

**Improved agronomic practices increase productivity of teff in a
water erosion-prone environment**

(水食が起こりやすい環境における改良栽培法によるテフの生産性
向上)

Fekremariam Asargew Mihretie

The United Graduate School of Agriculture Sciences

Tottori University, Japan

2021

**Improved agronomic practices increase productivity of teff in a water
erosion-prone environment**

(水食が起こりやすい環境における改良栽培法によるテフの生産性向上)

A dissertation submitted to The United Graduate School of Agricultural Science,
Tottori University in partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Global Dryland Science

Fekremariam Asargew Mihretie

The United Graduate School of Agriculture Sciences, Tottori University, Japan

Major Supervisor:

Atsushi Tsunekawa (Prof.)

Co-supervisors:

Nigussie Haregeweyn Ayehu (Prof.)

Mitsuru Tsubo (Prof.)

*This thesis is dedicated to **my father, Major**
ASARGEW MIHRETIE TESHAYE and **my mother**
AZEB DESTA BERHANE*

For their endless love, care and support

ACKNOWLEDGEMENTS

In the first place, I would like to forward appreciation to Prof. Atsushi Tsunekawa for his unreserved, kind support and guidance throughout the course of my doctoral study. He is one of the exemplary mentors that I have ever met who is extremely dedicated to nurture and coach junior research fellows like me. Beyond the scientific guidance, working with Professor Atsushi Tsunekawa was also another precious opportunity for me to learn and experience the power of positivity, kindness, patience, the art of listening and being structured.

My sincere thanks then goes to Prof. Nigussie Hargeweyn, Prof. Enyew Adgo, Prof. Misturu Tsubo and Prof. Masunaga Tsujiyuki for all their advice, support and encouragement all the way through designing field research activities to organization of this doctoral thesis. Again, I would like to thank Dr. Dereje Meshesha, Dr. Kindiye Ebabu, Dr. Asaminew Tassew, Ms. Yoshimi Katsumata and Ms. Yukari Inagaki for their restless facilitation and support during the implementation of field activities in Ethiopia. Special thanks goes to Mr. Anteneh Wubet and Mr. Nigus Tadesse, Ms. Agerselam Guadie, Mr. Fantahun Ferede, Mr. Abebe who were directly managing the data collection, monitoring and data encoding in my absence; it was extremely difficult for me to achieve this without their unlimited commitment given the past political instability and COVID pandemic in Ethiopia.

I also want to say thank you for the staff of Arid Land Research Center namely Yumi Sakai-san, Emako Tomemori-san and Junko Bandai-san for their continuous and kind support in facilitating and fixing all the administrative issues that really made my life in Tottori (Japan) very smooth and comfortable.

Above all, I would like to thank my mother (Azeb Desta), a strong woman behind all my success and for she is always there praying for me no matter how bad or good the situations are. My wife, Tilksew Awoke takes the top position for the successful completion of my doctoral study by being remained persistent in hardships and successfully managing the family in my absence. I should also thank my lovely sons, Christian Fekremariam and Ethel Fekremariam for they gave me another strong reason to live, work and hope in life.

Finally, I am grateful to The Ministry of Education, Culture, Sports, Science and Technology (MEXT) for providing the scholarship to attend graduate school at Tottori University, Japan and JICA-SATREPS for providing support for executing field research activities in Ethiopia. I also acknowledge Amhara Regional Agricultural Research Institute (ARARI) and Bahir Dar University for their technical and logistical support whenever I was in need of.

On top of all the above, I thank God for his blessings, always placing me ahead of my way, keeps me healthy, strong and confident.

Thank you, God, for giving me another new day, another opportunity to become a better person, and another opportunity to live!!

TABLE OF CONTENTS

LIST OF TABLES	V
LIST OF FIGURES	VII
1. Chapter 1 – General introduction	4
1.1. Background	4
1.1.1. Teff cultivation in Ethiopia	4
1.1.2. Crop management practices of teff	6
1.2. Rationale of the study	9
1.3. Research questions.....	10
1.4. The objectives of the study	11
1.5. Conceptual framework.....	11
1.6. Organization of doctoral thesis	13
1.7. Description of the study area	16
2. Chapter 2 - Exploring crop management and soil properties responsible for teff yield variability in northwestern Ethiopia	21
2.1. Introduction.....	21
2.2. Materials and methods	25
2.2.1. Sampling and data collection	25
2.2.2. Soil analysis	27
2.2.3. Data analysis	27
2.2.4. Economic analysis.....	29

2.3.	Results.....	30
2.3.1.	Variations of teff cropping practices.....	30
2.3.2.	Ranges of soil fertility parameters	34
2.3.3.	Variation of grain yields	35
2.3.4.	Economics of teff production.....	44
2.4.	Discussions	46
2.4.1.	Variations in cropping practices	46
2.4.2.	Variations of soil fertility	49
2.4.3.	Grain yield variation	50
2.4.4.	Economics of teff production.....	54
2.5.	Conclusion	55
3.	Chapter 3 - Tillage and crop management impacts on soil loss and crop yields in northwestern Ethiopia.....	58
3.1.	Introduction.....	58
3.2.	Materials and methods	60
3.2.1.	Site description.....	60
3.2.2.	Treatments and experimental setup.....	61
3.2.3.	Data collection and analysis.....	64
3.3.	Results.....	66
3.3.1.	Sediment concentration and soil loss	66
3.3.2.	Temporal trends in sediment concentration and soil loss	71
3.3.3.	Crop yield.....	75

3.4.	Discussion	77
3.4.1.	Sediment concentration and soil loss	77
3.4.2.	Temporal trends in sediment concentration and soil loss	80
3.4.3.	Crop yield.....	82
3.5.	Conclusions.....	83
4.	Chapter 4 - Agro-economic evaluation of alternative crop management options for teff production in midland agro-ecology, Ethiopia	85
4.1.	Introduction.....	85
4.2.	Materials and Methods.....	88
4.2.1.	Site description.....	88
4.2.2.	Experimental setup.....	89
4.2.3.	Data collection and analysis.....	90
4.3.	Results.....	92
4.3.1.	Teff growth	92
4.3.2.	Weed infestation	100
4.3.3.	Lodging	100
4.3.4.	Grain and straw yields.....	103
4.3.5.	Profitability	103
4.4.	Discussion	107
4.4.1.	Teff growth	107
4.4.2.	Weed infestation	108
4.4.3.	Lodging	111

4.4.4.	Teff grain and straw yields.....	111
4.4.5.	Profitability	114
4.5.	Conclusions.....	115
5.	Chapter 5- General conclusions.....	118
	SUMMARY	122
	概要.....	126
	LIST OF PUBLICATIONS	131
	REFERENCE	132

LIST OF TABLES

Table 2-1. Summary of crop-management practices applied on teff farms at the three study sites.....	32
Table 2-2. Agronomic calendar for teff cultivation at the three study sites	33
Table 2-3. Levels of selected soil-fertility parameters for topsoil samples from teff farms	35
Table 2-4. Mean grain yields (GY) and straw yields (SY) (kg ha ⁻¹) at the study sites.	43
Table 2-5. Cost of production, net return, and labor productivity associated with implementation of major agronomic practices for teff cultivation at the three sites.	45
Table 2-6. Major constraints on teff-producing smallholder farmers	46
Table 3-1. Agronomic practices applied during the three monitoring seasons (2017–2019).....	63
Table 3-2. Summary of results of analysis of variance (F-values) for the main and interaction effects of tillage (TL), planting method (PM), and trampling practice (T) on sediment concentration, soil loss, and runoff in 2017, 2018, and 2019 cropping seasons.	67
Table 3-3. The effects of tillage, planting method, and trampling practices on monthly and total soil loss (t ha ⁻¹) in 2017 and 2019 teff growing seasons.....	68
Table 3-4. Effects of tillage, planting method, and trampling treatments on total nitrogen (TN), total organic carbon (TOC), and bulk density of soil samples collected in 2017 (baseline, before experiment) and after the 3-yr experiment (2019).	68
Table 3-5. Monthly rainfall amount and minimum, maximum, and mean rainfall intensity observed during the three cropping seasons (2017–2019) using data collected from automatic rain gauges on site.	81
Table 3-6. Effects of tillage, planting methods, and trampling on teff grain and straw yield at harvest, combined over years.	81
Table 4-1. Soil parameters for a composite topsoil (0–20 cm) sample collected from the experimental plots before the start of the experiment in 2018.....	88
Table 4-2. Effects of tillage, sowing, and soil compaction methods on panicle length of teff in 2018, 2019, and 2020.....	95

Table 4-3. Effects of tillage, sowing, and soil compaction methods on leaf area index at the tillering (September) and post-flowering (November) stages in teff in 2019 and 2020.	98
Table 4-4. Effects of tillage, sowing, and soil compaction methods on teff plant population at emergence and maturity stages in 2018, 2019, and 2020.	99
Table 4-5. Effects of tillage, sowing, and soil compaction methods on weed population at first and second weeding in 2018, 2019, and 2020.	101
Table 4-6. Influences of tillage, sowing, and soil compaction methods on grain and straw yields of teff in 2018, 2019, and 2020.	105
Table 4-7. Partial cost–benefit analysis for the different tillage, sowing, and soil compaction practices.	106

LIST OF FIGURES

Figure 1-1. Annual Area coverage (Mha, million hectare), production volume (Mton, million ton) and yield (ton/ha) of cereal crops in Ethiopia (Data source: CSA, 2019).	6
Figure 1-2. Diagram that shows the conceptual framework how tillage, sowing methods and soil compaction influence teff yield and soil loss.....	12
Figure 1-3. Diagram indicates the structure of the PhD thesis.....	15
Figure 1-4. Map of the study areas.....	18
Figure 1-5. Long-term (2000–2019) climatic conditions at the three study sites. RF, rainfall; Tmax, maximum temperature; Tmin, minimum temperature; Rad, solar radiation.....	19
Figure 2-1. Mean teff grain yields of farms that rotated teff with different precursor crops (2018) at the three study sites.....	34
Figure 2-2. Teff grain yield variability among farms and study sites.	38
Figure 2-3. Regression tree showing relationships and variability of teff grain yield (GY) with different rates of N application and sowing density. N, number of farms (observations).	39
Figure 2-4. Regression tree showing the variability of teff grain yield with different levels of soil fertility parameters.....	39
Figure 2-5. Maximum grain yield prediction lines generated using the boundary points within scatter graphs of grain yield on the y-axis and fertilizer (P and N) application rates, sowing density, and days to planting/harvest on the x-axis.	40
Figure 2-6. Maximum grain-yield prediction lines generated from the boundary points within scatter graphs of grain yield and selected soil fertility parameters of farms at the three sites..	41
Figure 2-7. Crop management practices and soil fertility parameters identified as yield-limiting factors based on the percentage share of the frequency of observation over farms at the three study sites.	42
Figure 3-1. The individual effects of tillage (a), planting method (b), and trampling (c) on sediment concentration (SC) during the three monitoring seasons. Numbers of observations (n) were 24, 19, and 22 for 2017, 2018, and 2019, respectively.....	69

Figure 3-2. The combined effects of tillage, planting methods, and trampling on sediment concentration in 2019 (n = 22).	70
Figure 3-3. Relationships between daily runoff and soil loss in 2017 and 2019.	72
Figure 3-4. The trends of daily sediment concentration (SC) across months in 2017, 2018, and 2019.....	73
Figure 3-5. The pattern of teff biomass yield (BY) during the measuring season of 2019, as influenced by tillage (a), planting method (b), and trampling (c).....	74
Figure 3-6. The effects of tillage (a) and planting methods (b) on daily soil moisture content during the measuring period in 2019.....	76
Figure 4-1. Long-term (2000–2020) average monthly rainfall (RF-long-term), maximum temperature (Max-tem-long), minimum temperature (Min-tem-long), and solar radiation (Solar rad-long-term) in the study area.....	89
Figure 4-2. Mean teff plant height throughout the growing months (August to November) obtained with different tillage, sowing, and soil compaction practices.	94
Figure 4-3. Effects of tillage, sowing, and soil compaction practices on teff lodging in 2018, 2019, and 2020.	102
Figure 4-4. Average monthly soil moisture under different tillage (a), sowing (b), and soil compaction (c) practices in 2019 and 2020.	110
Figure 5-1. Diagram showing how reduced tillage (a) and row sowing (b) and avoiding soil compaction influenced teff yield.	121

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ARARI	Amhara Regional Agricultural Research Institute
BD	Bulk density
CIMMYT	International Maize and Wheat Improvement Center
CA	Conservation agriculture
CSA	Central statistics authority
CT	Conventional tillage
DAP	Diammonuim phosphate
FAO	Food and Agriculture Organization of the United Nations
GY	Grain yield
JICA	Japan International Cooperation Agency
m.a.s.l	Meter above sea level
MOA	Ministry of Agriculture
P level	Probability level
RO	runoff
RP	Row planting
RT	Reduced tillage
SATREPS	Science and Technology Research Partnership for Sustainable Development
SD	Standard deviation
SL	Soil loss

SLM	Sustainable land management
TN	Total nitrogen
TOC	Total organic carbon
UBNB	Uppper Blue Nile basin
UREA	$(\text{NH}_2)_2\text{CO}$
WLRC	Water and Land Resource Center
Yr	Year

CHAPTER ONE

GENERAL INTRODUCTION

Chapter one – General introduction

1.1. Background

1.1.1. Teff cultivation in Ethiopia

Agriculture contributes heavily to the Ethiopian economy by generating income, employment and foreign exchange. Agriculture contributes 41% of the country's gross domestic product (GDP), 84% of the total export and 85% of the employment (Baye, 2017). Crop production is the leading component of the agricultural economy and more than 12 million hectares of land is cultivated with grain crops and 32 million tons of grain is annually produced in Ethiopia (CSA, 2019). Teff [*Eragrostis tef* (Zucc.)], maize (*Zea mays*), sorghum (*Sorghum bicolor*) and wheat (*Triticum aestivum*) share 24%, 19%, 14% and 14% of the total grain crop production in Ethiopia, respectively (**Figure 1.1**). Teff is the most dominant cereal crop accounting for nearly 24% of the total food grain production while covering about 30% of the total food grain cultivated land in Ethiopia (Ferede et al., 2020). Amhara region is the largest supplier of teff in the country that share 40% of the total teff production of Ethiopia (CSA, 2019). Teff is the staple food crop and its straw is a major source of livestock feed in Ethiopia (Gelaw and Qureshi, 2020). Teff is used to make the traditional flat bread injera, as well as bread, pancakes, porridge, and alcoholic beverages (Mihretie et al., 2021a). Teff is mainly grown as a forage crop outside Ethiopia. Demand for teff grain products is increasing worldwide due to its increasing popularity as a gluten-free grain (Tietel et al., 2020). Teff grain is also rich in lysine, iron, and calcium compared to other cereals.

However, teff production in Ethiopia is a subsistence, and rainfall dependent enterprise with poor crop management systems exacerbated by uncertainties due to unpredictable weather conditions and land degradation (Di Falco et al., 2010). The rainfed teff production system in

Ethiopia is locked up by the traditional agronomic practices such as high frequency of tillage, mono-cropping and complete residue removal, use of low yielding crop varieties and occurrence lodging, prevalence of pests and diseases (Adimassu et al., 2019). These traditional agricultural practices are also the major drivers of natural resource degradation such as soil erosion and loss in biodiversity in Ethiopia (Taddese, 2001). Agronomic practices of the conventional teff cultivation system are the major reasons for low productivity ($<1.5 \text{ t ha}^{-1}$) and soil resource degradation (Berhanu et al., 2021). These problems have caused a low teff productivity that have led the once food secured communities to food insecurity and poverty.

Soil erosion from cultivated land in Ethiopia can reach as high as $72 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Ebabu et al., 2019). Soil loss from cultivated lands in Ethiopia is mostly driven by inappropriate land management practices, including excessive tillage, continuous cropping, and low organic matter addition (Tadesse et al., 2017). Proper management of croplands will thus play a huge role in reversing the problem caused by soil erosion and maximizing crop production in low-input, rain-fed agriculture. Because teff covers the majority of cultivated lands in Amhara region of Ethiopia, implementation of good agricultural practices that can improve teff productivity without harming soil resources would be crucial for the sustainable use and management of cultivated lands in erosion-sensitive areas in Amhara region and elsewhere.

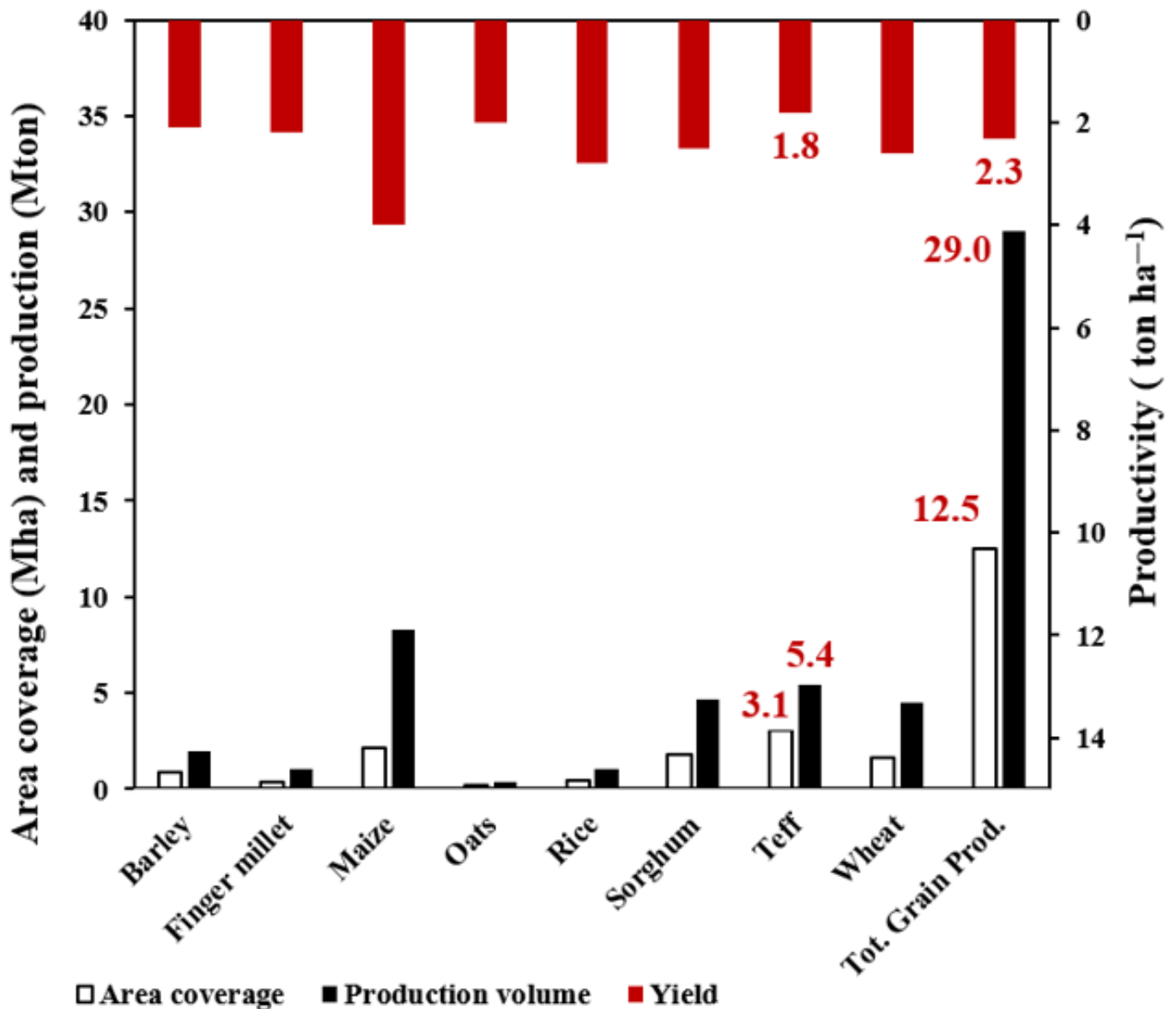


Figure 1-1. Annual Area coverage (Mha, million hectare), production volume (Mton, million ton) and yield (ton/ha) of cereal crops in Ethiopia (Data source: CSA, 2019).

1.1.2. Crop management practices of teff

The low yield in teff and land degradation caused by traditional crop management in Amhara region in particular and Ethiopia at large can be reversed by implementing good agricultural practices such as improved cultivars, reducing the number of tillage, crop residue

retention, intercropping and row sowing practices. Cultivation practices, primarily traditional methods, are also a major productivity constraint (Abera, 2017).

In traditional teff production, the land undergoes several ploughing (3-10 times) depending on the area using oxen or horse mounted ard 'maresha'. The aim of frequent ploughing is to create a fine seed bed for the small seed size of teff, reduce weed infestation, and allow rainwater infiltration and soil aeration (Lipiec et al., 2006). However, several ploughings expose farmers to high cost, aggravates organic matter loss, soil erosion in teff cultivation system (Mesene, 2017). Poor farmers are constrained by a shortage of oxen and limited family labor during peak times (Hailu et al., 2017). The effect of tillage is variable, depending on time farm, plot scale, tillage implement, crop type, soil type and climatic factors (Alskaf et al., 2020). To reverse the negative impacts of conventional tillage approaches, the concept of reduced tillage, which encompasses minimizing the amount of tillage, using mixed cropping or crop rotation, incorporating crop residues, and using pre-emergent herbicides to control weeds, was developed (Mäder and Berner, 2012). Reduced tillage conserves the natural resources by minimizing soil disturbance and avoids costs associated with frequent ploughing. Reduced tillage approaches have been shown to improve crop productivity, improve soil quality, and reduce soil erosion in major cereals such as maize (Ndoli et al., 2018), sorghum (Schlegel et al., 2018), and wheat (Khorami et al., 2018). However, because reduced tillage results in large weed populations, which can compete with the crop for nutrients and reduce the crop biomass that will be later used as feed for livestock or as an energy source for cooking, this approach requires application of pesticides that are potentially harmful to the environment (Khorami et al., 2018). Another drawback of reduced tillage is that it needs to be practiced for a long period of time before the desired changes in soil quality and crop yield are seen; this is problematic because farmers generally prefer to use technologies that offer an

immediate economic benefit (Bai et al., 2018). Despite these drawbacks, the implementation of reduced tillage activities in Ethiopia has been reported to reduce soil erosion and improve yield in maize (Ndoli et al., 2018) and sorghum (Burayu et al., 2006).

Farmers hand-scatter teff seed (broadcasting) at high seeding rate mainly to suppress weeds, save labor and also because of the ease of sowing and good quality straw for livestock (Vandercaesteelen et al., 2013). However, broadcasting method of sowing causes uneven distribution of seeds leads to less resource utilization (light, water and nutrient) and it's not convenient for farm operation and mechanization such as for weeding and herbicide application (Mihretie et al., 2020) and also wastes seed. When planted using broadcasting, as the fertilizer applied will not place near the root zone, it's highly subjected to weed competition (Blackshaw et al., 2002). High plant population results in low tillering capacity and thus reduced crop root formation that helps to a better anchorage and thus reduce lodging from the root base (root lodging). The production of weaker stems due to the high competition also aggravates lodging (Matsuyama and Ookawa, 2020). Row sowing is an alternative to broadcast sowing, and although the effects of row sowing are highly dependent on soil type, the tillering capacity of the cultivar used, timing and amounts of nutrients applied, and seeding density and spacing between rows, this approach has been shown in teff to improve growth and yield, and to use less seed than broadcast sowing (Mihretie et al., 2021a). In addition, unlike in broadcast sowing, in row sowing nutrients can be placed near the root zone (Vandercaesteelen et al., 2014). It has been suggested that the improvements in teff productivity brought about by row sowing are the result of efficient resource utilization, increased tillering, reduced lodging, and the facilitation of farm activities (Vandercaesteelen et al., 2018a) . In teff, row sowing has also been shown to be more economical than broadcast sowing and seedling transplantation (Mihretie et al., 2021a).

A unique practice in teff production is the process of compacting the soil by human or animal (cattle, donkey, or horses) trampling immediately before sowing (Gebretsadik et al., 2009). The purpose is to increase the contact area between the seed and the soil, reduce the risk of the seed being displaced by rain water, and seal the soil surface to reduce the loss of moisture through evaporation (Tefera et al., 2001a). However, compaction is a costly practice because it requires a large number of people or animals to thoroughly compact large planting areas. Compacting the soil is also known to aggravate soil loss via runoff by reducing rainwater infiltration (Amare et al., 2004).

1.2.Rationale of the study

The traditional practices are the main drivers of soil loss that leads to a low teff productivity in Ethiopia. Improved practices that could enhance teff productivity are thus highly required. Conservation-based agricultural practices that minimizes soil loss by the runoff by minimizing soil disturbance such as reducing the number tillage operations and avoiding soil compaction together with crop residue retention, crop rotation and intercropping practices improves crop productivity and farmer's income with no or less soil loss (Scopel et al., 2013). Among well-known options, the use of reduced tillage with improved sowing methods such as row sowing without soil compaction could improve the crop growth and yield while reducing in erosion-prone teff growing areas. Previous findings do also suggest that combining these practices may be a cost-effective means of improving teff productivity.

However, their agronomic performance and economic advantages have not been compared with those of the traditional practices in Ethiopia. This calls for the need for evaluating the comparative performance of different tillage and sowing methods for teff production. In the other

hand, little has been understood about the overall characteristics of the teff based cropping system, therefore, it is inevitable to explore major factors contributing for the low productivity and variability among teff farms before any research intervention. In this doctoral research, we hypothesized that integrated use of reduced tillage, row sowing without soil compaction improves teff productivity by creating a favorable soil conditions for crop growth and yield formation. Therefore, after an assessment was made to understand teff cultivation system and identify major crop management practices responsible for teff yield variation, a field experiment was conducted to examine whether the application of reduced tillage, row sowing and soil compaction practices, individually and in combination, could improve the agronomic and economic performance of teff in erosion-prone environment in northwestern Ethiopia.

1.3.Research questions

- What are the major crop management practices and soil properties responsible for teff yield variation?
- Do reducing tillage, row sowing and avoiding soil compaction minimize soil loss compared to conventional tillage, broadcast sowing with soil compaction?
- Do reducing tillage, row sowing and avoiding soil compaction improve growth and yield of teff compared to conventional tillage, broadcast sowing with soil compaction?
- Do reducing tillage, row sowing and avoiding soil compaction reduce cost of teff production compared to conventional tillage, broadcast sowing with soil compaction?

1.4.The objectives of the study

General objective: To evaluate improved agronomic practices on teff productivity in a water erosion-prone environment.

Specific objectives:

1. To assess yield variability and its influencing factors in traditional teff cultivation system.
2. To evaluate the impact of different tillage, sowing and soil compaction practices on soil loss and
3. To investigate the effects of different tillage, sowing and soil compaction practices on teff productivity.

1.5.Conceptual framework

As illustrated in the conceptual framework below (**Figure 1.2**), studies in this doctoral research project were initiated based on the hypothesis that reduced tillage and avoiding soil compaction practices could improve the crop growth and yield by minimizing of a surface disturbance that helps to increase biomass cover, conserve soil moisture and soil fertility, and prevents removal (washing) of applied seed and fertilizer by the runoff in water erosion-sensitive areas. Reduction in surface disturbance and sealing due to reduced tillage and avoiding soil compaction practices were assumed to finally influence the amount of runoff generated and the soil that could be lost with runoff. The less soil loss (nutrient loss) and runoff will result in better soil nutrient and moisture status that could be available for crop growth. Row sowing was assumed to improve crop yield by maximizing resource utilization (water, light and nutrients) through placement of the applied fertilizer near the root zone, optimization of the plant population and space utilization in

the crop-weed interface. Better resource utilization associated with improved sowing methods will untimely result in an increased light interception, soil moisture and nutrients around the root zone for teff growth, development and yield formation.

