# Yield/Biomass Measurements, Soil Sampling and Cropping Pattern Research Somali Region


**Interim Report submitted by:**

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## ABBREVIATION AND ACRONYMS

| | |
|---|---|
| AOAC | Association of Official Analytical Chemists |
| CEC | Cation Exchange Capacity |
| CSA | Central Statistical Agency |
| DM | Dry Matter |
| DSM | Dry Stone Measures |
| DVRPU | Dry Valley Rehabilitation and Productive Use |
| EC | Electrical Conductivity |
| FAO | Food and Agriculture Organization |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| ICRISAT | International Crops Institute for the Semi-Arid Tropics |
| SAS | Statistical Analytical System |
| SoRPARI | Somali Region Pastoral and Agro-pastoral Research Institute |
| SOC | Soil Organic Carbon |
| SOCS | Soil Organic Carbon Stock |
| SPSS | Statistical Package for Social Sciences |
| ToR | Terms of Reference |
| USDA | United States Department of Agriculture |
| WSW | Water Spreading Wear |

## Introduction

The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) is implementing the "Lowland Soil Rehabilitation Project (LSRP)", which is part of the global programme "Soil Protection and Rehabilitation for Food Security". The project operates in all districts of the Somali Region, eight districts in the Afar Region, and one district in the Oromia region. The project, in collaboration with its regional and local government partners, has developed a Dry Valley Rehabilitation and Productive Use (DVRPU) approach that integrates "technical, biological, economic, social, institutional and management measures" to rehabilitate dry valleys for the benefit of pastoral and agro-pastoral communities. The project introduced physical erosion control measures such as Water Spreading Weirs (WSW), Check Dams, and Dry-Stone Measures (DSM) to reduce the velocity of sporadic flash floods, which help to reduce soil loss and increase soil moisture accumulation and thereby increase biomass and crop yield. In collaboration with the International Crops Institute for the Semi-Arid Tropics (ICRISAT), the project has also started to pilot flood-based farming systems on some sites.

GIZ and its partners have built several WSWs and DSMs in different parts of the Somali region to rehabilitate degraded lands and enhance biomass and crop production in the WSW catchment area. A key aspect of this project is to develop flood-based farming systems that efficiently utilize the water resources in the catchment area for various agricultural purposes. For instance, farmers can grow crops such as maize and sorghum and produce fodder for livestock (e.g., elephant grass). The project evaluates the effectiveness of the dry valley rehabilitation measures by comparing the yield and biomass levels in the rehabilitated areas with a non-treated site (control site). The evaluation also involves soil sampling and testing for soil organic carbon sequestration during both the wet and dry seasons and an analysis of the cropping patterns during the cropping season.

Somali Region Pastoral and Agro-pastoral Research Institute (SoRPARI) has been contracted to carry out the yield and biomass measurements, soil sampling / cropping pattern analysis, and soil organic carbon sequestration in seven selected DVRPU intervention locations of the Somali region.

### Purpose and Scope of the Study

According to the Terms of References (ToRs), the project's main objective is to assess how dry valley rehabilitation measures affect crop yield and biomass production, soil organic carbon storage, and cropping patterns in the project intervention areas in the Somali region.

The specific objectives of this assignment were:

- Measure the increase in yield of maize and sorghum crops and biomass of fodder/forage crops in the rehabilitated dry valleys compared to the areas without rehabilitation measures (control sites).
- Assess the cropping patterns of the selected areas.

- Measure the soil organic carbon (SOC) sequestration and bulk density in the rehabilitated dry valleys and compare them with those without rehabilitation measures (control sites).
- Characterize soils of different selected areas of the Somali region to contribute to the national Soil Atlas (a minimum of three soil samples).

The assignment involved seven locations in three districts/woredas of the Somali Regional State, where GIZ and its partners have implemented the dry valley rehabilitation projects. The study evaluated the yield and biomass increase, as well as soil organic carbon sequestration in the areas with dry valley rehabilitation measures and compared them to areas without them. The study also examined the cropping patterns of the intervention areas. The contractor is expected to complete the entire task within the assignment period from 01.08.2023 to 31.12.2024:

**Study Questions**

1. How much has the yield of maize and sorghum crops increased in the rehabilitated dry valleys compared to the control sites?
2. How has the biomass of fodder/forage crops changed in the rehabilitated dry valleys compared to the control sites?
3. How has the cropping pattern of the selected areas evolved over time? What are the main drivers and constraints of this evolution?
4. How much has the soil organic carbon (SOC) sequestration improved in the rehabilitated dry valleys compared to the control sites?

**Project Indicators**

The project aims to increase the yields of the main crops (maize, sorghum, and fodder biomass) in the protected or rehabilitated areas. The expected yield increases are 100% for maize, 30% for sorghum, and 20% for fodder biomass.

The indicator to measure the achievement of this objective is the average yield per hectare of each crop in the rehabilitated areas compared to the untreated reference areas (control sites). The yield measurements will be conducted once per year during the cropping season for two consecutive years using standard agronomic methods.

The indicator could show the percentage of yield increase for each crop in the rehabilitated areas relative to the control sites.

**Limitations of the Assignment**

During our study, we encountered several challenges related to varying rainfall patterns and cropping calendars across the study areas (Jigjiga, Kebri Beyah, and Degehabour). The inconsistent distribution of rainfall significantly impacted our schedule. Unexpectedly, early rains allowed local farmers to plant and harvest their crops ahead of the usual timeframe. Consequently, our original plan to measure yields and biomass in October for most locations was not achieved.

Our pre-mission survey discovered that most locations, except for Bolidid and part of Amedle, had already harvested their yields. Fortunately, some farmers were engaged in second plantings, which required us to wait until those crops matured. These factors affected the timing and frequency of data collection and our assessments of crop yield and biomass. As a result, the project took longer than initially anticipated, according to the Terms of Reference (ToR).

In addition, continuous and open grazing of natural grasses by livestock in certain areas (Bolidid, Amedle, Hodale, and Togshuro) posed challenges for accurately estimating biomass. Furthermore, unexpected heavy rain during fieldwork obstructed the sampling process. There were occasions when the research team went for sample collection but had to return due to heavy rains, making soil and biomass sampling and measurement difficult.

