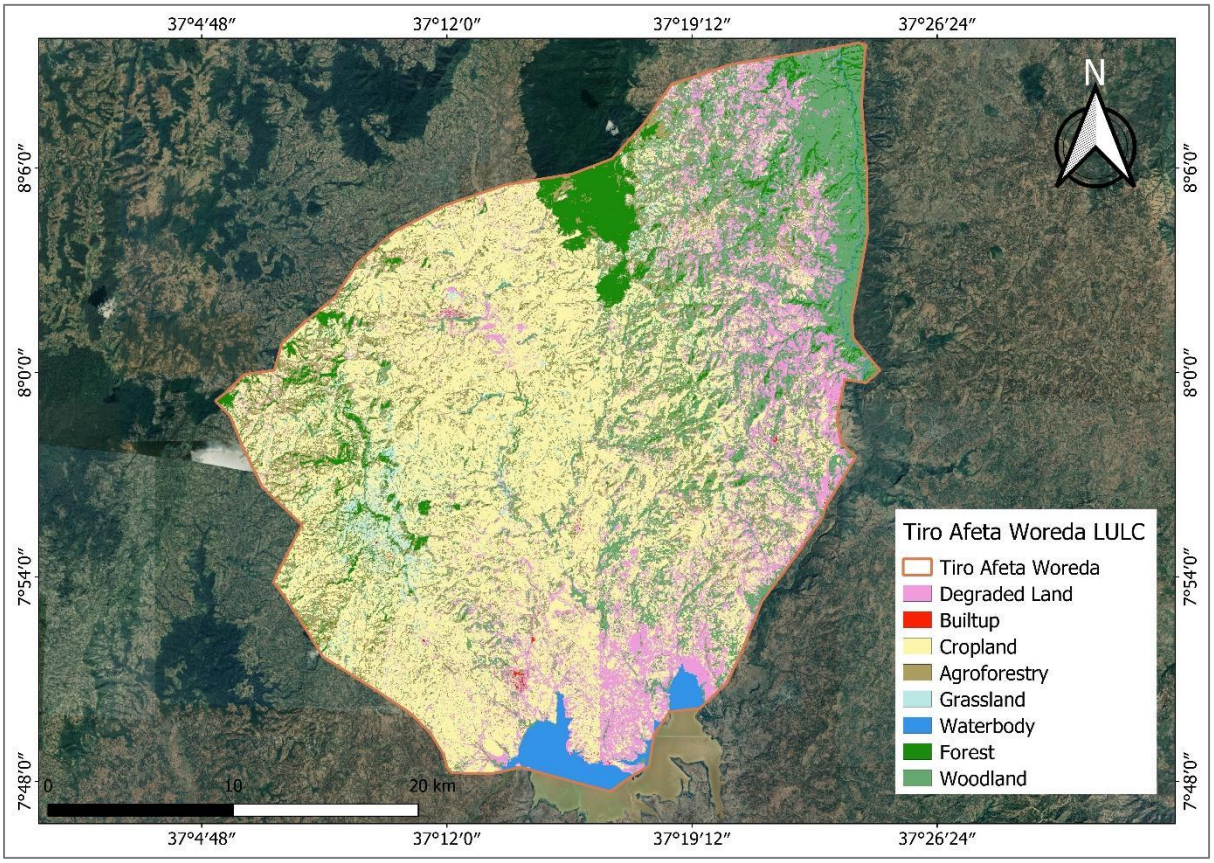


Figure A1.6. Land cover land use map of Tiro Afeta District

Area cover statistics

Table A1.4. Land use land cover area coverage of Tiro Afeta district

LULC classes	Area (ha)	% Area
Degraded land	1224.9	13.49
Built up	3.7	0.04
Crop land	4361.1	48.05
Agroforestry	760.9	8.38
Grass land	239.6	2.64
Water body	172	1.89
Forest land	341.2	3.76
Woodland	1973.5	21.74
Total	9076.9	100

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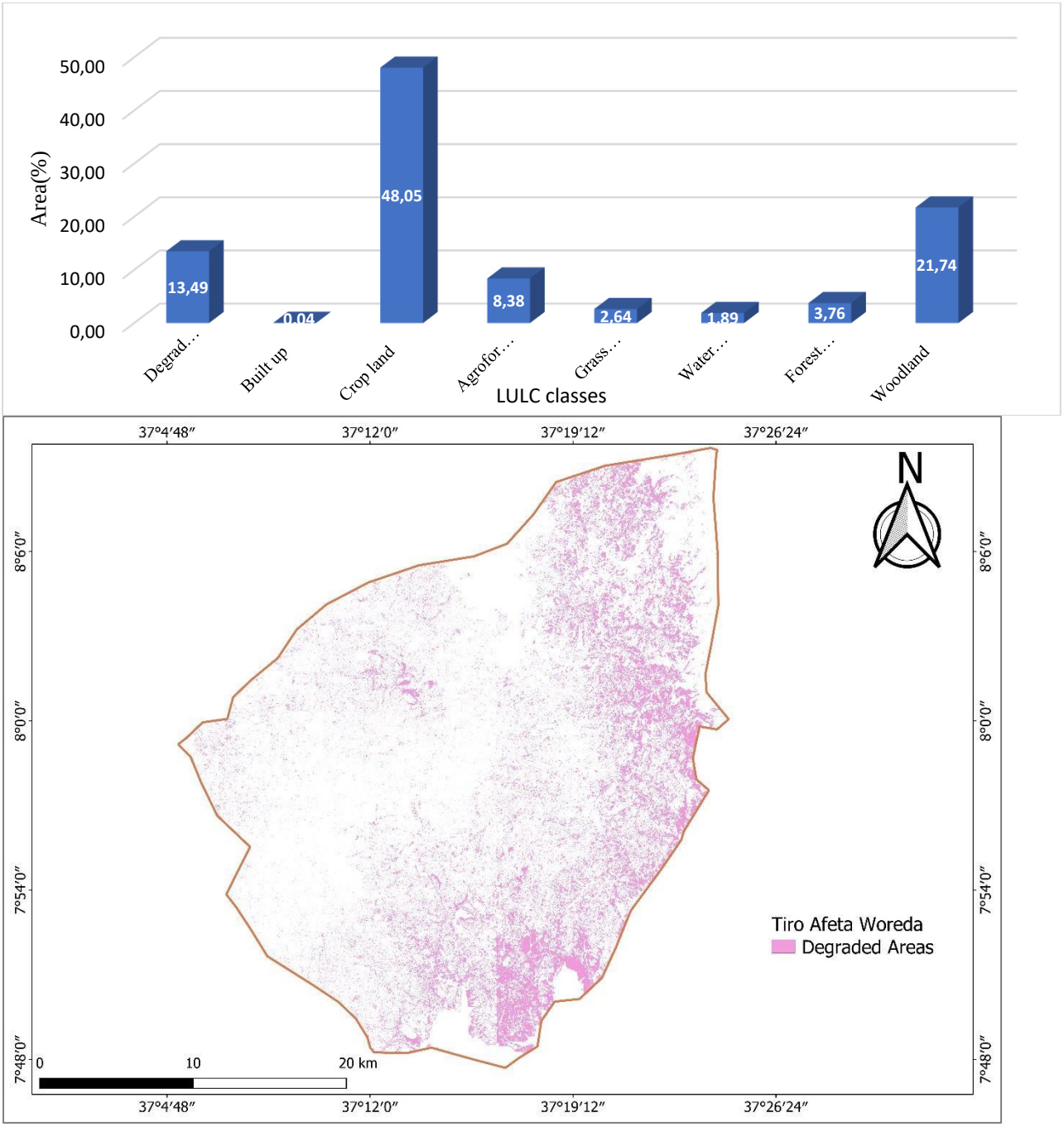

Figure A1.7. Degraded area distribution map of Tiro Afeta District

3.4. Summary of degraded land distribution across the project Districts

The total area coverage of the project districts is 36173.6 ha out of which 3255.7 ha of land is classified as degraded which is 9.0% of the total area (Table A1.5).

Table A1.5. Summary of land use land cover area coverage of the three-project district

District	Total Area _ha of the district	Degraded land_ha	Degraded land %
Kersa	10280.41	558.30	5.43068527
Omonada	16816.29	1472.5	8.75639273
Tiro-Afeta	9076.9	1224.9	13.4946953
Total	**36173.60**	**3255.6967**	**9.00**

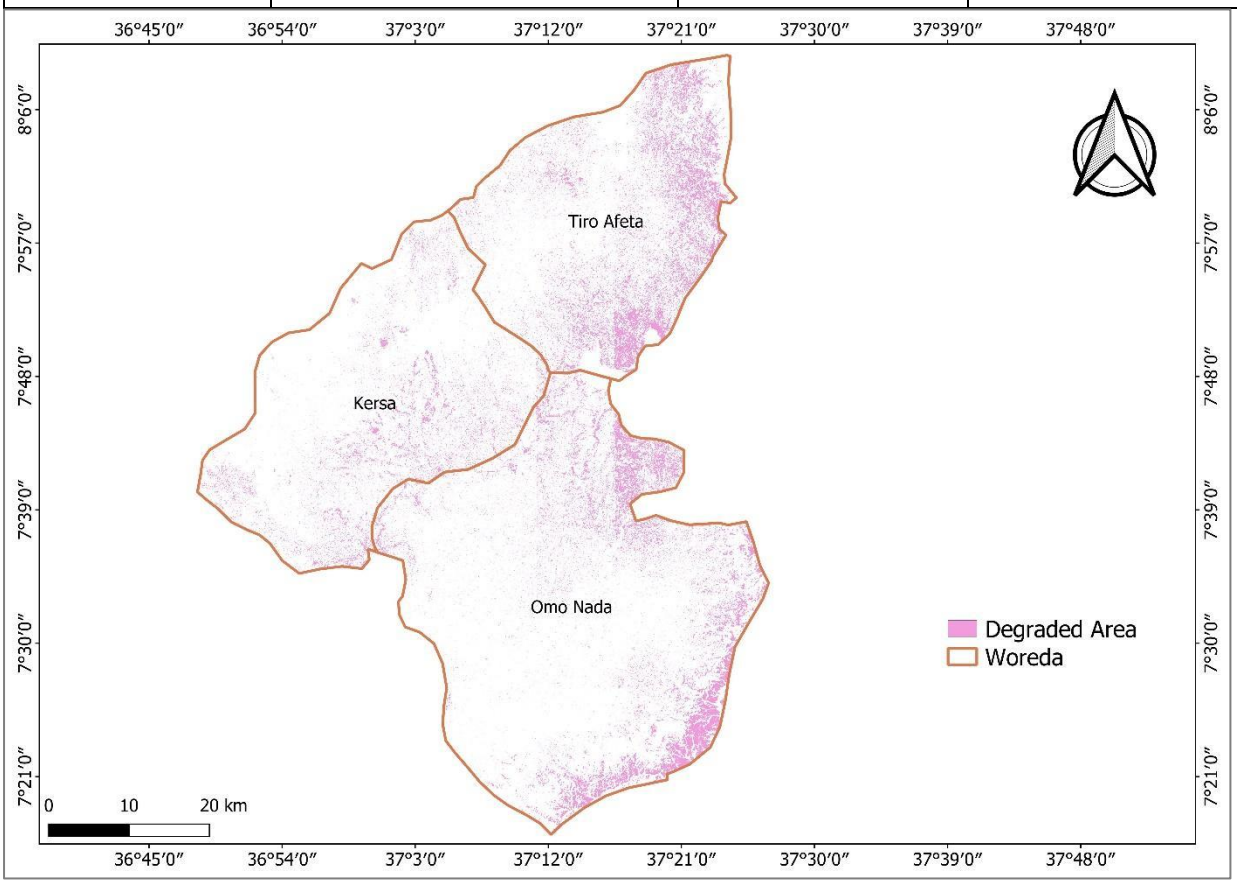

Figure A1.8. Degraded area distribution map of project districts

3.5. Accuracy assessment result

Table A1.6. Accuracy Assessment matrix of Omo Nada District

	DL	BU	CL	AF	GL	WB	FL	WL	user accuracy	Producer accuracy
DL	48	2	9	0	0	0	0	2	78.69	87.27
BU	4	61	0	0	0	0	0	0	93.85	96.83
CL	2	0	43	0	0	0	0	0	95.56	76.79
AF	0	0	1	3	1	0	0	0	60	100
GL	1	0	3	0	6	0	0	0	60	85.71
WL	0	0	0	0	0	35	0	0	100	100
FL	0	0	0	0	0	0	20	0	100	100
WL	0	0	0	0	0	0	0	14	100	87.5
									overall Accuracy	90.2
Kappa statistics = (total accuracy – random accuracy) / (1- random accuracy)										
Key:- DL: Degraded Land, BU: Built Up, CL:Crop land, AF: Agroforestry,GL: Grass land, WB: water body, FL:forest land , WL:woodland										

Table A1.7. Accuracy assessment matrix of Kersa district

	DL	BU	CL	AF	GL	WB	FL	WL	user accuracy	Producer accuracy
DL	64	0	6	0	0	0	0	1	90.14	96.97
BU	0	56	0	0	0	0	0	0	100	100
CL	1	0	53	0	0	0	0	0	98.15	86.89
AF	0	0	0	3	0	0	0	0	100	75
GL	1	0	2	1	9	0	1	0	64	100.00
WL	0	0	0	0	0	24	0	0	100	100
FL	0	0	0	0	0	0	25	0	100	96
WL	0	0	0	0	0	0	0	13	100	92.9
									overall Accuracy	95
Key:- DL: Degraded Land, BU: Built Up, CL:Crop land, AF: Agroforestry,GL: Grass land, WB: water body, FL:forest land , WL:woodland										

Table A1.8. Accuracy assessment matrix of Tiro Afeta district

	DL	BU	CL	AF	GL	WB	FL	WL	user accuracy	Producer accuracy
DL	60	0	4	0	0	0	0	0	93.75	83.33
BU	5	68	0	0	0	0	0	0	93.15	97.14
CL	3	2	60	0	0	0	0	0	92.31	92.31
AF	0	0	0	12	1	0	0	0	92.31	92.31
GL	2	0	1	0	5	1	0	2	45.45	83.33
WL	0	0	0	0	0	39	0	0	100	97.5
FL	0	0	0	1	0	0	20	0	95.24	90.91
WL	2	0	0	0	0	0	2	12	75	85.71
									overall Accuracy	91.39
Key: - DL: Degraded Land, BU: Built Up, CL:Crop land, AF: Agroforestry,GL: Grass land, WB: water body, FL:forest land , WL:woodland										

4. Conclusion

Land degradation is an outcome of many causes and the current status of land resources, and its use patterns are the result of many highly inter-linked factors including natural, socio-economic, etc and those related to agricultural practices. In this study we found the importance of using high resolution satellite images for classification and mapping of degraded lands in very wide areas of the districts. The result of the classification has paramount importance for researchers, NGOs and government agencies working on degraded land reclamation to design appropriate land management practices.

A-2: Reconnaissance Survey on Abandoned/ Degraded Cop Lands Using ODK data collection toolbox

1. 2.1. Objective

The objective of this reconnaissance survey was to assess the knowledge, practices and perceptions of farmers towards land degradation

2. 2.2. Methodology

2.2.1 General features of survey areas

The survey was carried out in OmoNada district, Jimma zone of Oromia regional state, southwestern Ethiopia in the October-November, 2021 cropping season. The study covered four *sub-districts (kebeles)* and 81 households. The kebeles were Doyo Yaya (A), Nada Challa (B), Alle (C) and Toli sabbata (D). Altitude ranges from 1743 m.a.s.l. at Toli sabbata (D) to 1849 m.a.s.l. at Doyo Yaya (A). These sites were purposely selected based on prior knowledge of the prevalence of land degradation in the district. In the initial mapping of degraded/abandoned land, we used the RandomForest classification method in Google Earth Engine covering a wide area. In this mapping process, the report pertaining to the 9% is the amount of land (in hectares) out of the total landmass that was claimed as degraded. A definition for degraded land is given in Table A1.1 (pp 7) which did not include degradation in crop lands. Therefore, following purposive selection of sites with degraded lands, farmers were randomly selected for the assessment of knowledge, practices and perceptions towards land degradation. Figure A2.1 presents the location map of the survey sites. More detailed features of the areas are presented in Section A-1 above.

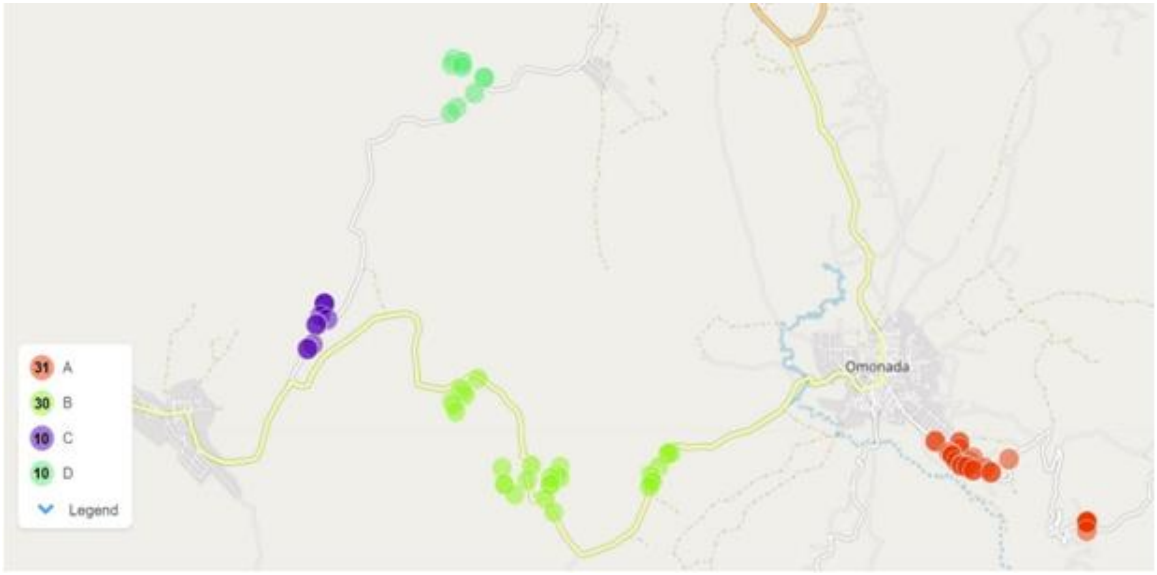

Figure A2.1. Survey areas of abandoned crop lands in southwest Ethiopia

2.2.2. Source of Data and Data Collection Method

Household surveys, personal observations and a semi-structured questionnaire (both open and closed-ended) were the tools used to collect primary data. A data collection tool (KoBoToolbox) was used for the semi-structured questionnaire. The questionnaire covers from farmers' knowledge of local soil classification through perceptions and drivers of land degradation to as well as the farmers' assessment of soil productivity.

3. Results

3.3.1. Total number of plots assessed per household and their distribution within the study areas

The survey showed that nearly 45% of the surveyed households had 3 plots affected by degradation whereas less than 15% of the households had more than 5 plots in the entire district (Figure A2.2A.). Sites at Doyo yaya (A), Nada challa (B) had the greatest percentages of households (~50%) with 3 plots, while Alle (C) with 4 (50%) (Figure A2.2B). There are little differences in the mean farmland holding among the total households.

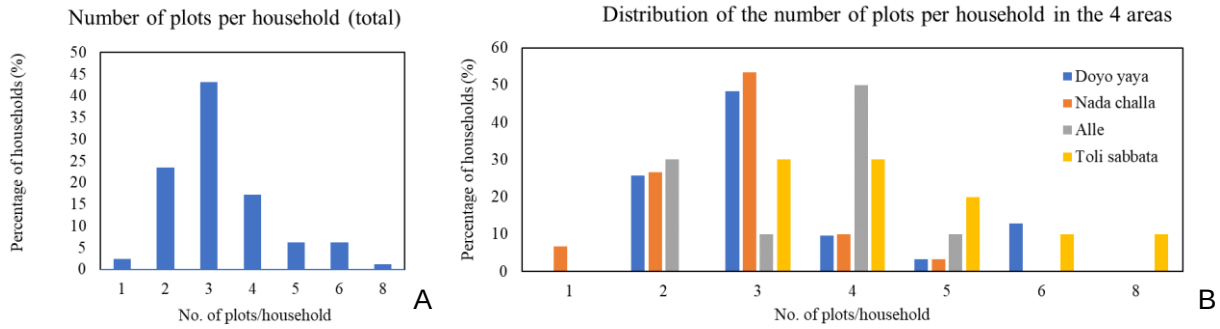

Figure A2.2. Percentage of households with number of plots affected by degradation (A) and the distributed across the sites

3. 3.2. Major types of soils in the survey (local soil classification)

Farmers used a holistic approach to recognize, classify and name local soils. The farmers' rationality while classification combines farmers' cognitive knowledge about soils (e.g., its color, permeability, water holding capacity, texture, and fertility status). Farmers in the survey areas reported more than 5 major types of soils based on soil color (red, brown, dark, red to brown, and black). Few farmers have also recognized brown to red, white, and red and dark mixed. In each site, the most commonly recognized soil type was red colored soil with a percentage of 49, 43, 44 and 62% at Doyoya (A), Nada challa (B), Alle (C) and Toli sabbata (D), followed by brown type soil with percent proportion of 25, 36, 21 and 20% respectively at each site (Figure A2.3. A-D). It is clear that farmers in the present study area have a tradition of associating soil variability with different local soil nomenclatures. The naming and classification indicators of most soil types are relatively homogeneous over a large area in the district of OmoNada and beyond in southwest Ethiopia. Unlike the standard procedure (e.g., WRB) that groups the soils of the study area as Nitisols, farmer's soil types are in detail and very diverse.

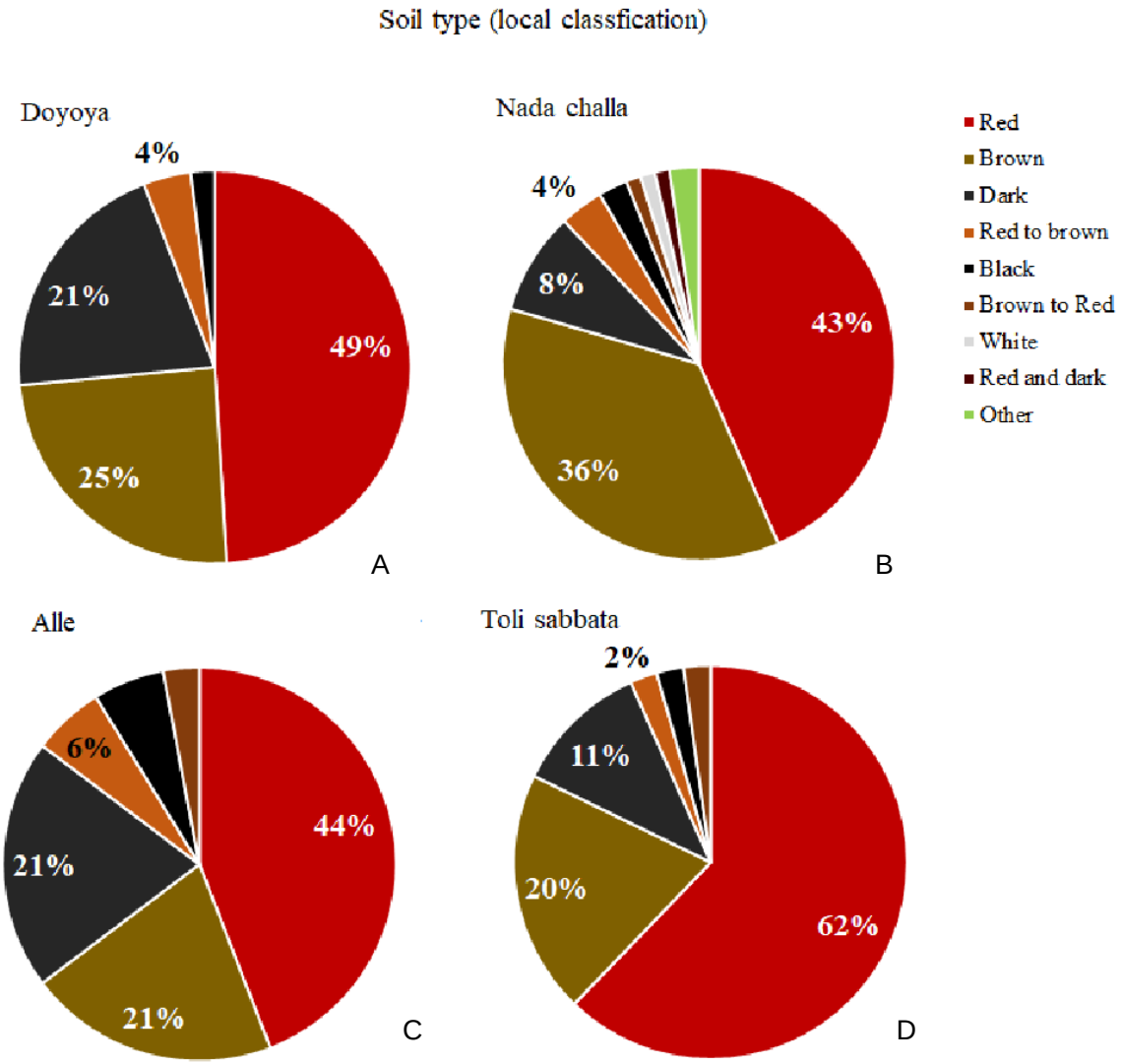

Figure A2.3. Major soil types based on farmers classification criteria

4. 3.3. Land use type and crop production

The total land area of OmoNada is about 16816 ha. In the survey sites, crop land is the major land use type (>80%) while crop-tree mixture (agroforestry) (<15% at Doyo yaya and < 10% in the rest), grazing and other land use types (abandoned lands, built-ups) are the other forms of land uses types (Figure A2.4).

Maize is the major cereal cultivated as a source of food followed by Teff in all the study sites whereas pepper and coffee are cultivated as the major cash crops as sources of income. Other cereals such wheat and fruit crops such as bananas and avocado are commonly grown as sources of food and cash across the study sites (Figure A2.5)

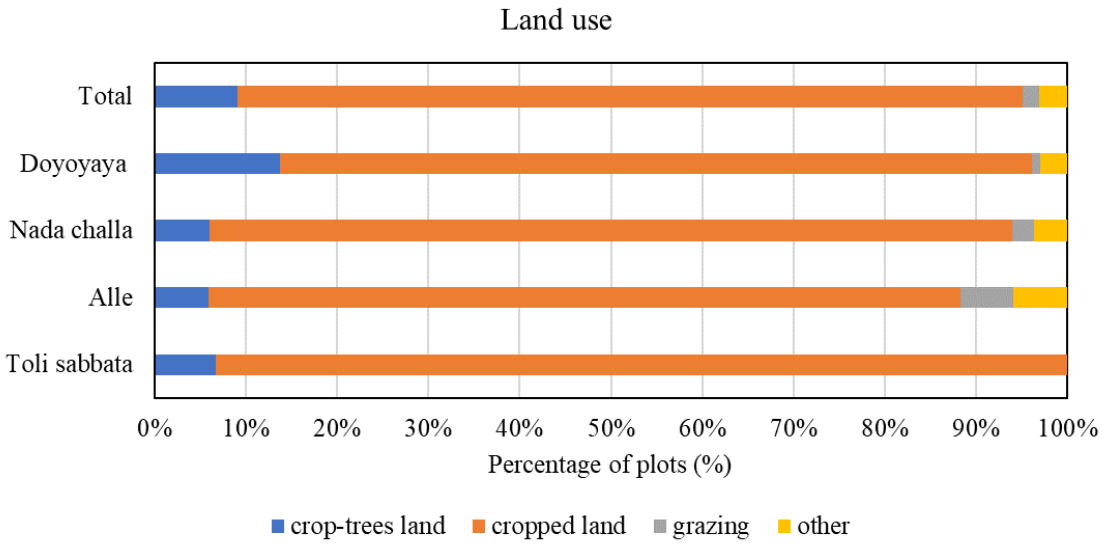

Figure A2.4. Major land use types in the study areas

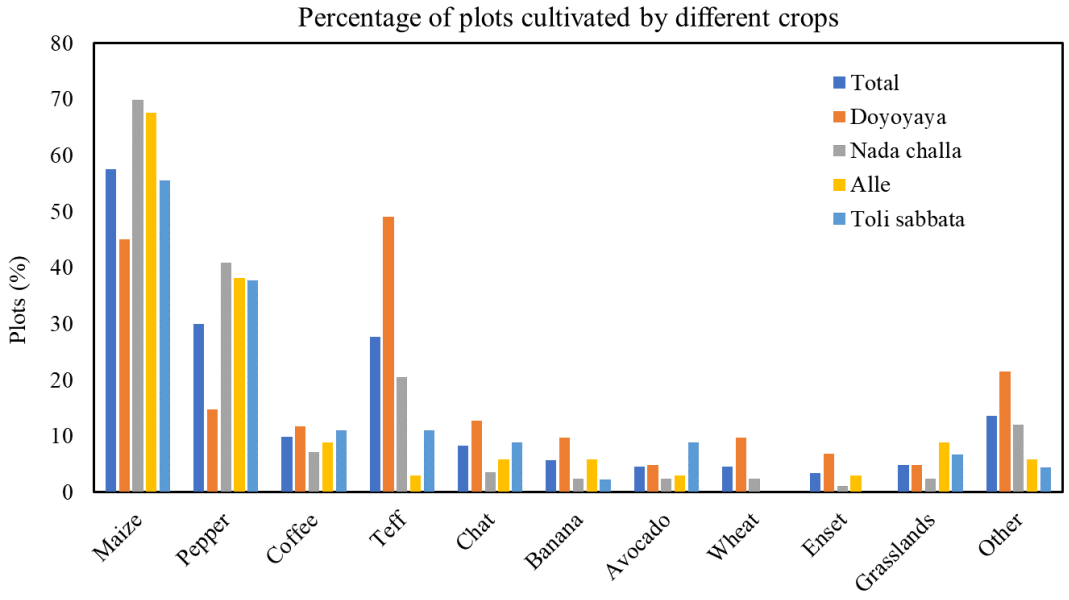

Figure A2.5. Major crop types grown in the study are and their percentage distribution

5. 3.4. Drainage and water state

The majority (>95%) of the surveyed plots in the study areas had a good drainage condition with a dry water state (Figure A2.6). This may be because that the major soil type in those areas is characterized as red soil which are naturally drained and dry and agriculturally suitable soils. Farmers have also recongized that a few plots had medium drainage with wet conditions and that could be associated with the black soil types where these types of soils are naturally poorly drained and are usually wet.