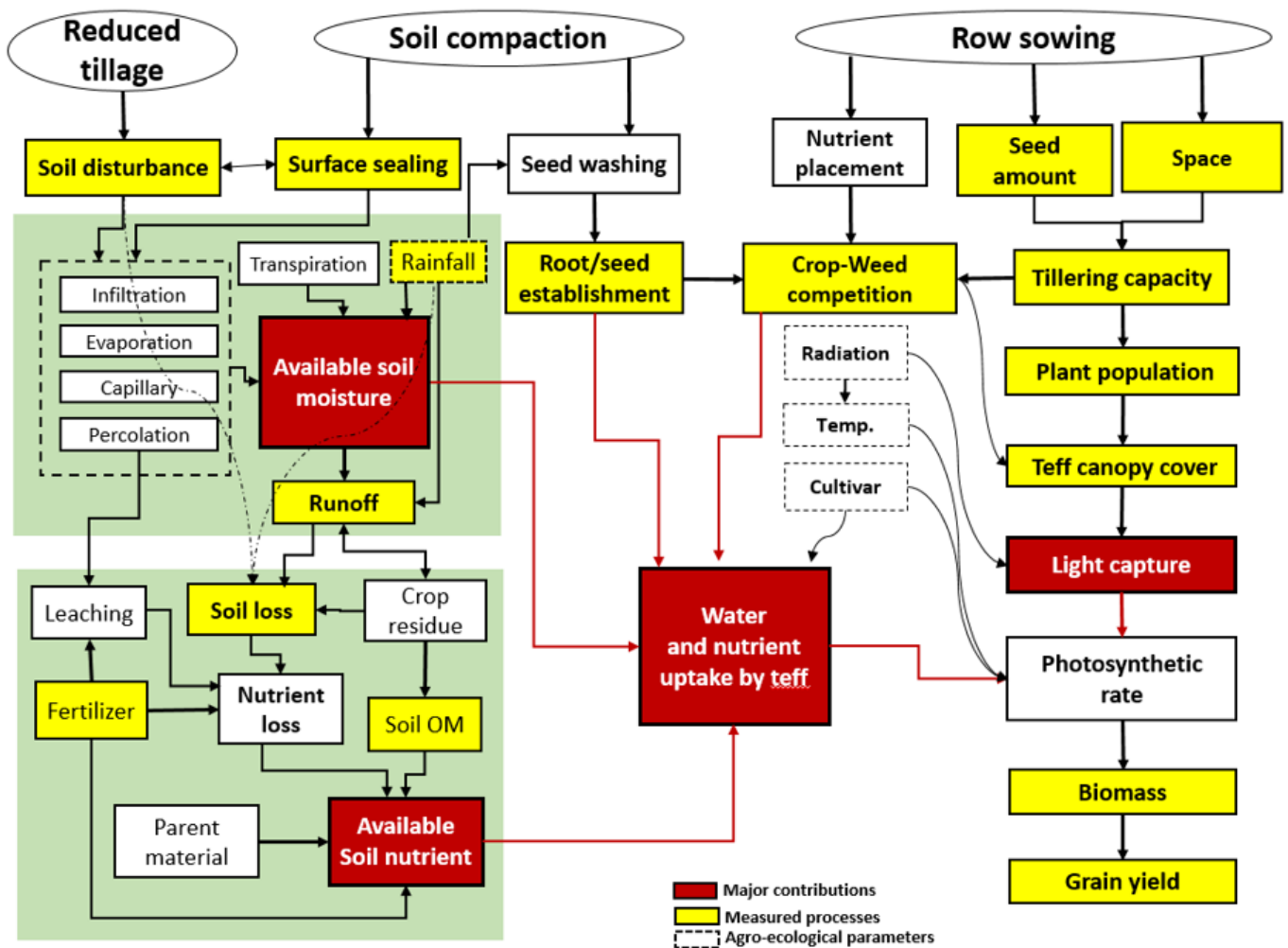


Figure 1-2. Diagram that shows the conceptual framework how tillage, sowing methods and soil compaction influence teff yield and soil loss.

1.6. Organization of doctoral thesis

The structure of the doctoral thesis that comprises five chapters is illustrated in **Figure 1.3** and shortly summarized as below.

Chapter one: This chapter introduces the overall picture of the crop production in Ethiopia in general and teff cultivation system. The chapter also indicates the constraints and opportunities for yield improvement in teff. Supported with a literature, it also addresses the theoretical background how reduced tillage and improved crop management practices can improve crop yield through better access to light, soil moisture and nutrient.

Chapter two: This chapter examines the teff cultivation system in three contrasting agro-ecologies of northwestern Ethiopia. In this chapter, the association of teff yield variability at farmer's field with crop management practice and soil properties were also discussed. Frequent tillage and the traditional sowing methods were found to be the major reasons for the low productivity and high cost of teff production that highlighted the need for testing and promoting improved agronomic options such as reduced tillage, row sowing without soil compaction, residue incorporation and crop rotation as means to enhancing teff productivity.

Chapter three: this chapter presents the findings of the evaluation of different tillage, sowing and soil compaction practices on soil loss and their association with topsoil conditions at one of the well-established regional learning watersheds (Aba-Gerima) in northwestern Ethiopia. Reduced tillage, row sowing without soil compaction practices improved soil fertility, biomass cover and soil moisture through reduction in runoff and soil loss compared to conventional tillage, broadcast sowing and soil compaction practices.

Chapter four: this chapter presents the result of evaluation of different tillage, sowing and soil compaction practices on teff productivity and profitability at Aba-Gerima watershed. Reduced tillage, row sowing without soil compaction practices were found improved teff productivity compared to conventional tillage, broadcast sowing and soil compaction practices.

Chapter five: this chapter synthesizes the findings from chapter two, three and four. The traditional teff cultivation system was found to be a low productive, not cost-effective and aggravates soil erosion. This chapter concluded that reduced tillage, row sowing without soil compaction practices can be promoted as an alternative agronomic options to improve teff productivity in a soil erosion-prone environment through enhancing favorable topsoil conditions for teff growth.

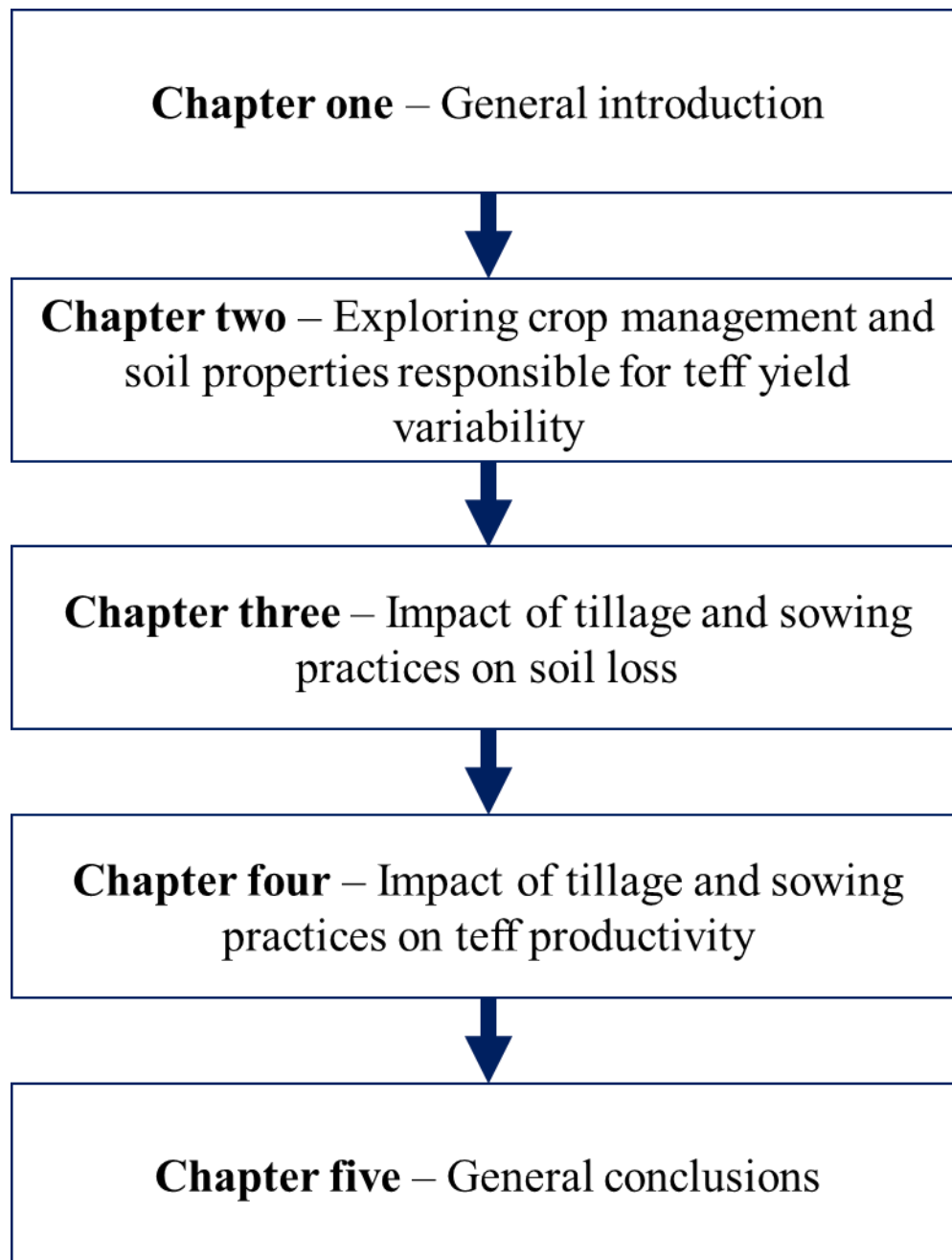


Figure 1-3. Diagram indicates the structure of the PhD thesis.

1.7. Description of the study area

The studies in this doctoral research were carried out in northwestern Ethiopia. First, the field survey activity (presented in chapter two) was done in contrasting agro-ecologies represented by three watersheds (Guder, highland; Aba-Gerima, midland; Dibate, lowland). After identification of possible research interventions for improving teff productivity from the field survey (chapter two), a field experiment (presented in chapter three and four) was done at Aba-Gerima watershed. Aba-Gerima watershed was selected for field experimentation because it was one of the well-established regional learning watershed for researchers, development practitioners and farmers in Ethiopia since 2012 where different sustainable land management (SLM) research and development programs have been implemented (Nigussie et al., 2018). Recent interventions by Water and Land Resource Center (WLRC) and SATREPS-JICA-Next-generation SLM can be mentioned as an example.

Moreover, Aba-Gerima watershed was selected as a field experimental site because it represents the midland teff growing agro-ecology with a well-established watershed management system that helps to monitor soil and crop characteristics, long-term weather data, established linkage with farmer research groups and the availability of baseline data (demography, biophysical and socio-economic), and easy access to skilled labor that offers a huge opportunity for effectively implementing agronomic field research studies with a better scientific accuracy and minimum investments.

Guder watershed, Aba-Gerima and Dibate watersheds are located in the Upper Blue Nile Basin, northwestern Ethiopia (**Figure 1.4**). Guder and Aba-Gerima are found in Amhara; and Dibate is found in Beneshangul-Gumuz regional states in Ethiopia. The elevation ranges are 2489–2882 m at Guder, 1487–1718 m at Dibate, and 1912–2126 m at Aba-Gerima. According to

Mekonnen (2016), the dominant soils are Acrisols and Luvisols at Guder, Vertisols and Luvisols at Dibate, and Luvisols and Leptosols at Aba-Gerima, based on the Food and Agriculture Organization classification system. Based on long-term (2000–2019) climate observations, the mean annual rainfalls are 2222 mm at Guder, 2182 mm at Dibate, and 1445 mm at Aba-Gerima (**Figure 1.5**). The three sites receive more than 80% of their annual rainfall from June to September. The mean daily temperatures are 20.0 °C at Guder, 23.8 °C at Dibate, and 22.2 °C at Aba-Gerima.

Rainfed agriculture is the mainstay of the livelihood of smallholder farmers (the average land holding is ~0.25 ha per household) at the three sites, and mixed crop–livestock farming is the dominant farming practice. The major cash crops grown are teff (*Eragrostis tef*), barley (*Hordeum vulgare*), triticale (*×Triticosecale*), potato (*Solanum tuberosum*), and acacia (*Acacia decurrens*) at Guder; teff, finger millet (*Eleusine coracana*), maize (*Zea mays*), groundnut (*Arachis hypogaea*), and hot pepper (*Capsicum frutescens*) at Dibate; and teff, finger millet, maize, and khat (*Catha edulis*) at Aba-Gerima.

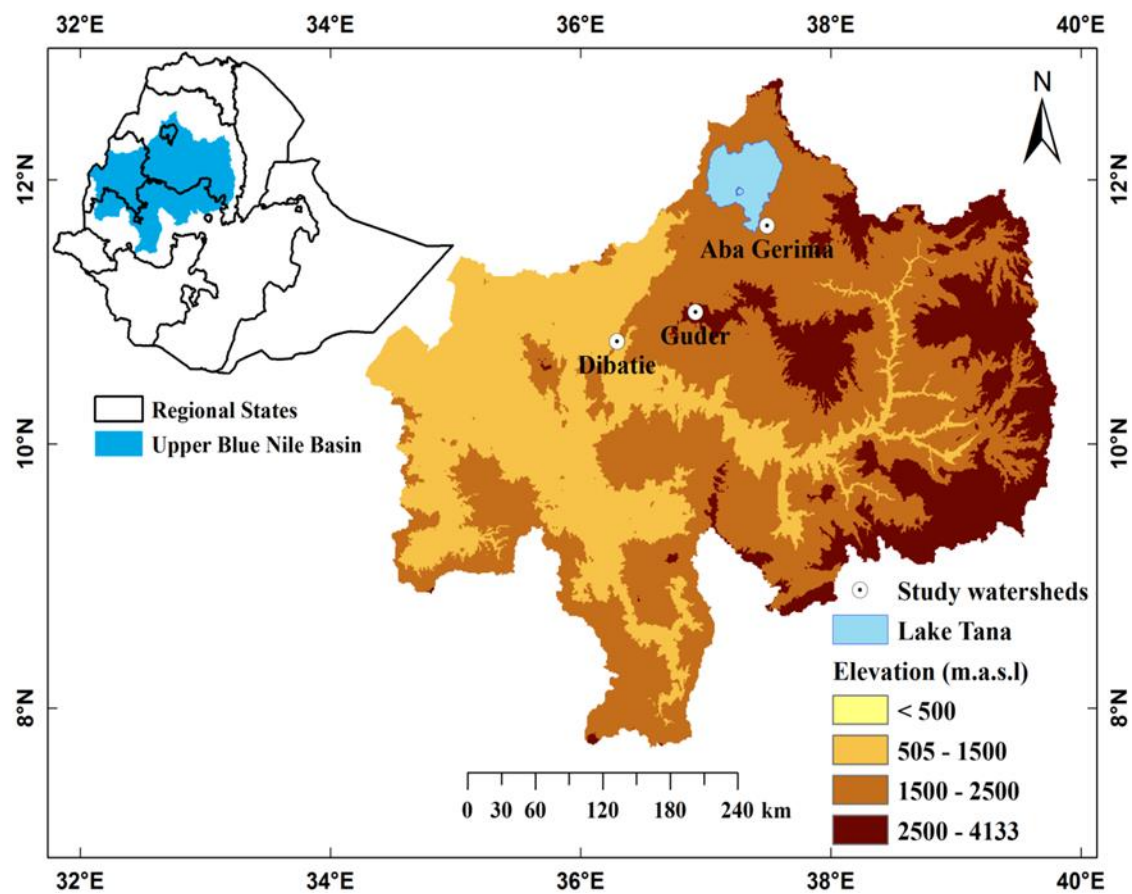


Figure 1-4. Map of the study areas

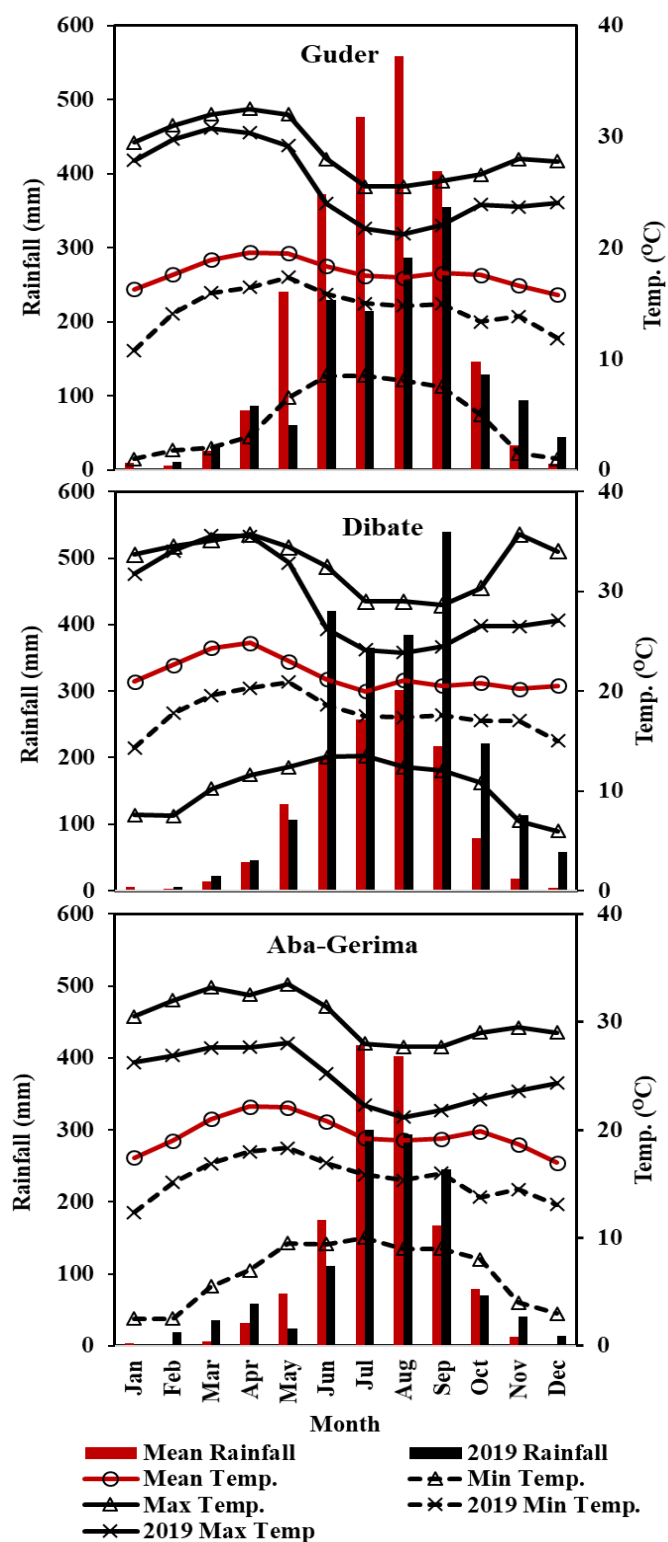


Figure 1-5. Long-term (1999–2019) climatic conditions at the three study sites. Mean rainfall; Max. temp, maximum temperature; Min. temp., minimum temperature.

CHAPTER TWO

**Exploring crop management and soil properties responsible
for teff yield variability in northwestern Ethiopia**

Chapter two - Exploring crop management and soil properties responsible for teff yield variability in northwestern Ethiopia

2.1.Introduction

In Ethiopia, teff (*Eragrostis tef* [Zucc.] Trotter) is an important food-security crop and a source of income for millions of smallholder farmers (Paff and Asseng, 2018). Its grain is widely used for human consumption, and teff straw is used as fodder for livestock (Assefa and Chanyalew, 2018). The majority of small-scale famers in Ethiopia prefer to grow teff because it is most adaptable to a wide range of environmental conditions. Compared with other cereals, teff can grow well in marginal areas and is highly tolerant of drought (Gelaw and Qureshi, 2020). Teff can also grow well under waterlogged conditions in the black soils (Vertisols) that account for more than 20% of the cultivated lands in Ethiopia (Haileselassie et al., 2011). Teff is less susceptible to diseases and postharvest pests than other cereals (Assefa et al., 2015), it is a gluten-free cereal suitable for celiac (gluten-allergic) patients, and it is rich in nutrients (e.g., lysine, Fe, and Ca) compared with other cereals (Barretto et al., 2020). The global demand for teff grain products is likely to increase because of its health benefits and growing adaptation in agroecological farming (Baye, 2014).

Teff yields (20%–40%) are lower than those of other small-grain cereals such as wheat and finger millet (Baye, 2014), but the market demand for and price of both teff grain and straw are higher than those for other cereals (Seyfu, 1997), in part because of the low volume of teff production. The Ethiopian government has consequently been forced to restrict exports of teff grain and flour to avoid domestic market shortages (Sankaranarayanan et al., 2020). An improvement in teff productivity is therefore needed to satisfy the requirements for food security in Ethiopia and to meet the growing demand on the international market (Abraham, 2015). The low productivity has been attributed mainly to lack of improved crop management practices and a

decline in soil fertility exacerbated by the high susceptibility of teff to lodging (Mihretie *et al.*, 2021).

The poor soil fertility and low teff productivity in the rainfed growing areas of Ethiopia are attributed mainly to continuous cropping, repeated tillage, inadequate addition of organic matter, complete removal of crop residues, and little or no compensation for removal by application of external inputs (Karlton *et al.*, 2013). There are also wide variations in grain yields among teff farms as a result of differences in the practices used to manage crops and in soil fertility (Fikadu *et al.*, 2019). The variations in crop yields among neighboring farms suggest that improvements in the practices used to manage crops and soil fertility could narrow the gaps in yields between smallholder farmers (Van Ittersum *et al.*, 2013). Raising the yields of low-yielding farms could contribute to substantial improvement of overall yields. However, the existing heterogeneity in crop yields among farms across different teff-growing agroecological zones, its relationship to crop management, and biophysical and socioeconomic conditions are not well understood and remain unexploited (Tesfaw *et al.*, 2021). The factors that control crop grain yield are complex, and controlling yield requires a thorough investigation of the interactions among genetic and environmental factors (Anderson *et al.*, 2016). According to Van Ittersum *et al.* (2013), a better understanding of the cropping system and of the relative importance of different management practices and soil attributes is necessary to increase productivity and yield at different spatial scales (farm, region, nation, world). In Ethiopia, it has been reported that the gap between the actual yields of local cultivars that farmers grow ($\sim 1500 \text{ kg ha}^{-1}$) and the potential yields of improved cultivars such as ‘Quncho’ and ‘Kora’ ($2500\text{--}2800 \text{ kg ha}^{-1}$) is very high (Haileselassie *et al.*, 2016). Even when farmers that practice traditional plant husbandry have grown improved teff cultivars, their yields have been much lower than the potential because of poor crop and soil management

practices (Asrat et al., 2010). In most cases, the farmers who achieve the best yields are those who grow improved cultivars and use improved management practices such as row sowing versus broadcasting and adequate application of N and P fertilizers (Vandecasteele et al., 2014). Differences in sowing density, N and P application rates, and weed-management practices are also major factors responsible for the variability of teff yields among farms and locations in Ethiopia (Mihretie et al., 2020).

Heterogeneity in soil fertility is an important cause of the variability of crop yields among farmers in Ethiopia (Haileselassie et al., 2011). The overall agroecological setup of a cropping system affects determinants of crop yields such as radiation, soil moisture, and nutrient utilization (Mann and Warner, 2017). Similarly, crop yields are highly variable from season to season because of differences in temperature and amounts of rainfall (Basso and Liu, 2019). Most rainfed teff is grown as part of a crop rotation system wherein a series of different types of crops is grown in the same area across a sequence of growing seasons. It was therefore more important in this study to examine the spatial variability than the seasonal variability of teff production.

Most previous studies have been based on farm experiments designed to understand the impact on crop yields of a single or a few crop-management and soil-management practices. In those studies, variables that were not of interest have been assumed to be constant (Tittonell et al., 2008). The relationship between crop yields and explanatory variables (crop management and soil properties) in such studies have been explained primarily with the use of standard correlation, regression, and principal component analyses (Delmotte et al., 2011; Tittonell et al., 2008). Furthermore, results of farm survey studies aimed at identifying the causes of the variability of crop yield performance at the farm level can be greatly influenced by the interactive effects of several uncontrolled environmental and socioeconomic factors (Sileshi et al., 2010). Unlike farm

experiments, data collected through farm surveys are usually skewed, and a mixture of categorical and continuous variables, missing observations, and multicollinearity can add complexity to the statistical analyses (Tittonell et al., 2008). Regression trees are now considered to be a more reliable method of analyzing data that are highly variable and represent actual agricultural systems (Tittonell et al., 2008). Regression and classification trees are non-parametric tools that can be applied to the analysis of skewed observations with a mixture of ordinal and non-ordinal variables and help deal with nonlinear relationships (Tittonell et al., 2008). Regression tree analysis is an important tool used in agricultural research for analyzing yield heterogeneity of different crops at different spatial scales in order to stratify variability into homogeneous groups and to reveal interactions of various crop-management practices and metrics of soil fertility (Lark and Stafford, 1997). Regression trees have been used to understand the spatial variability of grain yields and their relationships with the practices used to manage crop and soil fertility in the cases of rice (Delmotte *et al.*, 2011), maize (Tittonell *et al.*, 2008), and soybean (Zheng *et al.*, 2009).

Understanding the nature of a cropping system and the relative importance of crop-management and soil-related factors to variations of yields between farms is a key to improving the productivity of a target crop, because it enables farmers, experts, researchers, and policy makers to make informed decisions (Delmotte *et al.*, 2011). Little effort has been made to explain the major causes of variations in crop yields, differences among crop yields at the farm level, and the relative importance of different management practices and soil properties to crop yields in Ethiopia. This study was based on the hypothesis that there is a gap in teff grain yields among smallholder farmers that can be narrowed through improved management interventions. The spatial variations in crop yields were assessed at the farm level to identify important crop-management practices and metrics of soil fertility that could explain the differences in crop yields

among farmers in the same area and between locations in the Upper Blue Nile Basin of Ethiopia. This study had the following three objectives: (1) to understand the existing cropping systems used in teff-based, rainfed production systems in different environments; (2) to quantify the differences in grain yields among teff farms; and (3) to identify the major differences between environmental factors and management practices that explain the variability of grain yields among farms.

2.2. Materials and methods

The assessment was done at Guder, Dibate and Aba-Gerima watersheds located in Northwestern Ethiopia (**Figure 1.4**). Guder, Dibate and Aba-Gerima watersheds represent the highland, lowland and midland teff growing agro-ecologies, respectively (**Figure 1.4 and 1.5**).

2.2.1. Sampling and data collection

Before selection of the farms at each site, we undertook a series of field observations and consultations with local agricultural experts and key farmers to become informed about teff cropping systems and practices, identify teff-growing niches within the study sites, and draft a list of questions to ask during our interviews. A participatory transect walk involving one local agricultural expert and two farmers was then undertaken at each site to select the farms to be surveyed. Involvement of local farmers in this process helped us to identify the owners of farms. As a result, a total of 82 teff-growing farms (Guder, $n = 24$; Dibate, $n = 35$; Aba-Gerima, $n = 23$) were selected randomly along elevation transects.

Because farmers rotate different crops, we had no chance to evaluate the seasonal variability of teff yields from the selected farms. We therefore focused on exploring spatial variability based on the yield data for the 2017 cropping season, which had been forecast to be a representative (typical) growing season with favorable climatic conditions (adequate amounts of rainfall at all

sites) for teff cultivation (National Meteorology Agency, 2019). Farms were randomly selected by walking diagonally along a transect from one boundary to the other of each site. The number of farms thus varied across sites as a function of the number of teff-sown farms (Dibate > Guder > Aba-Gerima) and farmers' willingness to be involved in the study.

Afterwards, the head of each selected farm was interviewed with a survey questionnaire. The main content of the questionnaire focused on three major issues: (a) teff production and management practices (land preparation, cultivars used, sowing methods, sowing date, fertilizer application, weed control, and crop-rotation practices), (b) major constraints on teff production, and (c) the costs associated with all applied inputs (i.e., seed, fertilizer, and labor associated with crop management) during the 2019 cropping season. Prices of inputs and outputs were cross-checked with experts in nearby agricultural and cooperative offices.

When the crops were physiologically mature, crop cuts from each farm were taken for yield determination. Crop cuts were taken randomly (diagonally) at four sampling points in a 0.5-m² quadrat at teff farm, by hand. The harvest date for each farm was recorded during harvest time. Teff samples were transported to the laboratory and sun-dried for 4 days and manually threshed, and the grains were separated from the husks. The weights of the grains and straw were quantified on a Labman analytical balance and were used to extrapolate yields per hectare. After measurements had been completed, the samples were returned to the farmers. The economic value of both grain and straw were included in the profit calculation; prices were obtained from respective local market surveys during the harvest season.

Soil samples were taken immediately after harvest from farms at each site at the same spot where teff yield samples were collected. Eight topsoil samples were collected from each farm (4 spots × 2 samples) at a depth of 0–20 cm with a hand auger. A composite sample (500 g) was then

prepared from the 8 subsamples for laboratory analysis.