## Methods of Data Collection and Analysis

**Pre-mission field survey**

A preliminary field survey was carried out at all the selected sites. This involved direct observation of the study sites to understand their context and the spatial distribution of their resources. For this purpose, a transect walk was used, where the research team, along with some resident agro/pastoralists and development agents, walked across the rehabilitated sites in different directions. Likewise, an extensive transect walk was also conducted in different directions to identify control (non-rehabilitated) sites that had not been treated with rehabilitation measures. As stated in the ToR, control areas are those rainfed areas that are either outside the WSW treated areas or inside the cascade of treated areas but did not receive any moisture or flood from the project-supported measures.

During the transect walk, the exact locations for yield, biomass, and soil organic carbon measurements of both treated and control sites were identified and marked with GPS. Local communities were also informed about the testing schedule, and we negotiated with them regarding sample collection, daily labourer arrangement and other conditions.

**Assessment of cropping patterns**

Cropping pattern is the sequence and spatial arrangement of crops on a piece of land over time. It is influenced by various factors such as climate, soil, water, market, and socio-economic conditions. The cropping pattern assessment can help optimize crop production, land use, and resource management. There are different methods for assessment of cropping pattern in rural community, depending on the scale, data availability, and objectives of the study. This study, however, used Field survey method which involved collecting primary data from farmers or other stakeholders through observation, interviews, or group discussions.

- **Direct observation** was used for the assessment of cropping patterns, during which, major features of both treated (rehabilitated) and control (non-rehabilitated) sites, such as current land use type, level of intervention by resident farmers (introduced farming practices), types of management (protected and open), vegetation type, soil types and major crops grown were systematically noted. The assessment will be carried out during the harvesting season for two consecutive seasons/years. This would help to understand the proportion of land under cultivation of different crops at different points of time. The findings would be used to triangulate information obtained from key informant and focus group discussions.

- **Key informant Interviews** were used to obtain general information on the types of crops grown, the cropping sequence, cropping intensity, cropping diversity, the sowing and harvesting dates, the yield, the inputs used, the constraints faced, and the benefits obtained from the cropping system. Agro/pastoralists and experts who are knowledgeable on the local conditions were selected as key informants and discussions on different key areas were held with the help of a pre-tested checklist.
- **Focus Group Discussions** group discussions with different categories of farmers were conducted in each main study site for in-depth investigation of the overall conditions, and to understand variations in their perceptions about the impacts of water spreading weirs in rehabilitating degraded lands, improving grain yield and forage biomass, and influencing cropping system. The focus group discussions for all categories of farmers were conducted with the help of a pre-tested checklist.

**Sorghum and maize yield measurement using crop-cut method**

The crop-cut method is a widely used technique for estimating crop yield. It involves sampling a small subplot within a cultivated field and measuring the harvested crop. This method was developed in India in the 1950s and quickly became the standard practice for yield estimation. One of the main advantages of the crop-cut method is that it eliminates the error caused by unknown plot area, which is often a challenge in other methods. The crop-cut method has been recommended by organizations such as the Food and Agriculture Organization of the United Nations for many years (Sapkota et al., 2016). The method has also been implemented by the Central Statistical Agency (CSA) of Ethiopia since the early 1990s (Kosmowski et al., 2021).

Yield estimation through crop cutting method involves demarcation of a subplot within the field followed by measurement of production and area under the crop. Crop yield is then calculated as total production divided by total harvested area in the crop cut subplot(s) (Sapkota et al., 2016). For this study, in line with the ToR, a 50-meter transect was established and nine sampling plots of 1 $m^2$ each were marked along the transects. The sampling plots represented weak, medium, and strong crop performance areas along the transect, with three plots from each group. The GPS data of all sampling plots were taken.

The sorghum and maize crops within the demarcated area were harvested, threshed, winnowed, and cleaned. The grain weight was then measured with a weighing balance and converted to hectare basis after adjusting the grain moisture to the optimum level as shown below (Ghimiray et al., 2020).

$$Adjusted\ Moisture\ Content\ (MC(adj)) = \frac{(100-actual\ moisture)}{(100-desired\ moisture\ content)}$$

$$Yield\ (\text{kg ha}^{-1}) = \text{Average yield from all plots (kg)} * 10000\text{m}^2 * \text{MC (adj)}/1\text{m}^2$$

In addition to the grain yield, the biomass (straw) yield of sorghum and maize crops from the treated and control sites was measured. The crops were cut at a stubble height of 15 cm within the frame, placed in a labelled bag, and weighed to determine the total fresh weight by using a mechanically hanging balance. The fresh plant material was then transported to the laboratory for determination of dry matter biomass yield by oven drying at 70°C until a constant dry weight was achieved.

**Biomass measurement for forage & fodder (grasses, forage legumes and shrubs)**
Fodder/forage refers to any agricultural foodstuff that is grown or harvested to feed domesticated livestock. Fodder/forage can consist of various plants, such as grasses, legumes and herbs. It is important to sample and measure fodder/forage to determine the amount and quality of the feed that is available for animals in a given area. There are different methods for assessing both forage quantity and quality, depending on the accuracy, time and logistics required. For forage quantity assessments, some methods involve direct measurements of vegetation, where biomass is sampled and weighed, while others involve estimation techniques, where biomass is inferred from proxy variables or simulation models, or a combination of both (Angerer, 2011).

The quadrat method is a widely used technique for estimating forage production on grasslands and rangelands. A quadrat is a frame of a known area (circular, square or rectangular) that is placed on the ground. The vegetation biomass inside the frame can be clipped and weighed. For herbaceous plants (grasses, grass-like plants and forbs), only the aboveground parts (leaves, stems, flowers and fruits) are clipped from the quadrat (USDA, 2003). The samples are usually dried in an oven to remove water and measure the biomass on a dry matter basis. Since the area of the quadrat is known, the dry weight (e.g. kg) of the biomass can be scaled up to larger areas (e.g. kg of biomass/ha) to obtain an estimate of vegetation biomass for the site of interest. To establish a baseline for quadrat sampling, transect lines can be useful. A transect line is a straight line that crosses the area of interest. The start and end points of the transect line can be marked with a Global Positioning System (GPS) device (Angerer, 2011).