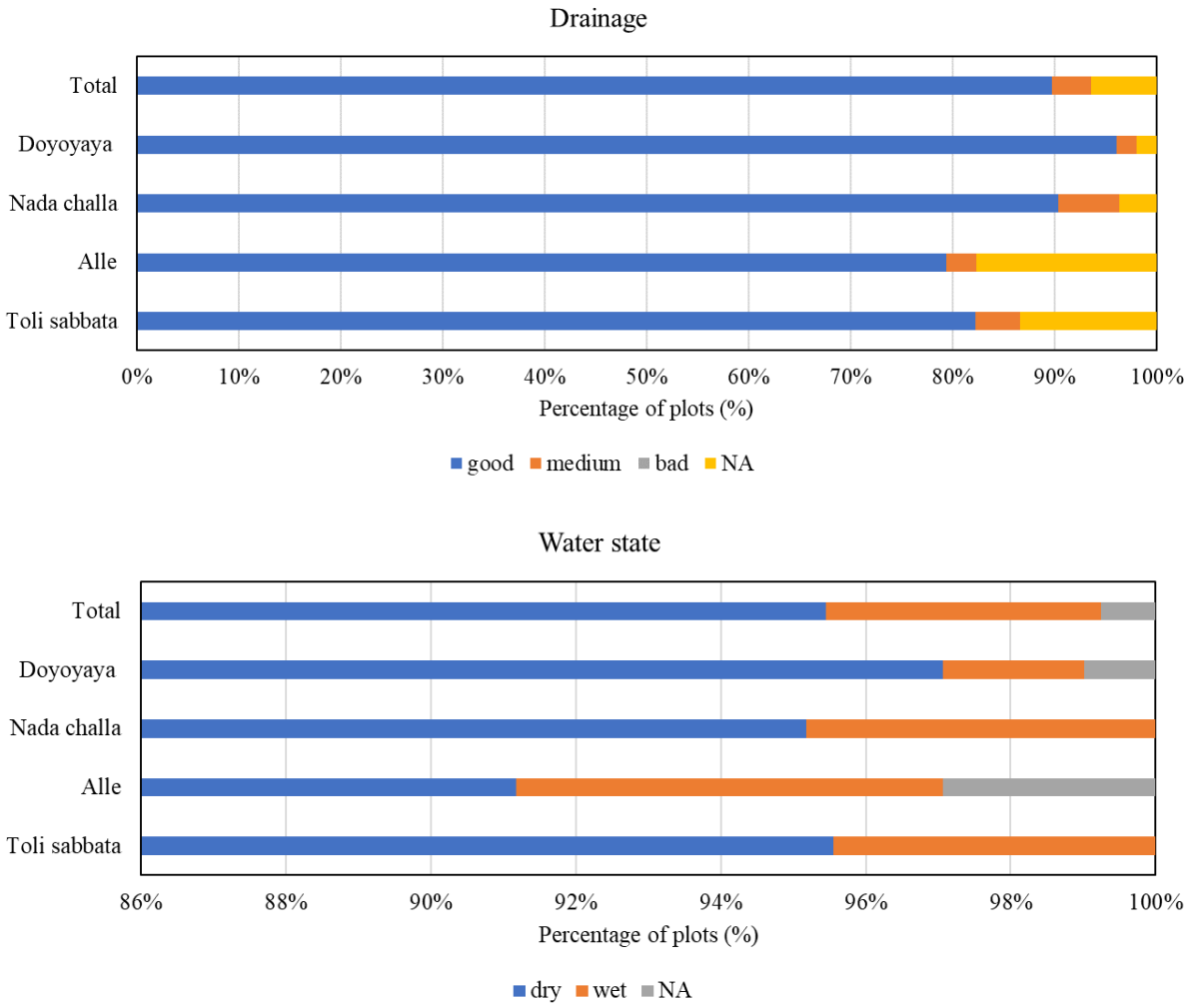

Figure A2.6. Drainage and water state of soils of the study area as perceived by farmers

6. 3.5. Perception of land degradation and loss of soil fertility

All respondent farmers (100%) perceived that the process of land degradation and loss of soil fertility is caused by anthropogenic/human-induced processes (Figure A2.7). Among others, deforestation, excessive plowing, and inappropriate farming are the main perceived causes (> 95%) of land degradation and loss of soil fertility in the study sites (Figure A2.8). Soil erosion, nutrient depletion and acidification have been identified as the main mechanisms and processes of soil fertility degradation. Those processes are very prevalent as the study areas are characterized by high rainfall. Most respondent farmers in the district believed that the decline in their soil's fertility is happening in the last 10 years. Some of these farmers justified that soil fertility decline or improvement is determined by the way the soil is handled and the soil fertility management system used. Continuous cropping with either cereal mono-cropping or cereal followed by cereal rotation that did not include leguminous crops was also perceived as one of the most causes of nutrient depletion which caused declining soil fertility which in turn resulted in decline of crop yields. Even though farmers are aware of the soil fertility declination problems, they continue to cultivate and overexploit the available soil nutrients due to land shortages pressurized by the increased human population.

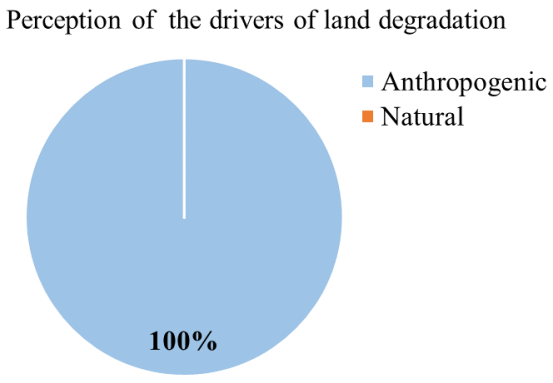

Figure A2.7. General perception of farmers on land degradation and loss of soil fertility

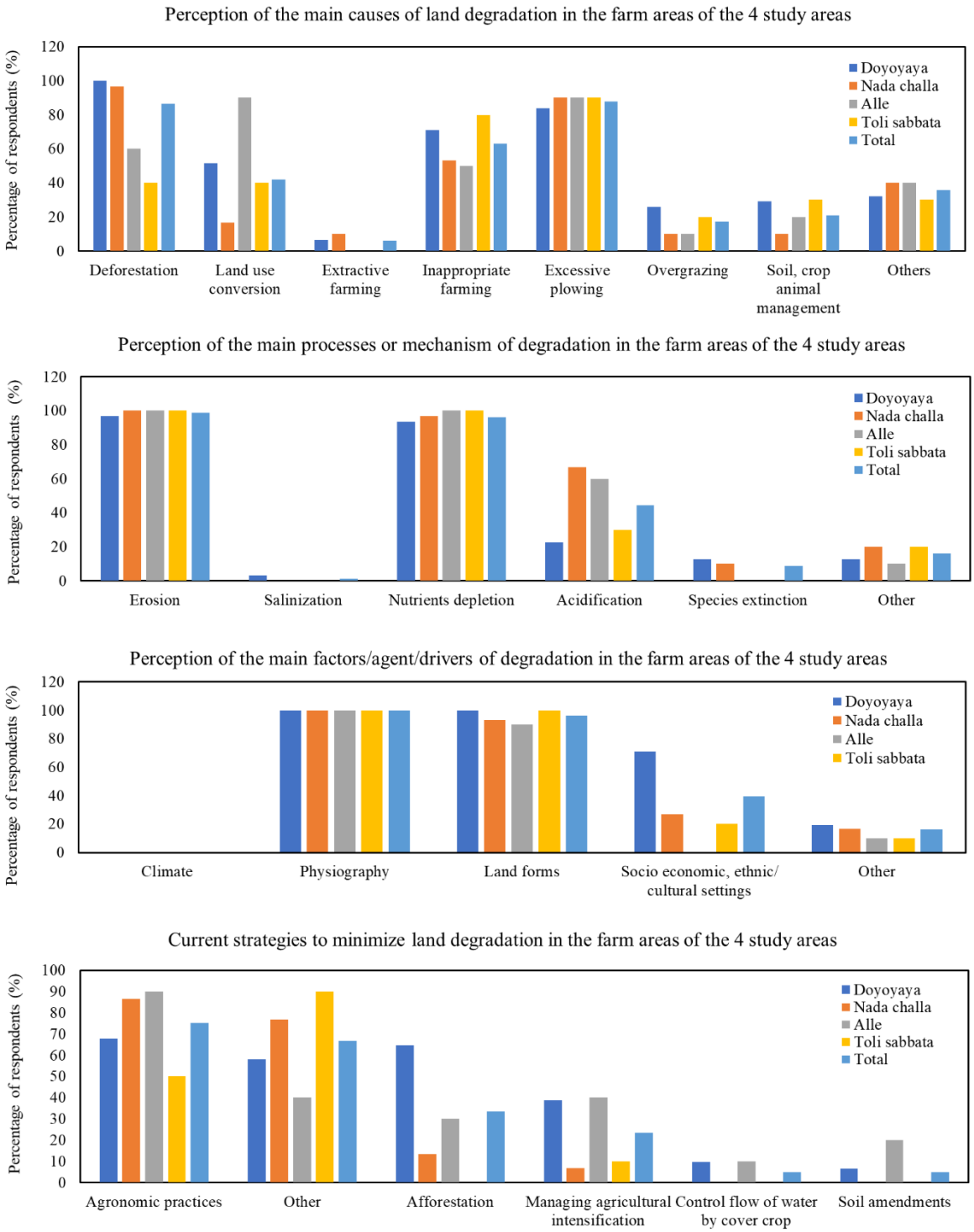

Figure A2.8. The main causes (A), mechanisms (B) and factors/drivers (C) of land degradation and loss of soil fertility and current strategies (D) used by farmers to minimize land degradation

7. 3.6. Land productivity/soil fertility assessment and restoration options by farmers

For each household, farmers were asked to classify their fields based on the 4 productivity categories. Accordingly, based on the indicators of soil productivity, the farmers were able to group their fields into four classes namely productive, moderately productive, degraded and severely degraded. Majority (>60%) of the farmers responded that their crop lands are degraded and about 40% of the farmers recognized as their farms are moderately degraded (Figure A2.9). Low crop yield, stunted growth and color changes of crops, changes in soil color and soil thickness, shift in weed biomass and weed species were the most important indicators of soil fertility status in the study area.

Farmers usually adopt different strategies to recover their degraded lands. Among others, fallowing of degraded fields for 3-4 years is quite practised by >50% of the farmers in Doyoya (A) whereas it is less common (<30%) in the rest of the study areas. The respondent farmers have different reasons to fallow their land. Among others, fallowing for the sake of grazing land, land rehabilitation are the major reasons behind fallowing (Figure A2.9 C).

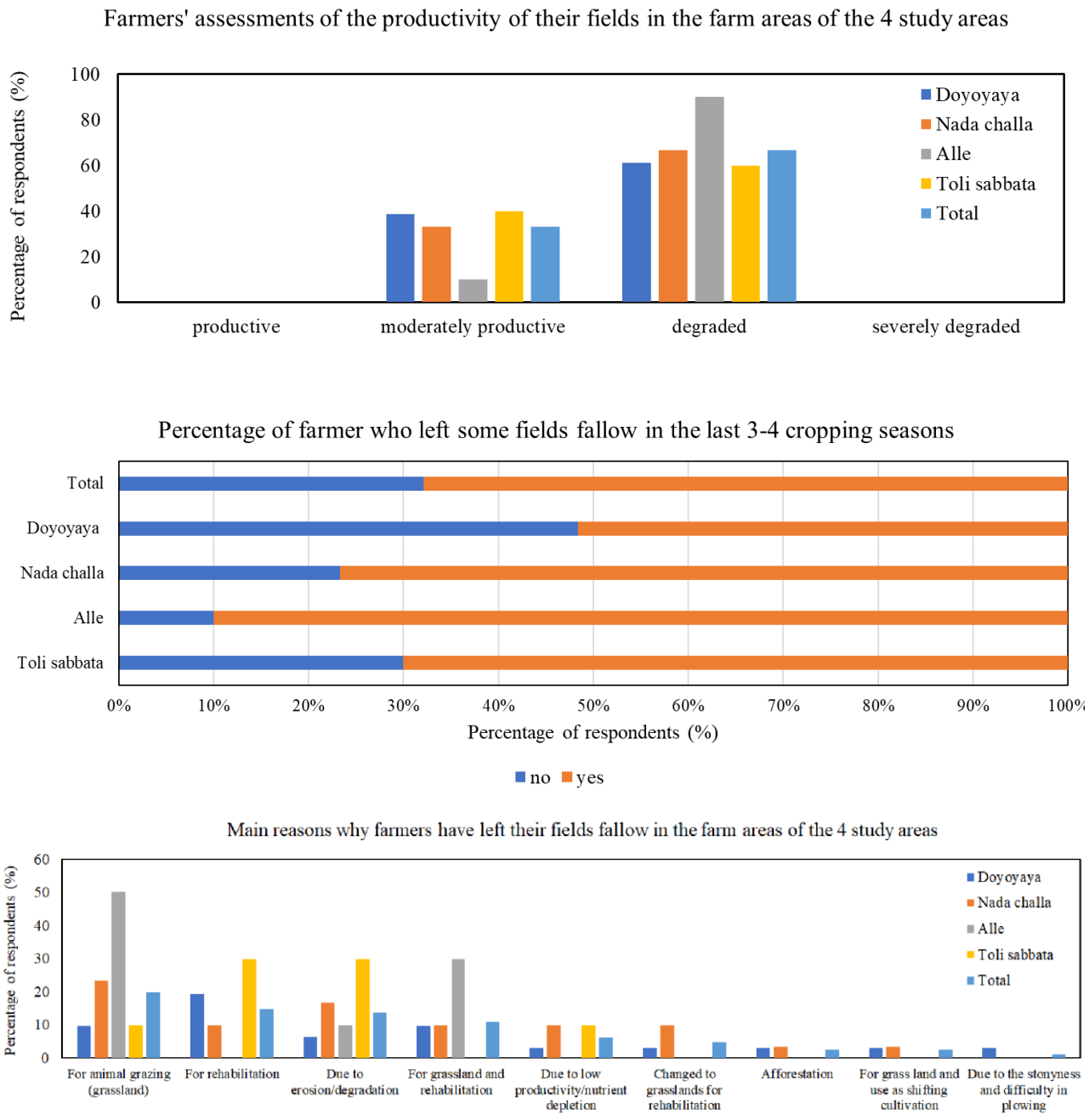

Figure A2.9. Land productivity assessment (A), practice of fallowing (B) and restoration options (C) adopted by farmers in the study area

8. 3.7. Farmers' perceptions on strategies to be adopted to rehabilitate degraded crop lands

The farmers of the study area have various measures of maintaining the fertility of their soils. The majority of the farmers (>80%) do believe that afforestation, fallowing, soil and water conservation practices and making soil bunds in that order are among the measures to rehabilitate degraded lands (Figure A2.10). Liming acid soils, adding compost and farmyard manure are also among the measures frequently adopted by farmers.

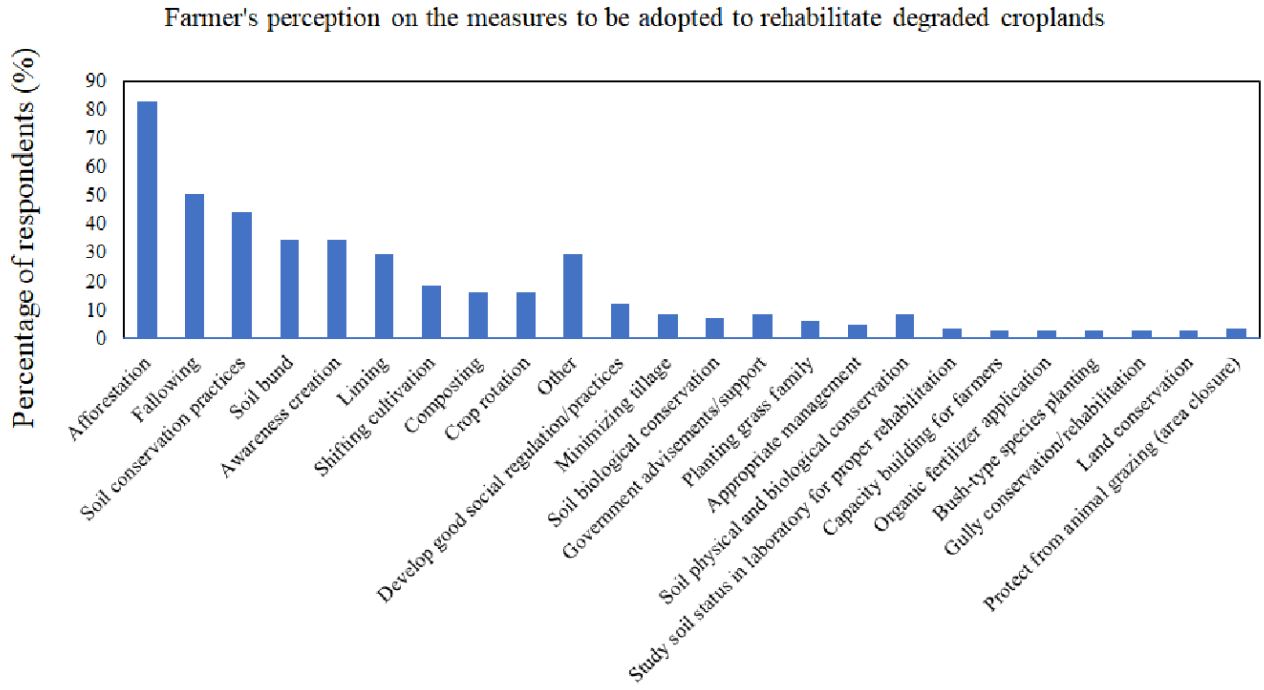

Figure A2.10. Farmers different measure to rehabilitates degraded crop lands

9. 3.8. Farmers' local indicators of soil productivity

Farmers categorized arable soils into 4 productivity classes namely productive, moderately productive, degraded and severely degraded based on dominant weed species, soil attributes and crop performance. Based on soil surface colour and growth of vegetation, farmers perceived that a black colour with some weed species such as "Muja" (*Snowdenia*

polystachya),Qobbo) and Tufoo (*Guizotia spp*) are considered as productive lands compared to other grassy and sedge weed spp (Figure A2.11). Datura and guizotia scarab are also among the broad-leaved weeds frequently observed by farmers in what they perceived is productive soil. Changes in crop yields over time are also perceived as an indicator of soil fertility decline. Based on soil surface colour, farmers recognized that a soil with a reddish colour and with no vegetation growth is categorized as least productive land.

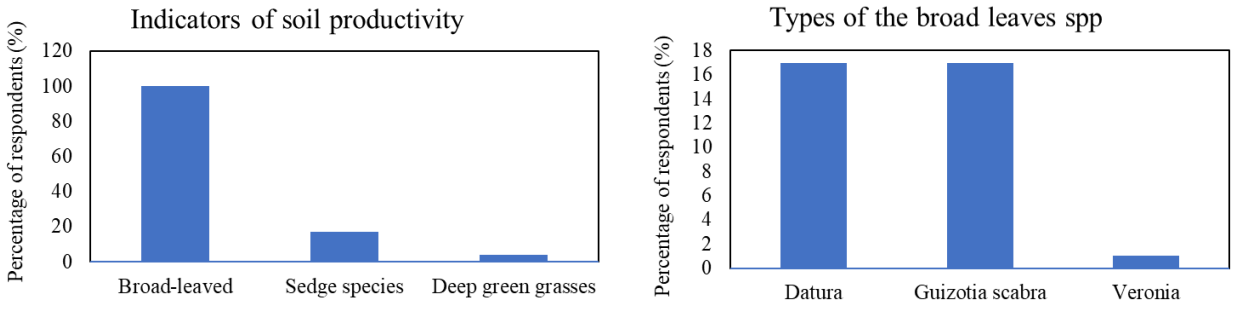

Figure A2.11. Local soil fertility indicators based on dominant weeds identified by farmers

4. Conclusions

In this reconnaissance survey, it was found that farmers have a clear understanding of soil variability and differences within and between their fields. The survey suggests that farmers' knowledge, practices and attitude are quite relevant for site-specific soil management decision-making processes. However, their knowledge and practices seem inadequate to identify yield-limiting nutrients, suggesting that the gaps need to be filled with field-based research trails and link it with farmers' knowledge and practices.

Section B: Assessment of soil fertility traits in selected abandoned/degrade croplands

1. Introduction

Food security and sustainable development are two fundamental and strategic goals in Ethiopia. Agriculture is important for the Ethiopian economy as it provides employment for about 85% of its inhabitants. However, among the factors that heavily threaten Ethiopian agriculture is land degradation and associated soil fertility declines (Agegnehu & Amede, 2017). In proper soil management practices in cultivated lands has led to a higher rate of soil erosion, a decreased crop and soil productivity which can result in abandoning of cultivated crop lands. Land degradation can also disturb the entire soil chemical properties associated with fertility.

Soil chemical parameters are important indicators of soil fertility and they are highly variable in space and time, especially in agricultural areas, with implications for crop production (Bogunovic et al., 2017). As soil properties vary spatially and temporally, understanding their spatial distribution, particularly for degraded crop lands is very relevant in agricultural planning for optimizing local land management, application of nutrients and fertilisers , thereby improving sustainable intensification of production systems.

The most frequently monitored soil fertility indicators of crop lands are pH, soil organic carbon (SOC), available nitrogen (AN), available phosphorus (AP), and available potassium (AK). They are the major indicators and determinants of soil fertility as they are strongly linked to crop growth and productivity (Chen et al., 2020). Therefore, it is very important to assess their spatial distribution for assessing the current status of the soil system and planning measures for the rational use of land resources. Thus, it will contribute to better management decisions to correct problems and at least maintain soil productivity and sustainability.

10. 1.2. Objective

The objective of this assessment was to determine the status of soil fertility by determining soil chemical properties

2. Methodology

2.1. Study area

The study was carried out in three districts (OmoNada, Kersa and Tiro-Afeta), in southwest Ethiopia (Figure B.1). The altitude of study sites ranges from 1737 m OmoNada (Biso gomob site) to 1940 m in Tiro-Afeta (Babo site). The soil fertility assessment was conducted for selected degraded croplands. A field survey was used for the identification and selection of the sampling sites.

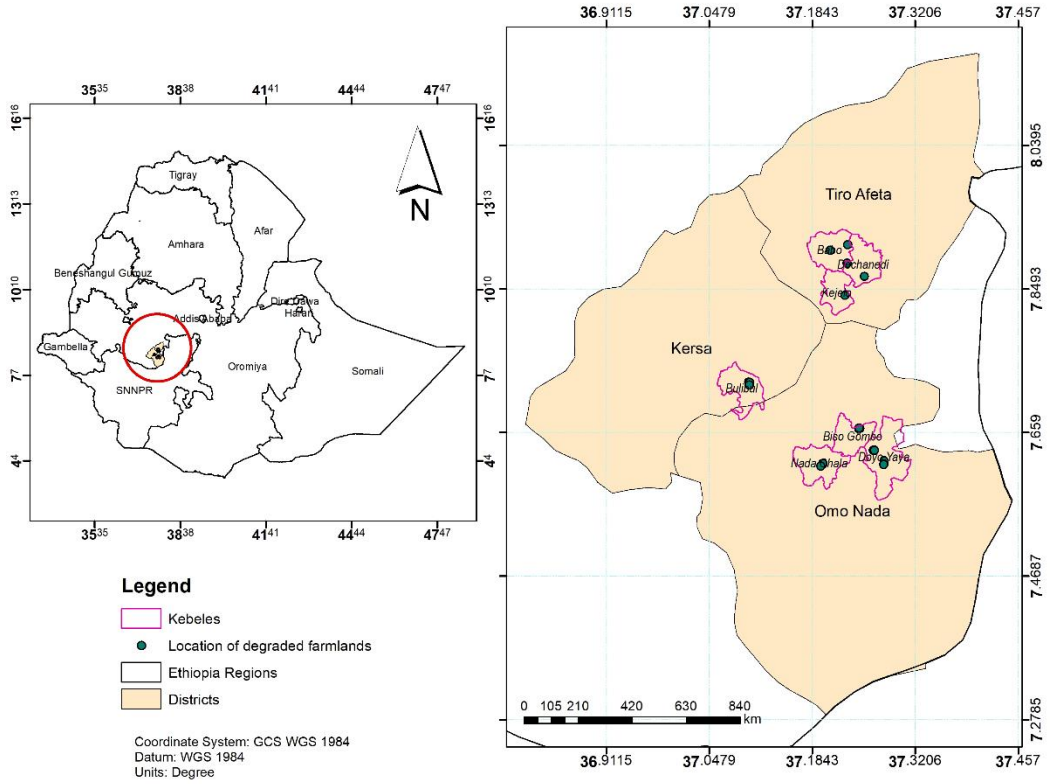

Figure B.1. Map of the soil sample collections areas in southwest Ethiopia

2.2. Soil sampling and analyses

Three sites in Omonada (Bioso gombo, Doyo yaya and Nada challa), three sites in Tiro-Afeta (Babo, Kejelo, and Nadi) and one site in Kersa (Bulbul) were selected for soil sampling. A total of 56 soil samples were collected at 0 - 30 cm depth across the entire districts using a random sampling technique in October and November 2021. At each sampling site, three topsoil samples were collected using an auger and mixed to obtain composite soil samples of about 1 kg and each composite sample was labeled in a plastic bag and sent to the soil laboratory of Jimma University College of Agriculture and Veterinary Medicine for analyses. The composite soil samples were air-dried, grounded, sieved to 2 mm size; analyzed for pH (H_2O), soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AvP), cation exchange capacity (CEC), and exchangeable cations (Ca, Mg, K and Na). The data was then subjected to simple descriptive statistics using MINITAB-16.

3. Results

The soil analytical results are presented in Table B.1 below. The most selective statistical parameter that indicates the overall variability of a soil chemical property from one data series to another is the coefficient of variation (CV) (Bhunia et al., 2018). Based on Warrick guidelines, the soil property shows low variability when CV is <15%, moderate variability when the CV is between 15 and 35%, and highly variable when the CV is >35% (Warrick, 1998). Accordingly, CEC, TN, K and AvP had the highest variability at Kersa and Tiro-Afeta. The variability was moderate for SOC, and exchangeable cations such as Ca, and Mg, Though, soils in the study area are strongly acidic, pH showed the least variability (CV <5%) across the study areas.