2.2.2. Soil analysis

The composite soil samples were analyzed for texture, total N (TN), organic C (OC), available P, pH, electrical conductivity (EC), cation exchange capacity (CEC), and micronutrients, namely Fe, Zn, Mn, and Cu. Soil texture was determined by the hydrometer method after each sample was shaken in a sodium hexametaphosphate (Calgon) solution (Bouyoucos, 1962). TN and OC were analyzed with a CN coder (Macro Corder JM1000CN, J-Science Lab, Kyoto Japan). Available P was determined by the Bray extraction method (Sims, 2000) and quantified on a spectrophotometer (UV-1800, Shimadzu, Japan). EC and pH were determined by the potentiometer principle (Hendershot et al., 1993): EC was measured with a conductivity meter (CM-30R, DKK-TOA, Japan), and pH was determined in a 1:2.5 soil-water solution with a pH meter (MM-60R, DKK-TOA, Japan). CEC was determined by mixing the soil with an excess of 1 N ammonium acetate solution. This procedure led to an exchange of the ammonium cations for exchangeable cations present in the soil solution (Chapman, 1965). Soil micronutrients were determined following extraction with pentetic acid (Liang and Karamanos, 1993) and quantified with an inductively coupled plasma atomic emission spectrophotometer (Shimadzu, Japan).

2.2.3. Data analysis

Data were analyzed in R v. 3.3.2 software (Core Development Team, 2013). All datasets were summarized to visualize the distribution and identify outliers. One observation from Aba-Gerima was identified as an outlier and was not considered in the statistical analysis. For crop management parameters with more than two levels (such as cultivars used and tillage frequency), mean grain yield was compared by the least significance difference procedure (Williams and Abdi, 2010) to detect differences. One-way analysis of variance (ANOVA) was used to test the significance of

differences in yield among farms at the 5% and 1% probability levels. A one-tailed *t*-test was used to test for differences of means of metrics between crop management practices, and a two-tailed *t*-test was used to test for differences of means of metrics between manure application, weeding frequency, and herbicide use.

Regression tree analysis, a predictive modeling approach that classifies observations into relatively homogeneous groups (Tittonell et al., 2008), was used to identify the major factors responsible for yield variability among sampled farms. The purpose of the regression tree was to predict the target variable (grain yield) on the basis of a set of predictor/explanatory variables (crop management practices and soil properties) using binary and recursive partitioning rules based on thresholds of predictor variables. To implement the regression tree, we adopted a minimum splitting criterion ($n = 10$) and fitted an optimum tree with minimum cross-validated errors. Explanatory variables that appeared at the top of the tree had stronger explanatory power than variables that appeared lower on the tree. Among the explanatory variables, those that did not appear in the regression tree were considered to be relatively (statistically) unimportant in explaining the observed yield variations. Explaining the observed yield differences using regular linear or multiple regression models would have been difficult because yields at the farm level were influenced by numerous, complex interactions that took place under uncontrolled environmental conditions (unlike designed farm experiments) (Delmotte et al., 2011). Use of regression trees was therefore the best way to reveal how yield variability could be predicted from the various explanatory variables (Delmotte et al., 2011).

After identification of the maximum possible yields (Shatar and McBratney, 2004), a boundary line approach was used to further clarify the most important yield-limiting factors. The maximum yield (Y-max) was predicted for each dependent variable at each value of the

independent variables (crop management and soil parameters). From a bi-dimensional scatter plot of each independent variable against yields, Y-max was predicted by using a boundary line fitted through boundary points of the corresponding highest observed yields. The Y-max predicted by the boundary line represented the maximum teff yield that could be achieved at each farm when limitations associated with crop-management practices or soil fertility parameters are limited. In accord with Liebig's law of the minimum (van der Ploeg et al., 1999), the lowest Y-max value predicted for all types of crop management and soil parameters was identified as the minimum of the maximum yield (Y-min). Crop management or soil fertility factors for which Y-min was frequently identified were considered to be yield-limiting factors. The comparative importance of a factor identified as yield limiting was further refined on the basis of its percentage occurrence at all teff farms ($n = 82$). Because consideration of a large number of observations leads to better statistical accuracy and because the trends of major results were similar across sites (no crossovers), the results from the three sites were combined (rather than analyzing each site individually) during the regression tree and boundary line analyses.

2.2.4. Economic analysis

Economic analysis was conducted by comparing the gross return and total cost of growing teff. Total cost was calculated from the cost of the inputs (seed and fertilizer) and labor (tillage, trampling, sowing, fertilizer application, weeding, harvesting, and threshing), and the gross return from the sales of grain and straw at market prices at harvest. Net return was then calculated as the difference between the gross return and the total cost of growing. The cost-benefit ratio was the ratio of gross return to total cultivation cost; a cost-benefit ratio of >1 is considered profitable. All input and output costs were converted to US dollars ($1 \text{ USD} \approx 32 \text{ Ethiopian birr}$). Our economic analysis did not consider the value of land, because most farmers own their land (renting farmland

is uncommon). The estimation of total cultivation costs was based on cost information collected directly from farmers, with the exception of the costs of renting animals (oxen or horses), which were set as the average rental costs obtained from the district agricultural and cooperative offices near each site.

The average teff grain prices (farm-gate) were 0.71 USD kg⁻¹ at Guder, 0.67 USD kg⁻¹ at Dibate, and 0.74 USD kg⁻¹ at Aba-Gerima. The average straw price was 0.02 USD kg⁻¹ at all three sites. The average seed cost was 0.85 USD kg⁻¹ for improved cultivars and 0.76 USD kg⁻¹ for local cultivars at the three sites. The regional average cost for NPS (9% N, 38% P, 7% S) and urea (46% N) fertilizers was 0.36 and 0.46 USD kg⁻¹ at the three sites. The labor cost per man-day was 2.6 USD at Guder, 2.1 USD at Dibate, and 3.1 USD at Aba-Gerima. The average rental cost was 4 USD day⁻¹ for a pair of horses at Guder and 6.6 USD day⁻¹ for a pair of oxen at Dibate and Aba-Gerima. A pair of oxen was assumed to plough 0.2 ha day⁻¹ (Jens *et. al.*, 2001). A pair of horses was assumed to plough 0.4 ha day⁻¹ (Gebregziabher *et al.*, 2016). Net return was calculated as total revenues minus total expenses.

2.3.Results

2.3.1. Variations of teff cropping practices

Observations on farms and interviews with farmers showed that teff cultivation practices were highly diverse across study sites and among farms (**Table 2.1**). The frequency of tillage ranged from 2 to 9 times a year and was higher at Guder than at Dibate and Aba-Gerima (**Table 2.1**). Most tillage was done between April and August at Guder and Aba-Gerima but was limited to June and July at Dibate (**Table 2.2**). At all sites, tillage was performed using a traditional ox-drawn ard, locally called a *maresha*, and the last tillage was performed on the day when teff was sown. The

range of the average depth of plowing with the *maresha* was 20–30 cm. With the exception of a few farmers at Dibate, farmers used cattle to compact (trample) the soil immediately before sowing (**Table 2.1**). Most farmers that we interviewed (95%) reasoned that trampling would facilitate contact of teff seeds with the soil and reduce lodging of teff plants. On average, sowing density was 8–50 kg ha⁻¹. It was greater at Guder than at Dibate and Aba-Gerima (**Table 2.1**). The window for teff planting was 15 July to 10 August at Guder, 20 August to 30 September at Dibate, and 15 July to 15 August at Aba-Gerima (**Table 2.2**).

With the exception of a few farmers at Aba-Gerima ($n = 10$) and Dibate ($n = 2$), farmers did not apply urea fertilizer (**Table 2.1**). However, all farmers at all sites applied NPS fertilizer. Farmers at Dibate applied more urea and NPS than farmers at Aba-Gerima and Guder. Manure application was not a common practice (**Table 2.1**). Most weeding was done only once, but a few farmers at Guder ($n = 7$) and Dibate ($n = 4$) weeded twice. The first weeding was usually done from 25 September to 25 October at Guder, from 1 September to 15 October at Dibate, and from 1 September to 30 October at Aba-Gerima. The second weeding was usually performed from 25 October to 15 November at Guder and from 25 September to 10 October at Dibate. Most farmers weeded by hand, but a few farmers at Dibate ($n = 8$) and Aba-Gerima ($n = 7$) applied herbicide (2,4-dichlorophenoxyacetic acid = 2,4-D) during the first weeding.

Cultivation of teff was rotated with cultivation of finger millet (*Eleusine coracana*), lupin (*Lupinus albus*), and maize (*Zea mays*) at Aba-Gerima; *Acacia decurrens*, potato (*Solanum tuberosum*), barley (*Hordeum vulgare*), and fallowing at Guder; and finger millet, groundnut (*Arachis hypogaea*), nug (*Guizotia abyssinica*), potato, and fallowing at Dibate (**Fig. 2.3**).

Table 2-1. Summary of crop-management practices applied on teff farms at the three study sites.

Agronomic inputs (unit)	Site		
	Guder (<i>n</i> = 24)	Dibate (<i>n</i> = 35)	Aba-Gerima (<i>n</i> = 23)
Land preparation and sowing			
Number of tillage operations	8 ± 1	3 ± 0	4 ± 1
Days to sowing date (from 1 Jul)	28 ± 7	63 ± 11	31 ± 10
Sowing density (kg ha ⁻¹)	31 ± 9	29 ± 11	22 ± 6
Days to harvest	160 ± 9	108 ± 19	137 ± 15
Number of trampled fields	24	34	23
Fertilizer application			
Number of urea-applied fields	—	2	10
Urea fertilizer rate (kg ha ⁻¹)	—	90 ± 14	63 ± 35
Number of NPS-applied fields	23	35	23
NPS fertilizer rate (kg ha ⁻¹)	47 ± 20	150 ± 46	121 ± 33
Number of manure-applied fields	5	—	—
Manure application rate (kg ha ⁻¹)	886 ± 893	—	—
Weed control			
Once-weeded fields	24	35	23
Twice-weeded fields	7	5	—
Number of herbicide-applied fields	—	8	7
Type of herbicide	—	2,4-D	2,4-D
Herbicide application rate (L ha ⁻¹)	—	0.9 ± 0.5	0.5 ± 0.1

The values indicated are means and standard deviations

Table 2-2. Agronomic calendar for teff cultivation at the three study sites (1, 2, 3). The information provided is based on field observations and interviews with farmers.

Agronomic operations	Sites	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tillage	Site 1												
	Site 2												
	Site 3												
Sowing	Site 1												
	Site 2												
	Site 3												
First Weeding	Site 1												
	Site 2												
	Site 3												
Second Weeding	Site 1												
	Site 2												
	Site 3												
UREA application	Site 1												
	Site 2												
	Site 3												
NPS application	Site 1												
	Site 2												
	Site 3												
Harvesting	Site 1												
	Site 2												
	Site 3												

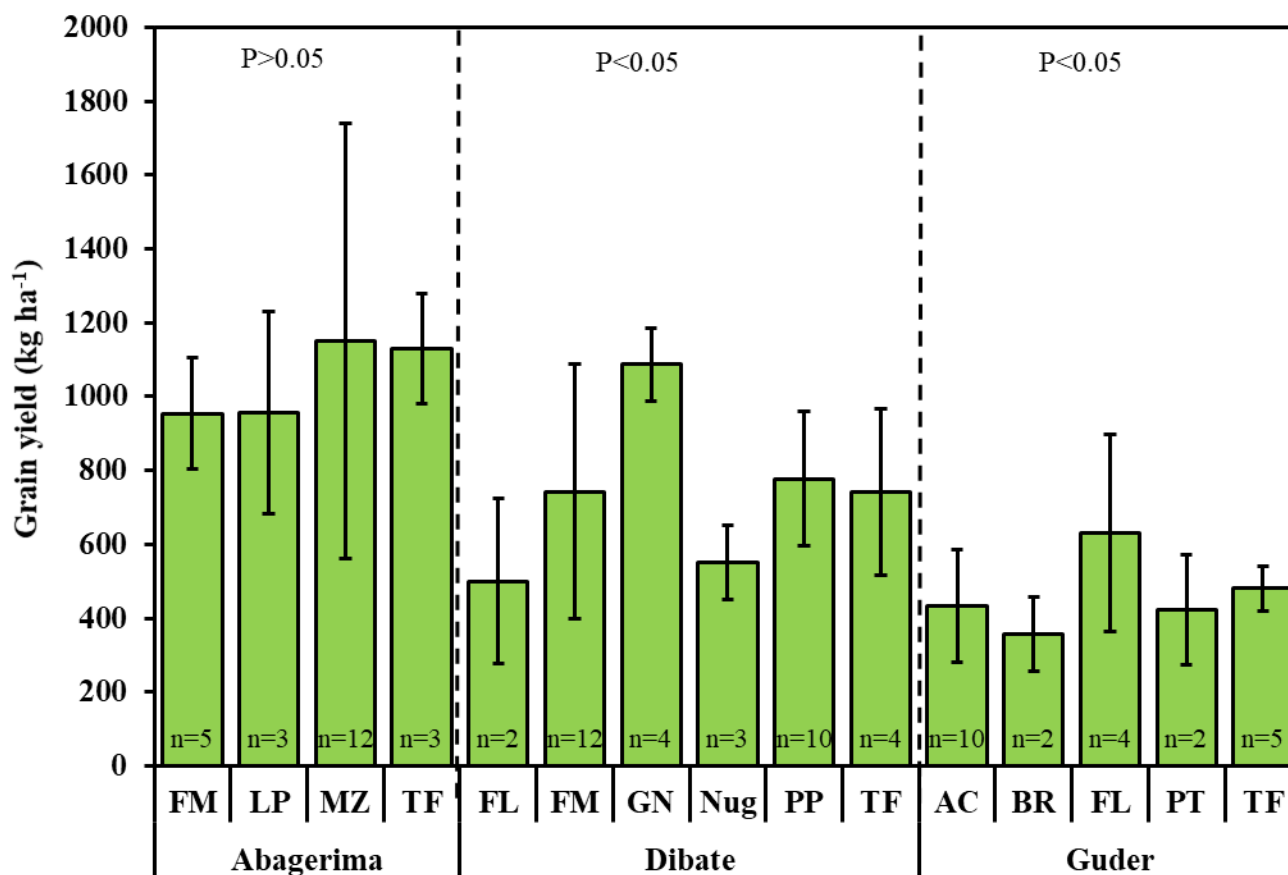


Figure 2-1. Mean teff grain yields of farms that rotated teff with different precursor crops (2018) at the three study sites. Means with the same letter are not significantly different at $P = 0.05$. n, number of observations. FM, finger millet; LP, lupin; MZ, maize; TF, teff; FL, fallow; GN, ground nut; PP, hot pepper; AC, acacia; BR, barley; PT, potato.

2.3.2. Ranges of soil fertility parameters

There was a substantial variation in soil properties among farms at the study sites. In general, the soil fertility decreased in the order of Dibate > Aba-Gerima > Guder (**Table 2.3**). Across the study sites, mean TN and OC contents of the topsoil ranged from 0.01 to 0.37 g TN kg⁻¹ and from 0.19 to 3.00 g OC kg⁻¹ (**Table 2.3**). Mean soil available P ranged from 2 to 54 ppm. Mean CEC ranged from 5.4 to 59.8 cmol kg⁻¹. Mean EC ranged from 0.02 to 0.13 dS m⁻¹ and pH (H₂O) ranged

from 4.9 to 6.5. Mean micronutrient values were 10.8–84.3 ppm Fe, 0.2–2.6 ppm Zn, 1.2–31.5 ppm Mn, and 0.6–2.9 ppm Cu (**Table 2.3**). Soils contained 10%–76% clay, 2%–68% silt, and 10%–74% sand.

Table 2-3. Levels of selected soil-fertility parameters for topsoil samples from farms at study sites during teff planting.

Parameter	Guder (n = 24)	Dibate (n = 35)	Aba- Gerima (n = 23)	Parameter	Guder (n = 24)	Dibate (n = 35)	Aba- Gerima (n = 23)
Sand (%)	42.8 ± 10.0	37.9 ± 21.7	33.0 ± 14.0	EC (ds m ⁻¹)	0.04 ± 0.01	0.06 ± 0.03	0.08 ± 0.02
Silt (%)	38.0 ± 12.8	20.4 ± 5.7	30.4 ± 14.5	pH (H ₂ O)	5.5 ± 0.2	5.6 ± 0.3	5.6 ± 0.4
Clay (%)	19.2 ± 13.5	41.8 ± 20.3	36.6 ± 16.4	Fe (ppm)	59.2 ± 15.7	24.6 ± 4.7	21.1 ± 7.8
TN (g kg ⁻¹)	0.03 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	Zn (ppm)	0.8 ± 0.4	1.1 ± 0.5	0.9 ± 0.5
OC (g kg ⁻¹)	0.4 ± 0.1	2.0 ± 0.9	1.4 ± 0.5	Mn (ppm)	14.1 ± 8.3	9.4 ± 3.7	10.3 ± 3.5
Av. P (ppm)	14.6 ± 18.0	30.0 ± 49.9	21.9 ± 18.0	Cu (ppm)	1.6 ± 0.5	1.8 ± 0.5	1.5 ± 0.4
CEC (cmol _c kg ⁻¹)	27.2 ± 6.9	33.7 ± 17.7	39.0 ± 8.3				

OC, soil organic carbon; TN, soil total N; Av. P, available P; EC, electrical conductivity. Values are means ± SD of observations on farms at each site.

The values indicated are means and standard deviations

2.3.3. Variation of grain yields

Teff grain yields varied significantly across study sites. The highest mean yield was recorded at Aba-Gerima, followed by Dibate (**Fig. 2.4**). Similarly, there were substantial variations in grain yields among farmers at all sites (**Fig. 2.4**). In general, yields were lower (150–2542 kg ha⁻¹) than the potential yield of the popular cultivar ‘Quncho’ (2800 kg ha⁻¹). Though 4 farmers at Aba-Gerima planted ‘Quncho’, the mean grain yield (987 kg ha⁻¹) was far below the potential (**Table**

2.4). The results of a one-way ANOVA in which farmers were treated as replicates showed that there was no significant difference ($P > 0.05$) among users of teff cultivars at Aba-Gerima. Only ‘Nech’ (white seed) was used at Dibate, and only ‘Dabo’ (red seed) was used at Guder (**Table 2.4**). The frequency of tillage, weeding, and herbicide application did not influence teff grain yields significantly ($P > 0.05$; **Table 2.4**). At Guder, teff grain yields were significantly higher ($P < 0.05$) at farms where manure was applied than at other farms **Table 2.4**.

By regression tree analysis, the crop management practices that were the most important in explaining grain yield variability among farms and farmers were the N application rate followed by sowing density (**Fig. 2.5**). Farms ($n = 82$) were split into two groups on the basis of N application rates: mean yields were 851 kg ha^{-1} on farms where rates were $\geq 13 \text{ kg ha}^{-1}$ ($n = 53$) and 594 kg ha^{-1} where rates were $< 13 \text{ kg ha}^{-1}$ ($n = 28$). The latter farms were further split into two groups: mean yields were 742 kg ha^{-1} on farms where rates were $\geq 2 \text{ kg ha}^{-1}$ ($n = 13$) and 466 kg ha^{-1} where rates were $< 2 \text{ kg ha}^{-1}$ ($n = 15$). The former farms were also split into two groups: mean yields were 819 kg ha^{-1} on farms where rates were $< 55 \text{ kg ha}^{-1}$ ($n = 44$) and 1007 kg ha^{-1} where rates were $\geq 55 \text{ kg ha}^{-1}$ ($n = 9$). Finally, the farms where rates were $< 55 \text{ kg ha}^{-1}$ ($n = 44$) were split into two clusters on the basis of sowing density (SD): mean yields were 790 kg ha^{-1} on farms where SDs were $< 44 \text{ kg ha}^{-1}$ ($n = 33$) and 904 kg ha^{-1} where SDs were $\geq 44 \text{ kg ha}^{-1}$ ($n = 11$).

Soil CEC and contents of Mn and sand were the most important soil parameters responsible for variations in teff grain yields among farms (**Fig. 2.6**). Predicted yields were 1288 kg ha^{-1} on farms with soil Mn $> 9 \text{ ppm}$ and sand content $> 27\%$; 890 kg ha^{-1} on farms with soil Mn $> 9 \text{ ppm}$ and sand content $< 27\%$; 871 kg ha^{-1} on farms with soil Mn $< 9 \text{ ppm}$ and sand content $> 37\%$; and 586 kg ha^{-1} on farms with Mn $< 9 \text{ ppm}$ and sand content $< 37\%$.

The boundary line approach (**Figs. 2.7, 2.8**) provided further support for the conclusions

reached on the basis of regression tree analysis (**Fig. 2.8**). The bell-shaped pattern of the boundary line curves generated for P and N application rates (**Fig. 2.7a, b**), number of days to planting when counted from 1 July (**Fig. 2.7e**), and days to harvest (**Fig. 2.7f**) indicated that the maximum teff yield was achieved at the median values of these variables. SD and number of tillage operations (NT) were negatively correlated with grain yield; maximum grain yield was achieved at the lowest SD and NT (**Fig. 2.7c, d**).

Examination of grain yield as a function of soil pH, EC, and contents of OC), Zn, and Mn revealed bell-shaped patterns. Those patterns indicated that maximum grain yield was achieved at the median values of the parameters (**Fig. 2.8a, b, c, e, f**). However, the curve for available P (**Fig. 2.8d**) was convex, and maximum grain yields were therefore achieved at the lowest and highest values of available P. More importantly, the percentage of cases when each variable (crop management practice or soil property) was identified as a yield-limiting factor when evaluated across the 81 farms (**Fig. 2.9**) indicated that soil Zn (25%), Mn (19%), number of days to harvest (19%), and P application rate (19%) were the most important factors that limited teff yields (>5%) at the study sites (**Fig. 2.9**).

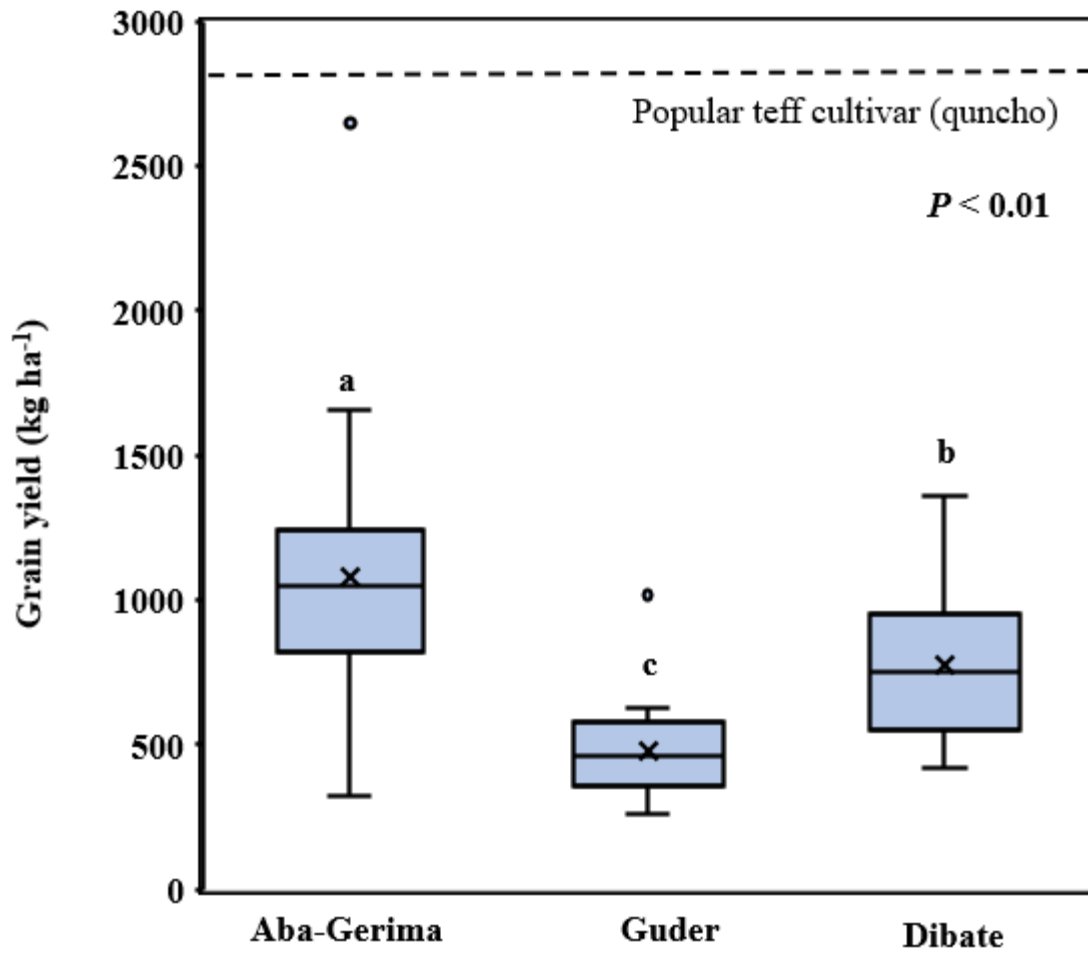


Figure 2-2. Teff grain yield variability among farms and study sites. Means with different letters are significantly different at $P = 0.05$.

The top and bottom of each box represent the upper and lower quartiles, respectively; the horizontal line and × within each box represent the median and mean, respectively; whiskers represent variability outside the upper and lower quartiles.

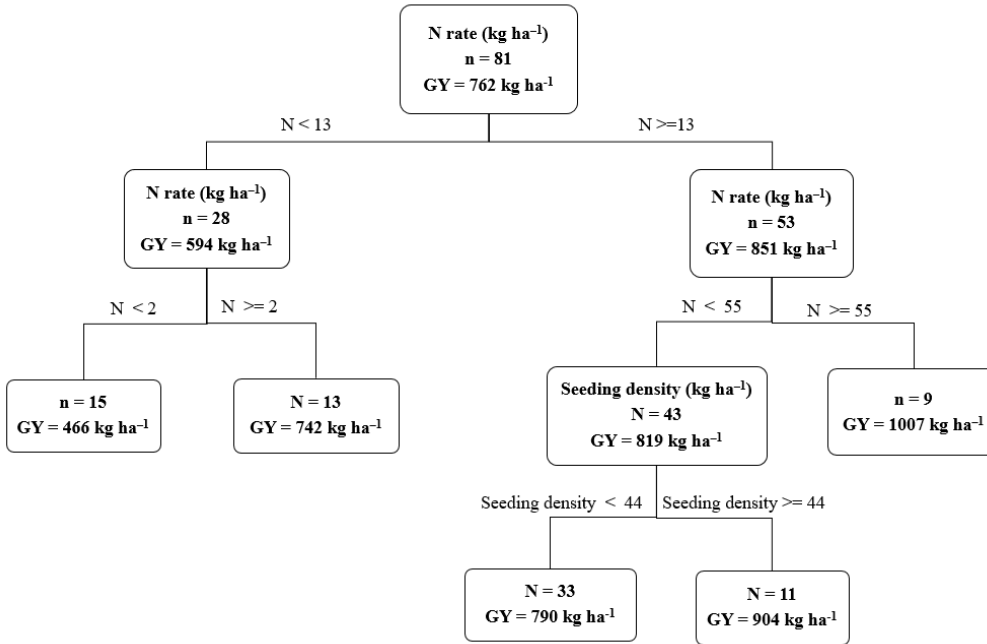


Figure 2-3. Regression tree showing relationships and variability of teff grain yield (GY) with different rates of N application and sowing density. N, number of farms (observations).

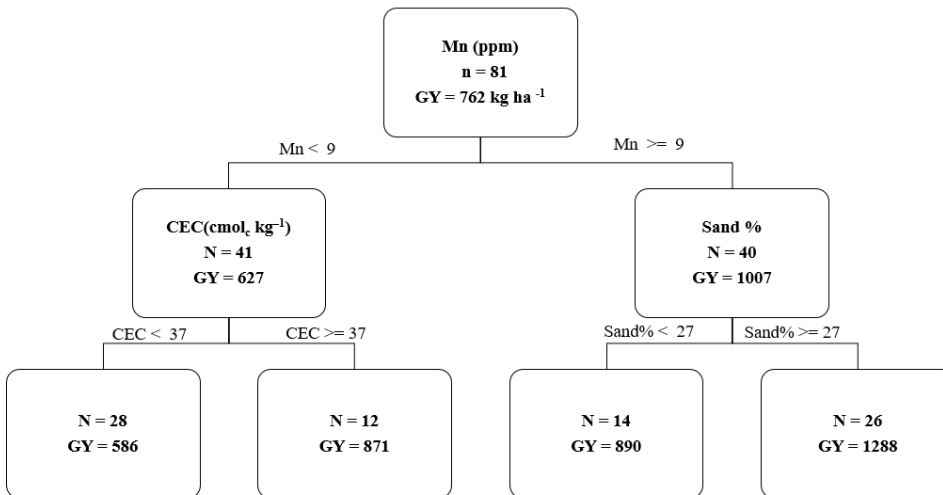


Figure 2-4. Regression tree showing the variability of teff grain yield with different levels of soil fertility parameters (Mn content, cation exchange capacity [CEC], and sand content).

N, number of farms (observations).