In line with the ToR, the sampling transects for this study were defined in a similar fashion as the measurement of crop yield, where transects of 50m were established, and a total of 9 sampling plots of 1m2 each were made along the transect for both treated and control sites. The sampling plots were selected from areas with weak, medium and strong biomass performance along the transect, and three samples from each category were taken. By using a quadrant (1m * 1m), three representative samples of fodder and forage (grasses, forage legumes, other plants eaten by livestock as well as crop residue (e.g. Maize, Sorghum)) were collected from each category by placing the quadrant randomly on the ground. Only the forage/fodder plants inside the quadrant were cut at 5 cm above the ground. Weeds and other plants not consumed by livestock were excluded from the sample. Before cutting the biomass, the fodder quality of each sample was assessed. The samples were taken when the grasses achieved almost 50% blooming, and the vegetative development ceased. The composites were combined, and the total fresh weight was measured on the spot using spring balance; they were then labelled, put in cloth bags, and taken to the laboratory to determine the dry masses (Mekuria et al. 2011; Muluken et al. 2015; Ayele et al., 2022). The dry matter yield of samples from each class was determined after drying the samples in an oven at 65o C for 72 h (AOAC, 1995). Based on the DM weights obtained from both sample sites (treated and control), the dry weight of each sampling class (kg m -2), mean dry weight of each class (kg m -2) and average dry biomass (tone ha-1) were computed.

**Soil Sampling, analysis, and carbon stock calculation**

Soil organic carbon (SOC) is the carbon fraction of soil organic matter, derived from plants, animals, and microorganisms. SOC sequestration is the process of transferring $CO_2$ from the atmosphere into the soil in the form of organic carbon, which can improve soil health and mitigate climate change. There are different methods to estimate soil organic carbon sequestration, such as direct measurement, modelling, or a combination of both. For this study direct measurement of SOC content was employed. The method involves quantifying the fine earth and coarse earth fraction, the organic carbon concentration and soil bulk density or fine earth mass (FAO, 2019)

As per the ToR, soil sampling and organic carbon measurement would be conducted twice per year during the dry season (February/March) and wet season (September/October). A systematic random sampling technique was employed to lay out the sample plot and collect soil samples from both the rehabilitated and non-rehabilitated (control) sites. In each of the sampling sites, transects lines were placed at 50m interval and three sampling plots of 15m × 15 m were laid in alternate positions along each transect at 50 m interval. Soil samples were collected at two depths (0-15 and 15-30 cm). Sampling was performed using the five-point sampling method in which soil was collected from five points (from each corner and in the middle of the plot) using soil auger and homogenizer to make a composite sample. Coordinates of each sampling points were taken using GPS.

The composite soil samples were properly packed in a plastic bag, labelled and transported to the laboratory. Upon arrival in the laboratory the samples were air dried ground and sieved to pass through 0.5 mm sieve for the analysis and determination of soil organic carbon (OC). The OC content of the soil will then be determined following the wet digestion method as outlined by Walkley and Black (1934).

For the determination of *bulk density*, a shallow pit of 30 cm length and 50 cm width will be opened in the centre of transect line. Undisturbed soil samples were then taken from each soil depth of the soil profile walls using a core sampler of known volume. In the laboratory, soil samples were dried in an oven at 105°C until constant weight is achieved, and bulk density was calculated as the mass of oven-dried soil (105 ºC) divided by its volume (Pearson et al., 2005).

$$\rho_b = \frac{W_d}{V_c}$$

where $\rho_b$= soil bulk-density (gm/ cm$^3$); $W_d$= weight of dry soil (gm); $V_c$= volume of core (cm$^3$)

The dried samples were sieved to remove coarse fragments such as stones or gravel that are larger than 2 mm in diameter and the weight of the coarse fragments and the fine soil fraction were weighted separately.

*Soil Organic Carbon Stock* (SOCS) was then calculated using the following equation (Martha et al., 2023)

$$\text{Soil organic carbon Stock} = D * \rho_b * (1 - CF/100) * \%SOC$$

Where, SOCS = Soil organic carbon stock (t/ha), D = Depth of the soil sample (cm), ρb = Bulk density (g $cm^{-3}$) of the soil layer, %SOC = Soil organic carbon content in (%) is determined in the laboratory following Walkley and Black (1934) method, CF= coarse fragment (>2mm) in percent.

The coarse fraction was determined using the following equation (Martha et al., 2023)

$$CF = (wt-wf/wt) *100$$

where wt represents the total weight of the soil samples and wf is the weight after the course fragment is separated.

The measurement of the soil organic carbon was conducted twice per year, during the dry and wet season.

**Statistical analysis and interpretation**

The survey data were analysed using descriptive statistics (mean, frequency, standard deviation and percentage) with the Statistical Package for Social Sciences (SPSS, version 20 for window, 2017). The yield, biomass and soil data were tested for significant differences between treated and control plots of each location using t-test.

**Timeline**

The Terms of Reference have set the overall timeline for the assignment. Currently, this timeline looks realistic. However, the rainfall patterns may vary across the study areas and affect the cropping calendar. This may influence the timing of data collection, crop yield and biomass measurements as well as the cropping pattern assessment.