According to the soil fertility status classification developed by EthioSIS (2014) (Table B.2), AvP was generally low (15-30 mg kg^{-1}), organic matter was optimum (3.0-7.0%), TN was low to optimum (0.1-0.3%). The soils showed low CEC (9-11 cmol(+) kg^{-1}), while the exchangeable Mg was low (0.3-1.0 cmol(+) kg^{-1}); Ca (<0.2 cmol(+) kg^{-1}) and K (<0.2 cmol(+) kg^{-1}) very were very low. In this assessment, exchangeable Na was below the detection limit and omitted from the analyses.

Table B.1. Average values of soil chemical properties of degraded crop lands and fertility status in three districts, Southwest Ethiopia

Variable	District	Mean	StDev	CoefVar	Minimum	Maximum	Status
CEC (meq/100g)	Kersa	9.87	3.79	38.34	3.06	12.78	Low
	OmoNada	10.48	2.37	22.58	3.52	15.22	Low
	Tiro-Afeta	11.88	2.88	24.24	5.14	15.34	Low
							Low
TN (%)	Kersa	0.21	0.08	36.26	0.16	0.39	Medium
	OmoNada	0.17	0.04	22.18	0.12	0.25	Medium
	Tiro-Afeta	0.16	0.03	22.46	0.10	0.24	Medium
K (cmol+/kg)	Kersa	0.10	0.06	56.88	0.02	0.21	Very low
	OmoNada	0.13	0.04	32.12	0.04	0.21	Very low
	Tiro-Afeta	0.08	0.02	29.33	0.04	0.11	Very low
Ca (cmol+/kg)	Kersa	1.24	0.34	27.68	0.47	1.64	Very low
	OmoNada	1.35	0.38	28.57	0.32	2.17	Very low
	Tiro-Afeta	1.16	0.28	24.29	0.68	1.71	Very low
Mg (cmol+/kg	Kersa	0.38	0.10	26.10	0.17	0.48	Low
	OmoNada	0.45	0.08	18.65	0.20	0.63	Low
	Tiro-Afeta	0.43	0.09	19.78	0.32	0.62	Low
pH (H_2O)	Kersa	5.30	0.17	3.15	5.04	5.54	Strongly acidic
	OmoNada	5.49	0.19	3.43	5.10	5.94	Strongly acidic
	Tiro-Afeta	5.35	0.22	4.03	4.98	5.76	Strongly acidic
%OC	Kersa	2.39	0.56	23.38	1.76	3.28	Optimum
	OmoNada	2.59	0.54	20.90	1.44	3.90	Optimum
	Tiro-Afeta	2.55	0.60	23.55	1.56	3.71	Optimum
Avp (ppm)	Kersa	26.35	10.90	41.37	16.77	48.20	Low
	OmoNada	19.13	5.84	30.54	11.83	36.76	Low
	Tiro-Afeta	20.40	9.85	48.29	12.23	51.88	Low

The low pH value of the soils could be due to the leaching of basic cations such as Ca Mg, and K from the surface soil as the area receives high rainfall. The low levels of AvP in most soils of Ethiopia decline by the impacts of P fixation associated with low pH, soil erosion and other losses through cultural practices.

The low levels of CEC of the study soils might be due to moderate organic matter content and the high soil acidity whereby, under acidic conditions, Al and H ions may occupy the

exchange sites on the clay surfaces. This soil fertility assessment result clearly indicated that the degraded croplands are seriously affected by soil acidity and very low to moderate levels of the essential plant nutrients which are not satisfactory for growth of most crops. Any agronomic or soil management options that can improve soil pH could increase CEC of soil and subsequently the overall soil fertility status.

Table B.2. Critical levels for classifying soil properties according to Ethiopian soil information system (adapted from EthioSIS, 2014)

Soil property	Status	Critical level
Soil pH(water)	Strongly acidic	<5.5
	Moderately acidic	5.6-6.5
	Neutral	6.6-7.3
	Moderately alkaline	7.3-8.4
	Strongly alkaline	>8.4
Organic matter (%)	Very low	<2.0
	Low	2.0-3.0
	Optimum	3.0-7.0
	High	7.0-8.0
	Very high	>8.0
Total Nitrogen (%)	Very low	<0.1
	Low	0.1-0.15
	Optimum	0.15-0.3
	High	0.3-0.5
	Very high	>0.5
Available P (mg/kg)	Very low	0-15
	Low	15-30
	Optimum	30-80
	High	80-150
	Very high	>150
CEC (cmol(+) kg^{-1}	Very low	<6
	Low	6-12
	Optimum	12-15
	High	15-24
	Very high	>24
Exchangeable Ca **(**cmol(+) kg^{-1}**)**	Very low	<2
	Low	2-5
	Optimum	5-10
	High	10-20
	Very high	>20
Exchangeable K **(**cmol(+) kg^{-1}**)**	Very low	<0.2
	Low	0.2-0.3
	Optimum	0.3-0.6
	High	0.6-1.2
	Very high	>1.2

4. Conclusions

The status of soil fertility in the study areas was apparently in a state of low fertility class. The soils had a strongly acidic reaction, low in the major fertility indicators (CEC, N, exchangeable cations). pH is one of the key soil chemical properties that controls availability of plant nutrients and growth and activities of microorganisms in the soil. Although the levels of N and C in a medium range, that will not be a guarantee for crop growth and development. Agronomic and soil management practices to improve soil pH should be an important aspect of recovering degraded croplands.

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Annex III:
Land Recovery Report for Burkina Faso

EWA-BELT PROJECT

Report of Abandoned Lands survey UNB and INERA – Burkina Faso

Section A and B

Content

Section A

1. Land recovery

1.1. Objective:

Identification and mapping of abandoned/degraded lands in the study area through physical and socio-economic data collection and processing

1.2. Methodology

1.2.1. Preliminary data processing

Database on soil degradation in Burkina Faso (BNDT, 2012) at the scale (1/1000 000) was used for the elaboration of the drafts of soil degradation maps of the investigation sites. Using the GPS coordinates, the maps of different sites were extracted from the soil degradation map of Burkina Faso (1/100 000) and processed in order to get site maps scaled at 1/10 000.

After determining the soil degradation level according to the parameters showed in Table A.1, sampling point were located in the maps. And, for each degradation class, at least three sampling points were selected.

The land survey consisted in opening pedological pits in the forehand selected sampling points and soil description carried out as determined by FAO (1976). After the description, soils were classified according to WRB (2015) and soil samples were collected per soil layer for laboratory analyses.

Table A.1. Standard for determination of soil degradation magnitude

Degradation magnitude	characteristics
Very low: Presence of vegetation cover wild animal with low anthropic effects, soil continue to play its biotic and abiotic functions	
Low: Modification of ecosystem by human action (crops production, greasing), the biotic and abiotic functions still existent	

Medium:
Physical and chemical degradation of soil due to erosion, decrease of soil organic matter

High:
treats of physical degradation due to erosion (bare and cracked soils) decrease of soil biotic functions: crops production, low vegetation cover (trees and herbaceous)

Very high:
Soil units are not able to play any biotic and abiotic functions. They are characterized by the following treats (Zone of ravines, gullies, and other erosion claws in abundance, loss of arable land and apparition of rock material, vegetation cover lower than 10 or 20%, on outcrops of breastplate or on rocks, or a strong spread of ferruginous gravel and pebbles, low herbaceous cover, slopy soil units).

1.2.2. Laboratory analyses

- ***Pre-treatment of soil samples***

The pretreatment of the soil samples consisted of sieving using a sieve of 2 mm mesh; the soil samples were pre- dried for 48 hours in a room where the temperature ranged between 28-39 °, and away from any sources of contamination that might influence their chemical composition. This operation was followed by the grinding, sieving, and packaging the pretreated soil in plastic bags and labeled for physico-chemical analyzes.

- ***Determination of physical and chemical soil parameters***

The choice of chemical parameters to be measured was based on their contribution in determining soil fertility for rainfed crop production (Table A.2).

Table A.2. Soil parameters considered and of determination

Soil parameters	Methods used for the determination
Carbon (C) and organic matter (M.O)	Walkley et Black (1934)
Phosphorus (total, available)	Bray et Kurtz,1945
Potassium (total, available)	Anderson,J,M and Ingram,J.S.I (1989)
Nitrogen (N)	Méthode Kjeldahl,1883
Nitrates	Bremner and Keeney, 1965
Cations exchange capacity	Metson, 1956 et Baize, 2000
Sum of exchangeable bases (S)	Metson, 1956 et Baize, 2000
Textural composition	Trois fractions par densimétrie

- ***Determination of soil fertility status***

The final soil fertility was determined using the sum of the contribution of: MO; N; P_{ass}; Pt; K_{av}; K_t; CEC; V; S; pHH_2O. the results obtained are ranged in the following Table A.3 in order to determine the fertility class of the soil.

Table A.3. Standards for the determination of soil fertility status

Fertility classes	Very poor	Poor	Medium	High	Very high
Somme of contribution of the parameters	< 20.9	21.0 – 26.9	27.0 – 32.9	33.0 – 38.9	> 39.0

Source: BUNASOLS[1], 1990

1.3. Results

1.3.1. General characterization of the surveyed sites

The land survey was carried out on six (6) sites in the administrative province of Tuy for of Béréba, Sara, Wakuy and Dohoun; and in the province Mouhoun for Kari-kamandena and Bondokuy (Figure A.1).

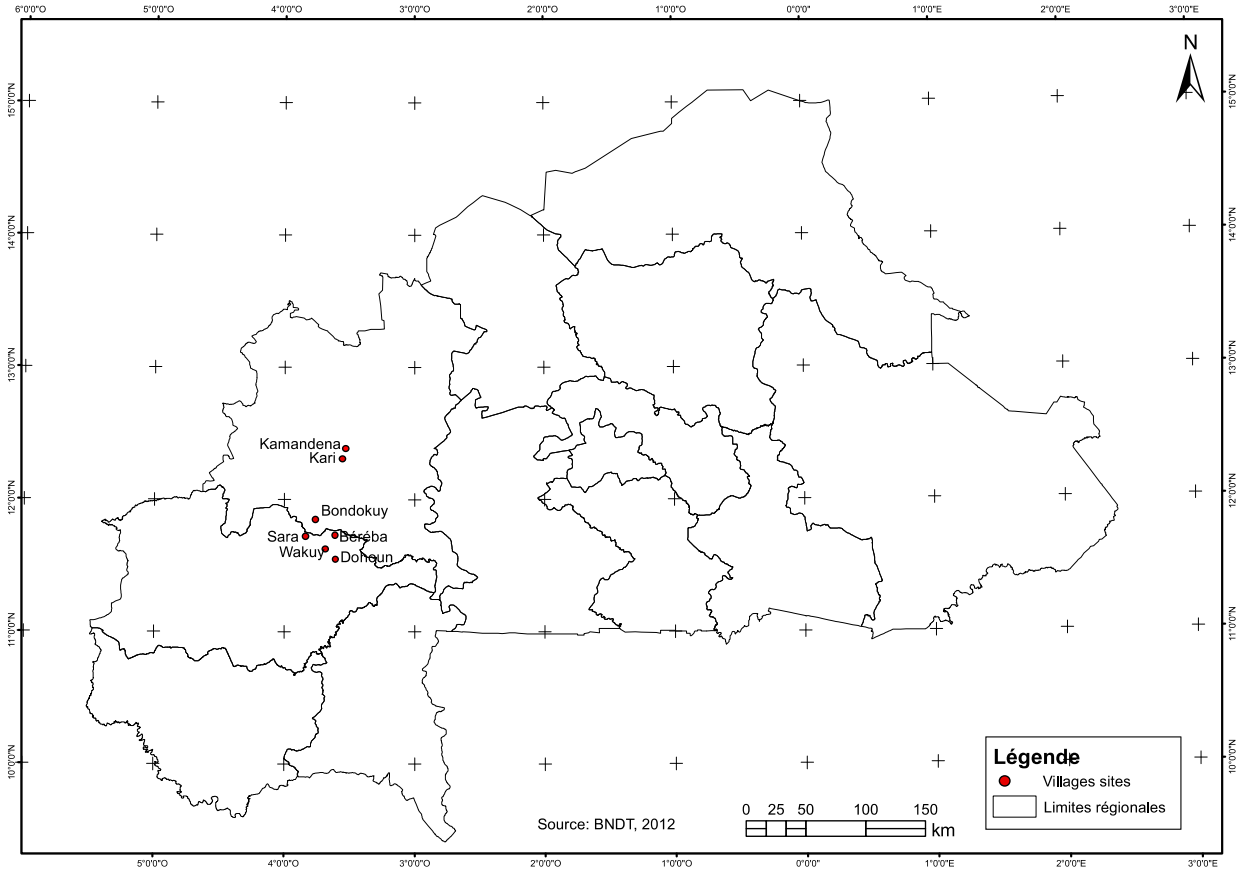


Figure A.1. Administrative borders of Burkina Faso

[1] BUNASOLS: National Office of Soil of Burkina Faso

1.3.2. Soil, Climate and vegetation

The most dominant soils in the two provinces of Tuy and Mouhoun are Lixisols formed from granitic materials. They are intrinsically poor in nutrients and due to their high content in sandy fraction; these soils are characterized by poor water and nutrients holding capacity. Concerning the climate, the province of Tuy belongs to the North Sudanese climate and the province of Mouhoun is in the Sudano-Sahelian zone. These two zones are characterized by a rainy season from May to October (Province of Tuy) and from June to October (Province of Mouhoun). Concerning the dry season (6 to 7 months), it goes from November to May and from November to March respectively in the province of Tuy and Mouhoun. Rainfall in the study sites ranges from 800 and 1000 mm per annum and the mean minimum and maximum temperatures from 18 °C to 38 °C[2]. The landscape is characterized by hills, plains, battleship shelves and valleys with a maximum high of 450 m.a.s.l. (meters above sea level).

The density of the natural vegetation of Tuy and Mouhoun areas is mainly composed of savannas (wooded and grassy). The main tree species are *Faidherbia albida* (Delile) A.Chev., *Adansonia digitata* L., *Afzelia africana* Sm. ex Pers., *Diospyros mespiliformis* Hochst. ex A. DC., *Allium paradoxum* (M.Bieb.) G.Don, *Bombax costatum* Pellegr. & Vuill., *Cassia* spp., *Detarium microcarpum* Guill. & Perr., *Lannea acida* A.Rich., *Mitragyna inermis* (Willd.) Kuntze, *Parkia biglobosa* (Jacq.) R.Br. ex G.Don, *Khaya senegalensis* (Desr.) A. Juss. The most frequent grass weeds species in vegetation are *Andropogon* sp., *Vetiveria nigritana* (Benth.) Stapf, *Diheteropogon* spp., *Cymbopogon* spp. and *Loudetia togoensis* (Pilg.) C.E.Hubb.

In the areas of the Central Plateau, the climate is arid with annual rainfall ranging from 450 to 700 mm, with a mean of 500 mm annually and Eto of 5.7 mm d^{-1}. The rainy season is limited to a short period, usually 4 months, from July until September and the daily

[2] https://en.weatherspark.com/ consulted on 11/05/2021

temperature ranges from 24°C to 39°C, with a mean of 28°C annually. The predominant texture is sandy clay loam (sand 55%, clay 35%, silt 10%). Plinthosols are the dominant soils in this region. According to the Soil Atlas of Africa, these Plinthosols have a petroplinthic horizon (an iron hardpan, formerly termed laterite) or pisoplinthic horizon (a layer containing abundant iron nodules) starting 50 cm below the surface.

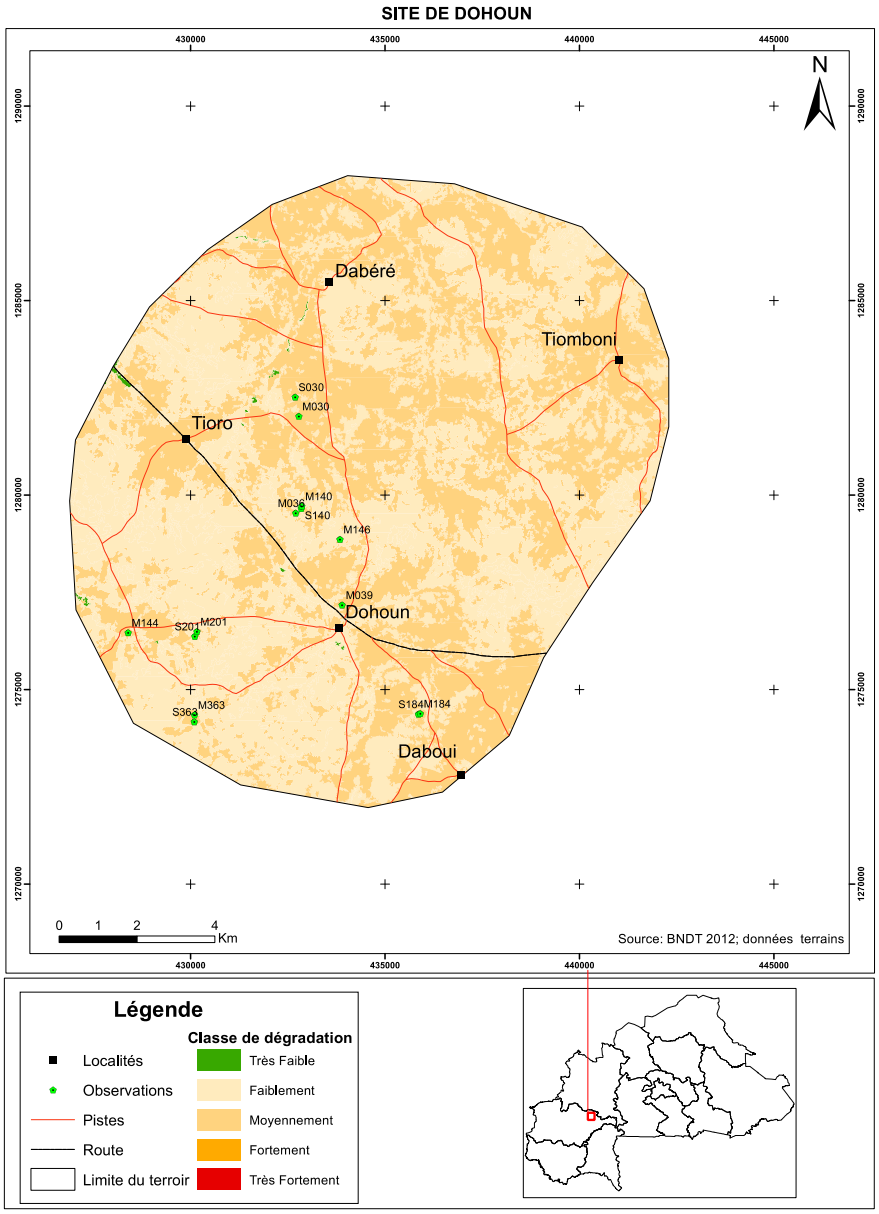
1.3.3. Farming systems and socio-economic context

The farming systems in the study areas of UNB and INERA are mainly based on cotton (cash crop) in rotation with cereals (food crops). In addition to crop production, most households breed cattle and use them as draft animals or for diversification of income sources in order to improve their living standard. The study area is characterized by poor access and inefficient use of organic and mineral fertilizers for food crops; poor level of nutrients cycling at the farm level and poor integration of cattle breeding to crop production. All this results in soil fertility depletion and a steady decrease in crop yields.

The main constraints are represented by the low access to new technologies and innovative techniques; difficulties for young and women farmers to access credit (high-interest rates); decreasing soil fertility and difficulties in finding organic fertilizer or improvers.

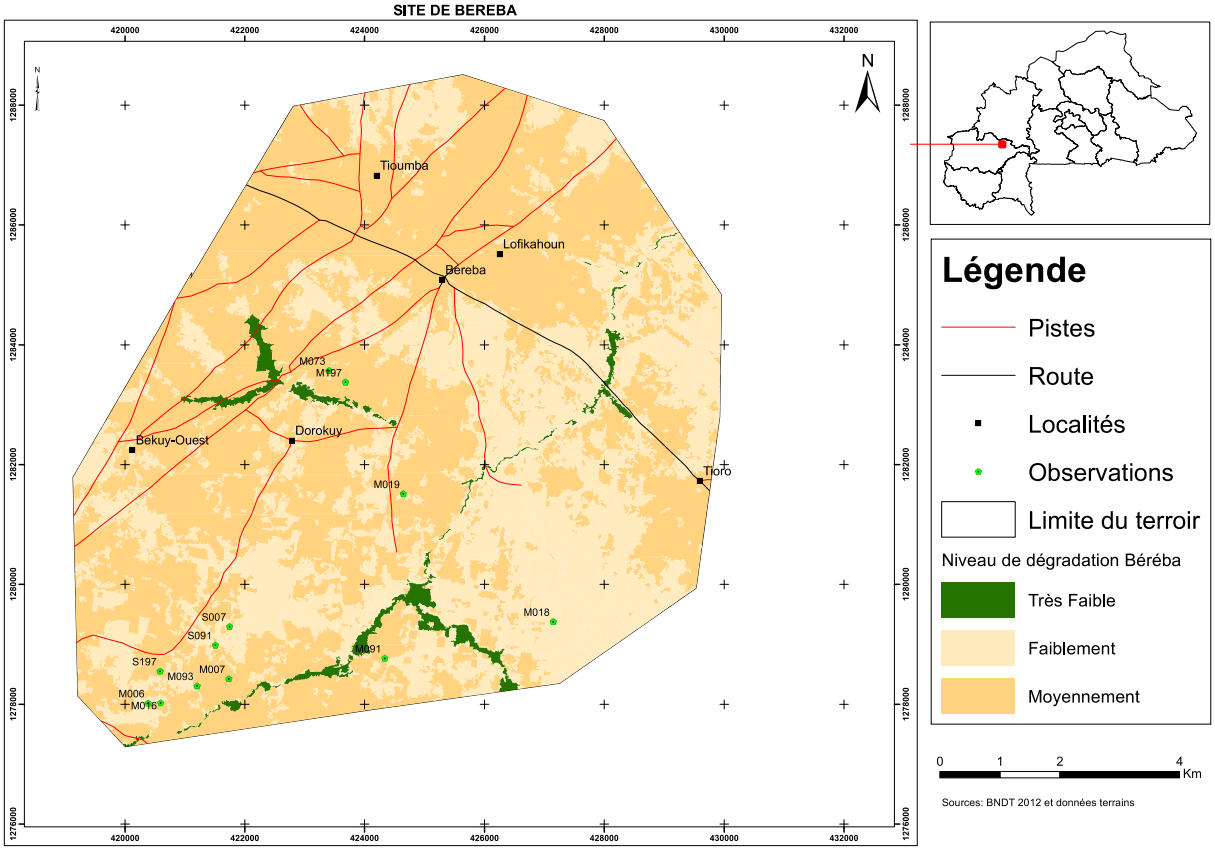
1.3.4. Level of soil degradation

Based on standards for the classification of soil degradation magnitude (Table A.1), soils in the investigated sites were ranged in (3) classes: *very lowly degraded* (Tres faible); *lowly degraded* (faiblement) and *moderately degraded* (Moyennement). The following maps give the extent of the different classes of soil according to the magnitude of the degradation.



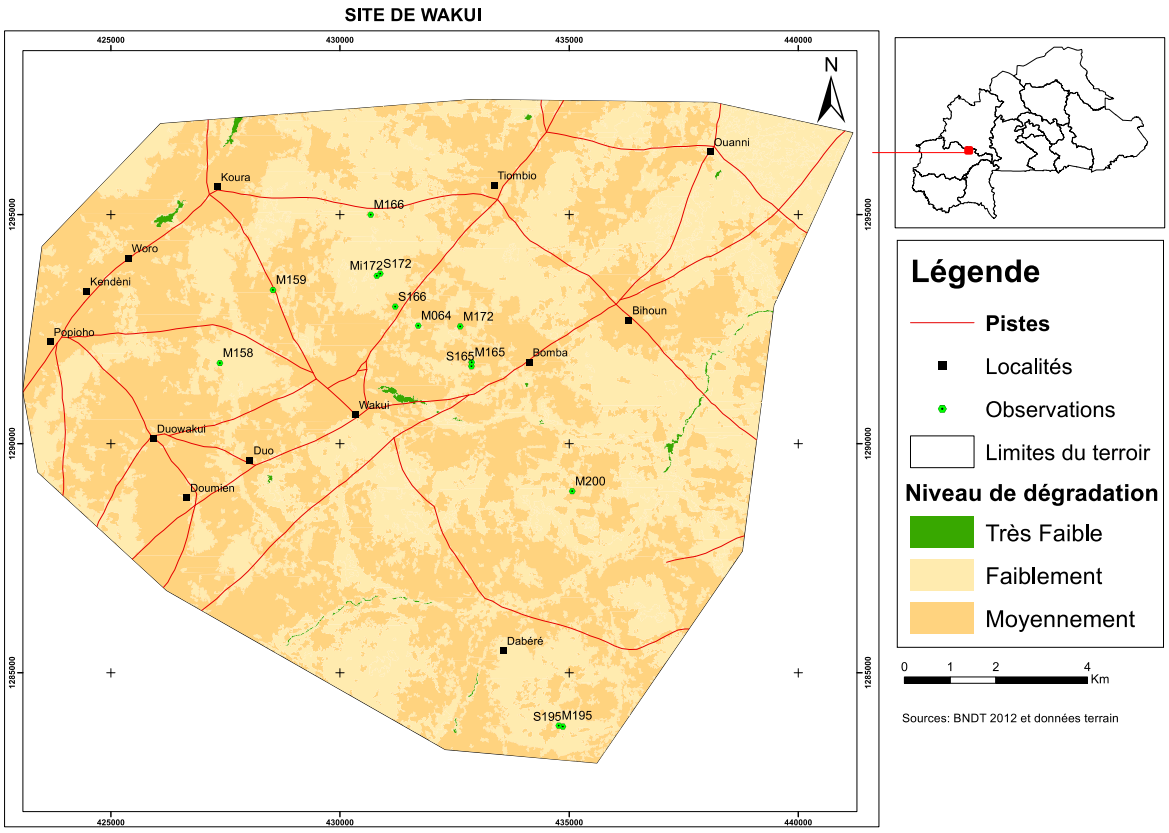
Extent of the degradation in Dohoun

Magnitude	%	Actual use
very lowly degraded	0.09	▪ Protected forests, ▪ fire wood collection areas, ▪ animal greasing
lowly degraded	47.84	▪ Crop production: cotton, maize and leguminous plant ▪ Cattle breading: Animal greasing
moderately degraded	52.06	▪ Cereals (sorghum, millet) and leguminous plants ▪ Animal greasing