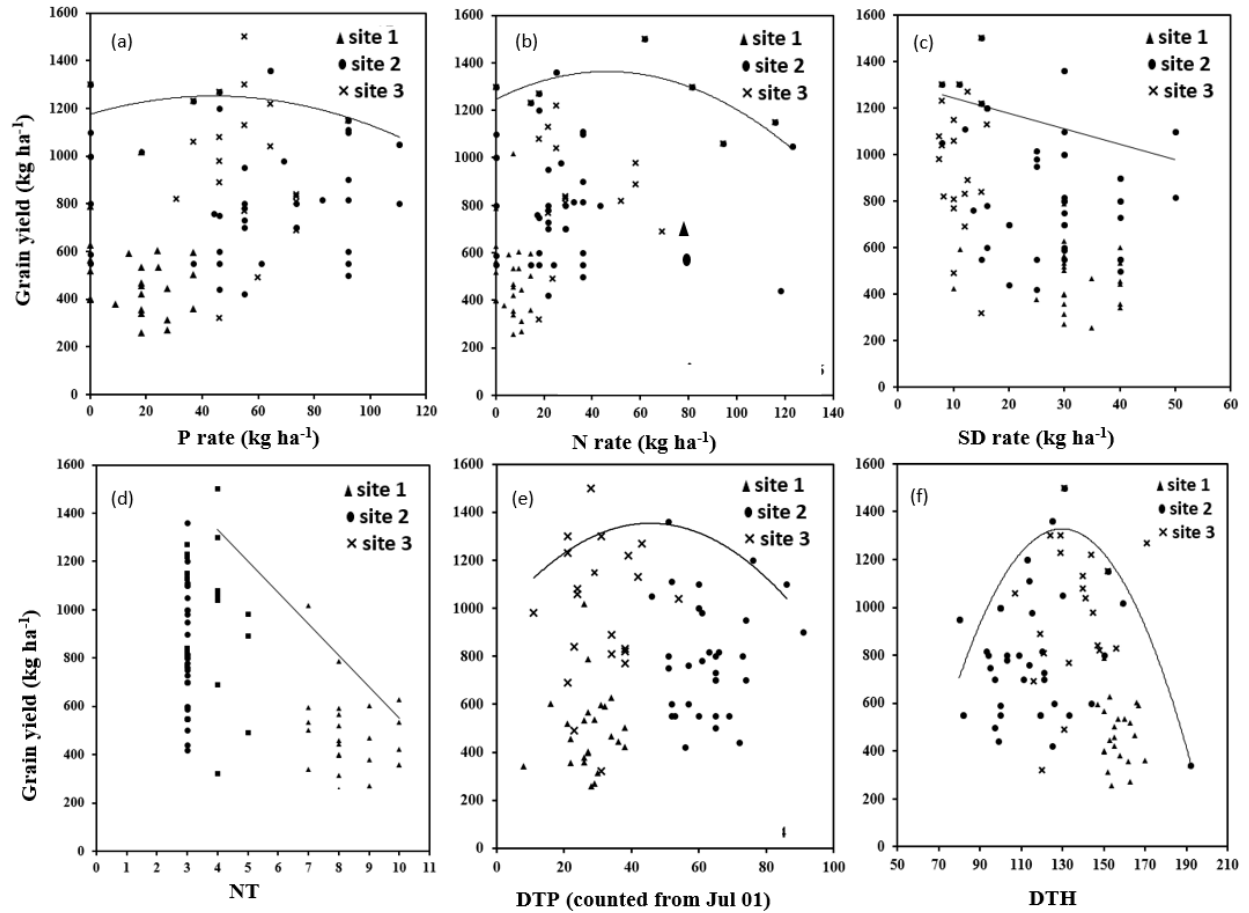


Figure 2-5. Maximum grain yield prediction lines generated using the boundary points within scatter graphs of grain yield on the y-axis and fertilizer (P and N) application rates, sowing density, and days to planting/harvest on the x-axis. In each plot, solid line indicates the boundary line equation (least squares–fitted) used to estimate maximum grain yield of teff for different fertilizer and sowing rates as well as timing of planting and harvesting.

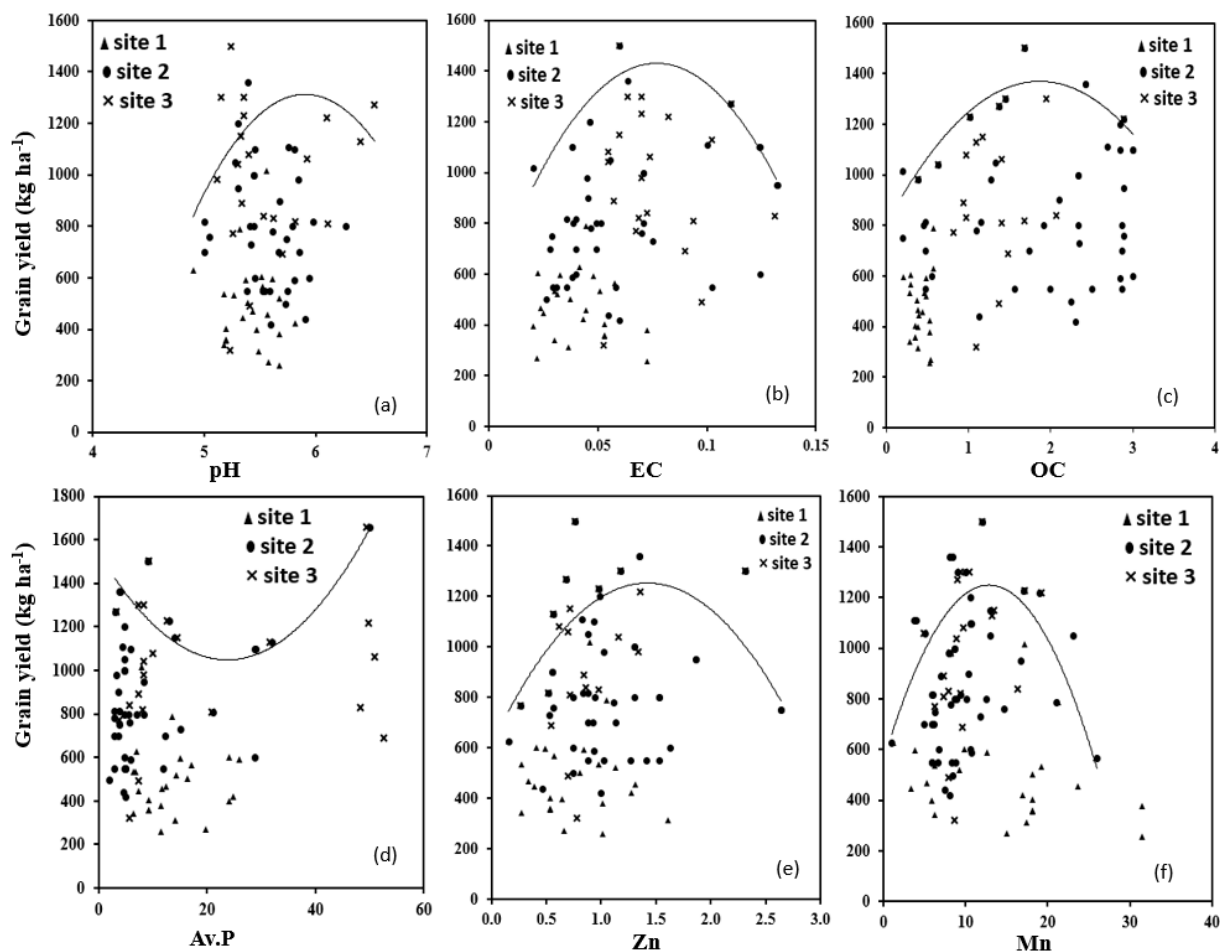


Figure 2-6. Maximum grain-yield prediction lines generated from the boundary points within scatter graphs of grain yield and selected soil fertility parameters of farms at the three sites. Solid lines indicate boundary line equation (least squares–fitted) used to estimate maximum grain yield for each soil parameter. Each plot is based on yield data. Soil samples were collected from fields of 81 farms. pH, soil acidity; EC, electrical conductivity; CEC, cation exchange capacity; OC, organic C; Av. P, available P.

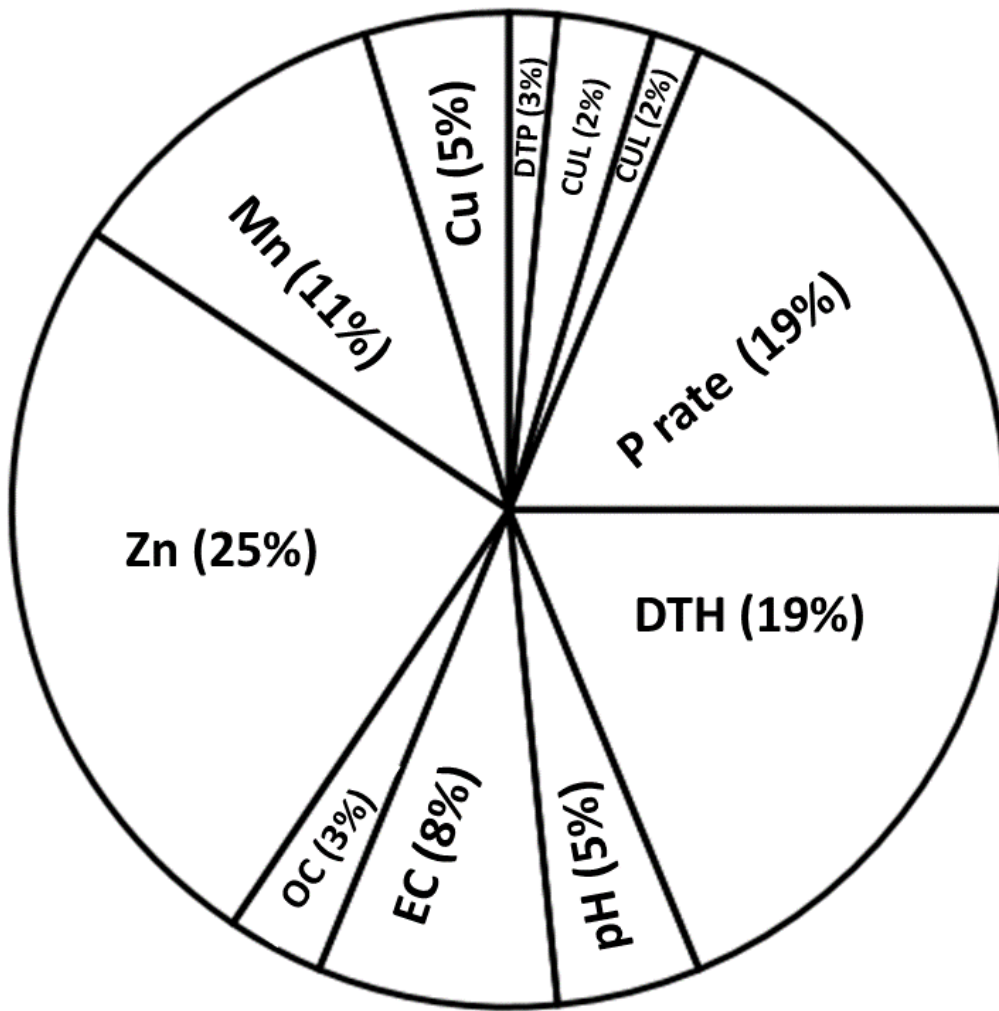


Figure 2-7. Crop management practices and soil fertility parameters identified as yield-limiting factors based on the percentage share of the frequency of observation over farms (n = 81) at the three study sites. NT, number of tillage operations; DTP, days to planting; CUL, cultivar; P rate, P application rate; DTH, days to harvest; pH, soil acidity; EC, electrical conductivity; OC, organic C.

Table 2-4. Mean grain yields (GY) and straw yields (SY) (kg ha⁻¹) of different teff cultivars and crop management practices at the study sites.

Crop management	Guder			Dibate			Aba-Gerima		
	<i>n</i>	Grain	Straw	<i>n</i>	Grain	Straw	<i>n</i>	Grain	Straw
Cultivars (local names)									
Ancharo	—	—	—	—	—	—	4	928	6188
CR-37	—	—	—	—	—	—	3	893	11000
Key tef	—	—	—	—	—	—	4	1188	15175
Mura	—	—	—	—	—	—	6	1030	9833
Quncho	—	—	—	—	—	—	4	987	14983
Nech	—	—	—	35	794	3231	—	—	—
Dabo	24	484	816	—	—	—	—	—	—
<i>F</i> -values	—	—	—	—	—	—	—	0.2 ^{ns}	1.0 ^{ns}
Tillage frequency									
3	—	—	—	—	—	—	10	1007	11250
4	—	—	—	35	794	3231	7	999	11286
5	—	—	—	—	—	—	4	787	6983
7	5	598	997	—	—	—	—	—	—
8	6	431	718	—	—	—	—	—	—
9	4	430	716	—	—	—	—	—	—
10	9	499	767	—	—	—	—	—	—
<i>F</i> -values	—	0.6 ^{ns}	0.2 ^{ns}	—	—	—	—	0.7 ^{ns}	0.1 ^{ns}
Manure application									
yes	5	626a	1043a	—	—	—	—	—	—
no	19	454b	757b	35	794	3231	21	1004	11252
<i>F</i> -values	—	5.0*	6.1*	—	—	—	—	—	—
Weeding frequency									
1×	6	429	714	35	794	3231	21	1004	11252
2×	14	520	836	—	—	—	—	—	—
<i>F</i> -values	—	1.0 ^{ns}	0.8 ^{ns}	—	—	—	—	—	—
Herbicide									
yes	—	—	—	8	730	3050	7	941	10400
no	24	484	816	27	806	3346	14	1035	11679
<i>F</i> -values	—	—	—	—	0.7 ^{ns}	0.8 ^{ns}	—	0.4 ^{ns}	1.4 ^{ns}

n, number of observations for each crop management practice.

ns, not significant.

* significant at 5% probability level

2.3.4. Economics of teff production

The total cost of production (direct costs) associated with crop management ranged from 368 to 662 USD ha⁻¹ across study sites. The total cost of production was higher at Aba-Gerima than at sites 2 and 1 (**Table 2.5**). At Guder, the majority of the costs were due to weeding (29%), tillage (18%), and trampling (17%). At Dibate and Aba-Gerima, the majority of the costs were due to trampling (26% and 24%, respectively), tillage (26% and 21%, respectively), and weeding (19% and 13%, respectively). The range of the total gross benefit obtained from selling grain and straw was 208–2432 USD ha⁻¹. The total gross benefit was highest at Aba-Gerima and lowest at Guder. Similarly, net return ranged from –583 to +1875 USD ha⁻¹. Mean net return was highest at Aba-Gerima, followed by Dibate and Guder. Cost–benefit ratios ranged from 0.4 to 4.0. The ratio was greater at Aba-Gerima than at sites 2 and 1 (**Table 2.5**).

Interviews with farmers (**Table 2.6**) revealed that lodging and shattering were the major constraints on teff production. The farmers also mentioned smut infestation at Aba-Gerima, cold stress and hail damage at Guder, and crop damage by animals at Dibate as important constraints on teff production.

Table 2-5. Cost of production, net return, and labor productivity associated with implementation of major agronomic practices for teff cultivation at the three sites.

Farm activity	Guder (<i>n</i> = 24)		Dibate (<i>n</i> = 35)		Aba-Gerima (<i>n</i> = 23)	
	Mean	% share	Mean	% share	Mean	% share
Inputs costs (USD ha⁻¹)						
Seed	25 ± 6	5	25 ± 8	5	37 ± 10	7
Fertilizer	18 ± 6	4	57 ± 21	11	54 ± 20	10
Animal traction costs (USD ha⁻¹)						
Tillage	85 ± 11	18	99	20	119 ± 26	21
Trampling	80 ± 0	17	132	26	132	24
Labor cost (USD ha⁻¹)						
Sowing	10 ± 0	2	8	2	12	2
Fertilizer application	5 ± 0	1	4	1	6	1
Weeding	135 ± 36	29	94 ± 58	19	73.9 ± 17	13
Harvesting	52	11	42	8	62	11
Threshing	52	11	42	8	62	11
Total cost (USD ha⁻¹)	463 ± 70	–	504 ± 68	–	558 ± 37	–
Gross return (USD ha⁻¹)	388 ± 137	–	544 ± 216	–	1102 ± 422	–
Net return (USD ha⁻¹)	–75 ± 172	–	40 ± 234	–	543 ± 433	–
Cost-benefit ratio	0.8 ± 0.3	–	1.3 ± 0.4	–	1.9 ± 0.7	–

1 United States dollar (USD) is equivalent to 32 Ethiopian birr. The values indicated are means and standard deviations

Table 2-6. Major constraints on teff-producing smallholder farmers and percentages of respondents at the three study sites.

Teff production constraints	Guder (<i>n</i> = 24)	Dibate (<i>n</i> = 35)	Aba- Gerima (<i>n</i> = 23)
Lodging and shattering due to rainfall at maturity	100	91	100
Crop damage by hail	95	—	100
Moisture shortage during germination and grain filling	8	—	—
Cold stress during tillering and grain filling	100	—	—
Smut infestation	—	14	39
Weed infestation	21	9	2
Limited access to inorganic fertilizers	20	6	—
Lack of improved cultivars and agronomic practices (labor-reduction technologies and planting methods)	42	6	4
Loss of soil and nutrients to runoff	—	11	—
Crop damage by animals and humans	—	45	—
Lack of oxen for plowing	—	9	4

2.4. Discussions

2.4.1. Variations in cropping practices

The diversity in teff cultivation practices was due mainly to the inherent heterogeneity of biophysical and socio-economic conditions that guided farmers' decisions about crop management

(Eshetu et al., 2020). At Guder, for instance, the poor fertility of the soil (**Table 2.3**) and the high rate of weed infestation due to the large amount and wide distribution of seasonal rainfall (**Fig. 2.2**) were among the reasons that more frequent plowing was required (Temesgen et al., 2008) than at Dibate and Aba-Gerima. The time of plowing was likewise very dependent on the rainfall pattern and availability of resources (oxen and human labor). Although tillage uproots weeds and enhances soil aeration, moisture availability, and organic matter decomposition, excess tillage has been reported to be the major cause of land degradation in Ethiopia (Temesgen et al., 2008) and elsewhere (Blanco-Canqui and Wortmann, 2020). Trampling is a unique practice performed by all teff growers to facilitate incorporation of teff seeds into the soil, enhance root anchorage, and maintain soil moisture during the early stages of growth (Mihretie *et al.*, 2021). In contrast, it has been argued that trampling has little or no impact on teff yield but aggravates soil erosion (Amare et al., 2006) and exposes farmers to unnecessary costs (Mihretie *et al.*, 2021). In Ethiopia, reduced tillage practices have been recommended to enhance productivity of teff with minimal impacts on soil resources (Mihretie *et al.*, 2021).

Farmers sowed seeds at a higher density at Guder, mainly to compensate for the lower plant population that resulted from the use of the local cultivar ‘Dabo’ (**Table 2.4**), which has a low tillering capacity, and for the higher rate of weed infestation that at the other sites (Mihertie *et al.*, 2021). Decisions about teff sowing densities were governed by a variety of factors, such as weed infestation rates (Alba et al., 2020), teff cultivars, planting methods, and soil fertility (Mihretie et al., 2020). Moreover, the sowing and harvest dates varied because of differences in rainfall patterns and temperatures (Endale et al., 2020). The higher temperatures and lower rainfall during the main growing season (June–October) (Fig. 2) were the main reasons for the late planting and early harvesting at Dibate relative to Guder and Aba-Gerima (**Table 2.1**). The later harvesting at Guder

was due to the lower temperature during the period of teff growth than at Dibate and Aba-Gerima (Fig. 2.2).

The generally lower fertilizer application rates at Guder may have been due to the lower N and P requirements of the dominantly used local cultivar ‘Dabo’ than those of the improved cultivars used at Dibate and 3 (Table 2.4). In most cereal crops, better growth, greater tillering capacity, and higher yields of improved cultivars are achieved with greater amounts of N and P than are required for local cultivars that have lower potential yields (Sinclair and Vadez, 2002). If insufficient N and P are applied, the yields of improved cultivars may otherwise be lower than the yields of local cultivars that are adapted to low-nutrient conditions (Folberth et al., 2013). The low fertilizer application rates at Guder might partly be explained by the fact that the dominant crop rotated with teff at that site was *Acacia decurrens* (Nigussie et al., 2020b), which has symbiotic N-fixing bacteria in its root nodules and was grown primarily to make charcoal (Nigussie et al., 2020a). We noticed that teff growth was vigorous (i.e., the plants were a deep green) at the sites on a farm where *A. decurrens* was grown. However, the amounts of organic matter added to the soil and N fixed by the bacteria in acacia root nodules that are available for the next teff crop are unknown.

Most farmers used NPS fertilizer, because it contains N, P, and S, whereas urea contains only N (Rurinda et al., 2020). Application of urea without P may aggravate lodging, as application of excess N ($>60 \text{ kg ha}^{-1}$) increased lodging, which reduces grain yield (Bayable et al., 2020). Application of manure to most farmed crops in Ethiopia is small relative to the large amounts of manure produced by livestock (Bayu et al., 2006). Manure is commonly used as cooking fuel, but it is required in large amounts to improve soil fertility and crop yields. The fact that few farmers at Guder used manure compared with farmers at Dibate and Aba-Gerima might have been due to the

greater number of livestock (cattle and horses) at Dibate and Aba-Gerima (Nigussie et al., 2020b). The low fertility of the soil in the study area calls for an integrated use of both organic and inorganic fertilizers. An alternative to manure as an energy source should be provided to release manure to enhance soil fertility and improve crop yields.

To minimize yield reductions due to weed infestation, weeding of teff is recommended at 30 and 55 days after emergence (Gebrehiwot et al., 2020). However, the frequency of weeding varies among farmers and locations and depends on the availability of labor, the species of weeds, and rainfall patterns (Gebrehiwot et al., 2020). The majority (98%) of farmers weeded only once. Farmers weeded more than once if the rate of weed infestation was high, family labor was readily available, and their financial status was good (Mihretie et al., 2020). The government of Ethiopia does not promote the use of herbicides because enough human labor is available for weeding, and herbicides can have adverse effects on the environment (Fikadu, 2020). Unlike other crops (e.g., wheat and maize), there are few types of herbicides (for example, selective herbicides) identified for control of weeds on teff farms, and there is a lack of market access to agrochemicals. There is hence little use of herbicides on teff farms in Ethiopia (Negatu et al., 2016).

2.4.2. Variations of soil fertility

Abebe et al. (2020); Ebabu et al. (2020) have reported soil TN concentrations of croplands in northwestern Ethiopia within the range of concentrations that we found. Soil TN concentrations in our study areas were very low ($<1.5 \text{ g kg}^{-1}$) compared with the standards recommended by Hailu et al. (2015); Landon and Manual (1991). We attributed the low TN concentrations to the low organic matter content that resulted from frequent plowing, loss of topsoil in runoff, complete crop residue removal, and monocropping in teff-based cropping systems (Ebabu et al., 2020). In contrast, available P ranged from medium (10–17 ppm) to high ($>17 \text{ ppm}$) (Cottenie (1980); Hailu

et al. (2015), probably on account of the many years of application of P-containing fertilizer . However, only a small percentage (<10%) of applied inorganic P is used by crops; most of it remains in an immobile and relatively insoluble form (Balemi and Negisho, 2012). The low pH of the soil at most of the farms would have limited P availability and prompted the application of large amounts of inorganic P to support plant growth (Balemi and Negisho, 2012). Application of lime might be an appropriate strategy to create a suitable pH range (6.0–6.5) for teff growth (Assefa et al., 2015) and to improve the productivity of teff in the study areas. On the basis of the critical levels of Fe (5 ppm), Zn (1.5 ppm), Mn (1 ppm), and Cu (0.5 ppm) for tropical soils (Hailu et al. (2015), the soils at most of our sites had adequate contents of micronutrients, with the exception of available Zn (Table 2). Because Zn is very likely adsorbed onto soils with a high clay content in most of the areas where teff is grown, Zn deficiency is common (Desta *et al.*, 2021). Our soil test results suggest the need for application of Zn fertilizers, but this conclusion will need to be further investigated to determine the effect of Zn fertilizer application on teff yields.

2.4.3. Grain yield variation

Poor crop management and use of local teff cultivars caused the grain yields at our sites to be far below those of the high-yielding and popular ‘Quncho’ in Ethiopia (**Fig. 2.4**). Even the average yield of farms planted with ‘Quncho’ ($n = 4$) at Aba-Gerima was low (987 kg ha⁻¹, Table 3), because Quncho is more productive when planted in rows (Mihretie et al., 2020) and when adequate amounts of N and P are supplied (Haileselassie et al., 2016). The insignificant differences in mean grain yields among the cultivars used at Aba-Gerima reflect the fact that improved cultivars were grown under local crop management practices (Kebebew et al., 2011). We attributed the higher grain yields at Aba-Gerima mainly to the use of improved cultivars and greater applied inputs of such as fertilizers there (**Table 2.1**). At Guder, the use of the low-yielding (but locally

adaptable) landrace ‘Dabo’, which is highly susceptible to lodging, the less favorable environmental conditions (e.g., lower temperature and less solar radiation due to greater cloud cover; **Fig. 2.2**), and low soil fertility (**Table 2.3**) were the key reasons for the low yields at Guder. Haileselassie *et al.* (2016) reported that teff is a widely adaptable C₄ cereal crop that can perform relatively well under conditions of high temperatures and improved soil fertility.

Differences in crop management practices in our study could not adequately explain the observed variations in teff grain yields (**Table 2.4; Fig. 2.7**), because crop yield variations at the farm level are governed by complex interactions between various biophysical and socioeconomic factors (Delmotte *et al.*, 2011). The relationships between crop yield performance and crop management practices at the farm level are unlikely to be captured by using the classical statistical methods such as correlation, regression, and principal component analysis because analyses need to deal with data that could be highly skewed, and relationships between variables may be very nonlinear (Tanaka *et al.*, 2015). Regression tree analysis allows splitting the yield data into relatively uniform clusters and identifying the most important factors that affect crop yields (Delmotte *et al.*, 2011).

Regression tree analysis demonstrated that N fertilizer application and sowing density were more important determinants of the variations in grain yields than the other crop management practices assessed in this study. Several studies have reported that teff is sensitive to N nutrition, which affects biomass production and the occurrence of lodging. Lodging is a major challenge for teff production because it can reduce yields by 11%–22% (Assefa *et al.*, 2017). The higher grain yields at greater N inputs (>55 kg ha⁻¹) in our study were consistent with previous studies that have reported an increase in teff yields with an increase in N inputs (Teklu and Tefera, 2005). However, application of N above 60 kg ha⁻¹ might reduce yields by inducing lodging (Tefera *et*

al., 2001a). The mean N application rate ($23 \pm 24 \text{ kg ha}^{-1}$) at the study sites was less than the blanket N application rate of $40\text{--}80 \text{ kg ha}^{-1}$ recommended for the study area by Assefa et al. (2006). Despite the low TN content of the soil (**Table 2.3**), farmers in our study area applied N at low rates because they used local teff cultivars that require comparatively low N inputs. Recommended fertilizer application rates are usually based on the requirements of improved cultivars (Haileselassie et al., 2016). The N requirement of a crop varies with soil organic matter content, the type of cultivar, and the stage of the crop (Olson and Kurtz, 1982). The results of our study suggest the need to revise recommended N application rates for teff production to take account of soil fertility, the type of cultivar, and economic feasibility. Similarly, the sowing density of plants determines crop yield performance by influencing utilization of resources (e.g., light, water, and nutrients), tillering capacity, competition with weeds, and lodging of most cereals (Ali, 2020). In our study, the greater teff grain yields achieved at higher plant densities when N was applied at lower rates ($<55 \text{ kg ha}^{-1}$) might have been due to the ability of the teff to better compete with weeds. An increased plant density can compensate for the low tillering capacity of the local teff cultivars (Mihretie et al., 2020) that were grown by most farmers at our study sites. The farmers applied seeds at a density ($24 \pm 12 \text{ kg ha}^{-1}$) that was high compared with the sowing density recommended for teff sown in rows (10 kg ha^{-1}) but within the range that has been reported for broadcast planting ($15\text{--}25 \text{ kg ha}^{-1}$) in these areas (Mihretie et al., 2020). Farmers in our study area used broadcast planting at relatively high seed densities to compensate for the low tillering capacity of local teff cultivars, to suppress weeds, and to increase the amount and quality (e.g., palatability and softness) of the straw produced for livestock (Mihretie et al., 2020). The amount of seed to be applied was determined by several factors, including the objective of production (forage vs grain), cultivar type, planting methods, and soil fertility (Ouedraogo et al., 2020).

Overall, maximum teff yield was attained when the optimum level of N inputs was coupled with an appropriate sowing density.