Table 1 Timeline for Milestones

| Phase | Tasks | Time frame | Outcome |
|---|---|---|---|
| Develop a methodological inception report | • Review the available experience | September 2023 | Draft Inception report |
| Pre-mission survey | • Conduct a rapid field appraisal assessment<br>• Identify the exact locations for the yield and biomass measurements; soil organic carbon measurements; soil sampling and cropping pattern assessment; soil profile testing<br>• Inform local communities about the testing schedule.<br>• Mark the locations with GPS points and negotiate the conditions with local farmers | September 2023 | |
| 1st field level survey (harvesting season) | • Yield & biomass measurements<br>• Cropping pattern analysis,<br>• Soil sampling and determination of soil organic | October 2023 | Interim report |

| | | | |
|---|---|---|---|
| | carbon sequestration and<br>• Full soil profile testing | | |
| 2nd field level survey (dry season) | • Soil sampling and testing for tracking soil carbon sequestration | Dry season December 2023 & March 2024 | Interim report |
| 3rdfield level survey (harvesting season) | • Yield and biomass measurements<br>• Soil carbon sequestration<br>• Cropping pattern analysis | August – October 2024 | Interim report |
| Report writing, compilation and submission | • Laboratory analysis, data analysis and final report writing for each parameter | | Final report |

**Key Deliverables**

The contractor is expected to deliver the following results:

- A draft report on the existing knowledge and methods for assessing and measuring yield/biomass, soil sampling and testing (carbon sequestration) and cropping pattern, based on the terms of reference.
- Annual interim reports of the field level surveys on yield/biomass measurement, soil carbon sequestration and cropping pattern analysis, with data, analysis and preliminary findings.
- Annual final reports that summarize the results of the measurements for each parameter

**Team composition, Roles and Responsibilities**

A multidisciplinary team covering a wide range of disciplines, areas of expertise and experience took part in the study. The core evaluation team is comprised of four team members.

Table 2 Team composition, roles and responsibilities

| Name | Area of expertise | Bio | Responsibilities |
|---|---|---|---|
| Tesfu Mengistu (PhD) | ✓ Soil Fertility Management<br>✓ Agronomy<br>✓ Climate Smart Agriculture<br>✓ Environmental Sciences | Senior researcher of soil fertility management, Soil and Water Research Directorate, SoRPARI<br><br>Assistant professor of Soil Science, Jigjiga University, Jigjiga, Ethiopia | Team leader, leads the crop yield/biomass measurement, soil sampling and analysis and soil profile characterization, |
| Dahir Yusuf | ✓ Watershed management<br>✓ Irrigation<br>✓ Natural resources management | Director, Soil and Water Research Directorate, SoRPARI<br>Lecturer of Natural resources management, Jigjiga University | Leads and facilitates the field and laboratory activities |
| Mohammed Oumer | ✓ GIS<br>✓ Watershed management | Researcher, Soil and Water Research Directorate, SoRPARI | Leads the cropping pattern assessment and designing and mapping of |

| | | | |
|---|---|---|---|
| | | | the study locations |
| Mustefe Ibrahim | | Researcher, Soil and Water Research Directorate, SoRPARI | Facilitate yield and biomass measurement |
| Nasri Mohamed | Agronomy, watershed management | Researcher, Soil and Water Research Directorate, SoRPARI | Facilitate the FGD, KII and field observation activities |

## Results and Discussion

### Cropping Patterns

For the assessment of cropping patterns, the study used field survey methods that involved collecting primary data from farmers or other stakeholders through interviews, group discussions, and observations.

### Household characteristics

The survey collected information from 60 respondents. The results for the socioeconomic characteristics indicated that, of the total household heads or their representatives who participated in the survey, 100% were male and there were no female participants. This indicates the low level of women involvement in farming and/or decision making. Moving on to age distribution, the majority of respondents fell within the 41-60 age range, with 37 respondents (61.7%) falling into this category. Interestingly, there were no respondents below the age of 30. Regarding marital status, all respondents were married. No single, divorced, or widowed individuals were included in the survey. The family size data revealed that most households had 7 or more children, with 24 respondents (40%) falling into the 7-9 children category. Education levels varied among the respondents. The majority (60%) were illiterate, while 38.3% had received informal education. Only one respondent (1.7%) had completed elementary education, and there were no respondents with secondary or post-secondary education.

Farm size was another important aspect. The crop landholding of most farmers fell within the 1-3-hectare range, with 48 respondents (80%) owning farms of 1-3 hectares. Only 3 respondents (5%) own farms larger than 4 hectares. The years of practice in farming showed that most respondents (55%) had been engaged in farming for 21-30 years.

Table 3 Household characteristics

| Variable | Frequency | Percentage |
|---|---|---|
| Sex | | |
| Male | 60 | 100 |
| Female | 0 | 0 |
| Age | | |
| <30 | 0 | 0 |
| 31-40 | 7 | 11.7 |
| 41-50 | 18 | 30 |
| 51-60 | 19 | 31.7 |
| >60 | 16 | 26.7 |
| Marital status | | |
| Single | 0 | 0 |
| Married | 60 | 100 |
| Divorced | 0 | 0 |
| Widowed | 0 | 0 |
| Number of Children | | |
| 1-3 | 0 | 0 |
| 4-6 | 12 | 20 |
| 7-9 | 24 | 40 |
| 10-12 | 12 | 20 |
| >12 | 12 | 20 |
| Education | | |
| Illiterate | 36 | 60 |
| Informal education | 23 | 38.3 |
| Elementary education | 1 | 1.7 |
| Secondary education | 0 | 0 |
| Post-secondary | 0 | 0 |
| Farm size (ha) | | |
| <1 | 0 | 0 |
| 1-2 | 24 | 40.0 |
| 2-3 | 24 | 40.0 |
| 3-4 | 9 | 15.0 |
| >4 | 3 | 5.0 |
| Years of practice in farming | | |
| <10 | 0 | 0 |
| 11-20 | 13 | 21.7 |
| 21-30 | 33 | 55.0 |
| 31-40 | 13 | 21.7 |
| >40 | 1 | 1.7 |

## Farming practices

*Dominant crops in the study areas*

Additionally, a minority of farmers (5%) reported cultivating sorghum, maize, and pepper together. Adding pepper suggests that some farmers are diversifying their crops beyond the staples. Only one respondent mentioned growing sorghum, maize, onions, and pepper simultaneously. This combination represents the least common scenario but highlights the potential for crop diversification and farmers' adaptability to different crops.

Generally, the prevalence of sorghum and maize cultivation underscores their importance in the study areas. Meanwhile, the inclusion of onions and pepper reflects farmers' exploration of diverse crops to meet various needs, including subsistence, cash income, and flavour preferences.