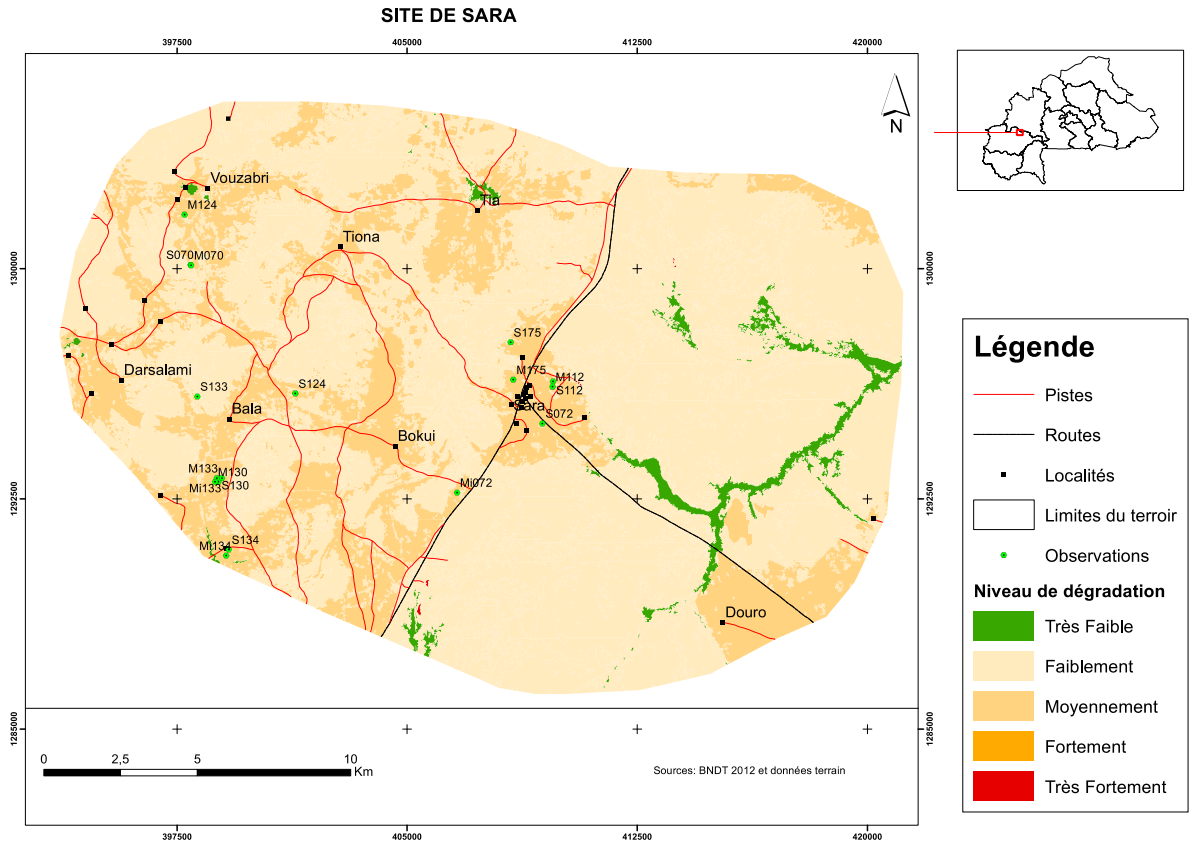
Extent of the degradation in Béréba

Magnitude	%	Actual use
very lowly degraded	0.31	▪ Protected forests, ▪ fire wood collection areas, ▪ animal greasing
lowly degraded	55.47	▪ Crop production: cotton, maize and leguminous pl ▪ Cattle breading: Animal greasing
moderately degraded	44.22	▪ Cereals (sorghum, millet) and leguminous plants ▪ Animal greasing



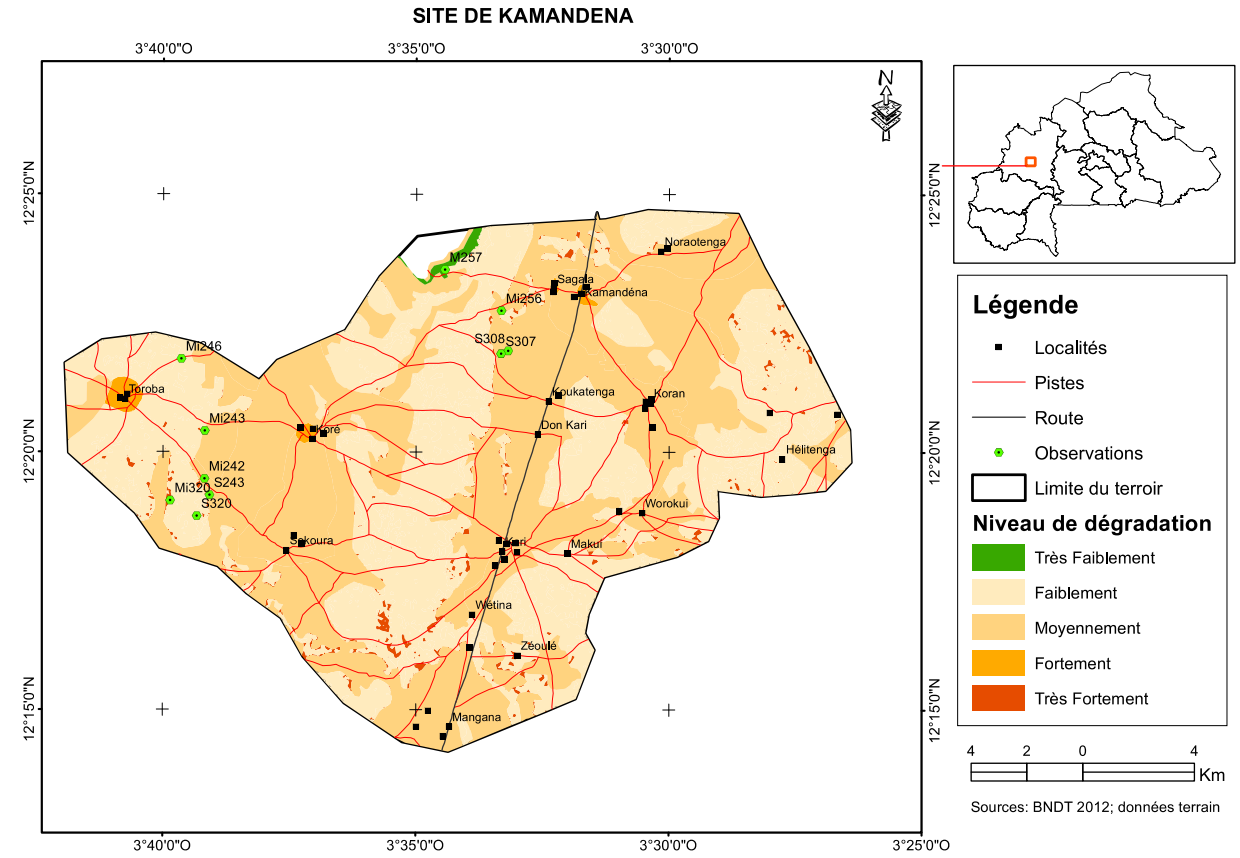
Extent of the degradation in Wakui

Magnitude	%	Actual use
very lowly degraded		▪ Protected forests, ▪ fire wood collection areas, ▪ animal greasing
lowly degraded		▪ Crop production: cotton, maize and leguminous plant ▪ Cattle breading: Animal greasing
moderately degraded		▪ Cereals (sorghum, millet) and leguminous plants ▪ Animal greasing



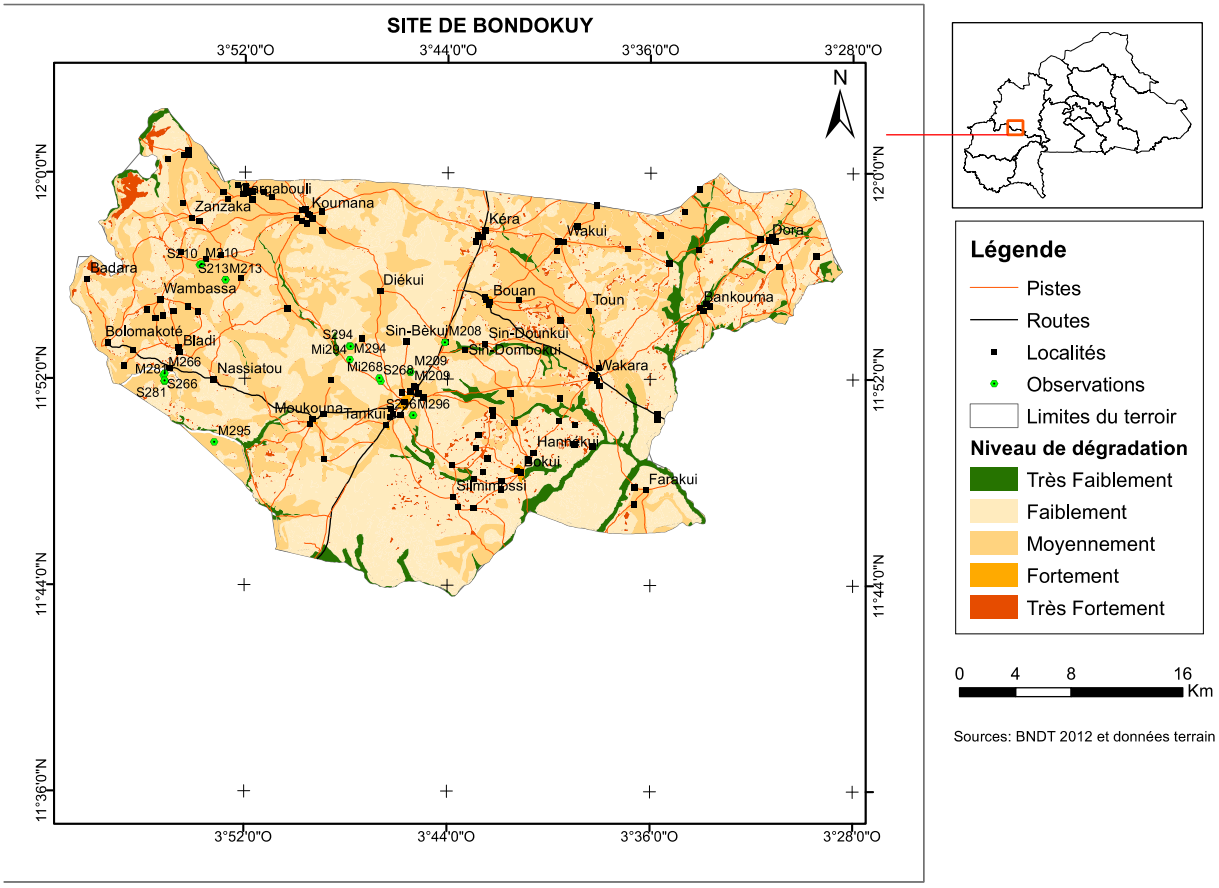
Extent of the degradation in Sara

Magnitude	%	Actual use
very lowly degraded		▪ Protected forests, ▪ fire wood collection areas, ▪ animal greasing
lowly degraded		▪ Crop production: cotton, maize and leguminous plants ▪ Cattle breading: Animal greasing
moderately degraded		▪ Cereals (sorghum, millet) and leguminous plants ▪ Animal greasing



Extent of the degradation in Kamandena

Magnitude	%	Actual use
very lowly degraded		▪ Protected forests, ▪ fire wood collection areas, ▪ animal greasing
lowly degraded		▪ Crop production: cotton, maize and leguminous plants ▪ Cattle breading: Animal greasing
moderately degraded		▪ Cereals (sorghum, millet) and leguminous plants ▪ Animal greasing



Extent of the degradation in Bondokuy

Magnitude	%	Actual use
very lowly degraded	4.92	▪ Protected forests, ▪ fire wood collection areas, ▪ animal greasing
lowly degraded	80.29	▪ Crop production: cotton, maize and leguminous plant ▪ Cattle breading: Animal greasing
moderately degraded	7.31	▪ Cereals (sorghum, millet) and leguminous plants ▪ Animal greasing
Strongly degraded	1.79	▪
Severely degraded	5.68	▪

Section B: Assessment of soil fertility traits in selected FFRUs with abandoned lands.

2. Determination of the baseline situation of soil parameters

2.1. Objective

The objective of this section was to identify soil types, their physical and chemical properties and suitability for the implementation of the FFRUs.

2.2. Soil survey and fertility assessment

2.2.1. Determination of observation points

The free land survey method was used and the observation spots were determined using the soil maps (1/10 000) of the provinces of Mouhoun-Balé and Tuy (BUNASOLS (2000, 2001, 2002), BNDT (2021)). The GPS coordinates of the different sites were generated on the soil maps. The different sites were then extracted from the soil maps and processed in order to get site maps scaled at 1/10 000.

The GPS coordinates of the FFRUs were generated on the soil maps in order to determine the location of the pedological pits for soil description. At least, three (3) pedological pits corresponding to soil types were selected for description for each soil type.

Digging and description of the soil pits

Soil pits were open and described according to the standards of FAO (1976), BUNASOLS (1989). The pits were opened to a depth of 120 cm if there is no induration Figure B.1.

The description of the pits followed FAO (1994) guidelines and soil classification according to soil CPCS (1967) and WRB (2006). For each pit, there were GPS coordinates was recorded; the description of the environmental condition of the pit such as vegetation, current land use status, topographic position, slope, moisture conditions, erosion traits, parental material, etc.

Figure B.1. Soil pits and soil description

2.2.3. Soil sampling

After the description and classification of soils, samples were collected according to the soil diagnostic horizons. The collected samples were packed in labeled plastic bags and send for laboratory analysis where analyses were carried out as described in section A Table A.2.

2.2.4. Determination of soil fertility status

- ***Standard for the determination of the individual contribution of soil parameters in soil chemical fertility***

For the determination of soil fertility, the contribution of the following soil nutrients will be used: 1) organic matter (OM); 2) total nitrogen (N); 2) assimilable phosphorus (Pass); 4) total phosphorus (Pt); 5) available potassium (Kav); 6) cations exchange capacity (CEC); 7) Sum of exchangeable bases (S= Ca^{2+}; Mg^{2+}; K^{+}; Na^{+}); 8) pH_{H2O} and pH_{KCl}.

Table B.1. Standards for the appreciation of the different parameters

		Very poor/unfavorable	Poor/low	Medium	High	Very high
MO	%	<0,5	0,5 à 1,0	1,0 à 2,0	2,0 à 3,0	> 3,0
	Contribution	1	2	3	4	5
N	%	<0,02	0,02 à 0,06	0,06-0,1	0,1 à 0,14	>0,14
	Contribution	2,0	2,5	3,0	3,5	4
P ass	ppm	<5	5 à 10	10 à 20	20 à 30	>30
	Contribution	2,0	2,5	3	3,5	4
Pt	Ppm	<100	100 à 200	200 à 400	400 à 600	>600
	Contribution	2,5	2,75	3,0	3,5	4,0
Kav	Ppm	<25	25 à 50	50 à 100	100 à 200	>200
	Contribution	2,0	2,5	3	3,5	4
K t	Ppm	<500	500 à 1000	1000 à 2000	2000 à 4000	>4000
	Contribution	2,5	2,75	3,0	3,5	4,0
CEC	Meq/100g	<5	5 à 10	10 à 15	15 à 20	>20
	Contribution	2,0	2,5	3	3,5	4
V	%	<20	20 à 40	40 à 60	60 à 80	>80
	Contribution	2,0	2,5	3	3,5	4
S	Meq/100g	<1	1 à 6	6 à 11	11 à 16	>16
	Contribution	1	2	3	4	5
pH_{H2O}	Values	>9,0 <4,5	8,5 à 9,0 4,6 à 5,0	7,9 à 8,4 5,4 à 5,5	7,4 à 7,8 5,6 à 5,5	6,1 à 7,3
	cotation	1	2	3	4	5

Source: BUNASOLS, 1990

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- ***Soil nutrients to be considered***

Laboratory analyses of samples collected on the soil sample consisted in determining: 1) total nitrogen (Nt); 2) total phosphorus (Pt) and assimilable phosphorus (Pass); 3) total potassium (Kt) and available potassium (K dis); sulfur (S), and boron (B); pH_{H2O} and pH_{KCl}; soil carbon content (organic matter); cation exchange capacity (CEC); sum of the exchangeable bases (S); particle size 3 fractions.

Soil content in each element was calculated according to the following formula (F1).

(F1): Mean content of the parameter $= \frac{D1*C1+D2*C2+\cdots+Dn*Cn}{(D1+D2+\cdots Dn)}$

D (cm) = thickness soil layer

C = concentration in the chemical element considered

D1+D2+……. + Dn = depth soil profile (pedological pit)

2.3. Results

2.3.1. Soil types in the investigation area

For the experimental site of Béréba, six (6) soil types were found (Figure B.2) and, the FFRUs were located on the three following soil types: the Gleyic gleysoil (FLTC), Endo plinthic lixisoil (FLIMP) and epi petric Lixisoil (FLIPP). The area and ratio of each soil type are summarized in Table B.2.

Table B.2. Area and ratio of each soil type in Béréba

	areas	
Soil types	(ha)	%
HPGS	6829,4	22,51
FLTC	6832,5	22,52
FLIMP	6539,2	21,56
FLIPP	1453,6	4,79
FLIS	8545,1	28,17
Li/c	133,6	0,44
Total	30333,4	100

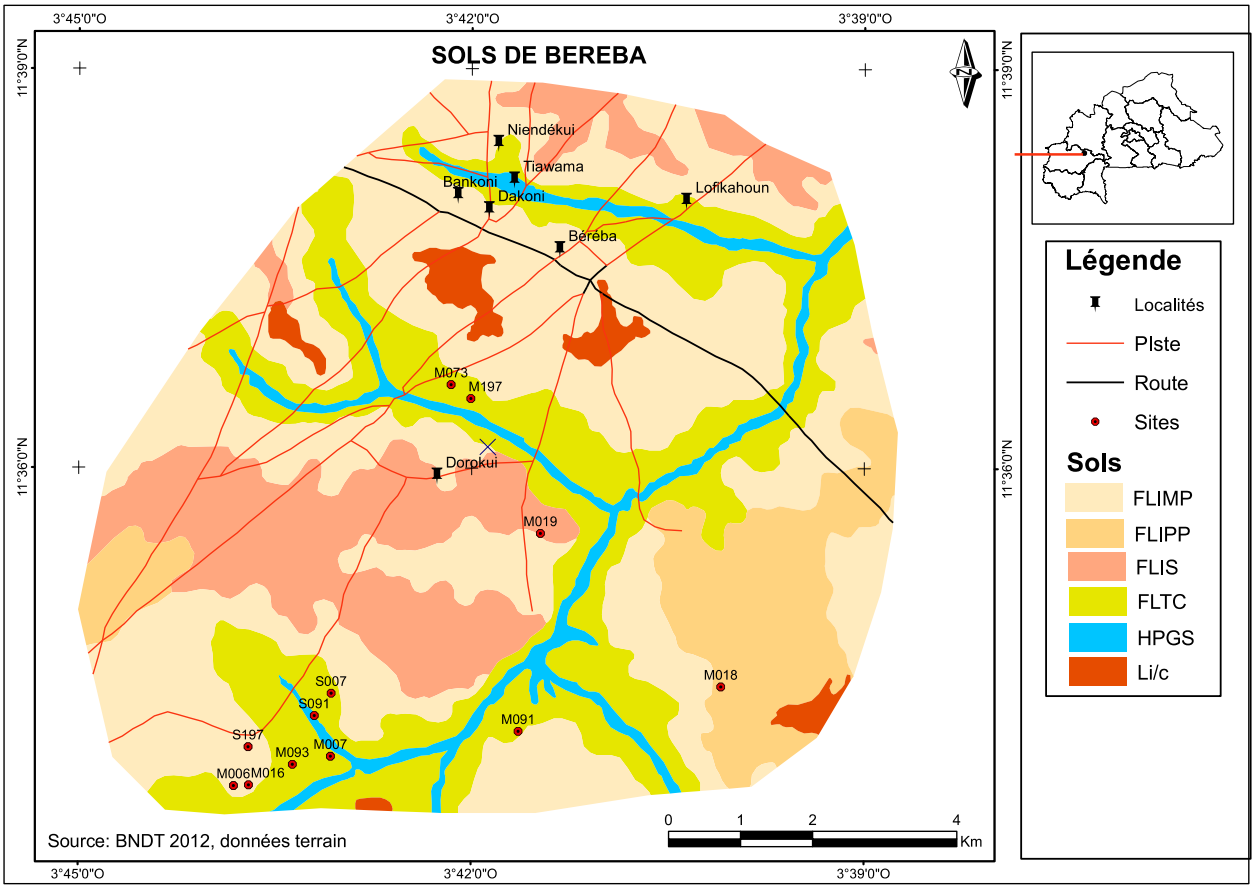

Figure B.2. Soil types in Béréba and FFRUs location

Eight (8) soil types have been In Douhoun (Figure B.3) the FFRUs were identified at Douhoun however, the FFRU were concentrated in the three following soil types. Epipetric plinthosoil (FLIS), Gleyic gleysoil (FLTC), Endo plinthic and Lixisoil (FLIMP). The area and ratio of each soil type are summarized in Table B.3.

Table B.3. Area and ratio of each soil type in Dohoun

Soil type	area	
	(ha)	%
BEHV	978,1	1,50
FLIMP	17331,7	26,51
FLIPP	23195,2	35,48
FLIS	1296,6	1,98
FLTC	13294,3	20,33
HPGS	3112,2	4,76
Li/c	5265	8,05
Li/r	906,3	1,39
Total	65379,4	100,00

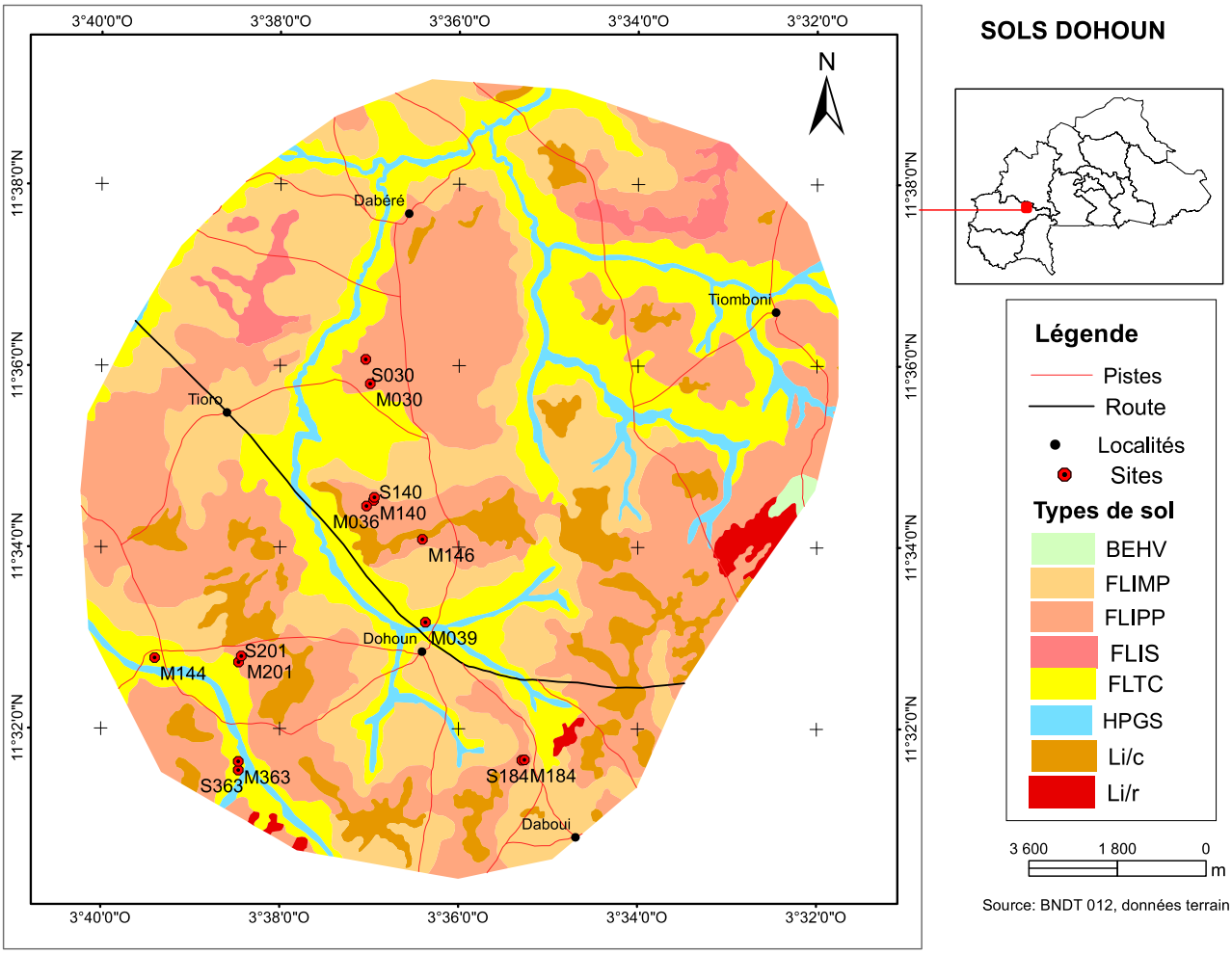

Figure B.3. Soil types in Dohoun and FFRUs location

In the experimental site of Sara Figure B.4, nine (9) soil types were identified. The FFRUs were concentrated on Epipetric plinthosoil (FLIS and FLIPP), Gleyic gleysoil (FLTC), Endo plinthic, Lixisoil (FLIMP) and Cambisoil (FRM). The area and ratio of each soil type are summarized in Table B.4.

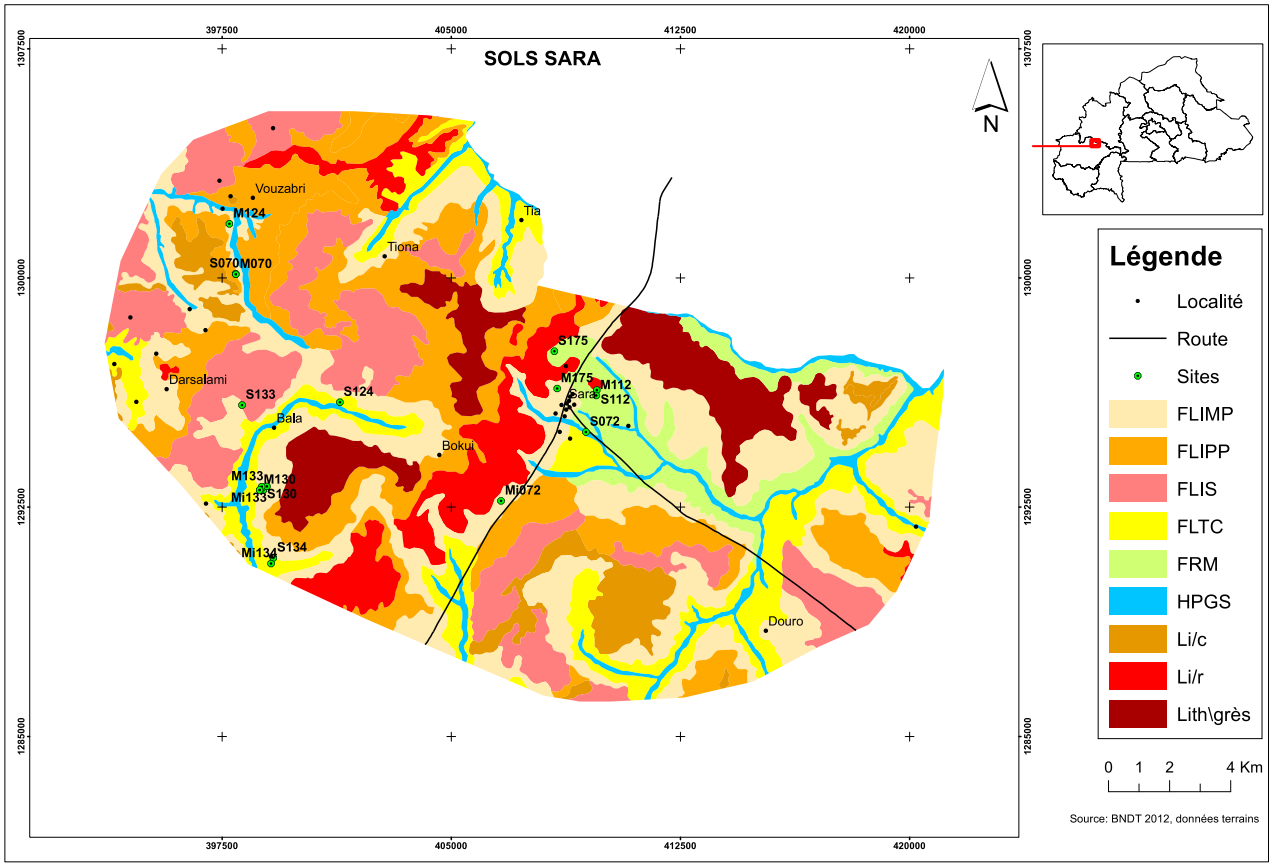

Figure B.4. Soil types in Sara and FFRUs location

Seven (7) soil types have been identified in Kari-Kamandena (Figure B.5) and the FFRUs were located on Epipetric plinthosoil (FLIS), Gleyic gleysoil (HPGS), bati plinthic and Lixisoil (FLIP)

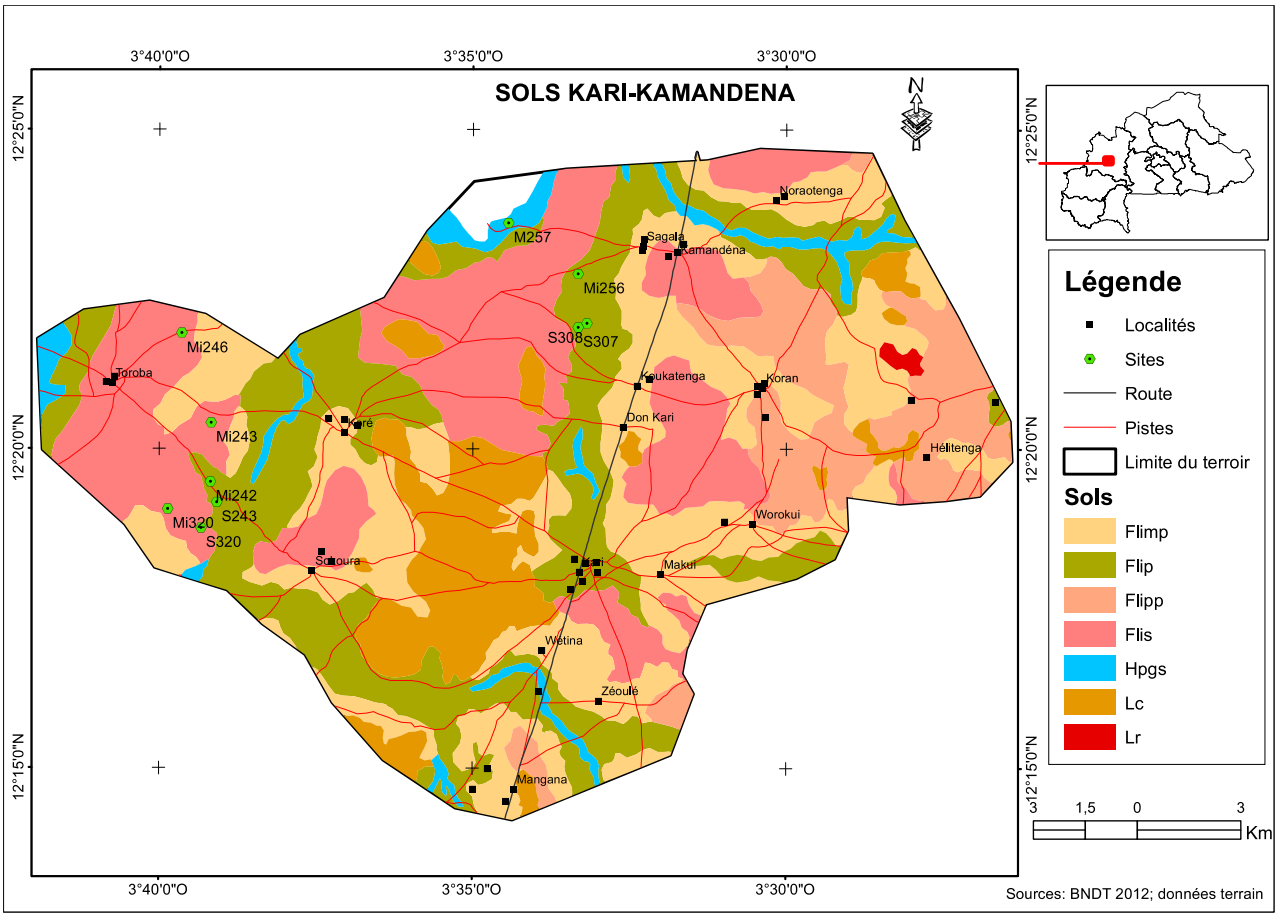

Figure B.5. Soil types in Kari-Kamandena and FFRUs location

Twelve (12) soil types have been identified in Bondokuy (Figure B.6); the FFRUs were located on Epipetric plinthosoil (L/r and FLiPP) and Gleyic gleysoil (HPGS). The area and ratio of each soil type are summarized in Table B.4.