Manganese (Mn) is an important micronutrient involved in photosynthesis, germination, and maturation. Differences in soil Mn levels might therefore contribute to variations in crop yields (Mousavi et al., 2011). High CEC is an indicator of high water-holding capacity and higher availability of nutrients for crop growth (Soinne et al., 2020). For plants like teff with small seeds that are highly susceptible to lodging, a relatively high soil sand content might provide better root penetration and thus anchorage during the early growth period (Sharma and Chaudhary, 1983). In addition to N inputs and sowing density, the regression tree analysis identified the Mn levels and sand content of the soil as the most important factors that explained variations in teff grain yields among farms.

Further examination of yield-limiting factors provided additional information about what prevented each farm from achieving the maximum possible grain yield (Beza et al., 2017). Crop management practices or soil properties identified as yield-limiting factors might not have been directly linked to variations in grain yields identified by the regression analysis, but they could prevent farms from achieving the maximum possible yields that were estimated with a boundary line drawn through boundary points (**Figs. 2.7, 2.8**). The bell-shaped pattern of maximum yields predicted for N and P application was caused by the lower growth rates and yields (Araya et al., 2010) and increased lodging at higher N fertilization rates (Bayable et al., 2020). Optimizing sowing and harvesting dates is a key to maximizing teff grain yields because it allows plants to grow under suitable environmental conditions (e.g., radiation, temperature, and moisture), reduces pest infestation, and lowers susceptibility to rain-induced lodging in rainfed teff production systems (Mihretie *et al.*, 2021). Similarly, optimizing soil nutrient availability, supply, and content

(neither too low nor too high) is a key to maximizing crop yields (Schütz et al., 2018). In accord with our findings, the P application rate is a major yield-limiting factor that could prevent cereal crops from achieving maximum yields in acid-prone areas (Foy, 1992; Horst et al., 1993). EC is also an indicator of nutrient availability, available water capacity, and conditions in the root rhizosphere. Differences in EC might influence the potential yields of crops (Kitchen et al., 1999). Application of essential micronutrients in addition to N and P in fertilizers has been shown to maximize teff grain yields (Eyob et al., 2015).

Production of teff is a relatively low-yielding, less-profitable, and resource-intensive enterprise, and the observed variations in yields among farms and the huge difference in yields from the high-yielding cultivar indicates that there is a big opportunity to improve teff productivity by implementing improved crop-management practices such as use of improved cultivars, reduction of tillage, and planting in rows without tramplng, together with integrated management of soil fertility.

2.4.4. Economics of teff production

The majority of expenses in teff production were associated with labor used for tillage, tramplng, and weeding (**Table 2.4**). Fikadu et al. (2019) have also reported that teff cultivation is relatively unproductive and labor-intensive compared with cultivation of other cereals (such as wheat and maize) in Ethiopia. Tillage and tramplng were the most labor-intensive activities used to establish crops and minimize weed infestation because of the small seeds, small plant stature, and shallow root system of teff (compared with other cereals), which requires careful preparation of soil before sowing (Tesfahunegn, 2015). The degree of land preparation required for teff cultivation is determined by soil type, weed seed density, rainfall patterns, and availability of labor and draft power (Hailu et al., 2017). The low cost of production at Dibate and Aba-Gerima was

due primarily to the high cost of labor and traction provided by oxen. However, horses are primarily used for tillage and trampling at Guder. Despite the greater amount of plowing at Guder, horses were cheaper and faster than oxen at plowing. However, the higher total income at Aba-Gerima, followed by Dibate, was due to the higher yields of grain and straw there owing to the use of improved cultivars and better use of inputs than at Guder (**Table 2.4**). The low profitability (net return) at Guder was therefore due mainly to the low yields there and partly to the high costs of animal traction and of labor for weeding (**Table 2.5**). We suggest that more use of labor-efficient improved tillage, integrated weed control, and soil-fertility management practices could substantially enhance teff production with only a small increase in the cost of production.

2.5. Conclusions

Overall, the spatial heterogeneity of teff yields across and within locations was due mainly to differences in N application rates, sowing density, and soil fertility. The major factors that reduced yields below the maximum expected were the P application rate followed by the time of harvest and soil Zn content. The high frequency of tillage, monocropping, and complete removal of crop residues were major causes of the low soil fertility. Although further studies are required, our study indicates that the soils of most farms have sufficient concentrations of micronutrients to support crop growth, with the exception of Zn. Because our study identified the major causes of only the spatial variability of crop yield in a single season during which teff was the major crop, further study is required to explore the variability of yields of other crops and to identify the biophysical factors that constrain rainfed production by consideration of both spatial variability and seasonal dynamics.

From this study, frequent tillage and poor agronomic practices were identified as the major challenges behind the low teff productivity, profitability and soil resource degradation. Implementation of improved crop management practices such as reduced tillage, incorporation of crop residues, crop rotation, and intercropping combined with appropriate practices to manage soil fertility could improve rainfed crop productivity with minimal increases of costs. Therefore, following this survey work, a field experiment was established to evaluate alternative crop management options at Aba-Gerima watershed. Aba-Gerima watershed was selected because it is of the active learning site for researchers, development practitioners and farmers in Ethiopia where different sustainable land management (SLM) programs have been implemented for the past years under Amhara regional state and non-governmental organizations; recent interventions by Water and Land Resource Center (WLRC) and SATREPS-JICA-Next-generation SLM can be mentioned as an example. Moreover, Aba-Gberima watershed was selected as a study site as it represents the midland teff growing agro-ecology with a well-established watershed management system that helps to monitor soil characteristics, long-term weather data, closely work with farmers and the availability of baseline biophysical and socio-economic information and easy access to skilled labor which is a huge opportunity for implementing our field research studies with a lesser time, resource and better access to quality data acquisition.

CHAPTER THREE

Tillage and crop management impacts on soil loss and crop yields in northwestern Ethiopia

This chapter is published as:

Mihretie, F. A., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Ebabu, K., Masunaga, T., Kebede, B., Meshesha, D. T., Tsuji, W., Bayable, M. and Berihun, M. L. Tillage and Crop Management Impacts on Soil Loss and Crop Yields in Northwestern Ethiopia. International Soil and Water Conservation Research (2021). <https://doi.org/10.1016/j.iswcr.2021.04.006>.
(available online)

Chapter three - Tillage and crop management impacts on soil loss and crop yields in northwestern Ethiopia

3.1.Introduction

Soil erosion is a major environmental problem worldwide, and it is of a particular relevance to the agricultural sector in Ethiopia (Haregeweyn et al., 2015; Hurni, 1983). The annual soil loss due to erosion by water from Ethiopian highlands ranges from 20 to 80 t ha⁻¹ yr⁻¹ (Adimassu et al., 2014; Berihun et al., 2020; Haregeweyn et al., 2017; Hurni, 1983), and the average soil loss rate from cultivated lands was estimated as 42 t ha⁻¹ yr⁻¹ (Hurni (1993). Soil loss from cultivated lands in the Upper Blue Nile basin is mostly driven by inappropriate land management practices (Ebabu et al., 2019), including excessive tillage, continuous cropping, and low organic matter addition (Oicha et al., 2010c). Proper management of croplands will thus play a huge role in reversing the problem caused by soil erosion and maximizing crop production in low-input, rain-fed agriculture.

The area under cultivation accounts for 15% of the total land in Ethiopia (Taffesse et al., 2012). The major cereal crops grown are teff (*Eragrostis tef* [Zucc.]), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), sorghum (*Sorghum bicolor* [L.] Moench), and maize (*Zea mays* L.). Among these, teff takes the major share of total crop production, with 3 million ha of land cultivated in teff (CSA, 2018). Teff supports millions of people as a staple food crop in Ethiopia. Teff is grown mainly as a forage crop outside Ethiopia, but demand for the grain is expanding worldwide owing to its nutritional benefits, mainly as it is gluten free and is rich in lysine, iron, and calcium (Assefa et al., 2011). However, its production system is highly challenged by decline in soil fertility exacerbated by poor agronomic practices (Habte Werede et al., 2018). In the conventional teff cultivation system, the land undergoes more than four tillage operations, using oxen as the main source of draft power, followed by soil compaction (trampling) using a large

number of cattle and donkeys immediately before broadcast sowing, with teff seeds randomly scattered over the compacted ground. The intended purposes of frequent plowing in the conventional teff cultivation are to create a fine seed bed for better crop establishment, reduce weed infestation, and enhance rainwater infiltration and soil aeration (Lipiec et al., 2006). However, repeated tillage may aggravate soil erosion by depleting soil organic matter and reducing plant cover (Ghimire et al., 2017; Zhang et al., 2019). Reduced tillage systems could reverse problems posed by traditional tillage practices (Temesgen et al., 2009; Unger and McCalla, 1980). Impacts of tillage methods on soil erosion are highly dependent on crop type; plot scale; tillage implement; time, frequency, and duration of tillage; soil type; and climatic variables (Temesgen et al., 2008).

Shelton et al. (1986) reported that, compared to broadcasting, planting in rows/strips is a good strategy for both increasing crop yield and minimizing on-site soil erosion. Row planting improves tillering capacity, seed distribution, and root development and reduce lodging in cereal crops (Shelton *et al.*, 1986). Compared to broadcasting, better biomass production and root anchorage in row planting might contribute in reducing soil loss (Zuazo and Pleguezuelo, 2009). Similarly, due to the small size of teff seed, trampling is mainly practiced to enhance root anchorage, provide a smooth surface for better seed contact with the soil, and prevent seeds from being washed away by rainwater immediately after planting (before germination), and prevent the soil surface from quick drying during drought spells in the early growth stages (Fufa et al., 2000). However, this soil compaction alters soil structure and has the potential to limit water infiltration and increase runoff and erosion (Bakken et al., 1987; Muche et al., 2014). Because trampling is a unique practice specific to teff cultivation, few studies have investigated its impacts on soil loss and crop yield.

Overall, agronomic practices of the conventional teff cultivation system are the major reasons for low productivity and soil resource degradation (Vandecasteele et al., 2013). Because teff covers the majority of cultivated lands in Ethiopia, implementation of good agricultural practices that can improve teff productivity without harming soil resources would be crucial for the sustainable use and management of cultivated lands in erosion-sensitive areas and elsewhere. Therefore, the government of Ethiopia has been promoting reduced tillage and row-planting practices without soil trampling as the most promising agronomic options to reduce soil erosion from teff fields and improve crop yield. However, no or little information is available about the effectiveness of these practices under the crop husbandry and production contexts of teff. Given all these facts, this study was initiated following the hypothesis that reduced tillage practices and row planting without trampling would be sustainable management options that can improve crop productivity by conserving soil resources. Therefore, this study investigated the impacts of different tillage, planting, and trampling practices on (1) sediment concentration and soil loss during the teff growing period (August–October), and (2) teff grain and straw yields.

3.2. Materials and methods

3.2.1. Site description

The study was conducted at the Aba Gerima watershed in the Upper Blue Nile basin of northwestern Ethiopia (**Fig. 1.4**). According to long-term climate data from the meteorological station near the experimental site (**Fig. 1.5**), the study area is characterized by a unimodal rainfall pattern with annual rainfall ranging from 895 to 2037 mm, most of which occurs from June to September; the minimum and maximum temperatures are 13 and 27 °C, respectively. Nitosols and Leptosols are the dominant soil types in the watershed based on the FAO soil classification system

(Mekonen, 2016). The study soil of (0–20cm) site has an average organic carbon content of 11 g kg⁻¹, total nitrogen of 1.1 g kg⁻¹, available phosphorus (Olson) of 16.5 mg kg⁻¹, pH of 5.6, and exchangeable K of 1.1 cmol kg⁻¹ and the texture is classified as clay (35% sand, 26% clay, and 39% silt).

3.2.2. Treatments and experimental setup

Two tillage practices, two planting methods, and two trampling practices ($2 \times 2 \times 2 = 8$ treatment combinations) were evaluated. The tillage practices were reduced tillage (RT), with one plowing at the time of teff planting, and conventional tillage (CT), with four plowings (once in April, twice in June, and once in July). The two planting methods were row planting (RP), with 25-cm row spacing and 10 kg of seed ha⁻¹, and broadcast planting (BP), with 25 kg of seed ha⁻¹. The two trampling practices were trampling immediately before planting (+T) and sowing without trampling (–T). Treatments were assigned to each experimental unit following a split-split-plot arrangement. Tillage practices were assigned as the main plot factor, planting methods were assigned as a subplot factor, and trampling practices were assigned as a sub-subplot factor. Therefore, there were eight sub-subplots, and the size of each was 30 m × 3 m (90 m²). Plots were runoff plots separated by iron sheets of 40-cm depth of which 20 cm was inserted below the ground. The plots were laid out on uniform land with a 12% slope gradient. Runoff and soil coming from each plot were collected by a trench measuring 3 m in length, 1 m in depth, 2.5 m in width at the top and 1.25 m at the bottom. The trenches were placed at the bottom of the runoff plot and lined with plastic geo-membrane. The volume of each trench was nearly 4.1 m³, determined by considering the highest rainfall and runoff coefficient of the area (Hudson, 1993). Graded soil bunds were constructed uniformly across the experimental site as a common soil and water conservation practice in the study area (Adimassu et al., 2018; Adimassu et al., 2014). The bund

has a bottom width of 1.2 m, height of 0.5 m; and 1:2 side slope as prescribed by the MoA (2001). As a result, each runoff plot was divided into four compartments (blocks/replications) separated by soil bunds.

In each cropping season, teff planting was performed in late July and harvesting was done in late November (for details, see **Table 4.1**). The popular locally adapted teff variety ‘Quncho’ was used. Nitrogen and phosphorous were applied to all plots at rates of 64 kg N ha⁻¹ and 46 kg P₂O₅ ha⁻¹, in the form of urea [(NH₂)₂CO] and diammonium-phosphate fertilizers, respectively. All P₂O₅ and half of the N was first applied and mixed with the soil before sowing teff seeds; the remaining N was applied at 30 days after sowing. Tillage and trampling activities were done manually by using human labor (It was not practical to use oxen for our tillage treatments and cattle for trampling due to the difficulties in managing them in such experimental plots). Tillage was done at the depth of ~25 cm using a hand-hoe. Trampling was conducted by walking over the plots. Farmers in the study area use human labor or oxen for tillage and trampling operations depending on the availability of resources (Temesgen *et al.*, 2009).

Table 3-1. Summary of treatments and agronomic practices applied during the three monitoring seasons (2017–2019).

Treatments			Seeding rate	Row spacing	Time of agronomic practices											
Tillage	Planting	Tramplng			1st tillage	2nd tillage	3rd tillage	4th tillage	Planting	1st weeding	2nd weeding	Harvesting				
RT	RP	+T	10	25	Jul 19,	-	-	-	Jul 19,	Aug 28,	Sep 26,	Nov 1,				
		−T	10	25	2017; Jul				2017;	2017; Oct	2017;	2017; Nov				
	BP	+T	25	-	25, 2018;				Jul 25,	10, 2018;	Sep 14,	5, 2018;				
		−T	25	-	Jul 29,				2018;	Sep 5,	2017;	Nov 27,				
						2019				Jul 29,	2019	Oct 2,	2019			
CT	RP	+T	10	25	April 21,	Jul 16,	Jul 19,	Jul 25,								
		−T	10	25	2017;	2017;	2017;	2018;								
	BP	+T	25	-	April 24,				Jun 14,	Jun 29,	Jul 29,					
		−T	25	-	2018;				2018;	2018;	2019					
						April 3,				Jun 6,	Jun 29,					

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; +T, with tramplng; -T, no tramplng.

3.2.3. Data collection and analysis

The runoff and sediment concentration from each plot were monitored during the main rainy season within the teff growing period (August–October). Runoff and sediment concentration samples were measured daily at each plot every morning at 8:00 a.m. local time. Daily rainfall was also recorded using an automatic rain gauge installed near the experimental plots. The volume of runoff collected in each trench was measured using a plastic bucket of known volume. The actual daily runoff volume for each plot was calculated by subtracting the estimate of rainfall directly received on the surface area of the trench (Ebabu et al., 2019). Total actual daily runoff volume was then converted to depth (mm) by dividing it by the plot area. After sufficient stirring, runoff samples of 1 L were taken using a plastic bottle (Ebabu et al., 2019; Hudson, 1993). Sediment concentration (g L^{-1}) was determined by filtering each sample using Whatman 42 no. 1 paper filter with a pore size of $1.2 \mu\text{m}$, and oven drying it at 105°C for 24 h. Total amount of eroded soil (soil loss) from each plot was then calculated by multiplying the sediment concentration and the actual runoff volume. Soil moisture was monitored daily by using a moisture sensor (Decagon EC-5, METER Group, Inc. USA) and data logger (EM 50) installed in each plot at a depth of 20 cm.

Five samples were collected and a composite soil sample was prepared from each plot at a depth of 0–20 cm before (in 2017) and after the 3-yr experiment (in 2019). The soil samples were analyzed for total nitrogen (TN), total organic carbon (TOC), available P, pH, and electrical conductivity (EC). TN was analyzed using the Kjeldahl method (Bremner and Mulvaney, 1996), and TOC was determined as described by Nelson and Sommers (1996). Available P was determined using the Olsen extraction method (Olsen et al., 1954). pH and EC were determined based on the potentiometer principle (Peech, 1965); pH was determined in 1:25 soil:water solution using a pH meter and EC was measured with a conductivity meter. For each plot, soil core

sampling was done pre-sowing and post-planting using a core sampler of volume 100 cm^3 (5-cm depth $\times$ 2.5 radius). The soil core samples were oven-dried at $105\text{ }^{\circ}\text{C}$ for 24 h. Bulk density was then calculated as a ratio of oven-dried soil to volume of the core sampler.

Every 15 days, teff biomass yield was sampled randomly at two sampling points in each compartment (replicate) within each runoff plot (8 samples per plot) using a 0.25-m^2 quadrat. The teff biomass sampling was started after 20 days after sowing. The collected teff biomass samples were oven-dried at $80\text{ }^{\circ}\text{C}$ for 24 h to determine the aboveground teff biomass over the growing period. At physiological maturity, grain yield and straw yield were quantified using 1-m^2 quadrats (8 samples per plot); teff samples were sun-dried for 4 days, manually threshed, and grains were separated from husks; weight of grains and straw was quantified using a LABMAN analytical balance.

Data were analyzed using R statistical software version 3.3.2 (Team, 2013). Before analysis, data were checked for a normal distribution by using the Shapiro–Wilk procedure (Shapiro and Wilk, 1965). Analysis of variance was performed, and means were separated using the least significant difference procedure (Williams and Abdi, 2010) to detect treatment differences. Correlation among parameters was determined following Pearson’s method as illustrated by Gomez and Gomez (1984). Regression analysis was performed to define mathematical relationships among parameters.

3.3.Results

3.3.1. Sediment concentration and soil loss

Averaged over treatments and years, sediment concentration ranged from 0.01 to 5.37 g L⁻¹. The daily mean soil loss ranged from 0.0002 to 0.08 t ha⁻¹, with a mean of 0.02 t ha⁻¹. The total soil loss (August–October) ranged from 0.2 to 0.5 t ha⁻¹, with a mean of 0.3 t ha⁻¹. When assessing the individual effects, sediment concentration and soil loss were significantly influenced ($P < 0.05$) by tillage and trampling practices in 2019, but the effect was not significant in 2017 and 2018 (**Table 3.2**). Planting method had no significant impact on sediment concentration in any year, but it significantly ($P < 0.05$) affected soil loss in 2017 and 2019 (**Table 3.2, Fig. 3.1b**). Except for the three-way interaction (tillage $\times$ planting method $\times$ trampling) effect on sediment concentration in 2019, no other interactions (tillage $\times$ planting method, tillage $\times$ trampling, planting method $\times$ trampling) significantly affected sediment concentration and soil loss in our study (**Table 3.2**). In general, the impact of the three practices on sediment concentration and soil loss became more significant in the third year (2019) than in the first and second years of the experiment. Sediment concentration and soil loss were lower in RT plots than in CT plots (**Fig. 3.1a, Table 3.3**).

Planting method affected the rate of soil loss. RP reduced soil loss by 19% in 2017 and by 7% in 2019 as compared to BP (**Fig. 3.1b, Table 3.3**). Our results indicated that avoiding trampling (–T) reduced soil loss by 15% compared to trampling (+T; **Fig. 3.1c, Table 3.3**), mainly due to the low bulk density (**Table 3.4**) owing to the absence of surface compaction and sealing. Despite it was not significant, the higher compaction of +T probably decreased infiltration and aggravated runoff and soil loss, particularly in the beginning of the growing season (August), when the soil was disturbed by tillage and planting and rainfall was higher.

The box-and-whisker plots (**Fig. 3.2**) indicated that there was substantial variability in sediment concentration among different combinations of tillage, planting method, and trampling practices. The combination CT/BP/+T (farmer's practice) resulted in the highest sediment concentration followed by CT/RP/-T and CT/RP/+T, whereas RT/BP/+T gave the lowest sediment concentration followed by RT/RP/-T and RT/BP/-T. Overall, based on the soil loss results, our findings reveal that the teff cultivation system that involves several tillage operations, broadcast planting, and trampling is not efficient compared to improved practices (reducing tillage, row planting, and avoiding trampling).

Table 3-2. Summary of results of analysis of variance (F-values) for the main and interaction effects of tillage (TL), planting method (PM), and trampling practice (T) on sediment concentration, soil loss, and runoff in 2017, 2018, and 2019 cropping seasons.

Treatments	Sediment concentration			Soil loss			Runoff		
	2017	2018	2019	2017	2018	2019	2017	2018	2019
Main effects									
TL	0.02	0.35	4.89*	0.21	—	4.66*	0.04	—	0.92
PM	0.01	0.07	1.47	0.02*	—	0.00*	0.18	—	0.63
T	1.50	0.67	6.82**	1.41	—	4.37*	0.19	—	0.45
Interactions									
TL × PM	0.84	0.67	3.64	0.01	—	1.40	0.01	—	0.77
TL × T	0.21	0.49	0.67	0.08	—	0.21	0.28	—	0.31
PM × T	0.42	1.32	3.25	0.52	—	0.65	0.36	—	0.59
TL × PM × T	2.1	0.83	6.69*	1.2	—	3.01	0.04	—	0.54

—, The runoff and soil loss data for 2018 were not available and not included in the analysis.

*P < 0.05; **P < 0.01

Table 3-3. The effects of tillage, planting method, and trampling practices on monthly and total soil loss (t ha^{-1}) in 2017 and 2019 teff growing seasons.

Treatments	2017 ($n = 24$)				2019 ($n = 22$)			
	Aug	Sep	Oct	Total	Aug	Sep	Oct	Total
Tillage								
CT	0.27	0.06	0.07	0.40a	0.18	0.04	0.05	0.26a
RT	0.29	0.04	0.07	0.39a	0.11	0.06	0.04	0.21b
Planting method								
BP	0.25	0.04	0.07	0.36a	0.14	0.07	0.06	0.27a
RP	0.20	0.03	0.06	0.29b	0.16	0.04	0.04	0.25b
Trampling								
+T	0.27	0.04	0.07	0.38a	0.16	0.06	0.05	0.26a
–T	0.28	0.05	0.07	0.39a	0.14	0.05	0.04	0.22b

Means with the same letter are not significantly different at $P < 0.05$. CT, conventional tillage; RT, reduced tillage; BP, broadcast planting; RP, row planting; +T, with trampling; –T, no trampling.

Table 3-4. Effects of tillage, planting method, and trampling treatments on total nitrogen (TN), total organic carbon (TOC), and bulk density of soil samples collected in 2017 (baseline, before experiment) and after the 3-yr experiment (2019).

Treatments	TN	TOC	Bulk	pH	Available P	Exchangeable
Baseline	12.0	1.03	1.12	5.6	16.0	1.1
Tillage						
CT	12.0b	0.9b	1.2	5.7	17.7	1.0
RT	13.8a	1.3a	1.2	5.5	15.4	1.2
<i>P</i> -values	0.04	0.02	0.10	0.23	0.29	0.90
Planting						
BP	12.0	1.1	1.2	5.6	16.3	1.1
RP	11.9	1.1	1.2	5.6	16.7	1.2
<i>P</i> -values	0.11	0.52	0.50	1.12	0.99	0.99
Trampling						
+T	8.7b	0.8b	1.2a	5.7	17.0	0.9
–T	13.0a	1.2a	1.1b	5.6	16.3	1.2
<i>P</i> -values	0.02	0.02	0.03	1.00	0.33	0.05

CT, conventional tillage; RT, reduced tillage; BP, broadcast planting; RP, row planting; +T, with trampling; –T, no trampling. Values are means of 32 observations (4 sub-plots* 2 samples/sub-plot* 4 replications).

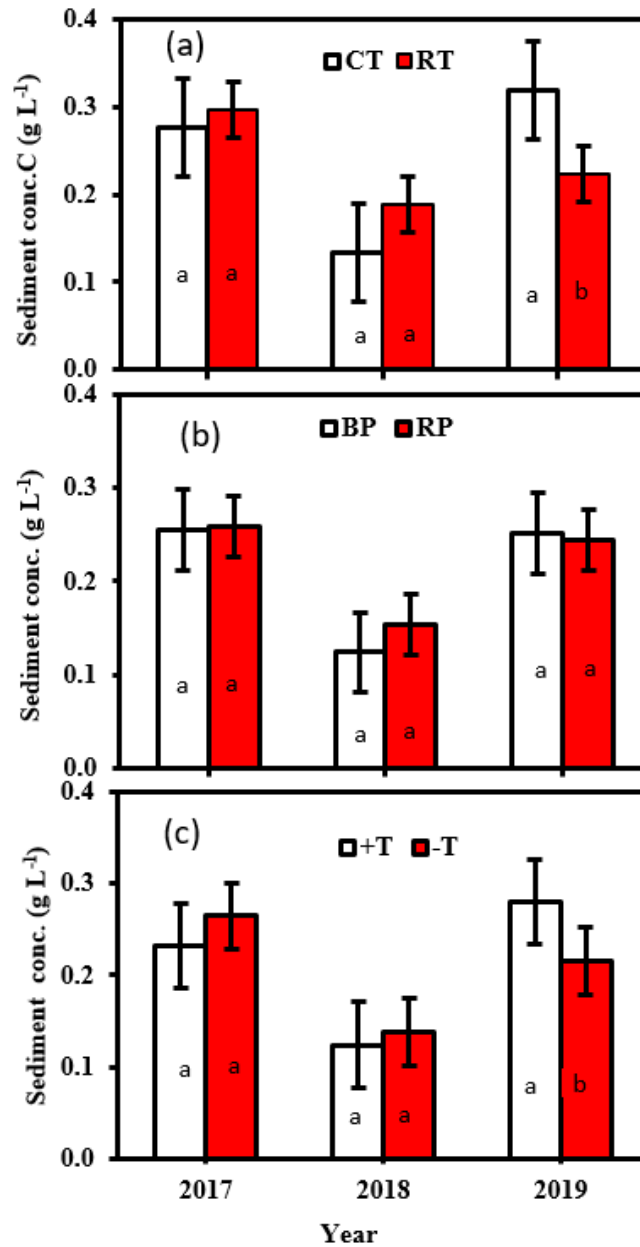


Figure 3-1. The individual effects of tillage (a), planting method (b), and trampling (c) on sediment concentration (SC) during the three monitoring seasons. Numbers of observations (n) were 24, 19, and 22 for 2017, 2018, and 2019, respectively. In each season, means with the same letter are not significantly different. CT, conventional tillage; RT, reduced tillage; BP, broadcast planting; RP, row planting; +T, with trampling; -T, no trampling. The error bars indicated are standard deviations.