Table 4 Major crops grown in the study areas

| Crops | Frequency | Percentage |
|---|---|---|
| Sorghum and Maize | 48 | 80 |
| Sorghum, Maize, and Onion | 8 | 13.3 |
| Sorghum Maize, and Pepper | 3 | 5.0 |
| Sorghum, Maize, Onion and Pepper | 1 | 1.7 |

Figure 1 Sorghum and maize crops planted in rehabilitated plots

*Reasons for crop selection in the study areas*

When asked about their primary reasons for choosing specific crops, 28 respondents (43.8%) cited drought tolerance as the most crucial factor. Given the region's unreliable rainfall distribution and frequent drought occurrences, farmers prioritize crops that can withstand prolonged dry conditions. Another group of respondents (15 individuals, 25%) emphasized higher yield as their primary criterion for crop selection. These farmers opt for crops with greater yield potential to maximize productivity. Such crops likely contribute significantly to food security and feed availability.

Interestingly, 12 respondents (20%) prefer a balanced approach, cultivating crops that combine resilience (drought tolerance) with productivity (high yield). In contrast, only 2 respondents (3.3%) specifically prioritize crops with disease resistance and high yield traits (as shown in Table 3).

Overall, farmers' choices reflect a pragmatic approach, considering both environmental challenges and productivity goals. Thus, breeding and research efforts should focus on developing crop varieties that combine these desirable traits.

Table 5 Reason for choosing the specific crops

| **Reason for choosing** | **Frequency** | **Percentage** |
|---|---|---|
| Drought tolerance | 29 | 48.3 |
| Higher yield | 15 | 25 |
| Disease resistance | 1 | 1.7 |
| Drought tolerance and higher yield | 12 | 20 |
| Disease resistance and higher yield | 2 | 3.3 |
| Drought tolerance and disease resistance | 1 | 1.7 |

*Purpose of growing specific crops in the study areas*

The findings from Table 4 shed light on the reasons behind major crop cultivation in the study areas. Most respondents 31 (51.7%) reported growing crops for both food consumption and livestock feed. This dual-purpose approach suggests an integrated farming system where crops fulfill multiple roles. About 14 (23.3%) of the respondents primarily cultivate crops to support their livestock production. These crops serve as essential feed for their animals. About 11 (18.3%) of the respondents focus on growing crops primarily for direct human consumption within their households. Ensuring food security for their families is their priority, contributing to a stable food supply. A smaller proportion of farmers (6.7%) indicated that their crops serve both household consumption/feed and the market. These farmers likely sell surplus produce in local markets, generating income while meeting their own needs.

In summary, the diverse purposes behind crop cultivation underscore the multifaceted nature of agriculture in the study areas. Striking a balance between food security, livestock requirements, and income generation is crucial for sustainable farming practices.

Table 6 Purpose of the crops grown

| **Crops** | **Frequency** | **Percentage** |
|---|---|---|
| Food (Home consumption) | 11 | 18.3 |
| Feed (Livestock feed) | 14 | 23.3 |
| Food and Feed | 31 | 51.7 |
| Food/feed and market | 4 | 6.7 |

*Best performing crops*

The survey results indicate that sorghum is the most popular crop among the surveyed farmers. This was stated by 39 respondents (representing 65% of the total). Maize follows closely, with 17 respondents (about 28.3%). Onion received only one mention (approximately 1.7%), while pepper was mentioned by 3 farmers (making up 5% of the responses). These preferences provide insights into crop performance and may be influenced by factors such as climate, soil type, and market demand. Further analysis could explore the reasons behind these choices and their impact on farm productivity.

Table 7 Best performing crop as perceived by farmers

| **Crops** | **Frequency** | **Percentage** |
|---|---|---|
| Sorghum | 39 | 65 |
| Maize | 17 | 28.3 |
| Onion | 1 | 1.7 |
| Pepper | 3 | 5 |

*Major cropping system practiced by farmers of the study areas*

The majority of farmers interviewed**,** 36 (60%), engage in simple forms of crop rotation. Crop rotation involves the systematic change of the type of crop grown in a field over time. This practice has been shown to improve soil health, manage pests, and enhance overall sustainability. Notably, most farmers in the study area rotate only sorghum and maize, which belong to the same family. However, including crops from different families, such as legumes, would be more beneficial.

As illustrated in Table 8, approximately 21 (35%) of the respondents continued to engage in monocropping, which entails cultivating a single crop on a given plot of land. Farmers who adhere to monocropping may prioritize maximizing yields of a specific crop. However, monocropping can result in soil nutrient depletion and heightened susceptibility to pests and diseases.

A few respondents, 3 (5%), employed intercropping (mixed cropping). Intercropping refers to the simultaneous cultivation of two or more crops in the same field. The practice of intercropping allows farmers to benefit from the complementary interactions between crops. Relay cropping involves the planting of a second crop before the harvesting of the first. Since there were no reported instances of relay cropping, it appears to be less common in the study areas.

The encouragement of diverse cropping systems, such as intercropping, can lead to more resilient and productive agriculture.

Table 8 Major cropping systems practiced by farmers

| **Crops** | **Frequency** | **Percentage** |
|---|---|---|
| Monocropping | 21 | 35 |
| Crop rotation | 36 | 60 |
| Intercropping/mixed cropping | 3 | 5 |
| Relay cropping | 0 | 0 |

**Impact of Water Spreading Weirs (WSWs) on Land Characteristics and Cropping System**

During our initial field survey, our team thoroughly explored all study locations and observed the remarkable impact of water spreading weirs (WSWs) in rehabilitating degraded lands. The key findings are described in the following paragraphs.

*Effective rehabilitation of gullies*

Many gullies, previously formed by water erosion, have now been filled with sediments and are levelled due to the strategically placed WSWs. These weirs effectively mitigate erosion, allowing the land to recover. Agricultural areas once abandoned due to severe gullies are now productive again.

**Farmer’s Testimony**

At Hare, a farmer shared a compelling story. His field had remained abandoned for over two decades because of a massive gully caused by water erosion. The gully was deeper than an average person’s height, rendering crop cultivation impossible. However, the construction of a series of WSWs along the gully line transformed the landscape. Now, this previously unusable land supports diverse crops. Other farmers echoed similar sentiments across all study sites. They expressed overwhelming gratitude for the positive effects of WSWs in restoring their once-wasted agricultural lands.