Table B.4. Area and ration of each soil type at Bondokuy

Soil types	Area (ha)	%
HPGS	12649,2	11,57
Lr	4258,8	3,89
Li/c	39,4	0,04
Lc	4158,7	3,80
FTM	122,1	0,11
FLIPP	36078	32,99
FLIS	1231,5	1,13
FLTC	3297,5	3,02
BEF	72	0,07
Li/r	117	0,11
FLIMP	47198,1	43,16
BEHV	136	0,12
Total	109358,3	100

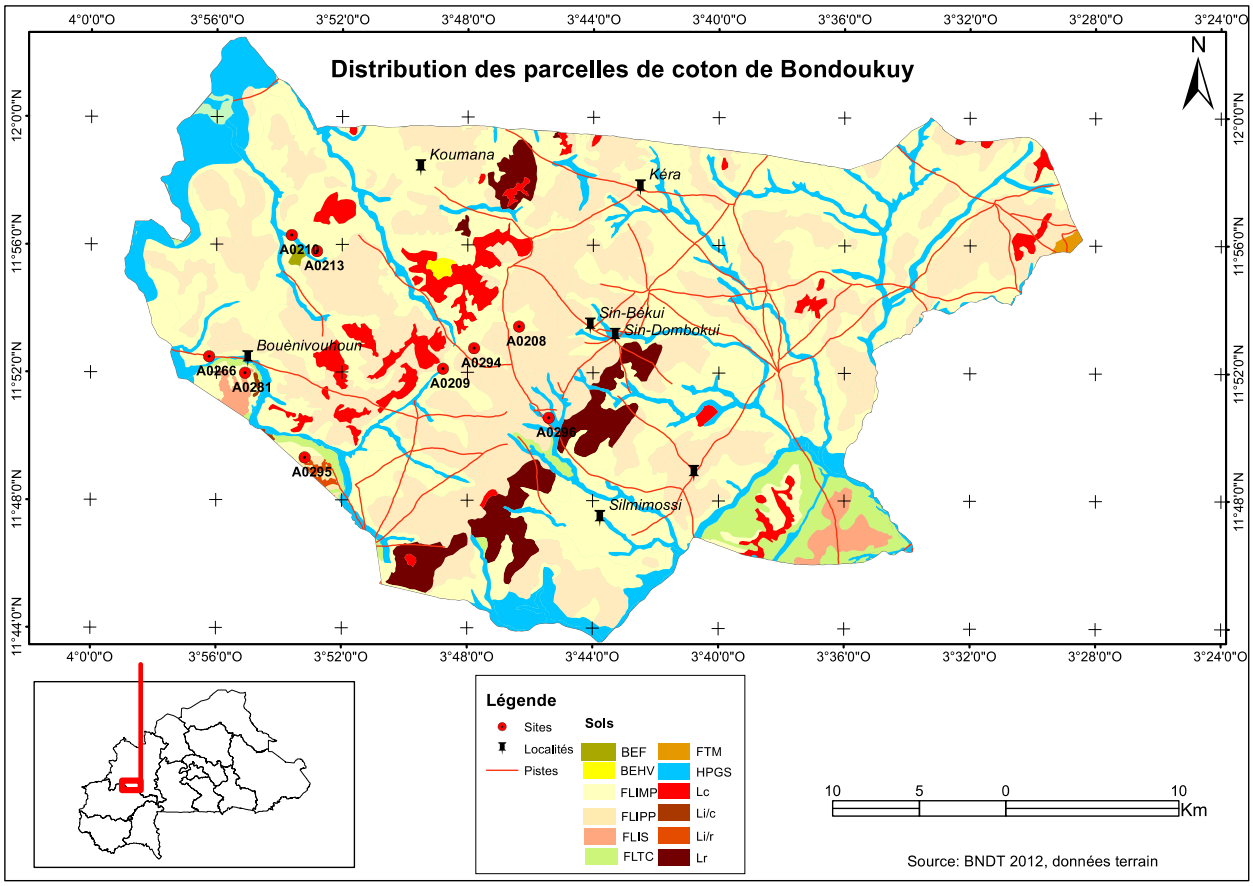

Figure B.6. Soil types in Bondokuy and FFRUs location

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2.3.2. Technological packages for the implementation of the FFRUs

In total four technological packages have been discussed and agreed upon with the farmers in the six sites these packages include:

- P1: Evaluation of minimum tillage and recycling of crop residues into compost on productivity and mineral balances in a cotton-cereal system
- P2: Effects of compost and intercropping on sorghum and cowpea productivity and soil properties
- P3: Effects of Fertilization on Sorghum and Maize Productivity in Cotton Farms
- P4: Study of the effectiveness of biochar and co-compost in cotton farms

Table B.5. Technologic package applied in the FFRUs in the different sites

Sites	Technologic packages
Béréba	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P4: Biochar and co-compost amendment of soils in cotton farms systems
Dohoun	P3: Efficient use of mineral fertilizers in order to improve sustainable soil productivity in Sorghum and Maize Productivity in Cotton Farming system P4: Biochar and co-compost amendment of soils in cotton farms systems
Ouakuy	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P4: Biochar and co-compost amendment of soils in cotton farms systems
Sara	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P2: Using compost and intercropping practices for improving sorghum and cowpea productivity and soil properties
Bondokuy	P4: Biochar and co-compost amendment of soils in cotton farms systems P2: Using compost and intercropping practices for improving sorghum and cowpea productivity and soil properties
Kari-Kamandéna	P1: Minimum tillage practice and recycling of crop residues into compost for improving crop productivity and soil mineral balances in a cotton-cereal system P3: Efficient use of mineral fertilizers in order to improve sustainable soil productivity in Sorghum and Maize Productivity in Cotton Farming system

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Annex IV:
Land Recovery Report for Tanzania

EWA-BELT PROJECT

Report of Abandoned Lands survey, Land Degradation Assessment, and Trade-off Analysis of SI Technologies in Arusha and Monduli Districts Tanzania

Sections A, B and C

Survey activities taking place in Arusha District, Tanzania

Contents

1. Land recovery.

1.2. Objective

Identification and mapping of abandoned/degraded lands in the study area through physical and socio-economic data collection and processing

2. Section A: Abandoned Land survey

2.2. General features of survey areas in Tanzania

The survey was carried out in Monduli and Arusha districts located in Arusha region in Northern part of Tanzaniaduring the December-January, 2021 cropping season. The study covered two districts with three villages each and 60 households. Monduli districts covered Enguiki (A), Emairate (B) and Lendikinya (C) villages while Arusha district covered Mussa (D), Nengungu (E) and Lekamba (F). These sites were purposively selected based on prior knowledge on the prevalence of land degradation in the district. Figure A.1 presents the location map of the survey sites.

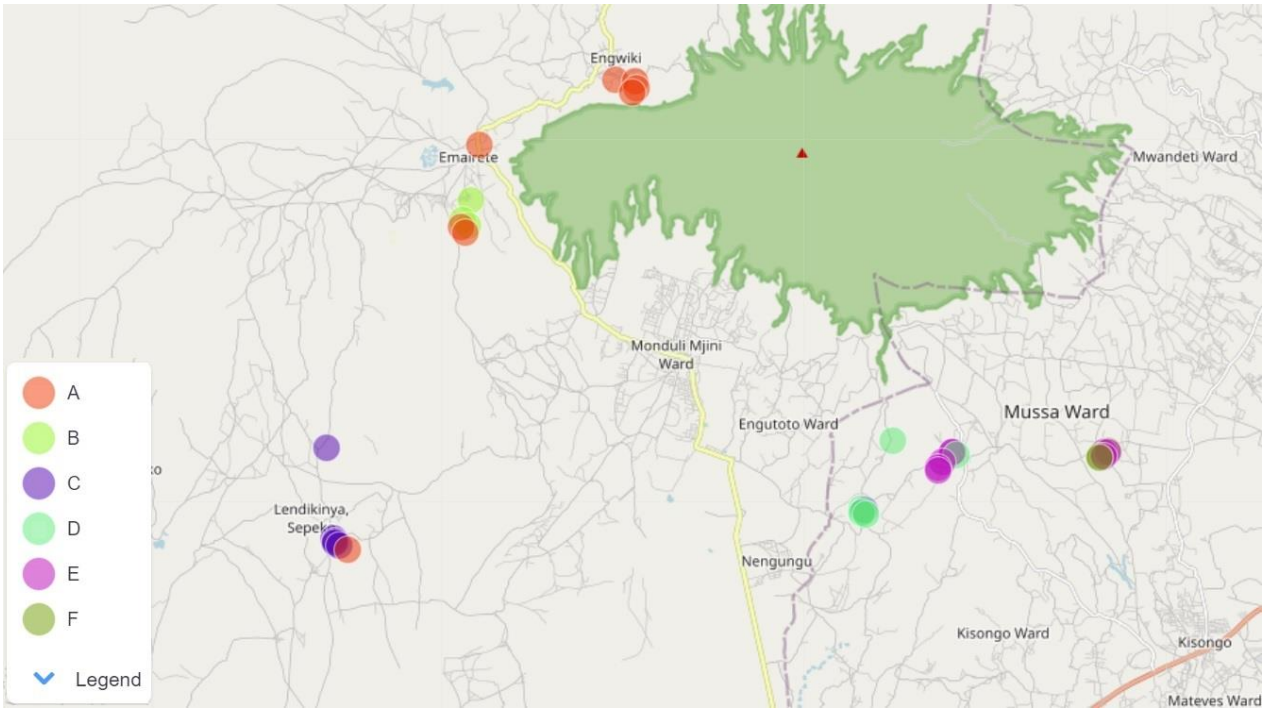

Figure A.1. Survey areas of abandoned croplands in Northern Tanzania

2.3. Source of Data and Data Collection

Household survey, personal observations, and a semi-structured questionnaire (both open and closed ended) were the tools used to collect primary data. A collection tool (KoBoToolbox) was used for the semi-structured questionnaire. The questionnaire covers from farmers' knowledge of local soil classification through perceptions and drivers of land degradation to as well the farmers' assessment of soil productivity.

2.4. Results

2.4.1. Total number of plots assessed per household and their distribution within the study.

The survey showed that nearly 65% of the surveyed households had 1 plot affected by degradation whereas less than 10% of the households had 5 or more plots in the entire district (Figure A.2. A). Sites at Enguiki (A), Emairete (B), Lendikinya (C), Nengungu (E) and Lekamba (F) had the greatest percentages of households (>50%) with 1 plot (Figure A.2. B).

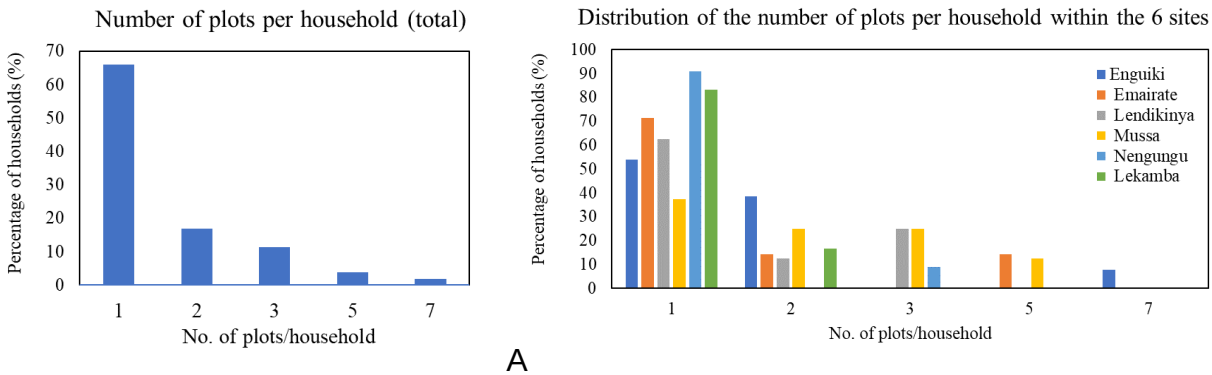

Figure A.2. Percentage of households with number of plots affected by degradation (A) and the distributed across the sites

2.4.2. Major types of soils in the survey

Farmers used a holistic approach to recognize and name local soils. The farmers' rationality while classification combines farmers' cognitive knowledge about soils (e.g., its color, permeability,water holding capacity, texture, and fertility status). Farmers in the survey areas reported more than 5 major types of soils based on soil texture and color i.e. loamy (silt loamy, black loamy, clay loamy), clayey, sandy, sandy loam and black. In each site, most of the farmers commonly recognized their soil type as loamy, using different names in the local language (e.g. tifutifu, engulukeni, inguluwok, losuvuco, etc.), with a percentage of 57, 85, 67, 85, 100 and 71% at Enguiki (A), Emairete (B), Lendikinya (C), Mussa (D), Nengungu (E) and Lekamba (F) respectively. The second most recognized type of soil was clayey (mfinyanzi) in Lendikinya (C), Mussa (D) and Nengungu (E) with 15, 17 and 8 % respectively at each site, clay loamy (Orobra = semi desert) and black in Lekamba (F) with 29% and 14% respectively, and silt loamy and black loamy (mweusi/tifutifu) with 8% both in Enguiki (A) (Figure A.3). It is clear that farmers in the present studyarea have a tradition of associating soil variability with different local soil nomenclatures.

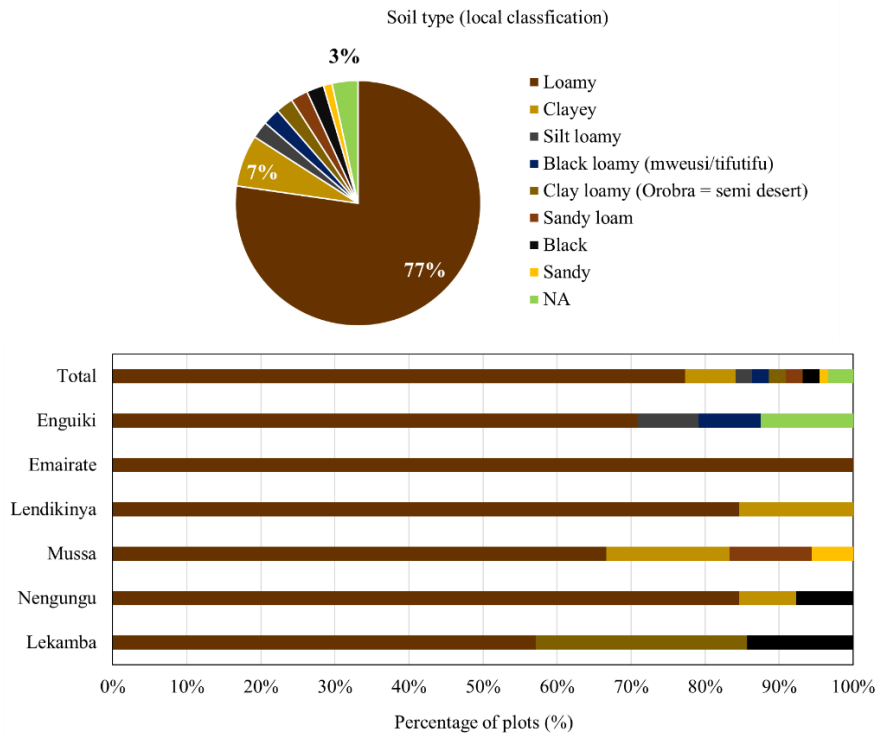

Figure A.3. Major soil types based on farmers classification criteria

2.4.3. Land use type and crop production.

In the survey sites, cropland is the major land use type (>92%) while fallow land (8%) at Lendikinyaand other land use types (abandoned lands, built ups) are the other forms of land uses types (Figure A.4). Maize and common beans are the major cereal cultivated as source of food followed by trees in allthe study sites whereas, tobacco is cultivated as the major cash crops as source of income (Figure A.5).

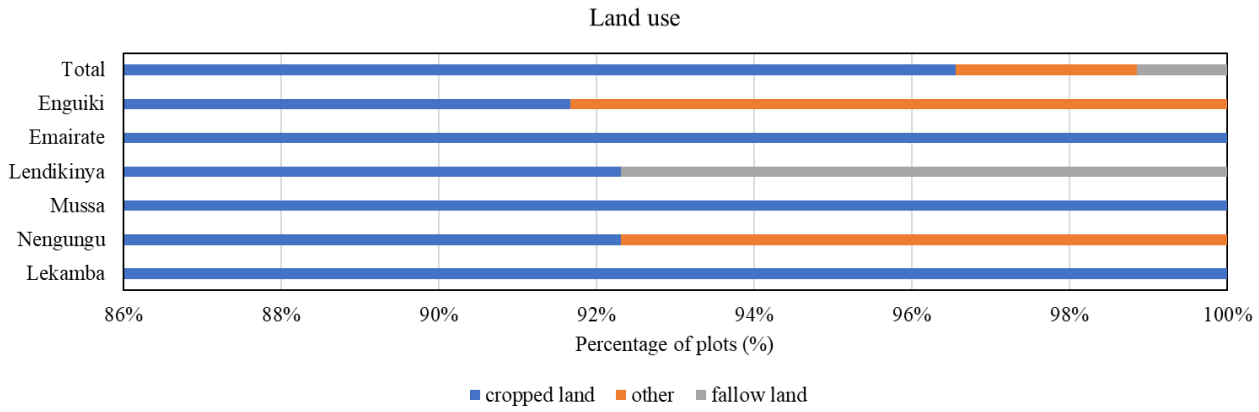

Figure A.4. Major land use types in the study areas

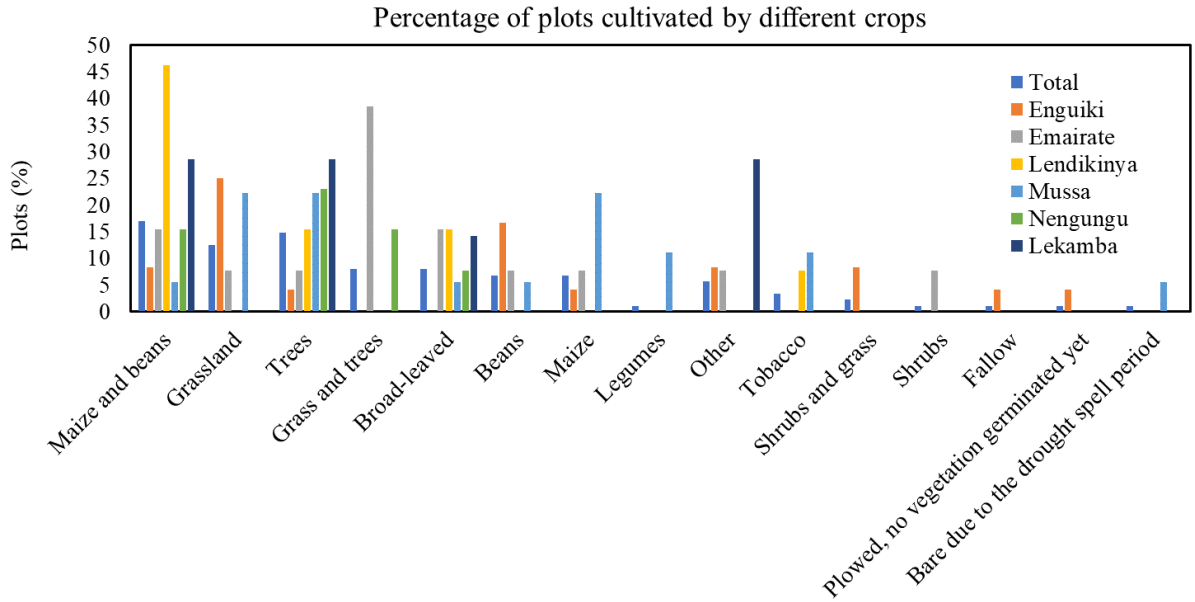

Figure A.5. Major crop types grown in the study are and their percentage distribution

2.4.4. Drainage and water state

The majority of the surveyed plots in the study areas had a medium (~51%) or good (~33%) drainage condition witha dry water state (Figure A.6).

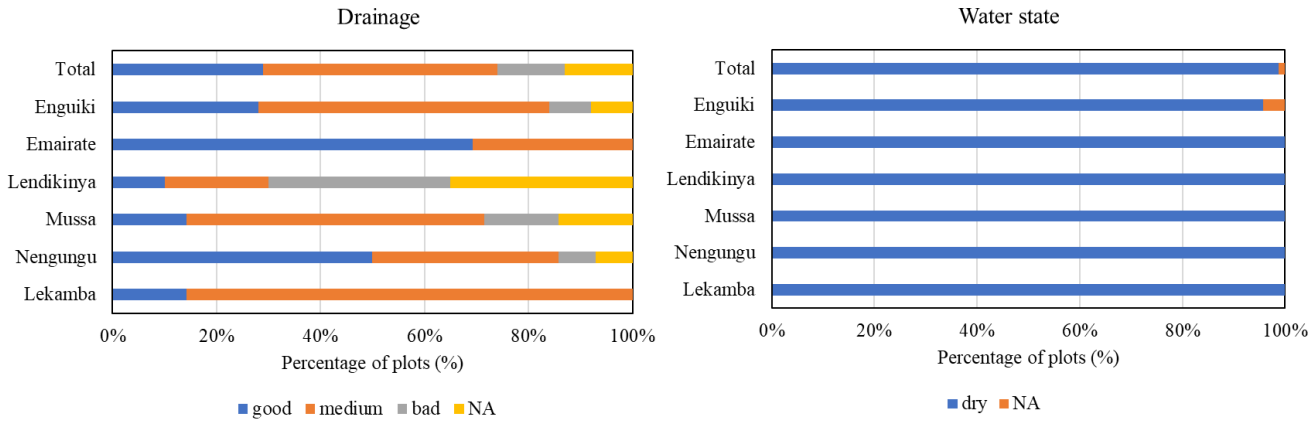

Figure A.6. Drainage and water state of soils of the study area as perceived by farmers

2.4.5. Perception of land degradation and loss of soil fertility

Of the interviewed farmers, the majority of the respondents (87%) perceived that the cause of land degradation and loss of soil fertility are related to anthropogenic/human-induced processes (Figure A.7). Among others, overgrazing (>60%), deforestation (~40%), inappropriate farming (~34%) and extractive farming (~26%) are the main mentioned causes of land degradation and loss of soil fertility in the study sites (Figure A.8). Soil erosion (~91%), nutrient depletion (~38%) and species extinction (~13%) are the main mentioned mechanisms and process of soil fertility degradation. The formers processes are very prevalent as the study areas are characterized by high rainfall.

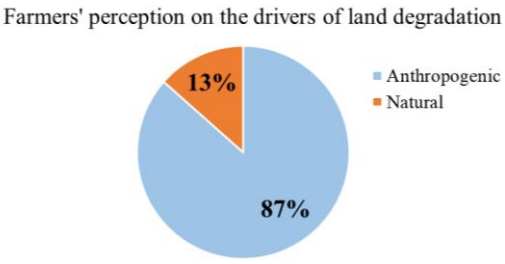

Figure A.7. General perception of farmers on land degradation and loss of soil fertility

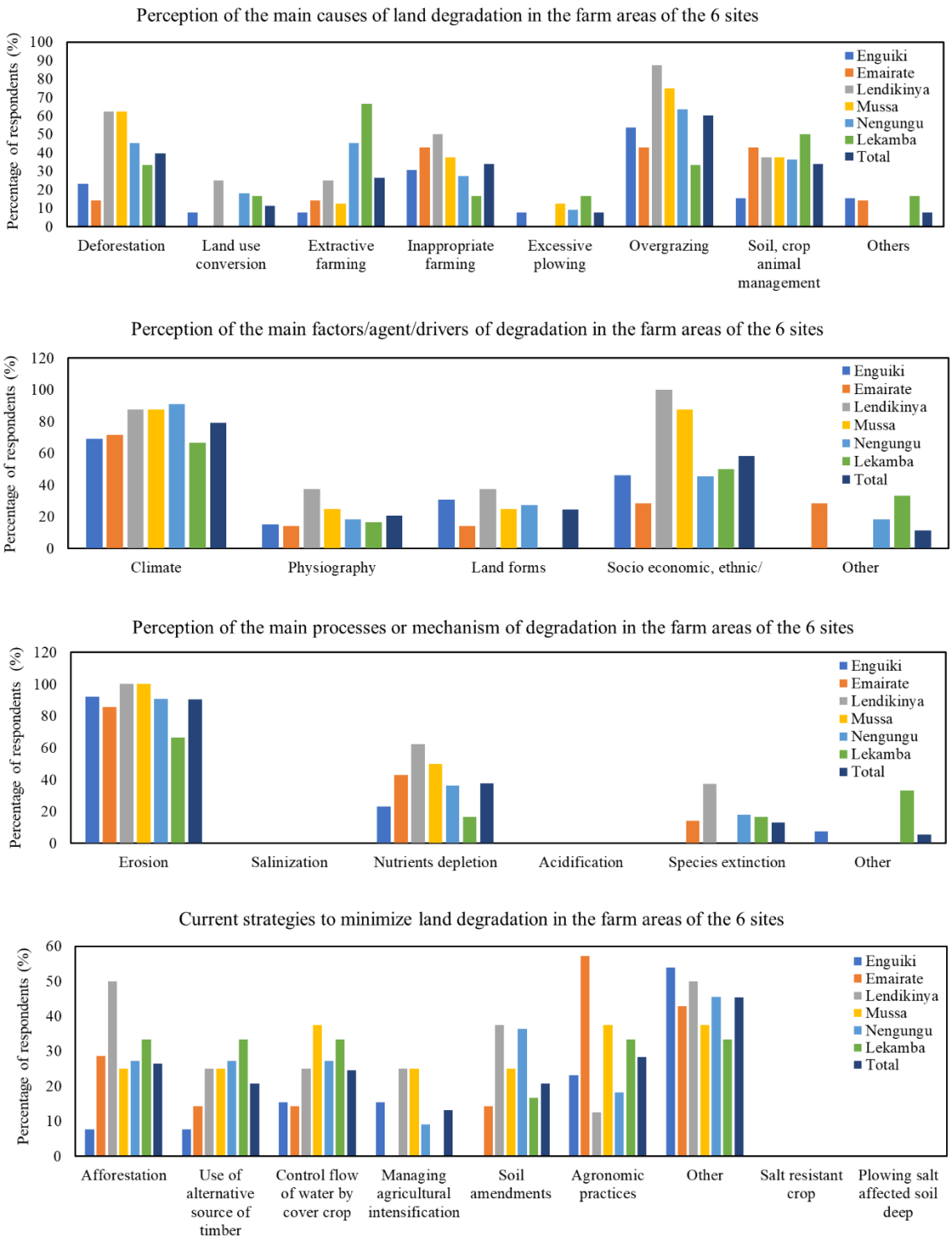

Figure A.8. The main causes (A), mechanisms (B), factors/drivers (C) of land degradation and loss of soil fertility and current strategies (D) used by farmers to minimize land degradation

2.4.6. Land productivity and restoration options by farmers

For each household, farmers were asked to classify their fields based on the 4 productivity categories.Accordingly, based on the indicators of soil productivity, the farmers were able to group their fieldsinto four classes namely productive, moderately productive, degraded and severely degraded. Most (> 56%) farmers responded that their croplands are moderately productive, around 38% of farmers recognized as their farms are productive while about 7% of the farmers recognizedas their farms are degraded (Figure A.9). Low crop yield, stunted growth, color changes of crops, changesin soil color and soil thickness, shift in weed biomass, and weed species were the most important indicators of soil fertility status in the study area. Farmers usually adopt different strategies to recovertheir degraded lands. Among others, fallowing of degraded fields for 3-4 years is quite practiced by >8% of the farmers in Enguiki (A) whereas the majority in the study wards do not practice fallowing.A reason given by the respondent farmers regarding to fallowing their land was to increase soil fertility organic matters and soil compatibility.