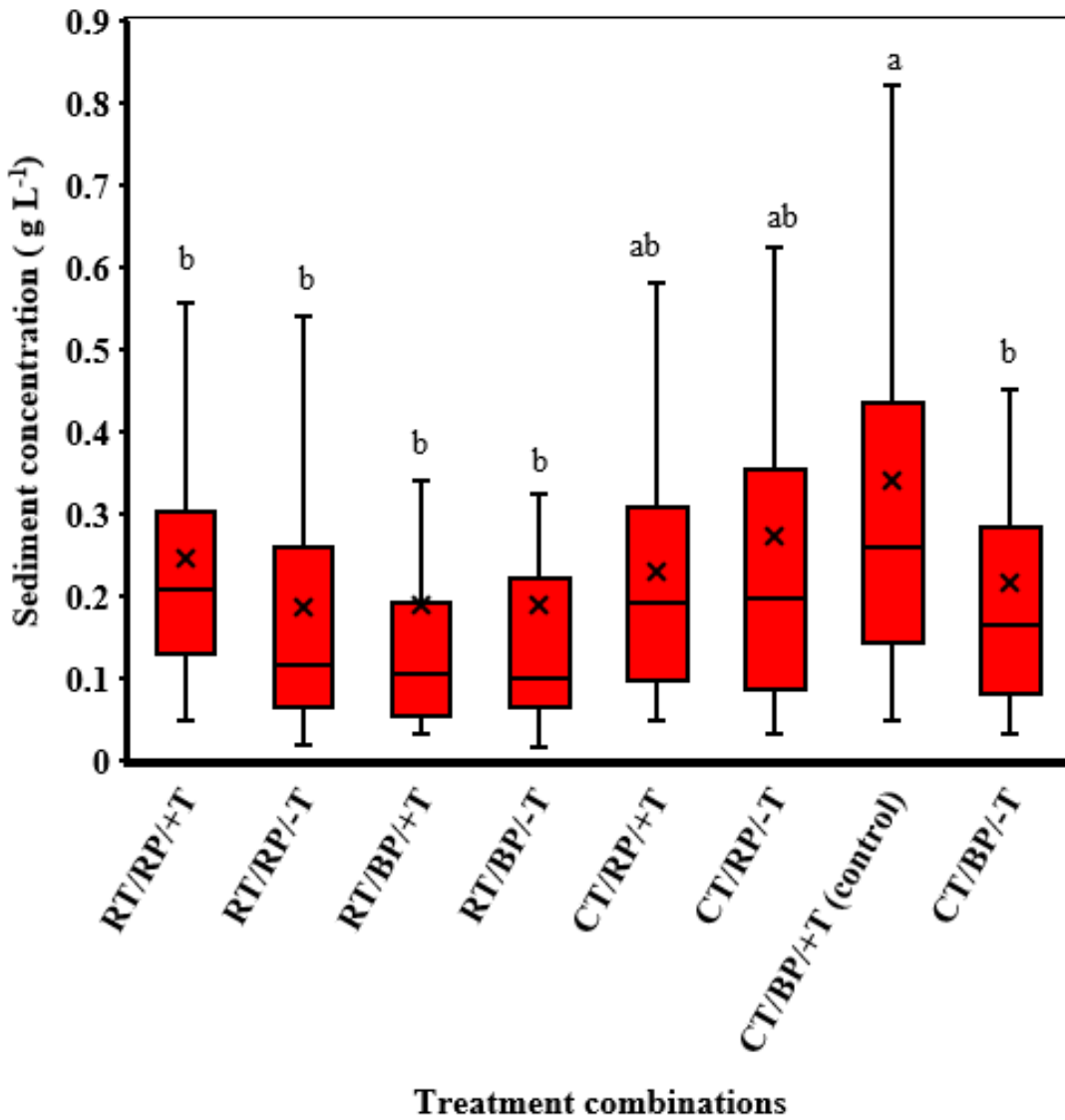


Figure 3-2. The combined effects of tillage, planting methods, and trampling on sediment concentration in 2019 ($n = 22$). The top and bottom of each box represent the upper and lower quartiles, respectively; the horizontal line and $\times$ within each box represent the median and mean, respectively; whiskers represent variability outside the upper and lower quartiles. CT, conventional tillage; RT, reduced tillage; BP, broadcast planting; RP, row planting; +T, with trampling; -T, no trampling.

3.3.2. Temporal trends in sediment concentration and soil loss

The average sediment concentrations in 2017, 2018, and 2019 were 0.29 ± 0.37 , 0.16 ± 0.31 , and 0.27 ± 0.45 g L⁻¹ (mean $\pm$ SD), respectively (**Fig. 3.3**). Similarly, total soil loss in 2017 (0.37 t ha⁻¹) was greater than that in 2019 (0.25 t ha⁻¹; **Table 3.2**). Seasons with more rainfall generated higher runoff that caused greater soil loss, as clearly demonstrated by the positive correlation between runoff and soil loss (**Fig. 3.3**). The monthly trend showed that sediment concentration and soil loss were relatively higher in August and September, and lowest in October in all the study years (**Fig. 3.4**). In August and September, the rainfall was higher (relative to October) and teff biomass cover was lower (**Fig.3.5**). However, some extreme rainfall events coupled with soil disturbance associated with weeding also generated high sediment concentration and soil loss in September.

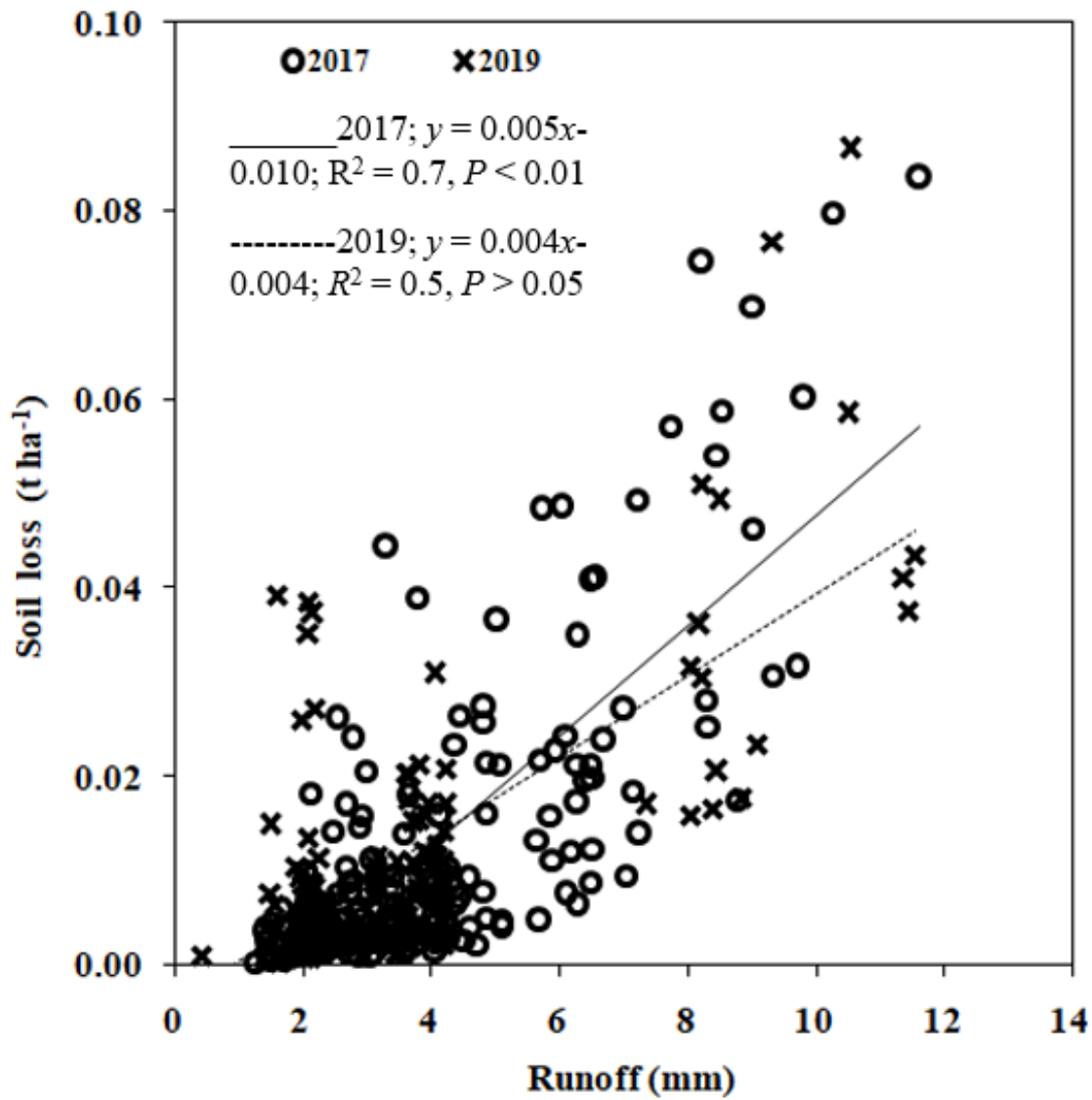


Figure 3-3. Relationships between daily runoff and soil loss in 2017 and 2019. The total numbers of observations (n) were 192 (24 daily records $\times$ 8 treatments) for 2017 and 176 (22 daily records $\times$ 8 treatments) for 2019. Runoff and thus soil loss data were not available for 2018.

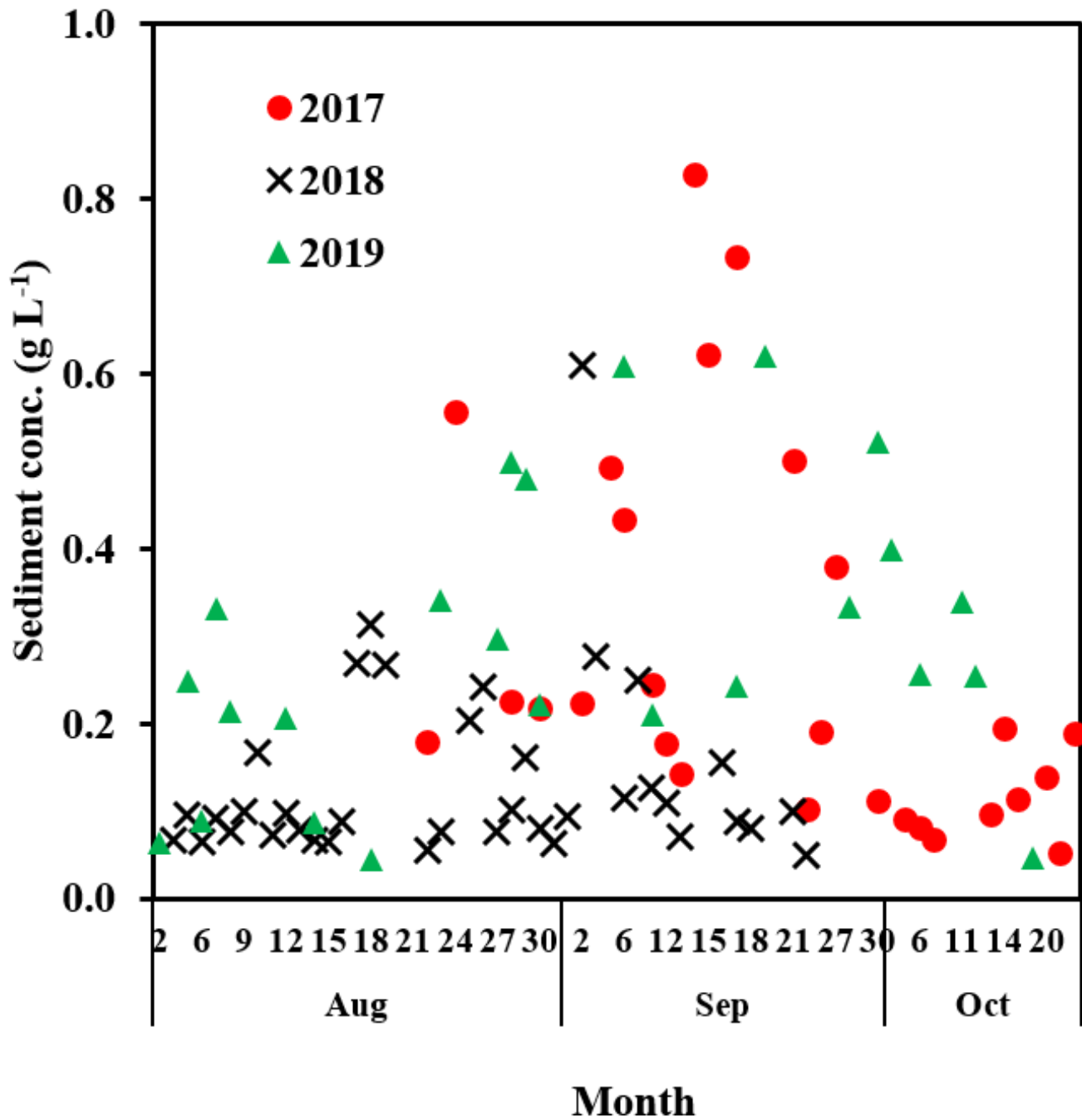


Figure 3-4. The trends of daily sediment concentration (SC) across months in 2017, 2018, and 2019. The total number of observations (averaged over treatments) were $n = 24$ events for 2017, $n = 18$ events for 2018, and $n = 22$ events for 2019.

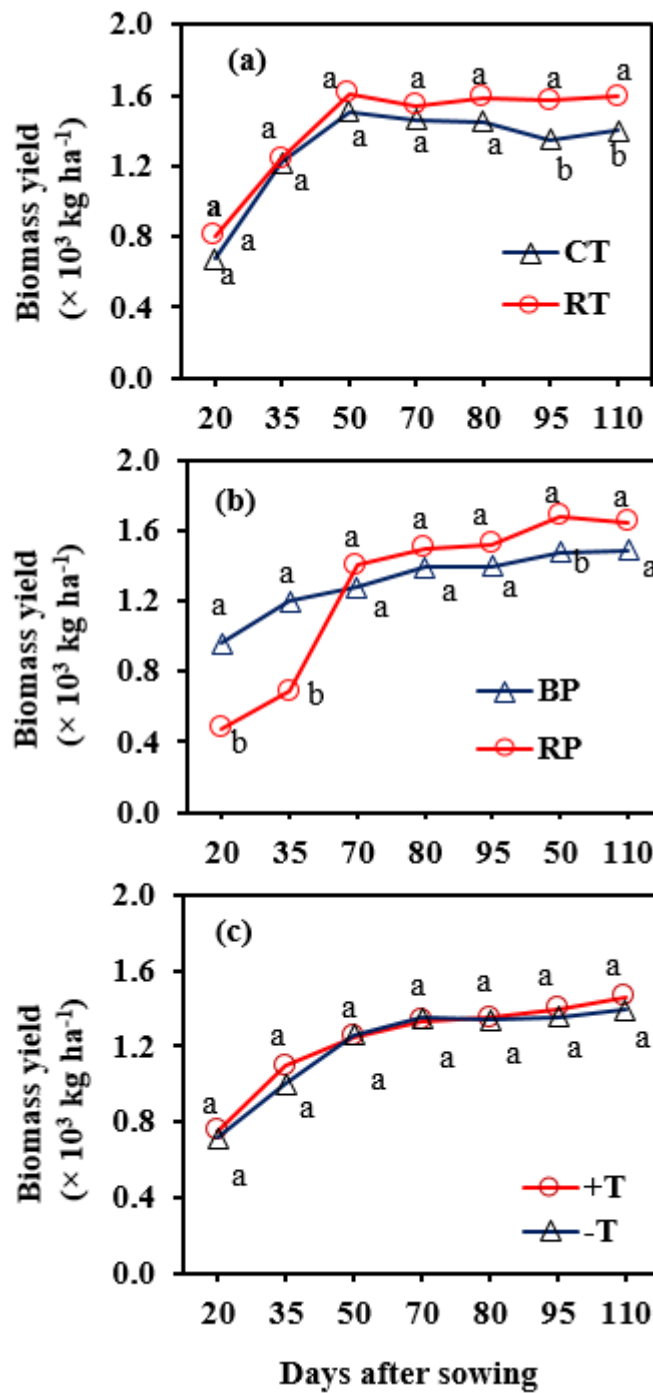


Figure 3-5. The pattern of teff biomass yield (BY) during the measuring season of 2019, as influenced by tillage (a), planting method (b), and trampling (c). CT, conventional tillage; RT, reduced tillage; BP, broadcast planting; RP, row planting. Points with Means with the same letter are not significantly different at $P = 0.05$)

3.3.3. Crop yield

Combined over years, tillage had a significant impact on teff grain yield ($P < 0.05$), whereas planting method and trampling did not ($P > 0.05$; **Table 3.6**). Teff straw yield, however, was significantly influenced by tillage, planting method, and trampling ($P < 0.05$). None of the interaction effects was found to be significant on grain yield and straw yield ($P > 0.05$). As compared to CT, RT resulted in greater grain yield and straw yield. Moreover, RP gave relatively greater grain yield and straw yield compared to those of BP. The improved teff growth conditions in RP were mainly due to the better soil moisture (**Fig. 3.6b**) and high tillering capacity. Although the difference in grain yield was not significant, +T resulted in higher straw yield compared to that of -T (**Table 3.6**).

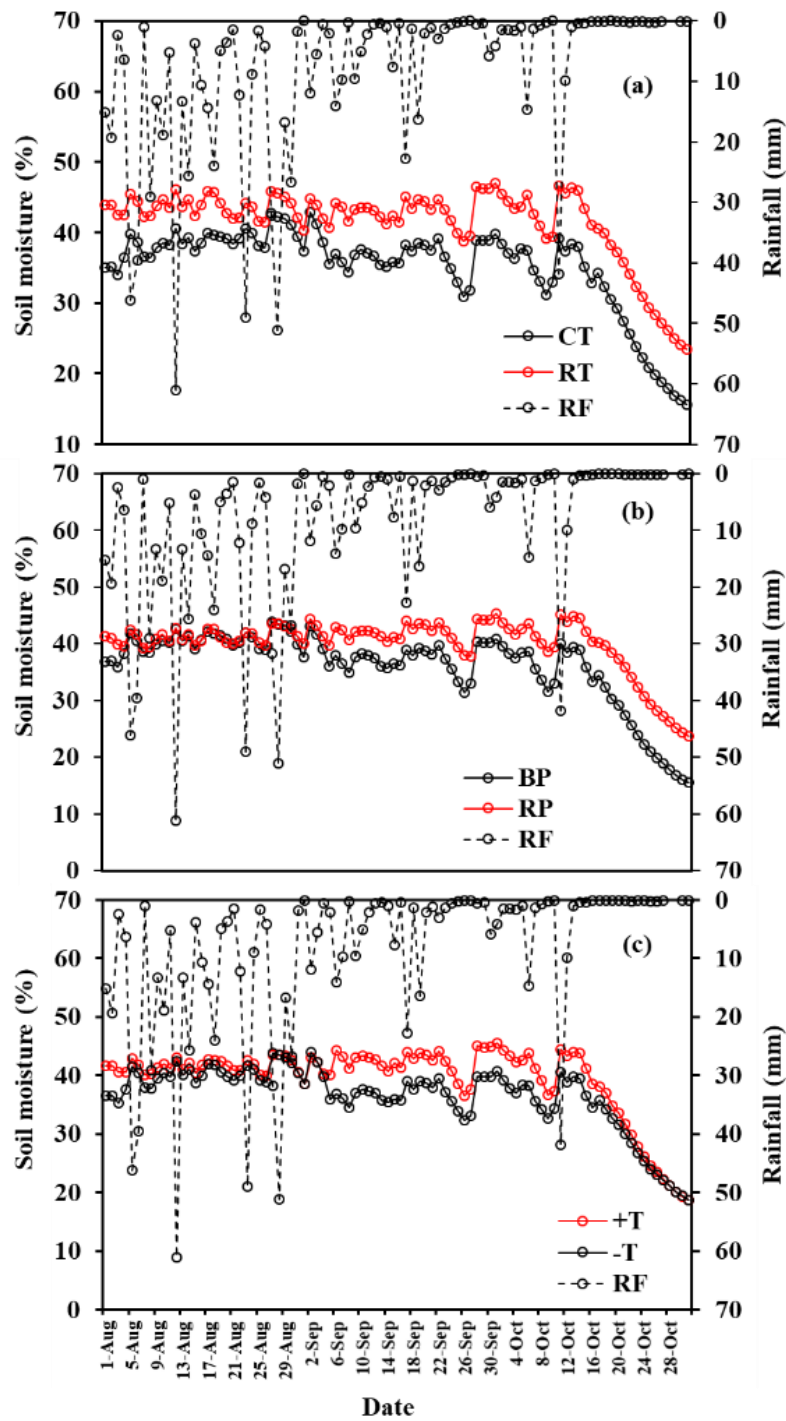


Figure 3-6. The effects of tillage (a) and planting methods (b) on daily soil moisture content during the measuring period in 2019. CT, conventional tillage; RT, reduced tillage; BP, broadcast planting; RP, row planting; RF, rainfall

3.4. Discussion

3.4.1. Sediment concentration and soil loss

In line with our study, Ebabu et al. (2019) reported that sediment concentration in crop land ranged from 0.04 to 5.13 g L⁻¹ in the Aba Gerima watershed. Generally, the soil loss observed in our study was lower than that reported in Ethiopian croplands in previous studies. According to Hurni (1993), soil loss from cultivated lands in Ethiopia might be as much as 42 t ha⁻¹ depending on the agro-ecological conditions. Other studies also noted that soil loss from agricultural lands is highly variable and dependent on rainfall, slope, soil type, land use, and plot size (Adimassu et al., 2014; Stroosnijder, 2005). The soil loss rates in the current study are far lower than those reported by Ebabu et al. (2019) for croplands in the Upper Blue Nile basin (0.01 to 5.00 t ha⁻¹). This discrepancy mainly reflects the fact that the monitoring period in this study was limited to the teff growing period (August–October), whereas much of the soil loss in the region may occur in June and July, when rainfall is higher and the land is bare and/or with limited crop cover (Brenner et al., 2013). Furthermore, the lower soil loss rates could be attributed to the sediment trapping efficiency of the graded soil bunds uniformly constructed in our experimental plots; soil bunds have been reported to reduce soil loss by 40% to 50% in Ethiopia (Herweg and Ludi, 1999) and by 60% to 86% in the Upper Blue Nile basin (Ebabu *et al.*, 2019). The significant interaction (tillage × planting method × tramplage) effect on sediment concentration marks the importance of the synergy than the individual effect of tillage, planting method and tramplage in relatively high rainfall seasons (Minella *et al.*, 2018).

The lower sediment concentration and soil loss in RT was mainly due to the favorable conditions for rainwater infiltration owing to minimal soil disturbance (minimal tillage); the less the disturbance, the lower the soil detachment and transportation by the rain and surface runoff

(Wang et al., 2019). The higher sediment concentration and soil loss in CT might be attributed to tillage-induced soil disturbances (Kurothe et al., 2014). Several studies reported that RT effectively reduced soil loss. For instance, Adimassu et al. (2019); (Kurothe et al., 2014) showed that minimum tillage with a sufficient amount of crop residue reduced soil erosion compared to CT systems. Minimum tillage also aids the gradual build-up of soil organic matter and protects the topsoil (nutrients) from being washed away by surface runoff. At 3 yr after the implementation of RT, our results also demonstrated improvements in soil TOC and TN (**Table 3.4**). Under minimum tillage systems, accumulation of soil organic matter facilitates the formation of soil aggregates, increases soil porosity, and improves soil infiltration capacity, which can help improve crop yield and reduce runoff and sediment loss (Zuazo and Pleguezuelo, 2009). The mechanism by which the RT system reduces soil erosion also improves soil properties (Myers and Waggoner, 1996), modifies microtopography, and improves soil coverage (Lal, 1995). As a result, traditional tillage practices with greater plow frequency and complete crop residue removal are among the major drivers of land degradation in Ethiopia (Tebebu et al., 2017). The soil moisture content in RT was higher than in CT plots (**Fig. 3.6**), indicating that RT enhanced rainwater infiltration. Minimum tillage increases crop biomass and yields by providing more available moisture, which can support better crop growth performance (Rockström et al., 2009). As a result, the teff biomass was consistently higher in RT than in CT plots (**Fig. 3.5**). Better teff biomass (vegetation cover) in RT plots enhanced soil protection against erosion by rainwater and explained the lower soil loss compared to that of CT. Sufficient vegetation cover is an integral part of successful soil erosion management (Rockström et al., 2009). RT practices will effectively reduce erosion only if coupled with sufficient crop residue and vegetation cover (Cooper et al., 2017; Minella et al., 2018).

The RP method provides greater biomass through the efficient utilization of soil resources (moisture, nutrients, and light). In BP, however, the seeds are randomly scattered at high plant density and weed competition is also higher. Our results indicate that planting practices that support good biomass production are important in minimizing soil erosion, and the effect is highly dependent on crop type, growing stage, and management factors (Shelton et al., 1986). In addition, the effectiveness of RP over BP in reducing soil loss might be due to the improved root development such as a better root length and formation of crown roots in cereal crops (Zuazo and Pleguezuelo, 2009) that create good anchorage and protect the soil from detachment and transportation.

Concurrent to our study, Amare et al. (2006) also reported that cattle trampling in teff increased runoff and soil loss. Soil compaction (trampling) due to farm activities can alter the soil structure, in turn hindering soil infiltration and aggravating soil erosion (Bakken et al., 1987; Muche et al., 2014). Other studies also illustrated that cattle trampling damages soil structure, hinders water infiltration, and aggravates soil loss from grazing lands with high livestock pressure for a longer period of time (Chai et al., 2019; Wu et al., 2020). However, the impact of trampling is governed by the purpose, level of compaction, trampling technique, and soil type (Savabi and Giffor, 1987). Few studies have addressed the impacts of trampling on soil loss in crop fields, but this is particularly important for teff, as it is the only crop that involves trampling during planting. Our findings indicated that trampling aggravates soil loss from teff fields despite its potential benefits in favoring better teff seed establishment, good root anchorage, and preventing soil from drying quickly (Fufa et al., 2000).

The traditional crop cultivation system aggravates soil loss from agricultural lands in Ethiopia (Berihun et al., 2019; Mariye et al., 2020). Kidane and Alemu (2015) suggested that

minimum tillage and improved agronomic technologies might reduce the risk of soil loss from teff-cultivated fields. Given that trampling is a unique practice in teff cultivation, reduced tillage practices were also proven effective in reducing soil erosion and improving soil quality (Ebabu et al., 2019). Furthermore, studies on teff (Oicha et al. (2010a), wheat (de Cárcer et al. (2019), and maize (Busari et al. (2015) reported that minimum tillage operations improved crop yield without affecting soil quality.

3.4.2. Temporal trends in sediment concentration and soil loss

The differences in sediment concentration and soil loss among years were attributed to variations in rainfall amount and intensity (**Table 3.5**), which were higher in 2017 than in 2018 and 2019, particularly in August when vegetation cover was low. However, soil loss was much greater in 2017 than in 2019, mainly due to the major soil disturbance that occurred during experimental plot establishment. Likewise, in our study the significant responses to treatments were more pronounced in 2019 than in 2018 and 2017 due to the carry-over effects and the relative stability of experimental plots later in the study period. Studies in similar areas of Ethiopia reported that sediment concentration is higher during the start of the rainy season (July and August), when soil is washed away by torrential rains and exacerbated by less ground cover (Ebabu et al., 2019; Gashaw et al., 2018). The higher the rainfall amount and intensity, the greater the detachment and transportation of soil particles (Chen et al., 2018; Renard, 1997). Greater biomass cover plays an important role in reducing the rainfall energy and gives more time for rainwater to infiltrate without detaching and transporting soil particles (Kort et al., 1998).

Table 3-5. Monthly rainfall amount and minimum, maximum, and mean rainfall intensity observed during the three cropping seasons (2017–2019) using data collected from automatic rain gauges on site.

Month	Rainfall intensity (mm/h)									Cumulative rainfall amount (mm)		
	2017			2018			2019			2017	2018	2019
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean			
Aug	0.01	6.23	1.49	0.06	5.86	1.20	0.00	24.00	1.38	388.2	314.8	360.8
Sep	0.01	1.08	0.47	0.01	4.60	0.86	0.00	0.70	0.11	220.2	175.4	297.8
Oct	0.00	2.57	0.30	0.00	8.77	0.54	0.01	0.32	0.11	38.7	85.5	90.5
Total	—	—	—	—	—	—	—	—	—	647.1	575.7	749.1

Table 3-6. Effects of tillage, planting methods, and trampling on teff grain and straw yield at harvest, combined over years.

Treatments	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)
Tillage (TL)		
CT	730 b	8700 b
RT	930 a	10350 a
<i>P</i> -values	0.04	0.02
Planting method (PM)		
BP	790	9170 b
RP	870	9880 a
<i>P</i> -values	0.41	0.05
Trampling (T)		
+T	820	9815 a
–T	730	8700 b
<i>P</i> -values	0.06	0.04
Interactions		
TL × PM	0.8	0.09
TL × T	0.11	0.16
PM × T	0.70	0.91
TL × PM × T	0.15	0.60
TL × PM × T × YR	0.09	0.50

CT, conventional tillage; RT, reduced tillage; BP, broadcast planting; RP, row planting; +T, with trampling; –T, without trampling; YR, year.