During the focus group discussions in Gerbile, farmers highlighted a reoccurring problem. Before water-spreading weirs (WSWs) were constructed, their crops and valuable topsoil were often swept away by high runoff water. This unfortunate situation left them unable to harvest biomass and grains. However, the introduction of WSWs had a transformative effect. These structures effectively mitigated the impact of high runoff water, reduced soil erosion, and conserved precious soil and water resources. As a result, crop growth was significantly supported.


Figure 2 Plots rehabilitated by water spreading weirs across different locations

*Crop diversity*

Sorghum and maize emerged as dominant crops in the rehabilitated fields across all locations. Interestingly, some farmers at Hare experimented with rain-fed onion cultivation, while others at Amedle and Gerbile included pepper cultivation. In Amadle, Togshuro, and Hare, fruit crops like mangoes, guavas, papayas, and avocados now thrive. These fruit crops were previously uncommon in these areas. Improved soil quality and water retention facilitated their successful growth.

Figure 3 Mango, Avocado, and Guava plantations in Amadle

Figure 4 Mango plantation in Hare

In addition to the fruit crops, eucalyptus tree seedlings were also observed thriving in the rehabilitated fields alongside the fruit crops in Hare and Togshuro. However, cultivating eucalyptus tree plants within crop fields is not a recommended practice. Eucalyptus has an allelopathic effect on other crops, suppressing their growth. This situation likely arises from a lack of awareness among farmers regarding the impact of eucalyptus on other crop plants. Consequently, there is a pressing need to raise awareness among farmers and provide training on how to utilize rehabilitated lands productively.

Figure 5 Eucalyptus plantation on rehabilitated fields at Hare (left) and Togshuro (Right)

*Double cropping*

The construction of WSWs has enabled double cropping in most study locations. This allows farmers to maximize their yields by planting multiple crops in a year. Our comprehensive field survey across Amedle, Hare, Deneba, and Hodale documented several noteworthy practices among farmers. These included the commendable practice of replanting for a second cycle after harvesting the initial sorghum or maize crop. This approach maximises land productivity and ensures a continuous supply of staple grains and fodder. In particular, farmers in Amedle, Hare, and Deneba were observed planting and harvesting sorghum biomass specifically for their livestock. The ratoon sorghum, which grows from the base of the original plant after the main harvest, provides valuable fodder for animals. This sustainable practice contributes to both food security and livestock well-being.

Figure 6 Sorghum ratoon crop growing after harvesting of the main crop (Deneba)

Figure 7 second planting made after harvesting of the first crop (Hare)

### *Water storage for livestock*

Water-spreading weirs (WSWs) serve as multifunctional structures and contribute significantly to land rehabilitation. In addition to their primary purpose of mitigating soil erosion and improving moisture retention and groundwater recharge, WSWs play a crucial role in water storage for livestock. WSWs effectively trap and distribute water across eroded landscapes, and the accumulated soil sediments fill the gullies and stabilise the land. Soil moisture is preserved, promoting crop growth and ecosystem restoration.

Farmers in Hare and Hodale shared their firsthand experiences. Following the construction of WSWs along gully lines, these structures serve as impromptu reservoirs. They store water until the weirs are fully filled and levelled by sediment. This stored water is a lifeline for livestock, especially during the rainy seasons. By providing a local water source, WSWs save farmers and their animals the arduous task of searching for water over long distances. The time and energy saved by utilising the stored water has a positive impact on the livelihoods of agro-pastoralists. Livestock no longer need to wander far in search of water, which ensures their health and productivity. Farmers can focus on other essential tasks, knowing that their animals have reliable access to water.

Figure 8 Water stored in half filled WSWs for livestock drinking

## Impact of Water Spreading Weirs on Crop Yield & Biomass

### Biomass measurements

The biomass yield measurement involved natural grasses from six locations and forage sorghum from two locations. As the current year rain started early, the sorghum and maize crops that are mainly planted for grain and livestock feed were harvested earlier than the usually anticipated time.

*Natural grasses*

The yields of fresh and dried biomass from natural grasses are presented in the table below (Table 9). As can be seen from the table, the treated plots exhibit higher biomass yields than the control plots. Notably, Amedle, Deneba, and Hare show highly significant ($P < 0.01$) improvements in fresh and dried biomass yield after rehabilitation. However, Bolidid, Gerbile and Hodale demonstrate only marginal differences. This can be attributed to the livestock's open grazing of the natural grasses in these locations. Bolidid, in particular, had small communal grazing land that was continuously and severely grazed by livestock. Generally, these findings demonstrate the effectiveness of water spreading weirs in enhancing natural grass biomass production across various locations.

Table 9 Fresh and dry biomass yield of natural grass on treated and control plots across different locations

| Location | Mean fresh biomass yield (kg/ha) | | P value of t-test | % Increase | Mean dry biomass yield (kg/ha) | | P value of t-test | % Increase |
|---|---|---|---|---|---|---|---|---|
| | Treated | Control | | | Treated | Control | | |
| Amedle | 7863.9 | 3917.2 | 0.0009 | 100.75 | 4531.1 | 2831.1 | 0.0072 | 60.05 |
| Bolidid | 4263.3 | 4210 | 0.3253 | 1.27 | 2883.3 | 2519.4 | 0.3497 | 14.45 |
| Deneba | 15900 | 7139.4 | 0.0048 | 122.71 | 11159 | 4317.2 | 0.0034 | 158.4 |
| Gerbile | 9006.1 | 7010.6 | 0.3784 | 28.48 | 5818.9 | 4333.3 | 0.2678 | 34.28 |
| Hare | 17083 | 6780.6 | 0.0094 | 151.94 | 11637 | 4091.1 | 0.0062 | 184.4 |
| Hodale | 8780.6 | 7332.2 | 0.2134 | 19.75 | 4763.9 | 4317.8 | 0.3641 | 10.33 |

*Forage sorghum*

Agro-pastoralists plant sorghum primarily as forage for their livestock. In our study, harvestable forage sorghum was obtained and measured from Bolidid and Deneba. At Bolidid, the treated plots yielded an impressive 32,973 kg/ha of fresh biomass, while the control plots produced only 13,833 kg/ha. This substantial difference corresponds to a remarkable 138.36% increase in biomass yield for the treated plots. The statistical analysis, represented by the p-value of 0.0190, confirms the significance of this difference (Table 8).