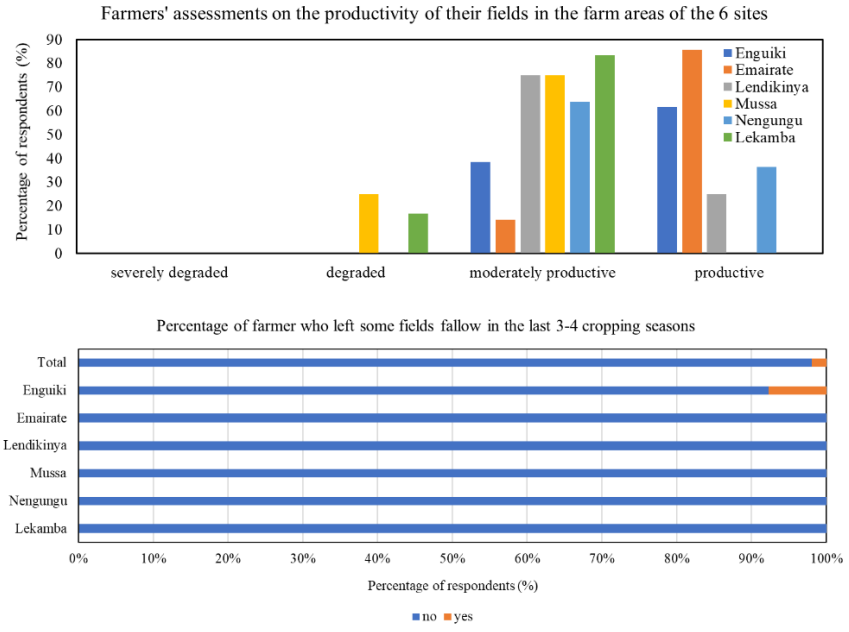

Figure A.9. Land productivity assessment (A) and practice of fallowing (B) adopted by farmers in the study area

2.4.7. Farmers' perceptions on strategies to be adopted to rehabilitate degraded crop lands.

The farmers of the study area have various measures of maintaining fertility of their soils. Majority of the farmers (>44%) adopt contour followed by organic manure application (>23%), reduced/zero grazing (>11%), crop rotation (>11%) and fallowing (>9%) among others (Figure A.10).

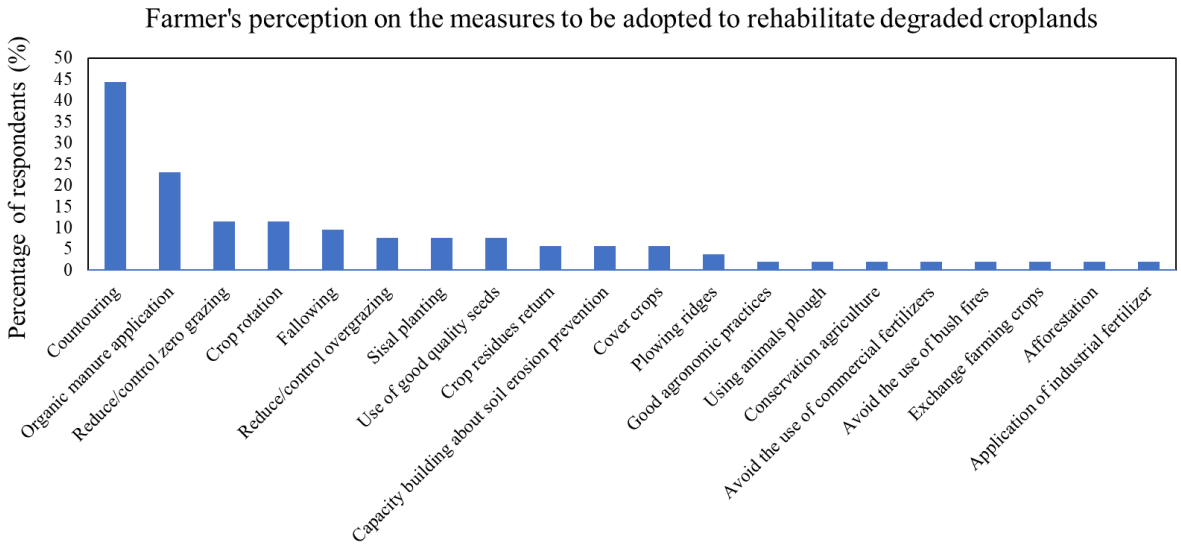

Figure A.10. Farmers different measure to rehabilitates degraded crop lands

3. Section B: Land Degradation Assessment using LDSF.

3.1. Background on the Land Degradation Surveillance Framework (LDSF)

The project will implement the Land Degradation Surveillance Framework (LDSF) in two landscapes within the EWA-BELT action areas. The LDSF provides a field protocol for measuringindicators of the "health" of an ecosystem:
http://landscapeportal.org/blog/2015/03/25/the-land-degradation-surveillance-framework-ldsf/
The LDSF was developed by the World Agroforestry (ICRAF) in response to the need for consistent field methods and indicator frameworks to assess land health in landscapes. The framework has been applied in projects across the global tropics, and is currently one of the largest land health databases globally with more than 30,000
observations, shared at http://landscapeportal.org. This project will benefit from existing data in theLDSF database, while at the same time contributing to these critically important global datasets through on-going data collection. Earth Observation (EO) data will be combined with the LDSF framework to develop the outputs for the project, including land degradation and soil health.

3.2. Methodology

For the biophysical assessment of selected abandoned lands, the “Land Degradation Surveillance Framework (LDSF)” approach was used. The LDSF work was led by ICRAF while TARI-Selina and NM-AIST providedstaff to participate in data collection as the task needed at least 10 people. LDSF is a landscape-based approachthat involves the collection of soil and vegetation data in a hierarchical sampling framework within a 100-km x100-km block called sentinel site (Figure B.1). In each sentinel site, soil and vegetation data was collected to assess the status of soil health and other indicators of land degradation such as vegetation structure, soil erosionprevalence, root penetration, and water infiltration rates. Soil samples collected were submitted to the ICRAFlaboratory in Nairobi for analysis of soil physio-chemical properties (Soil organic carbon, pH, Total nitrogen,Extractable P, Basic

cations etc.) using the MIR spectroscopic method. In addition, different types of vegetation growing within the selected abandoned land were identified. For the assessment of the vegetation structure, the LDSF uses the FAO Land Cover Classification System (LCCS), developed in the context of theFAO-AFRICOVER project.

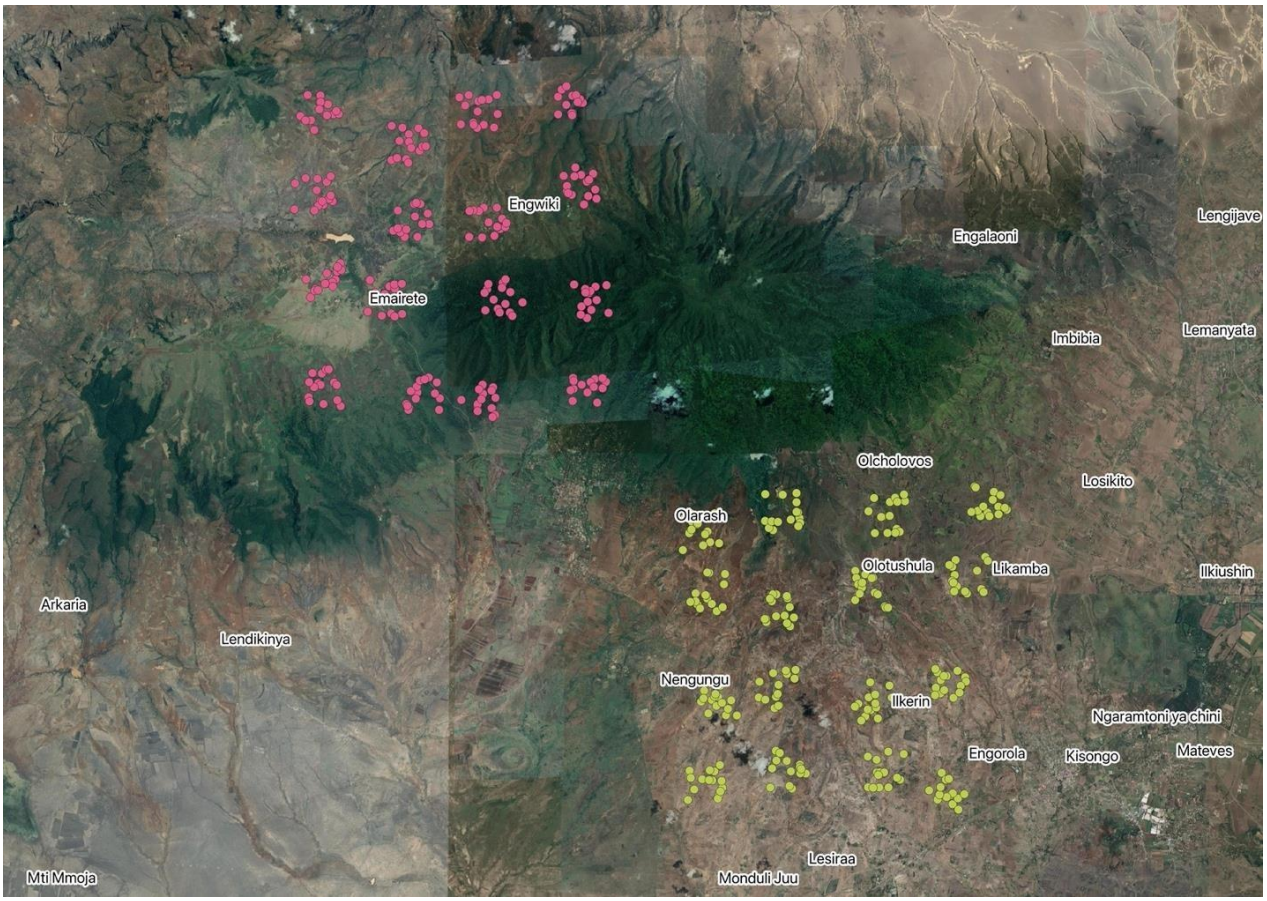

Figure B.1. Two LDSF sites in Mussa (Arusha District) and Emairete (Monduli District), Tanzania

In addition, soil profile pits (Figure B.2) were dug in selected areas in FFRUs for classification of soil types. Following physical assessment of soil horizons in the field, soil samples collected by horizons for analysis at the NM-AIST laboratory. Like in Burkina Faso, the description of the pits followed FAO (1994) guidelines and soil classification according to soil CPCS (1967) and WRB (2006). Following physical assessment of soil horizons in the field, soil samples collected by horizons for analysis at the NM-AIST laboratory. The

description of the pits followed FAO (1994) guidelines and soil classification according to soil CPCS (1967) and WRB (2006).

Samples for soil fertility assessment were collected from the 160 plots laid out in each sentinel sites for assessing land degradation using the LDSF approach in the FFRUs (Annex 3). The samples were collected using auger from four sub-plots at 0-20 and 20-50 cm, composited by depth and sub-sampled to get a composite sample per plot (Figure. B.2). About 1kg composite sample was collected from each depth, giving a total of 320 samples from 160 plots in each of the two sentinel sites. The collected soil samples were air-dried, ground and sieved through a 2-mm sieve at the Laboratory of NM-AIST. The samples were then packaged into paper bags (300g per sample) for shipping to the ICRAF laboratory in Nairobi for analysis of soil physio-chemical properties (Soil OC, pHw, Electrical conductivity, Total N, Extractable P, exchangeable bases, Exchangeable acidity etc), using the MIR spectroscopic method.

Figure B.2. Soil profile pit description and collection of soil samples for analysis in Arusha and Monduli districts, Tanzania (Photo Credit Joseph Kalonga)

3.3. Results

3.3.1. Land use and land cover change

Figure B.3 shows the maps of land use and land cover change (LULCC) in Emairete and Musa sites. Soil erosion prevalence in these sites in depicted in Fig. B4. The maps were generated based on the field data collected as part of the project in each of the sites using remote sensing satellite data and machine learning models to predict changes in croplands, grasslands, tree cover, forest cover, and soil erosion prevalence. The accuracy of these maps is between 85% and 89%. Overall, the LULCC analysis shows an increase in area under cropland in both sites (Fig. B3). In Emairete there appears to be an increase in erosion over the five-year period shown while there appears to be a decrease in erosion in Mussa (Fig. B4). This land degradation trend reflects a comparatively low adoption of soil water conservation (SWC) measures found in Emairete during the field survey as described below.

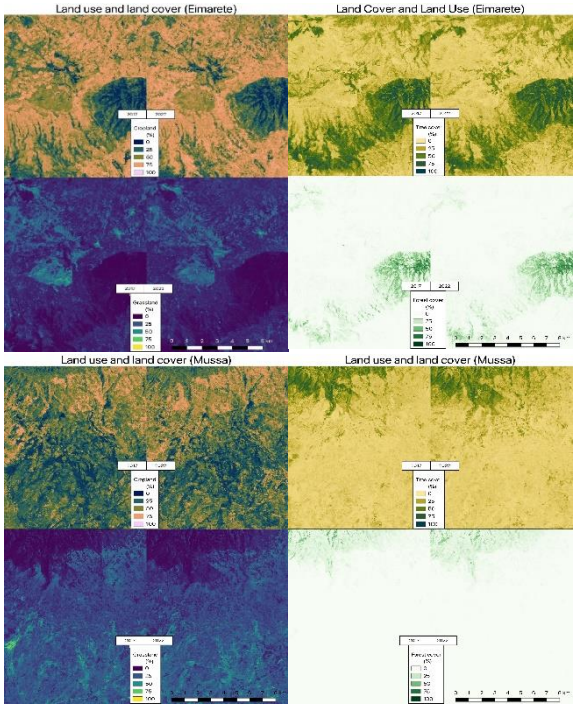

Figure B3. Land use and land cover change analysis for Emairete in Monduli District and Mussa in Arusha District, Tanzania.

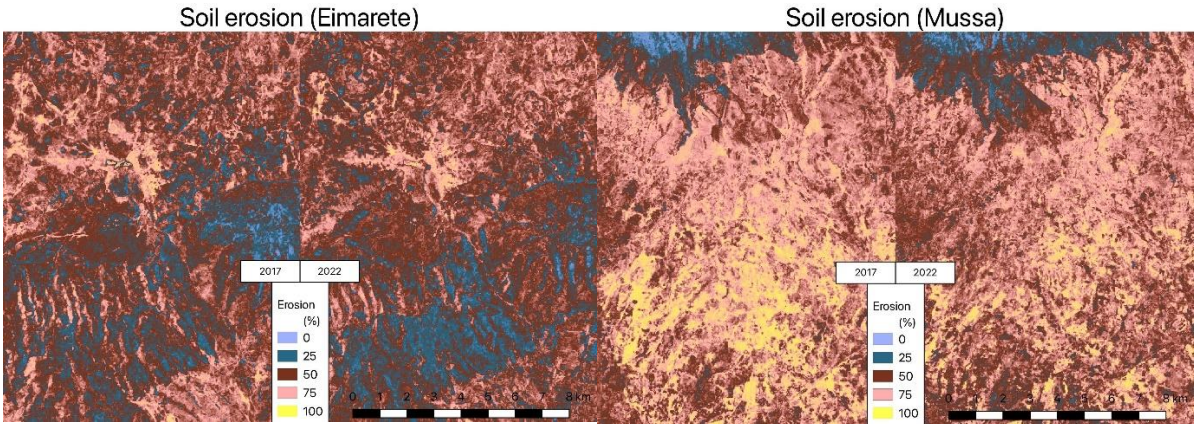

Figure B4. Soil erosion prevalence maps for Emairete in Monduli District and Mussa in Arusha District, Tanzania.

Land degradation was assessed in sampled plots according to the following criteria: i) cultivated or non-cultivated plot; ii) vegetation structure; iii) prevalence of soil erosion and iv) existence of soil water conservation (SWC) measures. In the Emairete site in Monduli district, 27% of the sampled plots were classified as cultivated, while in Musa the percentage of cultivated plots was 50%. Figure 14a and b show the dominant vegetation structure at each site (grassland, cropland, and forest in the Emairete site in Monduli District and cropland in Mussa site in Arusha District). Erosion was the most widespread form of land degradation (Figure B10). Sampled plots that had three or more subplots (75%) with erosion were classified as having severe erosion. In Emairete a lower erosion prevalence (40%) was recorded compared to Mussa (80%).

The SWC measures observed in the two sites were: Stone bunds or *zai pits* (labelled as “structural”), contour tree planting (labelled as “vegetative”), or a combination of both vegetative and structural (labelled as “both”) (Figure 14d). In Emairete, there were very few plots with any type of SWC measures being practiced. These results have implications for soil erosion and opportunities to employ sustainable land management

options to curb erosion prevalence.

3.3.2. Vegetation structure

The LDSF uses the FAO Land Cover Classification System (LCCS), which was developed in the context of the FAO-AFRICOVER project. Each sampled plot was classified by the vegetation structure. Figures B.5 and B.6 show the dominant vegetation structure at each site (grassland, cropland and forest at Emairete and cropland in Mussa).

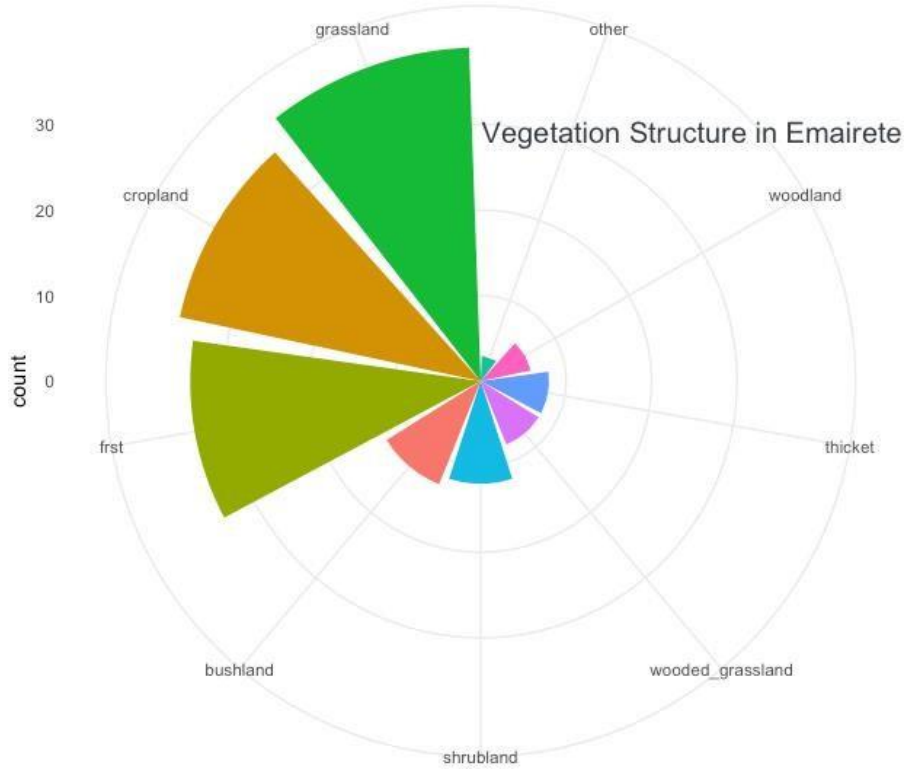

Figure B.5. Vegetation Structure in Emairete

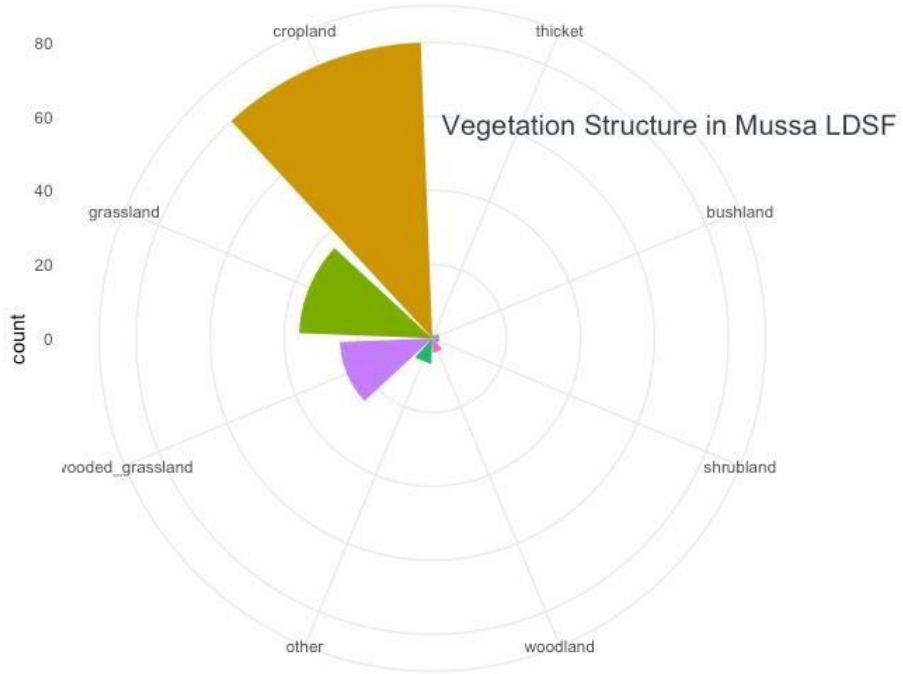

Figure B.6. Vegetation Structure in Mussa

3.3.3. Trees and Shrubs

In the LDSF, shrubs are classified as woody vegetation between 1.5 m and 3.0 m tall and trees are classified as woody vegetation above 3.0 m tall. All trees and shrubs are counted in each of the foursubplots per plots. Tree and shrub densities in cultivated and non-cultivated plots using box plots are shown in Table B.1 and Figures B.7 and B.8.

Table B.1. Average tree and shrub densities in cultivated and non-cultivated plots

Site	Plot Cultivated	Count	Tree Density (No of Tree ha^{-1})	Shrub Density (No of Shrubs ha^{-1})
Emairete	no	122	175	199
Emairete	yes	37	20	56
Mussa	no	78	70	163
Mussa	yes	79	28	217

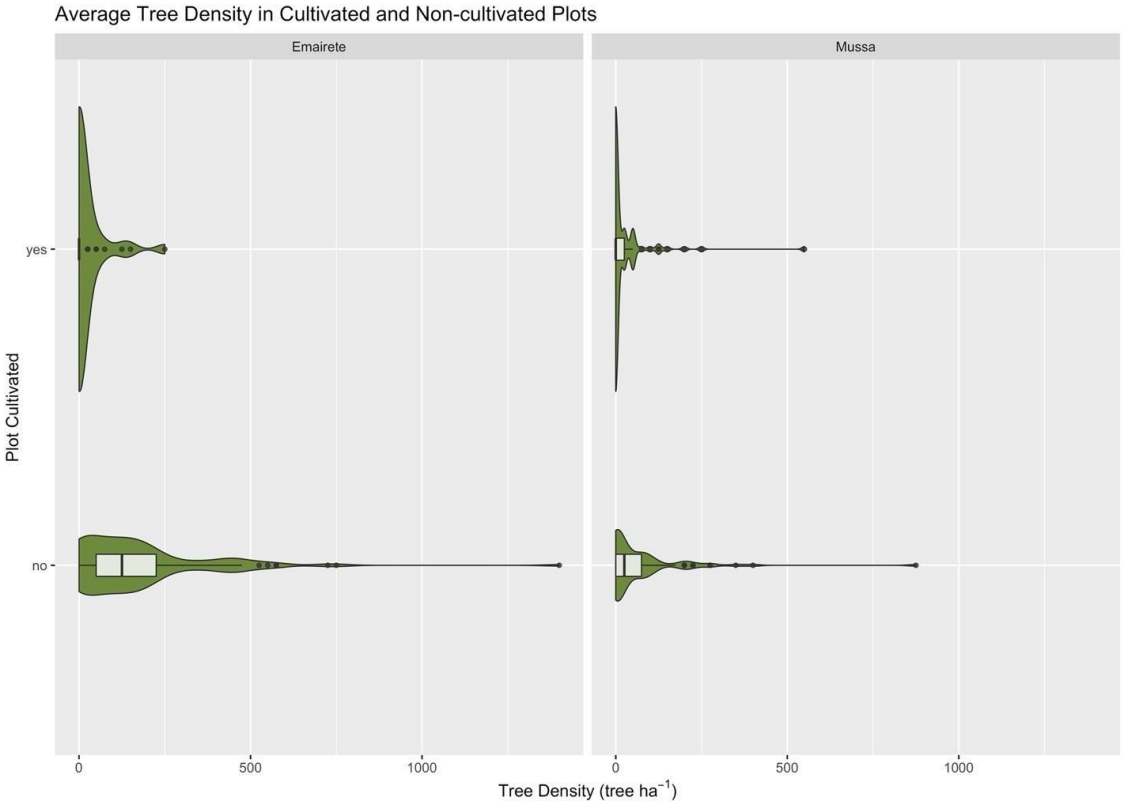

Figure B.7. Tree Densities in Emairete and Mussa LDSF plots

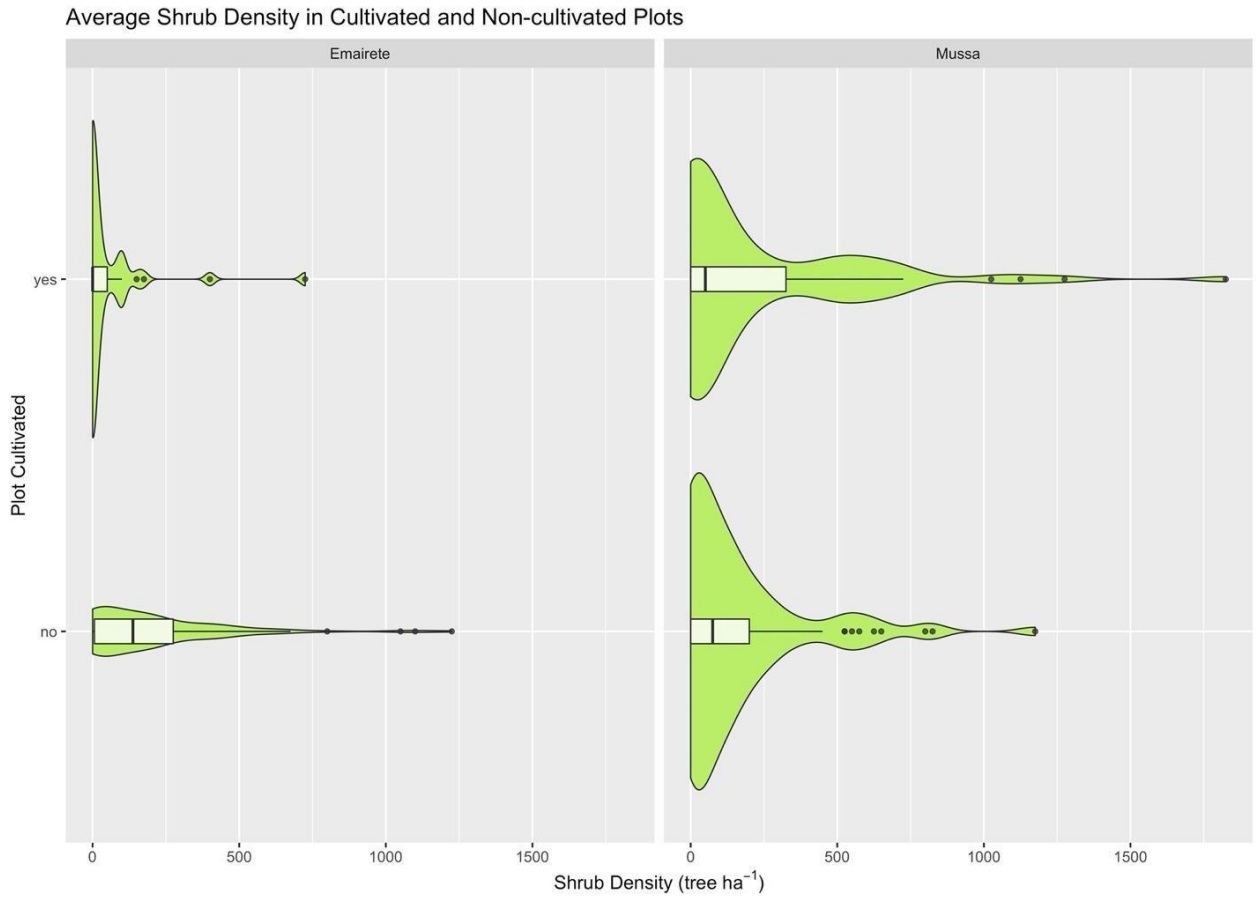

Figure B.6. Average shrub densities

3.3.4. Soil erosion prevalence

Erosion is the most widespread form of land degradation. During the LDSF field surveys, erosion was scored and classified in each subplot (n=4) per plot. Plots that had three or more subplots with erosion were classified as having severe erosion. Figure B.7 demonstrates the erosion prevalence in each cluster across the two sites. Emairete had the lowest erosion prevalence, with about 40% of the sampled plots, followed by Mussa (80%).