3.4.3. Crop yield

The difference was attributed to better growing conditions observed in RT plots, where both the soil moisture (**Fig. 3.6**) and soil N were higher (**Table 3.4**), which brought about enhanced teff growth (biomass gain) compared to CT (**Fig. 3.5**). Better soil fertility conditions in RT plots were indicators of improvements in soil organic matter due to the minimal disturbance and nutrient removal. In addition, the less soil loss in RT might have prevented the applied fertilizer (urea and diammonium phosphate) from being washed away by runoff (Smith et al., 2007). Therefore, our findings corroborated reports that RT can serve as one of the best agronomic practices for conserving soil nutrients and improving both grain yield and straw yield of teff. Bahrani et al. (2007); (Berner et al., 2008) also reported that RT increased crop yield. In contrast, other studies indicated that RT has no impact (Hofmeijer et al., 2019; Tulema et al., 2008) or caused a reduction in crop yield (Rusinamhodzi et al., 2011). In fact, the impact of RT systems on crop yield is highly variable and depends on factors such as crop species (Joshi et al., 2007), soil type (Carter, 1992), climate (Van Kessel et al., 2013), tillage implements (Larney and Bullock, 1994), amount of crop residue (Bescansa et al., 2006), plot scale (Raclot et al., 2009), and number of years of implementation.

Our results thus indicated that RP was an efficient agronomic practice to increase grain and straw yields with reasonable reduction in soil loss. Berhe et al. (2011) also suggested that RP can improve crop establishment during drought, tillering capacity, seed distribution, root development, and lodging resistance. The better straw yield from +T was probably due to better soil moisture (**Fig. 4b**), good crop establishment (root anchorage), reduced weed pressure, and lodging, which implied enhanced teff growth (**Table 3.6** and **Fig. 3.5**). Given there was no significant impact on grain yield, the high soil loss in the +T treatment highlights the importance of avoiding trampling

in the teff production system. Moreover, trampling is a labor-intensive activity that incurs extra costs to teff growers. Even though there was little evidence explaining the impact of trampling on crop yield, in a previous study, the positive impact of trampling on teff yield was associated with its role in good crop establishment and moisture conservation (Hailu and Seyfu, 2000). Our study also showed that +T plots slightly maintained better soil moisture compared to –T though not statistically significant ($P > 0.05$). Trampling in teff prevents the soil surface from drying quickly in the early growth stages (Fufa et al., 2000). Despite the immediate benefits observed in improving teff biomass, the high soil loss in +T might lead to soil degradation, decline in soil fertility and reduction in crop productivity in the long-term.

3.5.Conclusions

Based on our findings, we conclude that reduced tillage practices integrated with improved planting systems (row planting without trampling) effectively reduced soil losses and improved teff productivity. Reduction in soil loss was strongly associated with the better topsoil conditions and teff biomass cover. Temporal soil loss patterns in our study were attributed to trends in rainfall amount, rainfall intensity, and teff biomass cover. Better soil organic matter and moisture retention in reduced tillage and row planting led to greater growth and yields of teff. However, the benefits from reduced tillage practices can be maximized if properly integrated with crop residue management and mixed-cropping systems (intercropping and crop rotation). Thus, future research is crucial to investigate the long-term impact of agronomic practices including the effects of crop residue management and different cropping systems on soil erosion, changes in soil properties, and crop productivity.

CHAPTER FOUR

Agro-economic evaluation of alternative crop management options for teff production in midland agro-ecology, Ethiopia

This chapter is published as:

Mihretie, F. A., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Masunaga, T., Meshesha, D. T., Ebabu, K. and Bayable, M. Agro-Economic Evaluation of Alternative Crop Management Options for Teff Production in Midland Agro-Ecology, Ethiopia. *Agriculture* (2021), 11, 298. <https://doi.org/10.3390/agriculture11040298>. (available online)

Chapter four - Agro-economic evaluation of alternative crop management options for teff production in midland agro-ecology, Ethiopia

4.1.Introduction

Teff (*Eragrostis tef*) is an important crop for smallholder farmers in Ethiopia because it contributes to both their food security and income (Hassen et al., 2018). In Ethiopia, more than three million hectares of land are cultivated with teff annually (Fikadu et al., 2019). However, teff production there is constrained by lodging, drought, reduced soil fertility, and the need for continuous cropping (Woldeyohannes et al., 2020). These problems are worsened by traditional crop cultivation practices such as plant residue removal; frequent tillage and soil compaction; and a lack of knowledge and access to inputs such as improved seed, fertilizers, and irrigation technologies (Mihretie et al., 2021b). Usually, teff is cultivated using local cultivars and a high seeding rate ($>25 \text{ kg ha}^{-1}$); plowing is usually performed with oxen, and broadcast sowing, harvesting, and threshing are usually performed by hand (Chanyalew et al., 2019). Although smallholder farmers have their own reasons for using this approach, these practices are considered to be the inherent cause of low crop productivity and degradation of natural resources (Mihretie et al., 2021b). Thus, cost-effective crop management practices for increasing teff productivity are needed.

Traditionally, farmers will plow their teff fields four to eight times, depending on the area, to create a fine seedbed for better seed establishment and to minimize weed and pest infestations (Oicha et al., 2010b). However, excess tilling wastes money, and disturbing the soil increases erosion and organic matter loss (Haile and Fetene, 2012). To address these concerns, and potentially reverse the negative impacts of conventional tillage approaches, the concept of reduced

tillage, which encompasses minimizing the amount of tillage, using mixed cropping or crop rotation, incorporating crop residues, and using pre-emergent herbicides to control weeds, was developed (Cannell, 1985). Reduced tillage approaches have been shown to improve crop productivity, improve soil quality, and reduce soil erosion in major cereals such as maize (Xu et al., 2019), sorghum (Schlegel et al., 2018), and wheat (Khorami et al., 2018). However, because reduced tillage results in large weed populations, which can compete with the crop for nutrients and reduce the crop biomass that will be later used as feed for livestock or as an energy source for cooking, this approach requires application of pesticides that are potentially harmful to the environment (Khorami et al., 2018). Another drawback of reduced tillage is that it needs to be practiced for a long period of time before the desired changes in soil quality and crop yield are seen (Bai et al., 2018); this is problematic because farmers generally prefer to use technologies that offer an immediate economic benefit. Despite these drawbacks, the implementation of reduced tillage activities in Ethiopia has been reported to reduce soil erosion and improve yield in maize (Ndoli et al., 2018), sorghum (Burayu et al., 2006), and teff (Gebretsadik et al., 2009).

Another characteristic of traditional teff farming in Ethiopia is the use of broadcast sowing (hand-scattering at a high seeding rate) as a means of controlling weeds, producing high-quality straw for livestock, and reducing labor costs (Mihretie et al., 2020). However, broadcast sowing results in uneven seed distribution and low tillering capacity and allows weeds to compete with the crop for applied nutrients. Row sowing is an alternative to broadcast sowing, and although the effects of row sowing are highly dependent on soil type, tillering capacity of the cultivar used, timing and amounts of nutrients applied, and seeding density and spacing between rows, this approach has been shown in teff to improve growth and yield, and to use less seed than broadcast sowing (Fischer et al., 2019; Mihretie et al., 2020). In addition, unlike in broadcast sowing, in row

sowing nutrients can be placed near the root zone (Vandecasteele et al., 2014). It has been suggested that the improvements in teff productivity brought about by row sowing are the result of efficient resource utilization, increased tillering, reduced lodging, and facilitation of farm activities (Vandecasteele et al., 2018a). In teff, row sowing has also been shown to be more economical than broadcast sowing and seedling transplantation (Mihretie et al., 2020). Despite these many advantages, current adoption of row sowing in teff cultivation is very low due to the high labor costs associated with row-making, sowing, and weeding, and because this approach results in poor-quality (tough) straw for livestock.

A unique practice in teff production is the process of compacting the soil by human or animal (cattle, donkey, or horses) trampling immediately before sowing (Gebretsadik et al., 2009). The purpose is to increase the contact area between the seed and the soil, reduce the risk of the seed being displaced by rain water, and seal the soil surface to reduce the loss of moisture through evaporation (Tefera et al., 2001b). However, compaction is a costly practice because it requires a large number of people or animals to thoroughly compact large planting areas. Compacting the soil is also known to aggravate soil loss via runoff by reducing rainwater infiltration (Amare et al.). Recently, Mihretie et al. (2021b) have reported that trampling has little or no impact on economic yield in teff.

Although reduced tillage, row sowing, and avoiding soil compaction have been demonstrated to have agronomic, economic, and environmental advantages over traditional teff production practices, little is known about their impacts when applied in combination. However, previous findings do suggest that combining these practices may be a cost-effective means of improving teff productivity. Here, we examined whether application of these three farming practices, individually and in combination, could improve the agronomic (plant population, plant height,

panicle length, loading, and yield) and economic performance of teff cultivation in the northwestern highlands of Ethiopia.

4.2. Materials and Methods

4.2.1. Site description

The study was performed in the Aba-Gerima watershed (11°38'40.65"N, 37°29'30.02"E), which was selected as an area representative of the midland agro-ecological zone in the northwestern highlands of Ethiopia (Mihretie et al. (2021b)). Based on long-term observations (**Fig. 4.1**), the study area receives an average annual rainfall ranging from 900 to 2000 mm and an average monthly maximum temperature of 27°C and minimum temperature of 13°C. The main rainy season (growing season) falls from June to September. The soils in the study area are predominantly luvisols and leptosols; soil parameters measured for soil samples collected at the study site are shown in **Table 4.1**.

Table 4-1. Soil parameters for a composite topsoil (0–20 cm) sample collected from the experimental plots before the start of the experiment in 2018.

Parameter	Value
Total nitrogen (%)	1.2
Total organic carbon (%)	0.1
Bulk density (kg m ⁻³)	1200
pH	5.6
Available P (ppm)	16.6
Exchangeable K (cmol _c kg ⁻¹)	1.1

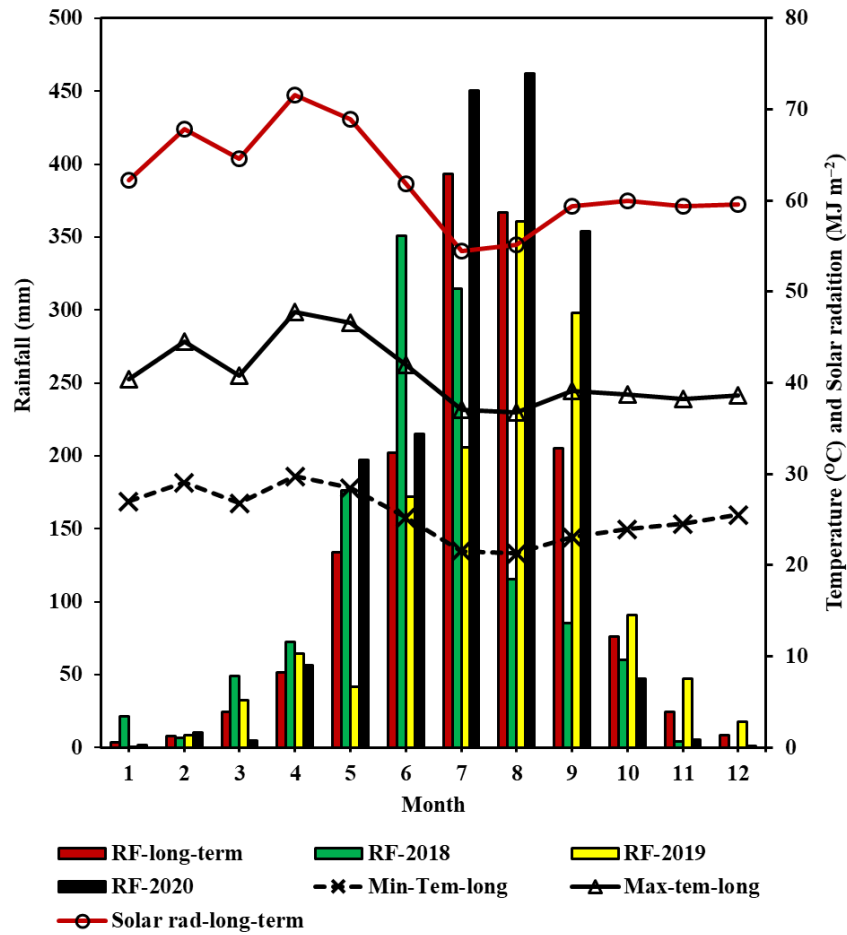


Figure 4-1. Long-term (2000–2020) average monthly rainfall (RF-long-term), maximum temperature (Max-tem-long), minimum temperature (Min-tem-long), and solar radiation (Solar rad-long-term) in the study area. The total monthly rainfall for the present study period (2018–2020) is also shown.

4.2.2. Experimental setup

Experimental plots were established to evaluate two tillage practices (conventional tillage, CT; reduced tillage, RT), two seeding practices (broadcast planting, BP; row planting, RP), and two soil compaction practices (with or without trampling) as follows:

Tillage: In accordance with current practice in the study area, CT plots were plowed four times: once in April, two times in June, and once in July. RT plots were plowed once at planting in July. In all plots, plowing was performed manually using a hand-hoe.

Planting: In accordance with current practice in the study area, BP was performed by manually scattering seed at a rate of 25 kg ha⁻¹. In RP plots, teff was planted in rows at a spacing of 25 cm and a seeding rate of 10 kg ha⁻¹.

Soil compaction: In accordance with current practice in the study area, soil compaction was performed immediately before planting by using human labor. No trampling was conducted in the plots without soil compaction.

Treatments were arranged following a split–split plot design with four replications. Tillage was assigned to the main plots, planting to the sub plots, and soil compaction to the sub- sub plots. The gross plot size was 5 m × 3 m; the net plot size was 4 m × 2 m; spacing between blocks was 0.6 m. Planting was done on July 25 in 2018, July 29 in 2019, and August 07 in 2020. The teff variety ‘Quncho’ was used. To help determine the amount of fertilizer to be applied, composite topsoil samples of the studied plots were analyzed for selected parameters (**Table 4.1, see also Section 4.2.3**). Nitrogen (N) and phosphorous (P) were applied at rates of 64 kg N ha⁻¹ and 46 kg P ha⁻¹, respectively. All P and half of the N was applied at planting; the remaining N was applied at 30 days after planting. Weeding was performed two times, at 30 and 45 days after sowing. Harvesting was performed on November 5 in 2018, November 27 in 2019, and December 2 in 2020.

4.2.3. Data collection and analysis

To evaluate the soil properties of the experimental plots, a composite topsoil (0–20 cm) sample from the experimental plots was collected before the start of the experiment (in 2018) and

analyzed for total nitrogen, total organic carbon, bulk density, pH, available P, exchangeable K, and electrical conductivity (**Table 4.1**). Total nitrogen was determined by using the Kjeldahl method (Bremmer and Mulvaney, 1996). Total organic carbon was determined as described by Nelson and Sommers (1996). Available P was determined by using the Olsen extraction method (Olsen et al., 1954). pH and electrical conductivity were determined based on the potentiometer principle (Peech, 1965); using a soil:water (1:25) solution, pH was determined using a pH meter and electrical conductivity was measured with a conductivity meter.

During the experiment in 2019 and 2020, soil moisture was monitored every 30 min by using a moisture sensor (Decagon EC-5, METER Group, Inc. USA) and data logger (EM 50) installed in each plot at a depth of 40 cm.

During the experiment in 2018, 2019, and 2020, plant height was measured every 15 days by randomly sampling 5 teff plants in each plot. Panicle length was measured immediately before harvesting by randomly sampling 5 teff plants from each plot. The plant population was counted within a 0.25-m² quadrat placed at randomly selected two points in each plot; counting was conducted twice during the growing period—at the early growth stage (20 days after sowing) and at harvest. The weed population was also counted within a 0.25-m² quadrat placed at randomly selected two points in each plot immediately before the first and second weeding. Lodging was visually estimated as a percentage of teff stands in each plot inclined below 45° during physiological maturity. Leaf area index was quantified with an LAI-2200C Plant Canopy Analyzer following standard procedures. Grain and straw yields were quantified using samples collected within a 1-m² quadrat at two spots from each plot during physiological maturity. The samples were sun-dried for at least 4 days and manually threshed; husks were manually separated from the grain by using sieves. Grain and straw yields were quantified by using a LABMAN analytical balance.

Labor costs of tillage, sowing, trampling, and the cost of seed were recorded to estimate the variable costs associated with the experimental practices. Non-variable costs such as the costs of fertilizers, harvesting, and threshing were assumed to be constant across treatments. A cost–benefit analysis was performed by using input costs (labor and seed), selling prices of teff grain, and straw yields documented by nearby cooperatives. All costs and benefits (in USD) were calculated as average values across the three monitoring seasons (2018, 2019, and 2020) and are expressed on a per hectare basis. Total variable cost was determined as the sum of the costs of seed and labor for the different tillage, planting, and soil compaction methods. Gross benefit was calculated as the sum of income obtained from grain and straw yield sales. Net benefit was calculated by subtracting the total variable cost from the gross benefit.

R statistical software version 3.3.2 (Team, 2013) was used to analyze the data. The Shapiro–Wilk test (Shapiro and Wilk, 1965) was used to check the normality of the data. The least significant difference test (Williams and Abdi, 2010) was used to detect differences between treatments. The statistical significance of each difference in the agronomic and economic parameters among treatments was tested at the 1% and 5% probability levels.

4.3.Results

4.3.1. Teff growth

Plant height: **Figure 4.2** shows the effects of tillage, sowing, and soil compaction on plant height. In all three study years (2018, 2019, and 2020), plant height increased rapidly from August to October and then increased slowly from October to November. Between treatments, the monthly plant height increase was greater with RT than with CT, with RP than with BP, and with compaction than without compaction. In 2018 and 2020, but not in 2019, plant height at maturity

(in November) was significantly higher with RT than with CT ($P < 0.05$). In all three years, plant height at maturity was significantly higher with RP than with BP ($P < 0.05$). In all three years, plant height at maturity was comparable with or without compaction. No interaction effects for plant height were observed for tillage, sowing, and soil compaction in all three years.

Panicle length: Table 4.2 shows the effects of tillage, sowing, and soil compaction on panicle length. In all three years, panicle length was significantly higher with RT than with CT ($P < 0.05$). In 2019 and 2020, but not in 2018, panicle length was significantly higher with RP than with BP ($P < 0.05$). In all three years, panicle length was comparable with or without compaction. No interaction effects for panicle length were observed ($T \times S$, $T \times C$, $S \times C$, and $T \times S \times C$). The combined effect of treatments was significant in all three years ($P < 0.05$). The longest panicle length was obtained with RT–BP–without in 2018, RT–RP–without in 2019, and RT–RP–with in 2020; the shortest panicle length was obtained with CT–BP–without in all three years.

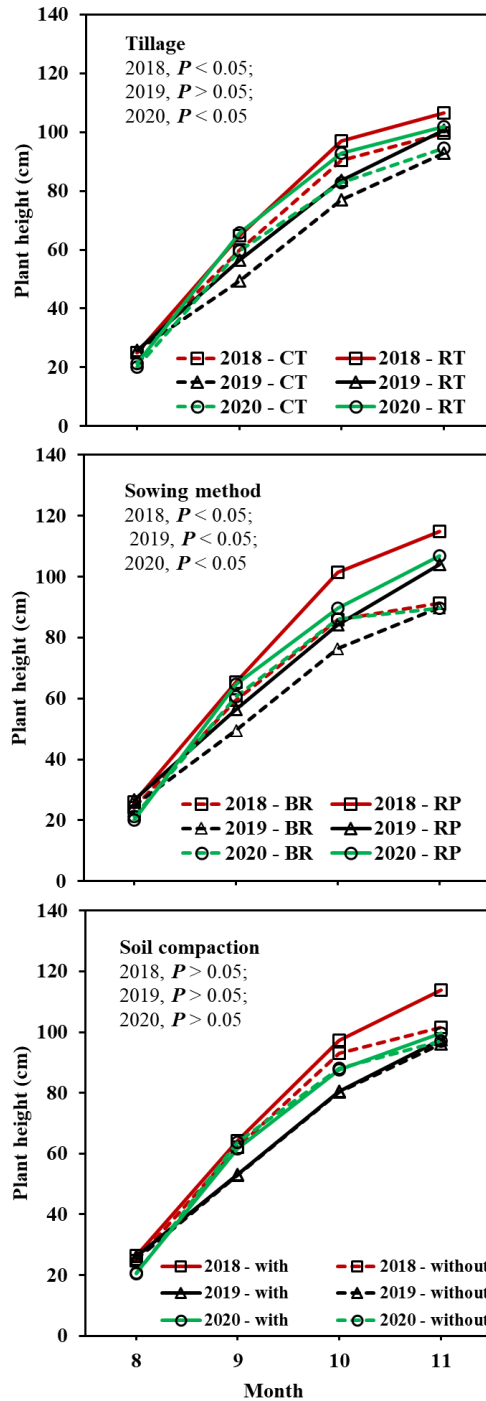


Figure 4-2. Mean teff plant height throughout the growing months (August to November) obtained with different tillage, sowing, and soil compaction practices. RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil

not compacted. Means for plant height at maturity (November) were considered significantly different when $P < 0.05$.

Table 4-2. Effects of tillage, sowing, and soil compaction methods on panicle length of teff in 2018, 2019, and 2020.

	Panicle length (cm)		
	2018	2019	2020
Tillage (T)			
CT	30.8b	36.2b	30.5b
RT	37.0a	40.3a	39.6a
<i>F-value</i>	11.5**	16.0**	40.9**
Sowing (S)			
BP	33.7	35.1b	32.5b
RP	34.1	41.4a	37.6a
<i>F-value</i>	0.05ns	38.1**	12.4**
Compaction (C)			
With	30.5	38.6	35.8
Without	31.4	37.9	34.3
<i>F-value</i>	0.08ns	0.5ns	1.1ns
Treatment combination (TRT)			
CT–BP–with	30.2c	35.1bc	28.1d
CT–BP–without	30.1c	32.2c	27.6d
CT–RP–with	30.5c	38.1b	32.8cd
CT–RP–without	32.7bc	39.3b	33.5cd
RT–BP–with	34.2abc	37.6b	38.6abc
RT–BP–without	37.3a	35.6bc	35.8b
RT–RP–with	36.8a	43.7a	43.7a
RT–RP–without	36.7a	44.6a	40.3ab
<i>F-value</i>	3.0*	8.5**	7.8**
Interaction (<i>F-value</i>)			
T×S	0.6ns	1.4ns	0.03ns
T×C	1.0ns	0.02ns	1.3ns
S×C	0.8ns	2.9ns	0.01ns
T×S×C	0.2ns	0.1ns	0.08ns
Year (YR)			
TRT×YR	0.03ns		
	1.3ns		

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted; T, tillage; S, sowing methods; C, compaction methods.

Means with different letters are significantly different at the 0.01 and 0.05 probability levels.

Leaf area index: Table 4.3 shows the effects of tillage, sowing, and soil compaction on leaf area index (LAI) in 2019 and 2020. A significantly lower LAI was obtained with RT than with CT at the tillering stage (September) in 2019 ($P < 0.01$) and at the post-flowering stage (November) in 2020 ($P < 0.05$). Similarly, a significantly lower LAI was obtained with RP than with BP at the tillering stage (September) in 2019 ($P < 0.01$) and at the post-flowering stage in 2020 ($P < 0.05$). LAI was comparable with and without soil compaction. No interaction effects for LAI were observed (TL×SM, TL×SC, SM×SC, and TL×SM×SC). The combined effects of tillage, sowing, and compaction on LAI was significant only at the tillering stage in 2019 ($P < 0.05$). The highest LAI at tillering was obtained with CT–BP–with in 2019 and with CT–BP–without in 2020; the lowest LAI at tillering was obtained with the combination RT–RP–without in 2019 and with the combination CT–BP–with in 2020. At the post-flowering stage in 2020, the highest LAI was not differed significantly among treatment combinations.

Plant population: Table 4.4 shows the effects of tillage, sowing, and soil compaction on plant population at emergence and maturity. The plant population was comparable between CT and RT at both emergence and maturity in all three years, except for at emergence in 2018 where the plant population was significantly smaller with RT than with CT. In all three years, the plant population was significantly larger with BP than with RP at emergence ($P < 0.05$). However, at maturity, the plant population was significantly larger with RP than with BP in 2018, was comparable between the two treatments in 2019, and was significantly smaller with RP than with BP in 2020. The plant population was comparable with and without soil compaction in all three years, except at emergence in 2018 when the plant population was significantly larger without compaction than with compaction. Both at emergence and maturity, no interaction effects on the

plant population were observed (TL×SM, TL×SC, SM×SC, and TL×SM×SC) except for TL×SM in 2018 ($P < 0.05$). The combined effects of TL, SM, and SC on the plant population was significant for all years at emergence but only for 2020 at maturity. The largest plant population at emergence was obtained with CT–BP–without in 2018, with CT–BP–with in 2019, and with CT–BP–without in 2020; the smallest plant population was obtained with RT–RP–without in 2018, with CT–RP–without in 2019, and with CT–RP–with in 2020. At maturity in 2020, the largest plant population was obtained with CT–BP–without and the lowest with CT–RP–with.

Table 4-3. Effects of tillage, sowing, and soil compaction methods on leaf area index at the tillering (September) and post-flowering (November) stages in teff in 2019 and 2020.

	Leaf area index in 2019		Leaf area index in 2020	
	Sep	Nov	Sep	Nov
Tillage (T)				
CT	2.7a	-	1.7	4.6b
RT	2.3b	-	1.8	5.0a
<i>F-value</i>	1.8**		0.4ns	2.1*
Sowing (S)				
BP	2.8a	-	1.6	5.4a
RP	2.2b	-	1.9	4.2b
<i>F-value</i>	2.9**		0.6ns	2.2*
Compaction (C)				
With	2.6	-	1.8	4.8
Without	2.4	-	1.7	4.8
<i>F-value</i>	0.4ns		0.02ns	0.1ns
Treatment combination (TRT)				
CT–BP–with	3.1a	-	1.1	5.31
CT–BP–without	3.0a	-	1.6	5.60
CT–RP–with	2.5ab	-	2.3	3.75
CT–RP–without	2.4b	-	1.6	3.87
RT–BP–with	2.6ab	-	1.6	5.49
RT–BP–without	2.5ab	-	2.2	5.11
RT–RP–with	2.3b	-	2.1	4.55
RT–RP–without	1.7c	-	1.5	4.68
<i>F-value</i>	6.7**		0.9ns	1.0ns
Interaction (<i>F-value</i>)				
T×S	0.01ns	-	1.4ns	0.9ns
T×C	0.15ns	-	0.001ns	0.5ns
S×C	0.11ns	-	3.9ns	0.1ns
T×S×C	0.08ns	-	0.00ns	0.1ns

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted; T, tillage; S, sowing methods; C, compaction methods. Means with different letters are significantly different at the 0.01 and 0.05 probability levels. ‘-’ data not recorded due to malfunctioning of the measuring instrument.

Table 4-4. Effects of tillage, sowing, and soil compaction methods on teff plant population at emergence and maturity stages in 2018, 2019, and 2020.

	Plant population at emergence ($\times 10^6$ plants $^{-1}$ ha $^{-1}$)			Plant population at maturity ($\times 10^6$ plants $^{-1}$ ha $^{-1}$)		
	2018	2019	2020	2018	2019	2020
Tillage (T)						
CT	4.8a	4.5	3.0	8.5	13.3	9.0
RT	3.0b	4.7	2.9	8.5	10.9	8.9
<i>F-value</i>	30.6**	0.6ns	0.2ns	0.001	0.6ns	0.2ns
Sowing (S)						
BP	5.7a	5.3a	3.7a	7.6b	12.7	9.7a
RP	2.0b	3.9b	2.1b	9.5a	11.6	8.1b
<i>F-value</i>	126.1**	25.7*	38.9*	6.4*	25.7**	38.9**
Compaction (SC)						
With	1.9b	4.7	2.7	9.4	12.6	8.7
Without	4.1a	4.5	3.1	8.4	11.7	9.1
<i>F-value</i>	7.3*	0.5ns	2.3ns	0.001	0.6ns	2.3ns
Treatment combination (TRT)						
CT–BP–with	7.1a	5.9a	3.9ab	9.5	13.7	9.9ab
CT–BP–without	7.4a	4.8abcd	4.1a	7.0	12.3	10.1a
CT–RP–with	1.9c	3.8de	1.9c	9.4	14.3	7.9c
CT–RP–without	2.3c	3.4e	2.0c	10.5	13.0	8.0c
RT–BP–with	3.8b	5.1abc	2.9bc	7.8	12.9	8.9ab
RT–BP–without	4.0b	5.4ab	4.0a	9.0	11.7	10.0a
RT–RP–with	2.0c	4.0cde	2.2c	8.4	9.3	8.2c
RT–RP–without	1.9c	4.3bcde	2.4c	8.9	9.8	8.4c
<i>F-value</i>	45.0**	4.6**	6.7**	2.2ns	1.5ns	6.7**
Interaction (<i>F-value</i>)						
T×S	16.2**	1.3ns	3.2ns	2.6ns	1.3ns	3.2ns
T×C	4.1ns	3.2ns	0.9ns	2.6ns	3.2ns	0.9ns
S×C	1.0ns	0.4ns	1.2ns	1.0ns	0.4ns	1.2ns
T×S×C	2.5ns	0.4ns	0.6ns	0.4ns	0.4ns	0.6ns
Year (YR)	11.3**			0.008		
TRT×YR	6.2**			3.068**		

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted; T, tillage; S, sowing methods; C, compaction methods.