Similarly, at Deneba, the treated plots exhibited a fresh biomass yield of 38,925 kg/ha, surpassing the control plots' yield of 26,899 kg/ha. Although the difference is statistically not significant ($P>0.05$), the increase of 44.7% remains noteworthy.

Regarding the dry biomass, the treated plots at Bolidid achieved a mean yield of 9,621.7 kg/ha, significantly higher than the control plots' yield of 4,776.1 kg/ha. This represents a substantial 101.45% increase in dry biomass production. The P-value of 0.0212 reinforces the statistical significance of this result.

In the case of Deneba, the treated plots yielded 21,484 kg/ha of dry biomass, while the control plots produced 14,646 kg/ha. This translates to a 46.69% increase in biomass yield for the treated plots. Although the p-value of 0.2061 indicates less statistical certainty, the trend remains consistent.

The consistent superiority of the treated plots in both fresh and dry biomass yield underscores the positive impact of water spreading weirs (rehabilitation). These findings have practical implications for agricultural practices, as they demonstrate the potential benefits of such interventions. Further research into the mechanisms driving this improvement would enhance our understanding and guide future efforts to optimize crop productivity.

Table 10 Fresh and dry biomass yield of forage sorghum on treated and control plots across different locations

| Location | Mean fresh biomass yield (kg/ha) | | P | % Increase | Mean Dry biomass yield (kg/ha) | | P | % Increase |
|---|---|---|---|---|---|---|---|---|
| | Treated | Control | | | Treated | Control | | |
| Bolidid | 32973 | 13833 | 0.0190 | 138.36 | 9621.7 | 4776.1 | 0.0212 | 101.45 |
| Deneba | 38925 | 26899 | 0.1839 | 44.7 | 21484 | 14646 | 0.2061 | 46.69 |

**Yield Measurements**

As the rain fall amount and distribution of this year was so good that planting and harvesting of the major crops- sorghum and maize was done earlier than the usually anticipated time in most of the study locations. While farmers could make second planting in most of the locations, we could get harvestable yield only from three locations: Bolidid (Sorghum), Amedle (Maize) and Hodale (Sorghum and Maize). The mean grains yield as well as the total dried aboveground biomass yield of the sorghum and maize from treated and control plots of these areas are presented in tables 9 and 10.

*Maize*

This study of maize yield examined the impact of water-spreading weirs on crop productivity across three locations: Amedle, Deneba, and Hodale. The treated plots, where weirs were implemented to restore degraded soils and enhance water availability, consistently outperformed the non-rehabilitated (control) plots. It is noteworthy that the treated plots in Amedle exhibited an impressive 79.48% increase in grain yield, while those in Deneba and Hodale demonstrated substantial improvements of 60.96% and 47.49%, respectively. These findings underscore the positive role of water management strategies in sustainable agriculture, benefiting both food and feed security and local livelihoods. The statistically significant differences ($P < 0.05$) observed for Amedle and Deneba highlight the efficacy of the weirs. Further research is required to investigate the long-term sustainability and scalability of these approaches, with the aim of optimising the benefits and addressing food security challenges in arid regions.

Table 11 Total above ground dry biomass and grain yield of maize on treated and control plots of different locations

| Location | Total above ground dry biomass yield (kg/ha) | | P | % increase | Grain yield (kg/ha) | | P | % Increase |
|---|---|---|---|---|---|---|---|---|
| | Treated | Control | | | Treated | Control | | |
| Amedle | 9566.1 | 6123.3 | 0.0175 | 56.22 | 4165.0 | 2320.6 | 0.0111 | 79.48 |
| Deneba | 8916.7 | 6167.8 | 0.0440 | 44.57 | 3387.2 | 2104.4 | 0.0488 | 60.96 |
| Hodale | 8853.3 | 6567.8 | 0.4147 | 35.00 | 3135.0 | 2125.6 | 0.1754 | 47.49 |

Similarly, we observed significant differences in comparing the total aboveground dry biomass yield between fields rehabilitated by water-spreading weirs (treated) and non-rehabilitated (control) plots. The treated plots consistently outperformed the control plots regarding dry biomass production across the three locations: Amedle, Deneba, and Hodale. The percentage increase in maize dry biomass yield ranged from 35% in Hodale to an impressive 56.22% in Amedle. These findings highlight the positive impact of soil and water management strategies, emphasizing the importance of water-spreading weirs in enhancing agricultural productivity and livelihoods. Further research should explore scalability and long-term sustainability to maximize these benefits.

*Sorghum*

Harvestable sorghum yield was obtained and measured only from two locations: Bolidid and Hodale. At Bolidid, the average grain yield from treated plots was 3469.4 kg/ha, while control plots yielded 2241.1 kg/ha. This represents a significant increase of approximately 54.81% in grain yield for the treated plots.

Similarly, in Hodale, treated plots produced an average of 3225.6 kg/ha of sorghum grain, compared to 1712.8 kg/ha from control plots. The percentage increase in grain yield for treated plots here is even higher at 88.32%. The P value of the t-test (a statistical test) for both locations is below the conventional significance level of 0.05, indicating that the differences in grain yield are statistically significant.

Regarding the total aboveground dry biomass, treated plots in Bolidid had an average total yield of 12,841 kg/ha, whereas control plots yielded 8419.6 kg/ha. This represents a 53.51% increase in biomass yield due to the WSWs treatment.

In Hodale, treated plots yielded an average of 15234 kg/ha of dry biomass, compared to 9453.3 kg/ha from control plots. The percentage increase in biomass yield for treated plots in Hodale is approximately 61.15%. The low P values ($P < 0.05$) of both locations suggest that the observed differences are unlikely due to random chance, reinforcing the validity of the findings.