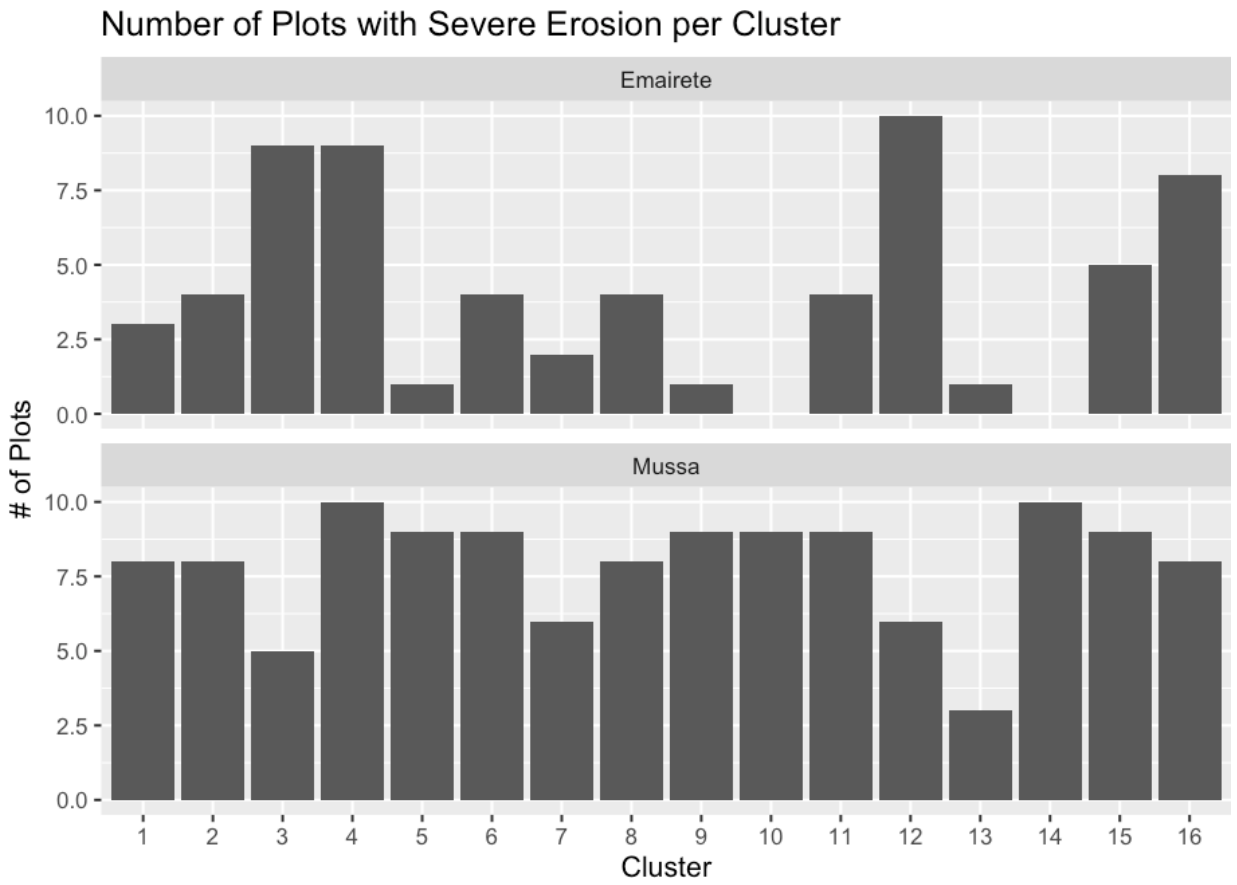

Figure B.9. Bar chart of the erosion prevalence across the LDSF sites

3.3.5. Soil Water Conservation (SWC) measures

Soil water conservation (SWC) measures were classified and counted at each plot. Examples of SWCmeasures could be stone bunds or zai pits (labelled as structural), contour tree planting (labeled as vegetative), or a combination of both vegetative and structural (labeled as both). Figure B.10 demonstrates the overall low use of SWC measures across the sites. In Emairete, there were very fewplots with any type of SWC measure being practiced. These data have implications for soil erosion and opportunities to employ options to curb erosion prevalence.

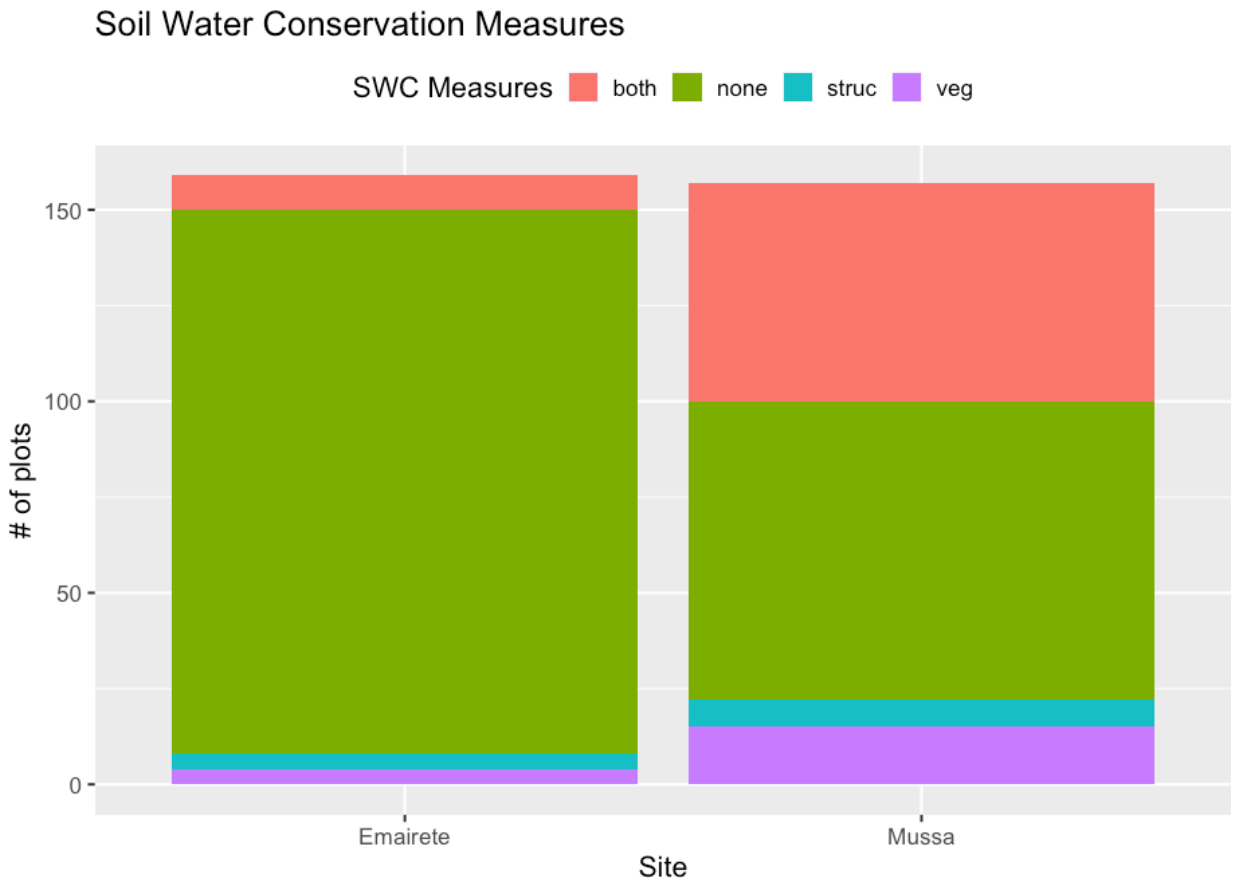

Figure B.10. Prevalence of soil water conservation measures across the five LDSF sites

3.3.6. Soil fertility in FFRUs

Soil chemical properties and nutrient contents in soils are essential in determining the nutrient availability to plants. The soil pH in Monduli (6.2) and Arush (7.1) are slight acidity and neutral (Table 2), which are within the optimum range for crop production according to Landon et al (2014). This is because pH values in this range are not expected to limit solubility and hence the availability of soil nutrients to plants and to cause plant root injury (Amur et al 2017). Soil OC inthe Emairet soils in Monduli was close to the optimum level (>0.2%) for crop production while itwas very low in Musa site in Arusha. Organic carbon in these soils is affected by low vegetationand tree cover due to extensive grazing as noted by low levels in the surveyed plots (Figure. B.9).

Nitrogen and extractable phosphorus levels in the soils in both sites are very low to supportoptimum crop production. The deficient levels (<15 mg P/kg) in these soils are due to the presence of exchangeable Aluminium and Iron which fix phosphorus into recalcitrant fractions in the soil. Soil exchangeable Ca and K were low while the levels of exchangeable magnesium were high in both sites. Soil pH and SOM are the major determinants of micronutrient availability in crops. Except for Boron, the levels of micronutrients (Fe and Cu) were sufficient in the soils. Whilemost of the elements measured were in the optimum range, the soils in both sites have low levels of critical elements for sustainable crop production, especially Nitrogen, Phosphorus, Potassium and Calcium; and low levels of organic carbon. Thus, overall soil fertility for the sites is very low and farmers will require to implement soil nutrient amendment practices to sustain crop production in addition to mitigating high land soil erosion and low vegetation cover noted in the field (Figure B.7 and B.8).

Table B.2. Soil physio-chemical properties in Arusha (Musa) and Monduli (Emairete) Districts, Tanzania

Parameter	Site		Status	
	Arusha	Monduli	Arusha	Monduli
Soil pHw (1:2)	7.09	6.58	Optimum	Optimum
Electrical conductivity (uS/cm)	102.47	113.96	Optimum	Optimum
Organic carbon (%)	1.24	1.88	Low	Optimum
Total N (%)	0.11	0.13	Low	Low
Extractable Phosphorus (mg/kg)	10.26	14.45	low	Low
Exchangeable calcium (mg/kg)	3575	3115	Low	Low
Potassium concentration (mg/kg)	244.94	173.88	Low	Low
Exchangeable magnesium (mg/kg)	591.48	536.23	High	High
Exchangeable manganese (mg/kg)	142.24	114.88	Optimum	Optimum
Iron concentration (mg/kg)	109.64	136.29	Optimum	Optimum
Copper concentration (mg/kg)	2.54	2.28	Optimum	Optimum
Sulphur (mg/kg)	13.23	15.12	Optimum	Optimum
Boron concentration (mg/kg)	0.57	0.58	Low	Low
Exchangeable aluminium (mg/kg)	940.13	940.46	Optimum	Optimum
Exchangeable Acidity (meq/100g)	0.330	0.336	Optimum	Optimum
Exchangeable sodium (mg/kg)	64.73	49.69	Optimum	Optimum
Phosphorus Sorption Index (PSI)	131.55	131.60	Optimum	Optimum
Cation Exchange Capacity (meq/100g)	29.28	27.58	Optimum	Optimum
Clay (%)	57.85	49.02	N/A	N/A
Silt (%)	23.70	28.87	N/A	N/A
Sand (%)	18.45	22.11	N/A	N/A
Textural Class	Clay	Clay	N/A	N/A

4. Section C: Trade-off Analysis and Socio-Economic Impacts of Sustainable Intensification Technologies.

4.2. Introduction

Sustainable intensification (SI) is an approach using innovations to increase productivity on existing agricultural land with positive environmental and social impacts. It includes highly innovative cost-affordable technologies, easily used in the field by both skilled and unskilled personnel. As part of its objectives, The EWA-BELT project aims at developing SI technologies in agriculture productions in organic agriculture, agroforestry, mixed crop and livestock farming systems in its areas of operation. The evaluation of the Soil and Water Conservation Programme in Arusha Region (SCAPA) which was conducted in Arusha region from 1990s to 2000s scaled up and led to the adoption of various SI technologies being implemented up to date. The EWA-BELT project team from the World Agroforestry (ICRAF) and Nelson Mandela Institute of Science and Technology (NM-IST) conducted a participatory trade-off analysis of six SI technologies namely 1) Contour/Terrace, 2) Conservation agriculture, 3) Water harvesting, 4) Cover crops, 5) Rippers and 6) Zero grazing and assessed their influence on the five socio-ecological domains of SI i.e. a) Productivity, b) Income, c) Land health, d) Human condition and e) Social.

4.3. Objectives

The objectives of conducting a participatory trade-off analysis of SI technologies were:

- To gather perspectives from various stakeholder groups on the influence of Sustainable Agricultural Intensification (SI) practices on socio-ecological domains i.e. (Productivity, Income, Land health, Human condition and Social aspects) in Arusha Dc and Monduli Dc,
- To identify key investments needed to minimize negative influences,
- To identify key data needs to assess the tradeoffs and synergies and
- To explore tradeoffs and synergies of the SI practices.

4.4. Methodology

4.4.1. Background and History of Arusha Dc and Monduli Dc

Both Arusha District Council and Monduli District Council have similar agro-ecological conditions inhabited by Maasai and WaArusha people who originally were nomadic livestock keepers. The Maasai and WaArusha people continue to face a shrinking land base, reducing their ability to survive by free-ranging livestock keeping therefore crop growing has become an important part of their economic survival. It is evident that both highland and plains are cultivated throughout the year. Few families depend on mixed crop production and livestock keeping, while others are completely on crop production for food and as source of income. As crop producers, farmers in Arusha and Monduli Dc have adopted various agricultural technologies from various projects such as SCAPA. These technologies align directly with the EWA-BELT project objectives. Other than scaling up these technologies, the EWA-BELT project is experimenting with other technologies to combat the effects of soil erosion and soil conservation in highlands through the research of a Ph.D. student from NM-IST.

4.4.2. Selection of study sites and farmers

Six (6) villages i.e. Likamba, Nengungu and Olcholvus villages from Arusha DC and Emairete, Mlimani and Enguiki villages from Monduli DC. The criteria for selecting these villages were 1) they should be the sites where EWA-BELT project is currently being implemented but also 2) they should be the sites where the SCAPA project scaled up its agricultural technologies from the early 1990s to 2000s. Similarly, farmers who were selected for trade-off activity were those who were having practical experience and/or practicing those of those SI technologies. The selection of both study sites and farmers was done byICRAF in collaboration with NM-AIST, extension officers, local leaders and cultural leaders. A total of 218 farmers of which 138 (64%) male, and 80 (36%) females participated in the trade-off analysis activities.

Table B.3. List of selected participants who participated in the trade off analysis ofTechnologies in Arusha and Monduli District council

Village	District	Male	Female	Total
Likamba	Arusha DC	31	17	48
Nengungu	Arusha DC	14	9	23
Olcholvus	Arusha DC	23	7	30
Emairete	Monduli	21	25	46
Enguiki	Monduli	28	5	33
Mlimani	Monduli	21	17	38
Total		**138**	**80**	**218**

4.4.3. Trade-Off Analysis Activity

A team of researchers from ICRAF Tanzania and Nelson Mandela Institute of Science and Technology (NM-IST) conducted a participatory trade-off analysis of all promising sustainable intensification (SI) technologies which are being implemented by farmers in Arusha DC and Monduli DC. The exercise was guided by a developed SI tool for the selected six (6) SI technologies i.e. 1) Contour/Terrace farming, 2) Conservation agriculture, 3) Rippers, 4) Water harvesting, 5) Zero grazing, 6) Cover crops. The six SI technologies were assessed on how they influence the five socio-ecological domains of the SI i.e. Productivity, Income, Human condition, Land health, and Social. The exercise was done into two main groups i.e. male and female groups. Within each male and femalegroup, they were subdivided into a more manageable small groups of a total maximum of six (6) participants per group. This was mainly to increase participation of each member ina group. A total of 41 groups where formed of which 26 (64%) were male groups and 15 (36%) were female groups from six villages in Arusha and Monduli District council (Table B.3).

Table B.4. List of farmer groups by location and gender who participated in trade off analysis

Village	District	Male-group	Female-group	Total
Likamba	Arusha Dc	5	3	8
Nengungu	Arusha Dc	3	3	6
Olcholvus	Arusha Dc	5	1	6
Emairete	Monduli	4	4	8
Mlimani	Monduli	4	3	7
Enguiki	Monduli	5	1	6
Total		**26**	**15**	**41**

4.4.4. Training on SI Technologies and Socio-ecological domains

All farmers were given a training on the six groups of the SI technologies The training was more on the ways on how each of the SI tech is done i.e. the layout and the components of the SI tech. Similarly, photos and sketches of each SI techs were displayed to farmers for clarity and increasing more understanding of the SI techs. Thereafter, farmers were trained on the participatory trade-off analysis. The training covered a wide range of things i.e. a) the meaning of trade-off analysis, b) how to differentiate SI tech's benefits and loss from the five domains of SI techs, c) how to calculate benefits and loss, d) how to sketch benefits and loss radar graphs, e) how to interpret the radar graphs, and f) steps of doing trade-off analysis.

In addition, participants were given an opportunity to air out their opinions and/or asking any question concerning the exercise. Thereafter, they were divided two main groups i.e. male and female and then subdivided them based on their experience on a specified SI technology to discuss and give scores to the specified SI technology. Each group was given all materials that were required when doing a trade-off analysis i.e. three maker pens of different colours, pens, pencils, papers/sheets, rulers and notebooks. After they had

completed the scoring exercise, each group had to find averages for both positive and negative scores and then drew the radar graphs of both positive and negative averages from each SI socio-ecological domain to show how they have traded-off each other. Thereafter, each group had to choose a presenter of their group work for presenting theirwork to their fellow farmers and answer any question relating to their group work.

Figure C.1. Female group from Emairete village in Monduli district discussing and finalizing theirtrade-off analysis group work. Photo credits: Emmanuel Temu

Figure C.2. A representative of male group from Olcholvus village in Arusha DC presenting his group work tohis fellow farmers. Photo credits: Emmanuel Temu

4.5. Results

4.5.1. Contour farming.

Contour/Bench terrace farming is the most common land restoration practices noted during the trade-off analysis fieldwork in Arusha and Monduli Districts, especially in highland areas where it is used for soil erosion soil erosion to sustain production of crops and fodder (Figure C.3). The technology was introduced in the study villages by the project called Soils Conservation and Agroforestry Project Arusha (SCAPA), which started in the late1990s. Farmers indicated that this technology has larger positive than negative impacts in all five SI domains because of the multiple benefits they have experienced in using this technology for several years (Figure C.4). Gender difference in the perception of the benefits contour/bench terrace technology was noted, with men giving an overall score of 3.84 out of 5 and female giving only a positive score of 0.76 for all the domains. Making

contours/bench terraces is a labor-intensive job and this could be the reason the technology was not popular for female farmers. Both male and female emphasize the need for training on good agricultural practices (GAP) in terraces to ensure sustainableincrease in crops production. In Mlimani village the farmers' opinion seems to favor thecontour technologies and it very socially inclusive, ensure food security and diversity ofnutrition. Because of the nature of high landscapes in Mlimani village, the contour and terrace technology is very applicable to all farmers and has proven to have positive impacts on all five social-ecological domains.

Figure C.3. Contour farming in Monduli District, Tanzania (Photo Credit Anthony Kimaro)

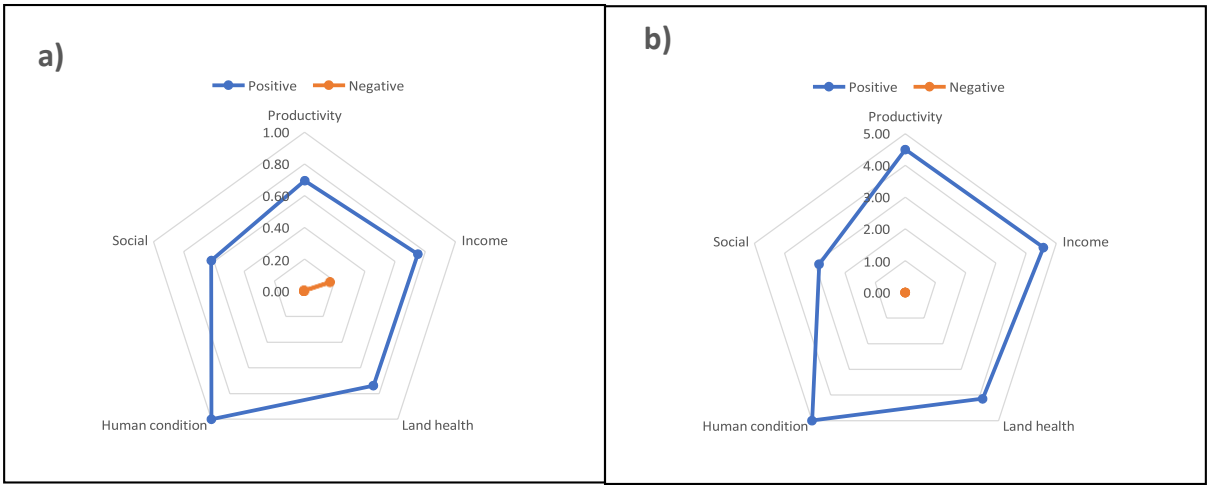

Figure C.4 Perception of Female (a) and Male (b) famers on the impacts of contour farming on SIDomains in Arusha district Tanzania

4.5.2. Conservation Agriculture

Both female and male farmers have higher positive scores on the effects of conservation agriculture (CA) on various SI domains (Figure C.5). The positive score for men across the five domains (4.13) averaged slightly higher than the corresponding values (3.89) for female farmers, reflecting gender difference in the perception of benefits of technologies. Larges difference was on the income domain where female gave a lower score, possibly because this is a part linked to labour inputs. Female provide most of the farm labour and could provide more precise estimate of the impacts in this domain compared to their male counterpart.

A possible reason for effectiveness and adoption of CA in Arusha and Monduli Dc could be due to the fact that often CA is being promoted together with other better cropping management practices such as timely weeding and improved seed varieties and becomes way better when the weather condition is conducive. The positive score indicates that CA improved both land conditions to support crop production and livelihood strategies in the study areas and thus it has high potential for wider adoption as a sustainable land management practice.

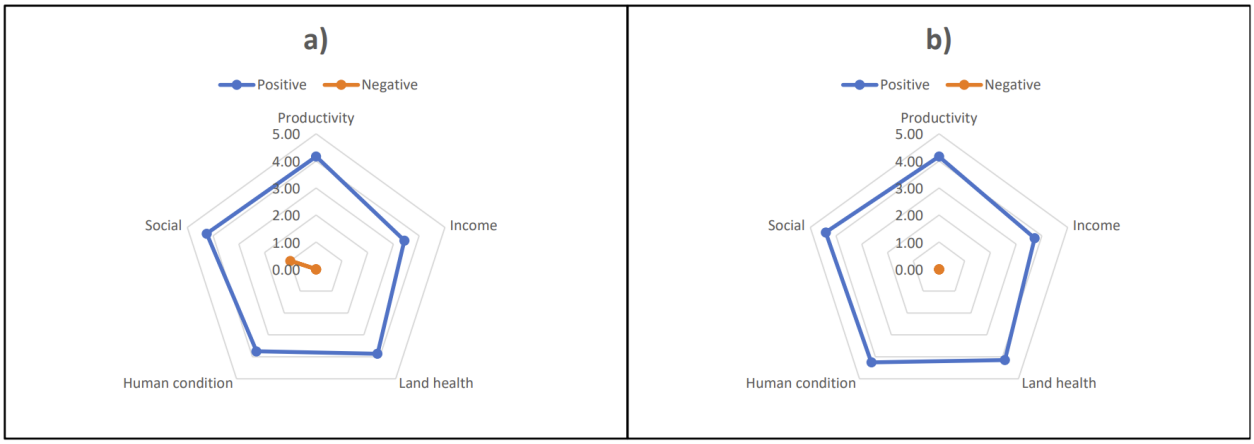

Figure C.5. Perception of Female (a) and Male (b) farmers on the effects of Conservation Agriculture on SI domains in Likamba Village, Arusha district Tanzania.

4.5.3. Cover crops technology.

It involves growing leguminous plants and pumpkins is also useful as it produces residues for livestock, conserve moisture, reduces soil erosion, increased organic matter, increased soil fertility and provides families with necessary nutrition. The cover crops are easily intercropped with other crops such as maize and tobacco. It is more preferred by female farmers because it is not much labor intensive, and farmers have the assurance of diversity of food crops and vegetables (Figure C.6). Most cover crops such as Pumpkin and legumes leaves.