Table 12 Total above ground dry biomass and grain yield of sorghum on treated and control plots across different locations

| Location | Total above ground dry biomass yield (kg/ha) | | P value of t-test | % increase | Grain yield (kg/ha) | | P value of t-test | % Increase |
|---|---|---|---|---|---|---|---|---|
| | Treated | Control | | | Treated | Control | | |
| Bolidid | 12841 | 8419.6 | 0.0421 | 53.51 | 3469.4 | 2241.1 | 0.0294 | 54.81 |
| Hodale | 15234 | 9453.3 | 0.0249 | 61.15 | 3225.6 | 1712.8 | 0.0089 | 88.32 |

## Impact of Soil Rehabilitation through WSWs on Soil Organic Carbon Stock (SOCS)

Soil organic carbon (SOC) sequestration refers to capturing atmospheric carbon by plants or decaying organic matter and its subsequent storage in soil. This process unfolds in three phases: firstly, $CO_2$ is absorbed from the air through plant photosynthesis; secondly, this carbon is incorporated into plant tissue; and thirdly, it transitions from the plant matter into the soil, becoming part of the SOC within a highly active pool. This particular pool has a rapid turnover rate, spanning from days to a few years, and includes fresh plant debris that soil organisms can easily break down, often leading to the release of $CO_2$ back into the atmosphere. Effective SOC sequestration strategies must, therefore, extend beyond mere $CO_2$ capture, focusing on methods to secure carbon within the more inert, slow SOC pool (FAO, 2017).

The table below (Table 11) shows the impact of soil rehabilitation through water-spreading weirs on the soil organic carbon stock (SOCS) in the top 30 cm of soil across seven different locations. The data indicates that treated plots have a higher SOCS compared to control plots in all locations (except for Togshuro), suggesting that water-spreading weirs have a positive effect on increasing soil organic carbon. This is beneficial as higher organic carbon content can improve soil quality, fertility, and water retention. The P values from the t-test provide insight into the statistical significance of the differences observed between treated and control plots. However, a statistically significant ($P < 0.05$) increase in SOCS was observed only for Amedle and Bolidid, while the P values for all other locations are higher ($P > 0.05$), suggesting that the observed differences might not be statistically significant. Of course, the process of increasing soil organic carbon is typically slow (decadal), and significant changes in soil organic carbon storage may take time to manifest.

The percentage increase in SOCS ranges from -5.20% in Togshuro to 47.72% in Hodale, highlighting the variability in the effectiveness of soil rehabilitation across different locations. Hodale showed the most substantial increase, which could be due to various factors such as initial soil conditions, the extent of degradation, and the effectiveness of the water-spreading weirs. In contrast, Togshuro's treated plots had lower SOCS than the corresponding control plots. This discrepancy may be attributed to disturbances caused by crop cultivation in the treated areas. This was also evidenced during sample collection that the WSWs are constructed in close intervals at Togshuro, and the plots in the cascade areas were all disturbed for crop cultivation. The cultivation practices might have led to the loss of SOC and a low stock of SOC.

Overall, the results suggest that water spreading weirs can significantly enhance the soil organic carbon stock, which is a crucial component of soil health and productivity. However, the effectiveness varies by location, and further research might be needed to understand the factors influencing these outcomes fully. Additionally, long-term studies could provide insights into the sustainability of the observed increases in SOCS.

Table 13 Soil organic carbon stock of WSW treated and control plots across different locations

| Location | Mean SOCS in top 30cm (Mg/ha) | | P value of t-test | % increase |
|---|---|---|---|---|
| | Treated | Control | | |
| Amedle | 57.033 | 47.729 | 0.0308 | 19.49 |
| Bolidid | 42.465 | 37.906 | 0.0497 | 12.03 |
| Deneba | 57.751 | 53.223 | 0.2647 | 8.51 |
| Gerbile | 54.240 | 44.550 | 0.0754 | 21.75 |
| Hare | 67.415 | 57.186 | 0.4500 | 17.89 |
| Hodale | 36.278 | 24.558 | 0.3193 | 47.72 |
| Togshuro | 49.486 | 52.158 | 0.4487 | -5.12 |

**Challenges in Utilizing Rehabilitated Fields**

Despite the evident success of water spreading weirs (WSWs) in restoring eroded lands, several challenges persist. Addressing these obstacles is crucial to maximizing the benefits of rehabilitated fields. Some of the key challenges were:

*Limited Awareness and Knowledge*: Many farmers remain unaware of the best practices for utilizing rehabilitated land effectively. In areas like Amedle, Hare, and Deneba, some farmers left their plots idle even after the WSWs had fully restored the fields. Educating farmers about crop rotation, soil management, and sustainable farming techniques is essential. Empowering them with knowledge will lead to more productive land use.

Figure 9 plots left fallow after rehabilitation at Hare (left) and Amedle (right)

*Excessive Moisture Retention*: In certain cases, the rehabilitated fields retained more moisture than expected due to the effectiveness of the WSWs. While this is beneficial for the growth of some crops, it also posed challenges for field operations. Targeted training and technical support can help farmers make the most of their reclaimed lands. Careful selection of suitable crops and maintaining a balance in soil moisture levels becomes critical to avoid waterlogged conditions.

*Seed Availability for Crop Diversification*: Some farmers lack access to improved seeds for cash crops other than sorghum and maize. In Deneba, for instance, the absence of quality seeds for some vegetable crops like onions and tomatoes restricts diversification. Efforts to provide better seed varieties can enhance crop options and promote diversity.

*Physical Damage to WSWs*: Some WSWs suffer from wear and tear. Internal cracks in the soil allow water to leak beyond the intended boundaries, undermining the effectiveness of the structures. In areas prone to heavy runoff or floods, reinforcement of the WSWs is crucial. Instances like the dismantling of a WSW in Gerbile due to strong flood currents highlight the need for robust construction.

Figure 10 Physically damaged WSWs at Gerbile (left) and Bolidid (right)

In summary, by addressing knowledge gaps, improving seed availability, and reinforcing WSW structures, we can overcome these challenges and create sustainable, productive agricultural landscapes.

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## Appendix

Pictures captured during field and laboratory activities

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