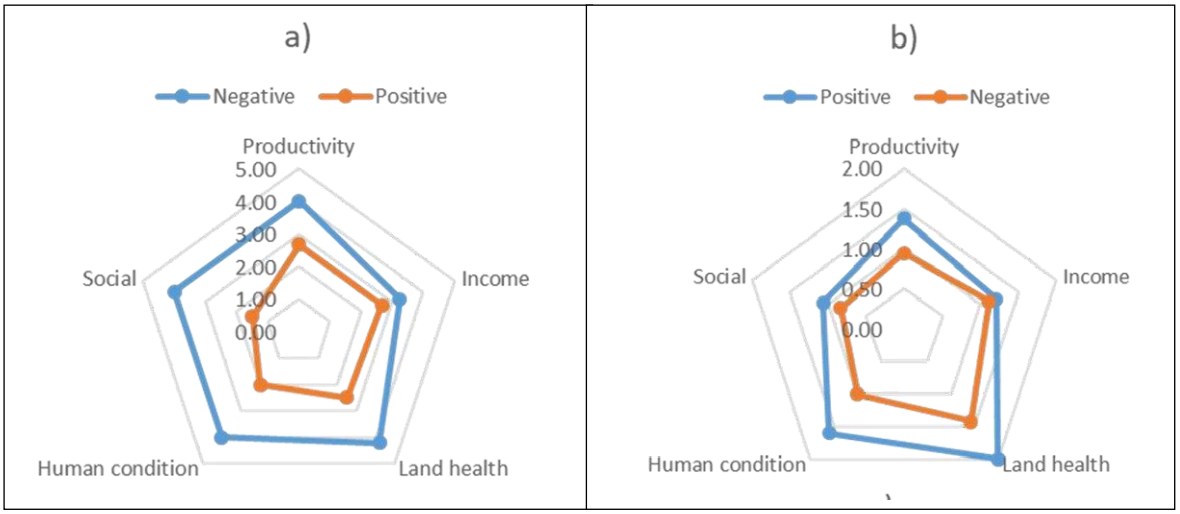

Figure C.6. Perception of Female (a) farmers on the effects of Cover crop technology on SI domains in Emairete Village, Monduli and (b) Overall performance of Cover crops technology in Arusha and Monduli District Tanzania

4.5.4. The minimum tillage technology

This technology is not practiced by many farmers in Monduli and Arusha Dc and it was evident from the less familiarity and little understanding of many participant farmers. limited education and it is not applicable to highland areas and in areas with contours which in their village most of the agricultural land must have contour and terracing to avoid soil erosion.It is practiced by a few farmers who are well off economically and can afford all the required tools and materials. The average performance of minimum tillage technology indicates that it is socially inclusive to both men and women (Figure C.6).

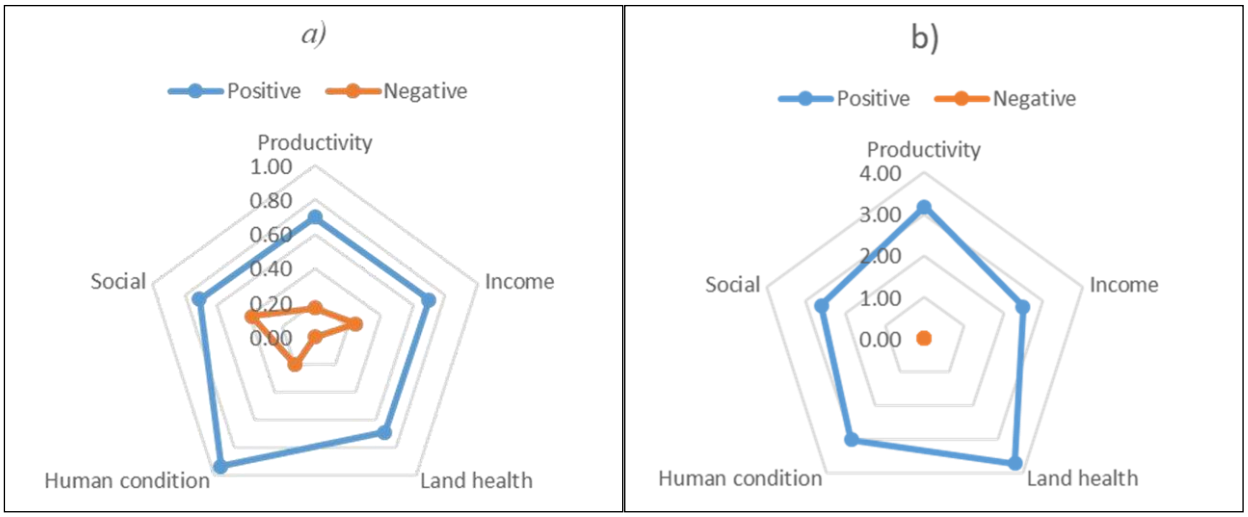

Figure C.7. (a) The overall perception of Female farmers in Arusha and Monduli and (b) Male farmers on the effects of Minimum tilllage on SI domains in Nengungu Village, Arushadistrict Tanzania

4.5.5. Water harvesting technology.

The potential of water harvesting for improved crop production received great attention due to the widespread droughts in Arusha which left a trail of crop failures and a serious threat to human and livestock life, this resulted into introduction of various water harvesting technologies. The main objectives are to combat the effects of drought by improving plant production and in some areas rehabilitating abandoned and degraded landespecially in highland areas in Arusha and Monduli District. Because of shrinking land for agriculture, farmers have decided to cultivate in highlands, and therefore has to practices more than SI technologies such as water harvesting and terrace making. The general perception of farmers in Arusha and Monduli is that Water harvesting technology is very important. It has a mean score of positive 2.2 out of 5 for men and 1.16 score for females,but with big differences between negative and positive scores (Figure C.8).

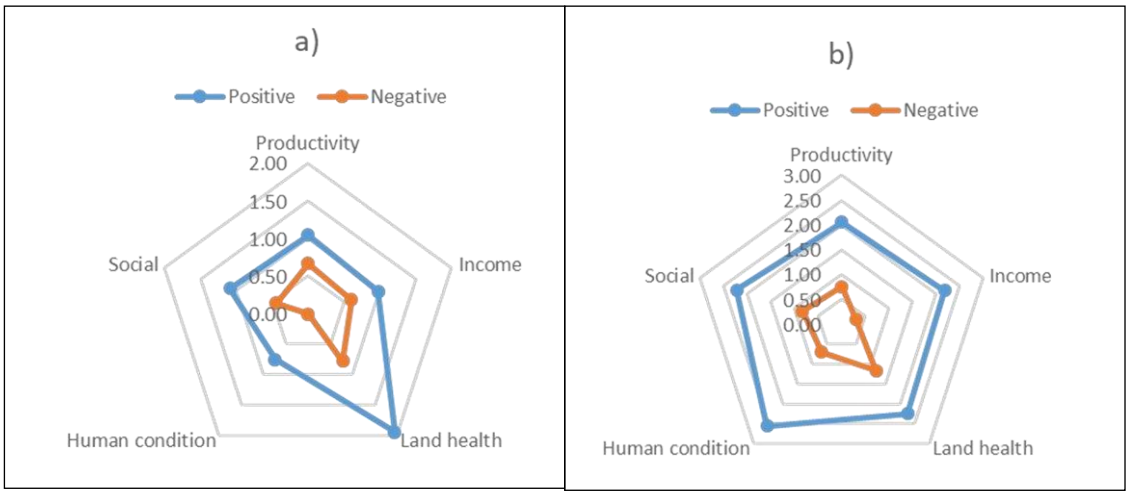

Figure C.8. Overall performance of water harvesting technology (a) for male and (b) for female on SI domains in Arusha and Monduli district Tanzania

The overall performance of the Sustainable Intensification (SI) has impacted positively every social-ecological indicator and is highly adopted in all farmers in Monduli and Arusha. The selection and preferences of a particular SI technology are influenced by agro-ecology and landscape of the farmland, family resources and education availability on SI technologies. The technologies adopted is socially inclusive because all groups of peopleincluding Youth, women and elders' practice one or more technologies. (Table B.5)

Table B.5. Gender based perception of across SI technologies evaluated in Arusha Dc and Monduli Districts, Tanzania.

SI DOMAIN	Female		Male	
	Negative	Positive	Negative	Positive
Productivity	0.44	1.63	0.90	2.51
Income	0.65	1.52	1.38	2.35
Land health	0.52	1.76	1.58	2.83
Human condition	0.40	1.87	0.53	2.44
Social	0.78	1.52	1.53	2.25
Mean	**0.56**	**1.67**	**1.19**	**2.48**

4.5.6. Conclusions and Recommendations

We suggest that Si technology generation, dissemination and adoption interventions be strengthened. Moreover, the linkage among researchers, extension, Universities and farmers needs to be enhanced by facilitating a multi stakeholder innovation platform. Each group had some recommendations after making a presentation of their outputs from the trade-off activity. Most of them concentrated on how farmers could obtain loans to expand their capitals and invest in SI technologies. Recommended for education for few free-range livestock keepers to turn to zero grazing and crop cultivation and agroforestry to avoid conflicts on resources such as land and water. It is important that these SI technologies are scaled up and disseminated to all farmers.

5. Section D: Land recovery experiment on salt-fluoride affected soils.

5.2. Introduction: Rationale and Objectives of the trial.

The survey was carried out in Monduli and Arusha districts located in Arusha region in Northern part of Tanzaniaduring the December-January, 2021 cropping season. The study covered two districts with three villages each and 60 households. Monduli districts covered Research on the identification of potential soil amendments for salt-fluoride is led by NM-AIST in Tanzania. The intent of this trial was to check if the seaweed which are abundant in the coastal environment can be utilized in fluoride contaminated zones as an organic fertilizer while locking-off the bioavailable fluoride in the soil. Therefore, the objective of the study was to investigate the remediation efficiency of soils contaminated by fluoride using a Fermentation Product of Seaweed (*Eucheuma cott*onii).

5.3. Description of the technology.

Bio-adsorption is one of the most important techniques for the removal of environmental contaminants. It has advantages of abundance, cost-effectiveness, eco-friendly, and efficiency. Seaweed is amongst the biomasses fitted for their use as bio-adsorbents. The seaweed improves important soil properties such as soil organic matter (SOM), pH,

microbial diversity, and nutrient composition and is therefore used as a natural fertilizer worldwide. Seaweed also contains polysaccharides, proteins, and sulphate which act as the binding sites for ions present in the soil solution. The polysaccharides undergo other chemical transformations which additionally alter their chemical interaction with the soil elements. Because of these properties, seaweed has been successfully investigated and used for remediation of soils contaminated with heavy metals, however, not yet been investigated for anionic species particularly, fluoride in the soil. This study, therefore, examines the efficiency of fermented seaweed (*Eucheuma cottonii*) in reducing the amount of bioavailable fluoride in the soil while monitoring its impact on the soil's physical, chemical, and microbial properties.

5.4. Methodology

5.4.1. Study Area

The soil used for this study was collected at Ngarenanyuki which is one of the 17 wards of Meru district, Arusha, Tanzania (Fig. D1). It is part of the East Africa Rift Valley surrounding Mount Meru which is an active Volcano. Ngarenanyuki ward has five villages (*Uwiro, Olkung'wado, Ngabobo, Kisimiri chini and Kisimiri juu*). The annual mean temperature is between 20 ± 2 and 29 ± 2 °C. The study area has an Afro-Alpine semi-arid climate characterized by a wet and dry season. The major wet season begins from June through September and accounts for approximately 70 % of the annual rainfall while another wet season which is minor accounts for the remaining 30 % of annual rainfall from mid-February through mid-May and the mean annual rainfall is estimated to be 535 mm.

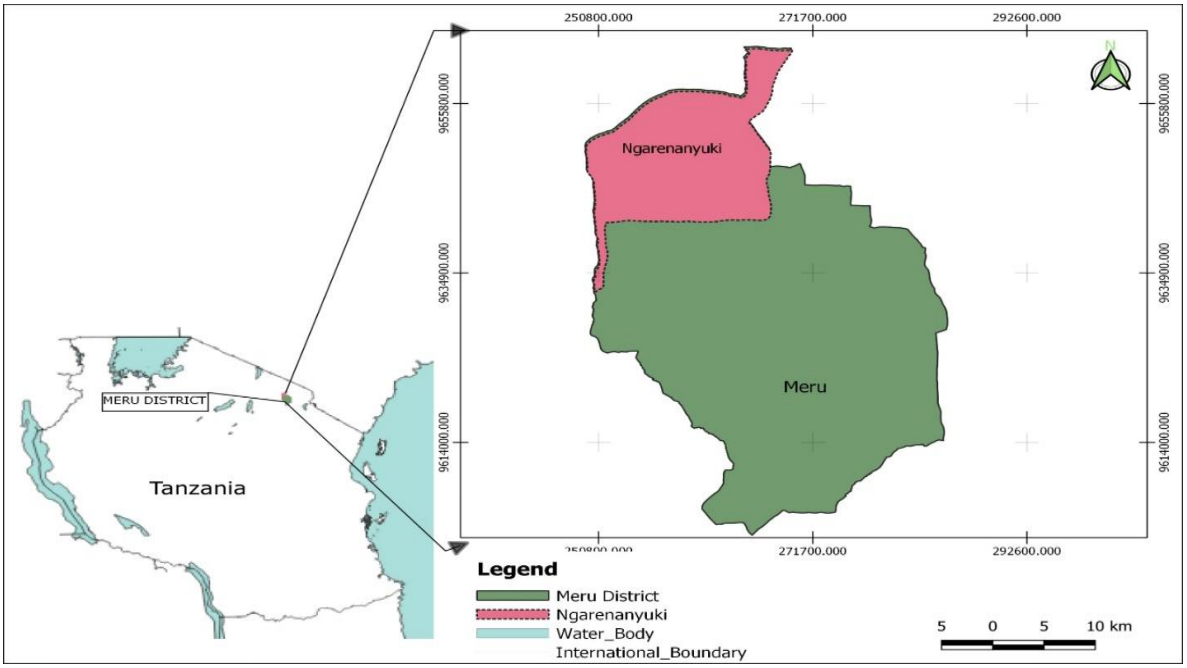

Figure D1. Location of the study area.

The main source of food and income in this area is small-scale farming whereby people are involved in the cultivation of food and cash crops some of which includes, tomatoes, cabbage, potatoes, onions, maize, and beans. The volcanic activities in this area have led to the accumulation of volcanic material containing fluoride at the topsoil, surface water, and groundwater and have attracted the majority of fluoride research activities.

5.4.2. Soil sampling and analysis

The composite soil samples were collected from agricultural fields located along the slopes of Mount Meru, Arusha, Tanzania, (3◦10’35” S 36◦51’35” E) at a vertical profile of 0-20 cm. The composite samples were packed in plastic bags and brought to the laboratory. The samples were further air-dried and sieved to pass through a 2 mm sieve to remove debris and plant materials and then stored in containers that were cleaned with nitric acids before analysis.

The seaweed used was *Eucheuma cottonii* collected from the Tanga region, Tanzania. The seaweed samples were brought to the laboratory where it was cleaned thoroughly with distilled water, sun-dried, then powdered using an electric grinder. Afterward, the 500 g of the seaweed powder was transferred to a container where it was mixed with the inoculum (anaerobic sludge from the septic tank), distilled water, and 100 ml molasses. The molasses contains high quantities of sucrose and fructose which is an easily available food source for the anaerobic biomass. Subsequently, 4 ml of iodoform was added to prevent the methanogenesis process from taking place, thereby encouraging acidogenesis and acetogenesis processes (Plácido & Zhang, 2018). After mixing, the container was closed to stimulate the fermentation process. The container was kept in a shaker (110 rpm) at 37 ℃, free from light until the seaweed was entirely soft (5 weeks). The fermented seaweeds were oven-dried at 50 ℃ to obtain a hard solid which again milled into a fine powder.

5.4.3. Experimental set-up

The soil samples (1 kg) were packed into the experimental pots and then mixed thoroughly with either 1.25, 3, or 5 % (w/w) of the fermented seaweed powder (FSW) equivalent to the control samples labelled 0 %. Thereafter, the soil was humified to 70 - 75 % saturation and incubated in a shaded area, at room temperature (24 ± 3 ℃). The first soil sample was collected within 24 h of inoculation, and the fluoride fractions, as well as pH, were measured and quantified. The incubation process continued for 4 months while sampling and analysis were conducted every 30 days. The monitored parameters were pH, soil organic matter (SOM), cation exchange capacity (CEC), electrical conductivity (EC), fluoride fractions (water-soluble (Ws-F), Exchangeable-fluoride (Ex-F), fluoride-bound to iron/manganese (Fe/Mn-F), organic matter bound-fluoride (Or-F), and residual-fluoride (Res-F)), phosphorus (P), nitrogen (N) and the exchangeable bases (calcium (Ca2+), magnesium (Mg2+), potassium (K+) and sodium (Na+). Each treatment was replicated three times, and the experiment was conducted in a completely randomized design.

5.4.4. Laboratory analysis

The hydrometer method was used to measure the soil particle size distribution. The content of SOM was calculated using the loss-on-ignition (LOI) method. An electrical conductivity meter and pH meter were used to measure the electric conductivity (EC) and pH. The cation exchange capacity (CEC) was measured using the barium chloride-triethanolamine method (pH 8.2). The water absorption capacity was measured by the centrifugation method (Jumaidin, Sapuan, Jawaid, Ishak, & Sahari, 2017). The specific surface area of the soil was determined using the ethylene glycol monoethyl ether (EGME) method according to procedures by Yeliz and Abidin (Yukselen & Kaya, 2006). The exchangeable bases were quantified using the atomic absorption spectrophotometer (AAS) and the X-ray fluorescence (XRF) was used to analyze the total elemental composition. Total fluoride was determined according to McQuaker and Gurney's (1977) procedure (McQuaker & Gurney, 1977). Sequential extraction of fluoride was conducted as per our previous study (Moirana, Mkunda, Perez, Machunda, & Mtei, 2021). In short, 2.5 g of soil sample was placed into a 50 mL centrifuge tube and various species of fluoride were extracted by adding 25 ml of the extracting solutions as shown in Table D1.

Table D1. Extraction processes of various fluoride fractions in the soil

Fluoride specie	Extraction process
Water-soluble fluoride (Ws-F)	distilled water Shake for 30 min at 60°C
Exchangeable fluoride (Ex-F)	1 mol L^{-1} $MgCl_2$ Shake for 1 h at 25°C
Fe/Mn bound fluoride (Fe/Mn-F)	0.04 mol L^{-1} NH_4.HCl Shake for 1 h at 60°C
Organic matter-bound fluoride (Or-F)	Step 1: 3 ml of 0.02 mol L^{-1} HNO_3 + 10 ml 30% H_2O_2 Step 2: 12 ml of 3.2 mol L^{-1} NH_4 acetate Shake for 30 min at 25 °C
Residual fluoride (Res-F)	Tot-F minus the above for species of fluoride

Gas chromatography (GC) was used to analyze the amount of volatile fatty acids (VFAs) present in the fermentative sap using the flame ionization detector (FID). For analysis, the samples were collected from the fermented sap and then centrifuged at 1,500 rpm for 10 minutes to obtain a clear liquid. The liquid was acidified to pH 1.8 with formic acid. Due to analytical limitations, the VFAs results were given as the total volatile fatty acids (TVFAs) expressed as g acetic acid/l (gAc/l). The C: N ratio of the seaweed was measured using the CHNS analyzer and the rest of the analyses were carried out as the soil samples. All the chemicals used were of analytical grade and distilled water was used throughout.

5.5. Results

Gas chromatography (GC) was used to analyze the amount of volatile fatty acids (VFAs) present in the fermentative sap using the flame ionization detector (FID). For analysis, the samples were collected from the fermented sap and then centrifuged at 1,500 rpm for 10 minutes to obtain a clear liquid. The liquid was acidified to pH 1.8 with formic acid. Due to analytical limitations, the VFAs results were given as the total volatile fatty acids (TVFAs) expressed as g acetic acid/l (gAc/l). The C: N ratio of the seaweed was measured using the CHNS analyzer and the rest of the analyses were carried out as the soil samples. All the chemicals used were of analytical grade and distilled water was used throughout.

Soil physico-chemical analysis before and after fermented seaweed (FSW) amendment. The FSW amendment revealed a positive influence on the soil properties as presented in Table D2. The amount of water absorption capacity, clay content, SOM, CEC, and exchangeable bases increased after the amendments whereas the soil pH of each treatment decreased. The impact of FSW on the soil quality was directly related to the amendment dosage such that the higher the dosage the higher its impact on the soil quality parameters.

Table D2. The influence of fermented seaweed (FSW) amendment on selected soil properties at the end of the experimental phase (120th day)

		Soil	Soil + FSW (120th day)			
		Initial %	0 %	1.25 %	3 %	5 %
Soil Texture (%)	Sand	68 ± 1	67 ± 1	65 ± 3	62 ± 3	55 ± 5
	Silt	21 ± 4	20 ± 1	21 ± 6	21 ± 3	22 ± 3
	Clay	11 ± 2	13 ± 2	14 ± 2	17 ± 4	23 ± 6
Water absorption (gH_2O/g soil)		0.02 ± 0.1	0.02 ± 0.1	0.06 ± 0.1	0.17 ± 0.1	0.23 ± 0.1
pH		9.3 ± 0.0	8.9 ± 0.3	7.8 ± 0.1	7.4 ± 0.1	7.0 ± 0.0
CEC (meq/100g)		32.8 ± 0.9	30.5 ± 0.5	34.5 ± 1.7	35.3 ± 1.7	37 ± 1.3
Phosphate (PO_4^{3-}) (mg kg^{-1})		17.2 ± 0.4	15.8 ± 2	12.5 ± 0.4	14.0 ± 0.9	16.4 ± 0.8
Echangeable Bases (mg kg^{-1})						
	Na^+	8.48 ± 1.7	6.09 ± 1.9	12.8 ± 0.2	13.4 ± 3.3	14.3 ± 1.3
	Ca^{2+}	4.63 ± 0.3	4.66 ± 2.1	5.1 ± 0.5	4.7 ± 0.6	5.8 ± 0.9
	Mg^{2+}	2.03 ± 0.7	1.57 ± 0.6	2.5 ± 0.3	2.9 ± 0.4	3.2 ± 1.6
	K^+	7.37 ± 1.8	7.68 ± 2.3	10.5 ± 0.8	11.6 ± 3.5	13 ± 2.8
Electrical conductivity (EC) (µs cm^{-1})		453.9± 2.3	451 ± 1.6	444 ± 1.3	443 ± 0.4	440 ± 2
Soil organic matter (SOM) (%)		2.5 ± 0.1	2.6 ± 0.4	3.5 ± 0.6	4.2 ± 0.3	5.4 ± 0.3

5.5.1. The impact of FSW on pH of the soil

The influence of the amendments on the pH of the soil is presented in Fig D3.. The initial pH of the soil was 9.3 ± 0.0. There was no statistically significant change in pH of the control samples throughout the experiment except for the 60th day when pH dropped to 8.9 ± 0.3 and remained constant thereafter. In the first 24 h, pH dropped from 9.3 ± 0.0 to 9.1 ± 0.2, 9.0 ± 0.1 and 8.4 ± 0.0 following, 1.25, 3 and 5 % amendment dosages, respectively. The pH continued to drop from 9.3 ± 0.0 to 7.8 ± 0.1, 7.4 ± 0.1 and 7.0 ± 0.0 correspondingly, by the 120th day. The pH drop indicates that the process responsible for its behaviour was progressing slowly and attained stability on the 60th day. There was a significant pH difference ($p<0.05$) between the treatments and the control. Even though the pH amongst treatments was significantly different, the 3 and 5 % amendments were not statistically different ($p>0.05$) throughout the experiment.

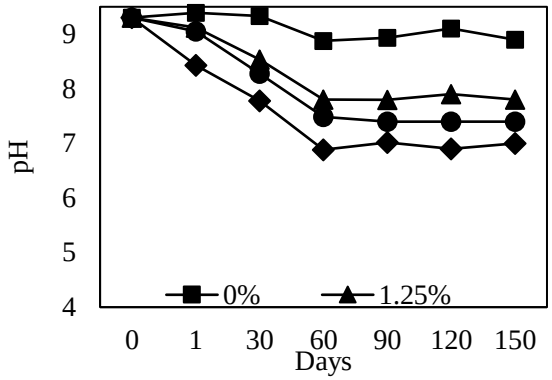

Fig D3. The impact of fermented seaweed amendment (FSW) on the pH pf the soil.

The four fractions of fluoride were monitored throughout the experiment and the results are presented in Fig D3. The initial pH of the soil was 9.3 ± 0.0. There was no statistically significant change in pH of the control samples throughout the experiment except for the 60th day when pH dropped to 8.9 ± 0.3 and remained constant thereafter. In the first 24 h, pH dropped from 9.3 ± 0.0 to 9.1 ± 0.2, 9.0 ± 0.1 and 8.4 ± 0.0 following, 1.25, 3 and 5 % amendment dosages, respectively. The pH continued to drop from 9.3 ± 0.0 to 7.8 ± 0.1, 7.4 ± 0.1 and 7.0 ± 0.0 correspondingly, by the 120th day. The pH drop indicates that the process responsible for its behaviour was progressing slowly and attained stability on the 60th day. There was a significant pH difference ($p<0.05$) between the treatments and the control. Even though the pH amongst treatments was significantly different, the 3 and 5 % amendments were not statistically different ($p>0.05$) throughout the experiment.

5.5.2. The impact of FSW amendment on the behavior of fluoride fractions in the soil

The influence of the amendments on the pH of the soil is presented in Fig D3. The four fractions of fluoride were monitored throughout the experiment and the results are presented in Fig D4. The amendments decreased the amount of water soluble-fluoride (Ws-F) from 81. 7 ± 3.1 mg/kg to 42.7 ± 2.4, 33.7 ± 1.2, 19.6 ± 0.9, and 12 ± 1.3 mg/kg following 0, 1.25, 3 and 5 %, dosages, respectively. The 5 % amendment could reduce the amount of Ws-F below the recommended level of 16.4 mg/kg (Rizzu et al., 2020). Unlike Ws-F, the amount

of exchangeable-fluoride (Ex-F) and fluoride-bound to iron and manganese (Fe/Mn-F) increased following the FSW amendment. The Ex-F increased from 5.5 ± 0.1 mg/kg to 14.8 ± 0.7, 19.1 ± 2, 20.3 ± 0.8 and 21 ± 1.6 mg/kg after 0, 1.25, 3 and 5 %, amendments. The Fe/Mn-F increased from 8.7 ± 0.1 mg/kg to 16.3 ± 3.5, 24.4 ± 2, 24.8 ± 2.1, and 25.7 ± 1 succeeding 0, 1.25, 3, and 5 % amendment which is the lesser bioavailable form compared to the abovementioned two. There was no observed impact of the amendments on the amount of fluoride-bound to organic matter (Or-F).

There was a significant difference ($p< 0.05$) in the amount of Ws-F observed between 0, 1.25, and 3 % to that of 5 % amendment within the first 24 h of the incubation. The amendment dosage was inversely proportional to the amount of Ws-F in the soil such that, as the dosage increased, the amount of Ws-F in the soil decreased. Within 30-day incubation, the amount of Ws-F was significantly different ($p< 0.05$) between the treatments and the control (0 %). The significant difference between 1.25 and 3 % to the 5 % amendment was also noticed but the two (1.25 and 3 %) were not significantly different ($p> 0.05$) up until the 60th day. From the 60th day to the 120th day, there was a significant difference in the amount of Ws-F among all treatments.

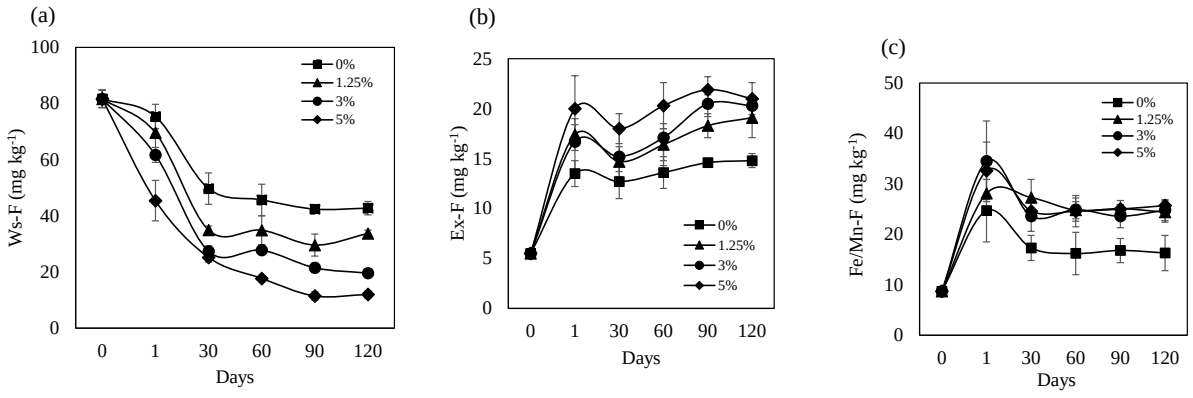

Figure 1. The Impact of Fermented Seaweed (FSW) Amendment on Fluoride Fractions of the Soil (a) Water Soluble-Fluoride (Ws-F), (b) Exchangeable-fluoride (Ex-F), (c) Fluoride-Bound to Iron/Manganese (Fe/Mn-F)

Further information regarding this study were published in an open source and can be found through this link: https://www.hindawi.com/journals/aess/2022/6967031/