Means with different letters are significantly different at the 0.01 and 0.05 probability levels.

4.3.2. Weed infestation

Table 4.5 shows the effects of tillage, sowing, and soil compaction on the weed population. In all three years, the weed population was significantly larger with RT than with CT at both the first and second weeding ($P < 0.05$), except at the second weeding in 2019 when the weed populations in the RT and CT plots were comparable. At the first weeding, the weed population was significantly larger with RP than with BP in 2018 and 2019 ($P < 0.05$); in 2020, the weed populations were comparable between the two treatments. At the second weeding, no differences in weed population were observed. Similarly, a significant difference in the weed populations between with compaction and without compaction was observed only at the first weeding in 2018. The combined effects of TL, SM, and SC on the weed population at the first and second weeding were significant in 2018 and 2020. The largest weed population across both the first and second weeding was obtained with RT–RP–without in 2018. The largest weed population at the first weeding was obtained with RT–RP–without and at the second weeding with RT–RP–without, both in 2018. The smallest weed population across both the first and second weeding was obtained with CT–BP–with in 2018.

4.3.3. Lodging

Figure 4.3 shows the effects of tillage, sowing, and soil compaction on lodging. Comparing RT and CT, there were no significant differences in lodging in 2018 and 2020; however, lodging was significantly higher with RT than with CT in 2019 ($P < 0.05$). Comparing planting practices, lodging was significantly lower with RP than with BP in 2018 and 2020 ($P < 0.05$), and was comparable in 2019. Comparing compaction treatments, there were no significant differences in lodging in 2019 and 2020; however, lodging was significantly higher without compaction than

with compaction in 2018 ($P < 0.05$). The lodging percentage varied substantially across the years in the order of 2018 > 2019 > 2020 ($P < 0.05$). No interaction effects were observed for lodging (TL×SM, TL×SC, SM×SC, and TL×SM×SC) (**Fig. 4.3**).

Table 4-5. Effects of tillage, sowing, and soil compaction methods on weed population at first and second weeding in 2018, 2019, and 2020.

	Weed population at			Weed population at		
	2018	2019	2020	2018	2019	2020
Tillage (T)						
CT	1.7b	1.2b	1.1b	0.9b	0.8	0.9a
RT	1.9a	1.4a	1.8a	1.2a	0.8	0.6b
<i>F-value</i>	22.9**	1.3ns	21.9**	9.2**	0.04ns	30.8**
Sowing (S)						
BP	1.7b	1.2b	1.0	0.9	0.8	0.7
RP	1.9a	1.4a	1.0	1.1	0.8	0.8
<i>F-value</i>	14.1**	5.6*	0.001ns	3.3ns	0.00ns	3.1ns
Compaction (C)						
With	1.6b	1.3	1.0	0.9	0.8	0.7
Without	1.8a	1.3	0.9	1.0	0.9	0.8
<i>F-value</i>	4.9*	0.07ns	3.2ns	0.07ns	1.6ns	2.3ns
Treatment combination (TRT)						
CT–BP–with	1.4b	1.0	0.9bc	0.7b	0.8	0.7b
CT–BP–without	1.6b	1.2	0.8c	0.8b	0.9	0.9ab
CT–RP–with	1.6b	1.5	0.8c	0.9b	0.9	0.9ab
CT–RP–without	1.8ab	1.3	0.8c	0.9b	0.8	1.1a
RT–BP–with	1.5b	1.1	1.2a	0.7b	0.7	0.6c
RT–BP–without	1.8ab	1.4	1.0ab	1.0ab	1.0	0.6c
RT–RP–with	1.8ab	1.7	1.2a	0.7b	0.7	0.6c
RT–RP–without	2.1a	1.4	1.1ab	1.3a	0.9	0.6c
<i>F-value</i>	11.4**	1.6ns	4.2**	3.4*	0.4ns	6.0**
Interaction (<i>F-value</i>)						
T×S	3.5ns	0.004ns	2.8ns	0.8ns	0.01ns	3.1ns
T×C	2.1ns	0.007ns	1.1ns	2.2ns	1.06ns	2.7ns
S×C	0.9ns	4.1ns	0.6ns	1.9ns	0.37ns	0.3ns
T×S×C	1.1ns	0.15ns	0.02ns	0.6ns	0.008ns	0.001ns
Year (YR)	188**			11.1**		
TRT×YR	6.8**			3.5**		

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted; T, tillage; S, sowing methods; C, compaction methods. Means with different letters are significantly different at the 0.01 and 0.05 probability levels.

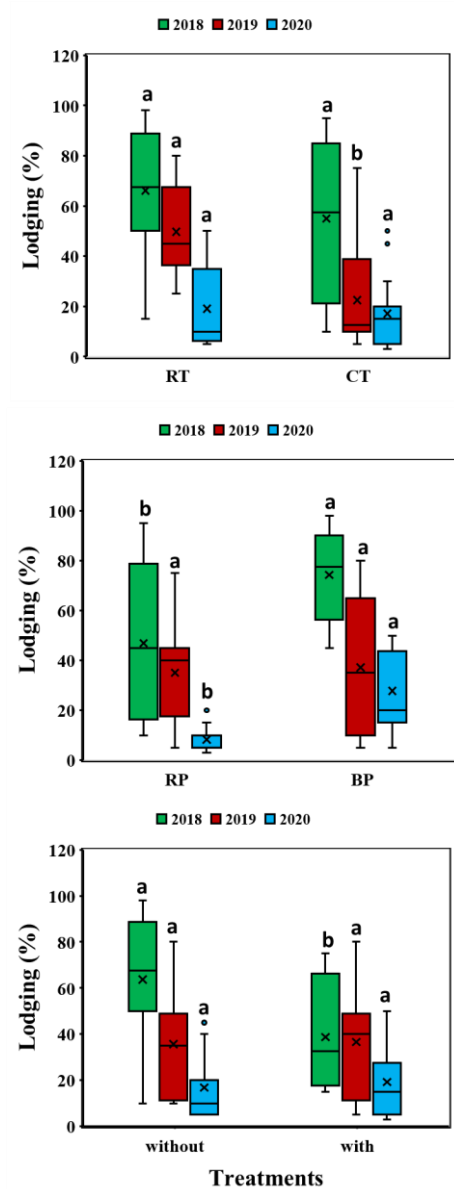


Figure 4-3. Effects of tillage, sowing, and soil compaction practices on teff lodging in 2018, 2019, and 2020. The top and bottom of each box represent the upper and lower quartiles, respectively; the horizontal line and the multiplication symbol (×) within each box represent the median and mean, respectively; whiskers represent variability outside the upper and lower quartiles. RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted. Within each year, means with different letters are significantly different at $P < 0.05$.

4.3.4. Grain and straw yields

Table 4.6 shows the effects of tillage, sowing, and soil compaction on grain and straw yields. In all three years, grain and straw yields were significantly higher with RT than with CT ($P < 0.05$). The effects of SM on grain yield was significant only in 2019 when RP gave a higher grain yield (2.2 t ha^{-1}) than did BP (1.6 t ha^{-1}) ($P < 0.05$). Straw yield was not significantly impacted by SM ($P > 0.05$). Both grain yield and straw yield were not significantly influenced by SC ($P < 0.05$). Grain yield was significantly impacted by the combined effects of TL, SM and SC methods in all the years ($P < 0.05$). The highest grain yield was obtained with RT–RP–with in 2018, and with RT–RP–without in 2019 and 2020. The lowest grain yield was obtained with CT–RP–with in 2018, with CT–BP–with in 2019, and with CT–RP–without in 2020. The highest straw yield was obtained with RT–RP–without; the lowest was obtained with CT–RP–without. No interaction effects were observed for grain yield and straw yield (TL×SC, SM×SC and TL×SM×SC), except for grain yield in 2020 ($P < 0.05$). In addition, significant interactions between treatment combination and year were observed for both grain yield and straw yield. In general, grain yield and straw yield were both significantly increased year on year in the order $2018 < 2019 < 2020$.

4.3.5. Profitability

Table 4.7 shows the results of a partial cost–benefit analysis conducted for the different combinations of farming practices. As expected, the labor costs for tillage were significantly higher for combinations involving CT than for those involving RT, for those involving RP than for those involving BP, and for with compaction than without compaction (all $P < 0.05$). Similarly, seed cost was significantly higher for combinations involving BP than for combinations involving RP ($P < 0.05$). Total variable cost was significantly different among the different combinations of TL, SM, and SC ($P < 0.05$); CT–RP–with incurred the highest total variable cost, and RT–BP–without

incurred the lowest total variable cost. Total gross benefit also significantly varied among the different combinations of TL, SM, and SC ($P < 0.05$); RT–RP–with afforded the highest total gross benefit (2216 USD) and CT–RP–without afforded the lowest total gross benefit (1235 USD). Net benefit significantly varied among the different treatment combinations ($P < 0.05$); RT–RP–with afforded the highest net benefit (1631 USD).

Table 4-6. Influences of tillage, sowing, and soil compaction methods on grain and straw yields of teff in 2018, 2019, and 2020.

	Grain yield (kg ha ⁻¹)			Straw yield (kg ha ⁻¹)		
	2018	2019	2020	2018	2019	2020
Tillage (T)						
CT	639b	1640b	728b	6543	21724b	7933b
RT	782a	2161a	1013a	7158	27083a	10693a
<i>F-value</i>	6.9*	9.5**	9.8**	1.3ns	5.3*	16.4**
Sowing (S)						
BP	767	1629b	846	7191	22310	9443
RP	655	2172a	894	6510	26498	9182
<i>F-value</i>	4.2ns	10.3**	0.3ns	1.6ns	3.2ns	0.1ns
Compaction (SC)						
With	530	1827	874	5803	23968	9434
Without	736	1974	866	7000	24839	9191
<i>F-value</i>	0.7ns	0.76ns	0.008ns	0.4ns	0.14ns	0.1ns
Treatment combination (TRT)						
CT–BP–with	664bc	1313d	850abc	6811	17090	8665abc
CT–BP–without	724abc	1609cd	800bc	7288	21620	8338bc
CT–RP–with	530c	2017bc	703c	5803	26540	8085bc
CT–RP–without	579bc	1622bcd	558c	5796	21645	6643c
RT–BP–with	580bc	1672bcd	853abc	7516	23589	10135ab
RT–BP–without	809a	1922bcd	883abc	7094	26940	10635ab
RT–RP–with	1102a	2306ab	1093ab	7440	28655	10850ab
RT–RP–without	755ab	2744a	1225a	7221	29150	11150a
<i>F-value</i>	3.1*	3.6**	2.6*	1.3ns	1.6ns	2.8*
Interaction (<i>F-value</i>)						
T×S	0.5ns	1.19ns	7.1*	1.8ns	0.05ns	1.6ns
T×C	1.1ns	1.35ns	0.9ns	0.1ns	0.20ns	0.9ns
S×C	0.9ns	0.55ns	0.001ns	0.2ns	1.75ns	0.2ns
T×S×C	0.8ns	1.69ns	0.3ns	0.4ns	0.50ns	0.1ns
Year (YR)	0.5ns			0.3ns		
TRT×YR	2.5*			3.0*		

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted; T, tillage; S, sowing methods; C, compaction methods.

Means with different letters are significantly different at the 0.01 and 0.05 probability levels.

Table 4-7. Partial cost–benefit analysis for the different tillage, sowing, and soil compaction practices.

Cost or benefit (USD ha ⁻¹)	CT– BP– with	CT– BP– without	CT– RP– with	CT– RP– without	RT– BP– with	RT– BP– without	RT– RP– with	RT– RP– without
1. Labor cost								
Tillage	368a	368a	368a	368a	92b	92b	92b	92b
Compaction	78	–	78	–	78	–	78	–
Sowing	16b	16b	49a	49a	16b	16b	49a	49a
Weeding	375a	376a	460a	453a	378a	399a	358a	397a
2. Seed cost	20a	20a	8b	8b	20a	20a	8b	8b
3. Total variable cost	858ab	780b	963a	878ab	585c	527c	585c	546c
4. Total gross benefit	1427ab	1253b	1460ab	1235b	1764ab	1447ab	2216a	1665ab
5. Net benefit	569bc	474bc	498bc	358c	1179ab	920abc	1631a	1120ab

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted. Means with different letters are significantly different at $P < 0.05$.

4.4. Discussion

4.4.1. Teff growth

We observed a greater plant height and panicle length in RT plots compared with those in CT plots, which we attributed to lower soil disturbance and better organic matter accumulation (Mihretie et al., 2021b) leading to better soil moisture availability (**Fig. 4.4**). Our findings are consistent with those of Erkossa et al. (2006) who reported that reduced tillage practices improved crop growth in teff. However, Gebretsadik et al. (2009) have reported that tillage practices do not have an effect on crop growth components in teff. We also observed a greater plant height in RP plots compared with that in BP plots, which we attributed to better placement of resources (moisture, light, and nutrients) close to the root zone (Murphy et al., 1996). These findings are consistent with those reported by Mihretie et al. (2020); (Vandecasteele et al., 2013), which have indicated that RP results in better teff growth compared with that obtained with BP.

With respect to LAI, we did not observe a clear impact of tillage across growth stages and years. LAI is a complex trait affected by a range of factors including leaf arrangement and orientation and so it might not be directly influenced by tillage (Murphy et al., 1996). RP plots produced a greater LAI than did BP plots, probably due to efficient utilization of space (even plant distribution) whereas the random scattering of plants (in patches) produced by BP produces some open spaces regardless of the number of stands within a given area. Indeed, one of the disadvantages of BP in cereals is that uneven distribution of stands results in poor light interception (low LAI) and higher intra-plant competition (Ball, 1986). The present findings are in agreement with previous reports that LAI in RP crops is greater than that in BP crops in teff (Mihretie et al., 2021b) and other cereals such as maize (Bavec and Bavec, 2002).

With respect to the plant population, a larger plant population at emergence was observed in BP plots, which we attributed to the higher seeding density (25 kg ha^{-1}) than that used in the RP plots (10 kg ha^{-1}) (Mihretie et al., 2020). However, the plant population at maturity was higher in the RP plots than in the BP plots, probably because of rapid compensation in the teff stands through enhanced tillering (Hussain et al., 2012; Mihretie et al., 2020). We also attributed the high tillering observed in the RP plots to the presence of open spaces (Mihretie et al., 2021b), better availability of resources around the root zone compared to that in the BP plots (Hussain et al., 2013), and to the high tillering capacity of the teff cultivar (Quncho) used in the study.

To summarize our findings related to growth performance, the present data indicate that RT and RP resulted in better teff growth performance compared with that obtained with CT and BP, respectively. In addition, the application of soil compaction was found to have little to no impact on teff growth.

4.4.2. Weed infestation

Tillage in the dry season (April–June) creates not only a favorable ground for teff seeds to germinate but it also damages and exposes the weed plant (seed, stem, and root) to desiccation by sunlight (Temesgen et al., 2008). Not unexpectedly then, we found that the weed population in RT plots (plowed one time) was higher than that in CT plots (plowed four times). Indeed, greater weed density has been reported in RT plots than in CT plots in teff (Mihretie et al., 2021b), wheat (Hofmeijer et al., 2019), and maize (Streit et al., 2002). It is well known that reduced tillage practices are most effective when accompanied by appropriate weed management practices such as mulching and the use of pre- and post-emergent herbicides. Despite RP allowing better access to applied N and P, the weed population is usually higher than that in BP plots due to the open spaces between rows (Marwat et al., 2011). In addition, during the first weeding (approx. 30 days

after sowing), when tillering is not yet properly started, the plant population was lower (**Table 4.4**) in the RP plots due to the low seeding rate (10 kg ha^{-1}), which might have allowed weeds to flourish more than in the BP plots where a higher seeding rate (25 kg ha^{-1}) was used. These findings highlight the fact that the agronomic benefits from planting teff in rows can only be maximized when coupled with appropriate weed control practices.

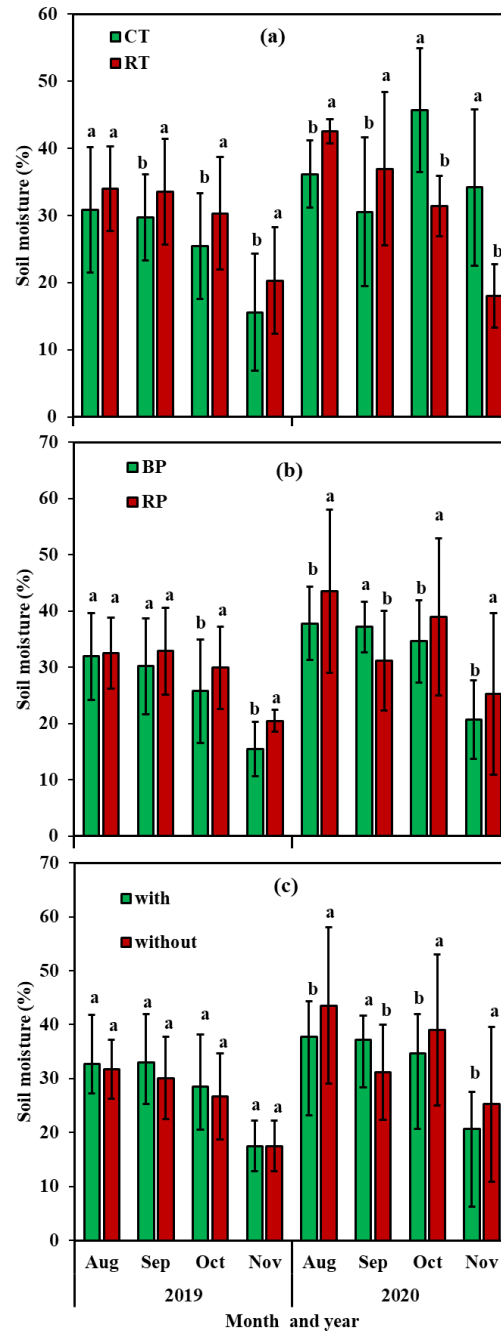


Figure 4-4. Average monthly soil moisture under different tillage (a), sowing (b), and soil compaction (c) practices in 2019 and 2020. RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; with, soil compacted; without, soil not compacted. In each month, bars labeled with different letters significantly differed at $P < 0.05$.

4.4.3. Lodging

The significant reduction of lodging observed in the RP plots compared with that in the BP plots was attributed to the growth of strong stems as a result of better nutrition (Bayable et al., 2020). Our findings are consistent with those of Mihretie et al. (2021b) and Vandecasteele et al. (2018b) who have also reported reduced lodging when teff is planted in rows. One of the reasons teff is highly susceptible to lodging is due to its weak stems (Van Delden et al., 2010). The high tillering potential afforded by RP may promote the formation of crown roots (Webb and Stephens, 1936), and because lodging in teff is partly caused by failing from the root (Van Delden et al., 2010), crown roots may provide better root anchorage (Ben-Zeev et al., 2020). However, the stronger stems may make the resultant teff straw less palatable to animals, preventing it from being used as livestock feed (Barretto et al., 2020). Indeed, in addition to high labor costs, poor-quality straw has been cited as one of the reasons for the slow adoption of row planting in teff (Vandecasteele et al., 2013). As long as an alternative feed is provided to the farmers, row planting could be one strategy to reduce lodging in teff production.

4.4.4. Teff grain and straw yields

The better teff growth (**Fig. 4.2**) and soil moisture conditions (**Fig. 4.4**) afforded by RT resulted in greater grain and straw yields compared with those obtained with CT. The lower soil disturbance caused by RT may have reduced the removal of soil organic matter and applied fertilizer in runoff, which would have provided an immediate advantage for RT over CT in terms of soil nutrition (Klik and Rosner, 2020). It is surprising that our use of RT resulted in greater teff yields in the short-term, which is in contrast to several studies (e.g., Büchi et al. (2017) showing that RT requires a longer timeframe (>5 years) before marked effects on crop yield are observed as a result of improved soil qualities. The short-term impact of RT on teff in our study might be

linked to the immediate benefits afforded by improved soil moisture compared to that obtained with CT (**Fig. 4.4**), because one of the major bottlenecks of rain-fed teff production is the shortage of moisture immediately after planting and at flowering time (Araya et al., 2010). In agreement with our present findings, Gezahegn et al. (2019) and Desta et al. (2021) have both reported that RT increased crop yield in the short-term. However, others have reported a reduction of crop yield in the first 2–3 years of using RT (Hobbs and Giri, 1997).

Without considering the tillage and weeding costs, our study suggests that RT improved teff yield in the short-term. Traditionally, more than 90% of the teff biomass is removed as an economic product; we suggest that future studies investigate the impacts of mulching or residue incorporation as part of a reduced tillage approach, because this is something we did not consider in the present study.

The greater grain yield obtained with RP than with BP in 2019 was attributed to better growth (**Fig. 4.2**), better soil moisture (**Fig. 4.4**), and reduced lodging (**Fig. 4.3**). Mihretie et al. (2020) have suggested that RP may offer a 30% yield advantage when practiced with optimum seeding density and row spacing. In addition to the yield advantage, RP saves teff seed and makes farm operations easier (Mihretie et al., 2020). However, the impact of RP on grain yield is highly impacted by several factors such as the type of cultivar used, soil type, seeding density, and row spacing (Donkor et al., 2016; Liu and Song, 2012). In addition, this practice has a high labor requirement and produces a low-quality straw, resulting in poor adoption among smallholder farms in Ethiopia (Vandecasteele et al., 2013). Also, some studies have reported that RP has no impact on teff grain yield and sometimes might even afford a lower yield than BP when a local cultivar with a low tillering capacity is used (Mihretie et al., 2021b). In the present study, we found that that RP improved grain yield but had no impact on straw yield compared with BP.

With respect to the impacts of soil compaction on grain and straw yields, we found no differences between whether soil compaction was used or not, indicating that the choice of whether to use soil compaction has relatively little importance in teff production. Despite finding no impacts on grain and straw yield, we did find that soil compaction improved soil moisture (**Fig. 4.4**), slightly reduced weed infestation and lodging, and slightly improved teff growth and yield, although this latter finding was not statistically significant (**Table 4.5**) and the responses were not consistent across the study years and were not strong enough to contribute to the final harvest (grain and straw yields). These findings support the farmers' perception that soil compaction locks in soil moisture by preventing surface drying, resulting in better root anchorage (Hundera et al., 2001). In contrast, Amare et al. (; Mihretie et al. (2021b) have suggested that sealing the soil surface by compaction might reduce infiltration of rain water and aggravate soil loss by runoff. In general, because the mechanisms of how soil compaction influences soil properties and teff root development are not fully understood, further studies are required to explore its impact in different soil types and at different compaction levels, as well as the effects of different approaches to soil compaction (human, animal, or tractor).

To summarize our findings regarding the effects of the different combinations of farming practices, combinations containing both RT and RP (RT–RP–without in 2019 and 2020; RT–RP–within 2018) afforded greater grain and straw yields due to better growth, better soil moisture, and reduced lodging. Moreover, the differences in teff yield performance across the study years (2019 > 2020 > 2018) are attributed to the greater rainfall and distribution of rainfall throughout the growing season in 2019 than in 2020 and 2018. The occurrence of high rain fall during maturity (Nov) in 2018 and 2020 might have induced lodging, resulting in a drastic loss in teff yield. Indeed, one of the major driving factors that triggers lodging is unexpected rain fall during physiological

maturity, which also induces teff plant failure and seed shattering, and causes panicles to develop mold (Bayable et al., 2020).

4.4.5. Profitability

Despite the RT plots producing a higher yield than the CT plots, the RP plots producing a higher yield than the BP plots, and soil compaction not influencing teff yields, the associated costs of labor and seed will likely be the main determinants of the uptake of these practices by farmers. The low total variable cost and higher net benefit of RT–RP–with and RT–RP–without are a result of the lower cost of labor for plowing and the higher grain and straw yields (**Table 4.7**) compared to the high total variable cost and the lower net benefit of the combinations containing CT (high cost of labor for plowing and lower grain and straw yields). CT in teff production is labor intensive and RT might offer an economic advantage by minimizing plowing costs (Mihretie et al., 2021b), even when there is little to no yield advantage over CT. However, implementation of RT is more economical and effective when integrated with other crop intensification options such as crop residue management, crop rotation, and proper weed management (Adimassu et al., 2019).

In our study, RP had a high cost for sowing that could be compensated for through lower cost of seed and high yields compared to BP. In agreement with our study, Mihretie et al. (2020) have shown that RP improves teff yields and reduces seed costs, which balances the labor costs of sowing. Our present findings suggest that soil compaction could be of benefit due to higher grain and straw yields, even with the additional high costs of labor. It should be noted here that farmers normally use cattle for tilling and soil compaction in teff cultivation; however, in the present study we used human labor because it was difficult to operate animals in the small experimental plots. Although our study clearly indicated comparative differences in costs and benefits among tillage, sowing, and soil compaction practices, quantification of the real costs associated with cattle tillage

and trampling in larger plot size is required. In traditional teff production systems, farmers are highly constrained by the availability of oxen for plowing and trampling. Because men are usually the ones who perform the plowing operation in Ethiopia (Aune et al., 2001), oxeless and widow female farmers face difficulties and might be forced to share their teff produce in exchange for oxen (Degefa et al., 2017). Even those farmers who can afford to own oxen will incur additional costs for providing feed, shelter, and healthcare for the animals, and these animals could be the one of the factors driving overgrazing and land degradation (Teklewold and Mekonnen, 2017). In addition, frequent plowing is a major cause of soil loss and land degradation in Ethiopia (Araya et al., 2011; Mihretie et al., 2021b). Therefore, RT may be a promising approach for resource-poor farmers who do not have access to oxen or whose land has degraded. Overall, we found that RT–RP–with and RT–RP–without were the most economical combinations of treatments for teff production in the study area. Since there was no significant difference among the two in net benefit, we recommend the use of RT–RP–without, especially for farmers who have limited access to labor or animals for soil compaction.

4.5.Conclusions

Here, we found that alternative tillage and sowing practices could have a substantial impact on the agronomic and economic performance of teff cultivation. Reduced tillage significantly improved teff growth and yield, mainly through better soil moisture availability and reduced cost of production compared with conventional repeated tillage. However, the greater weed population that results from reduced tillage calls for effective weed control strategies. The grain yield with row seeding was significantly higher compared with that with broadcast sowing due to good tillering and efficient use of moisture and nutrients. However, row planting incurred a high cost of

labor for sowing and weeding and requires the use of small-scale labor-reduction technologies. Despite slight improvements in soil moisture, teff growth, and yields, soil compaction should be discouraged due to the high cost of labor. Overall, we conclude that reduced tillage, row seeding, and sowing without soil compaction are promising alternative practices for improving teff productivity by reducing the cost of production and pressure on soil resources.

CHAPTER FIVE

General conclusions

Chapter five- General conclusions

In this doctoral research, we understood that traditional teff agronomic practices (high frequency of tillage, mono-cropping, and complete removal of crop residues) were major causes for soil resources degradation that led to the low teff productivity. According to our survey result, the teff yield variability was majorly attributed to differences in crop managements such as N application rates, sowing density, and soil fertility status among farmers. Alternative crop management options such as reduced tillage, incorporation of crop residues, crop rotation, and intercropping could improve teff productivity in erosion-prone areas by reversing the soil resource degradation that was caused by traditional agronomic practices.

The results of the field study (**Fig.5.1**) revealed that reduced tillage minimized soil loss compared to conventional tillage due to the minimal soil disturbance and higher biomass cover that reduced the soil detachment and transportation by the rain and surface runoff. The increased biomass production and presence strips/hedges under row sowing was likely contributed for the reduction in soil loss compared to broadcast sowing. Avoiding trampling (soil compaction) reduced soil loss compared to trampling, mainly due to the high bulk density owing to the absence of surface compaction and sealing that might have enhanced infiltration and decreased runoff. The differences in sediment concentration and soil loss over the study years were attributed to variations in rainfall amount and intensity. Soil loss was higher during the start of the rainy season (July and August), and when soil is washed away by torrential rains and exacerbated by less ground cover.

Reduced tillage resulted in better top soil conditions due to higher biomass production and less burning of organic matter due to the less disturbance. As a result, reduced tillage improved soil moisture status compared to the conventional one due to the less runoff (more infiltration) and

less volume of soil exposed to evaporation (less disturbance). Again, row sowing improved soil moisture compared to broadcast sowing as a result of less runoff. Trampling slight improved soil moisture compared no trampling. Improvements in top soil conditions and moisture retention capacity of improved agronomic practices (reduced tillage and row sowing) contributed to the better teff yield performance observed in our study.

In our study, reduced tillage significantly improved teff growth and yield, mainly through better soil moisture availability and reduced cost of production compared with conventional tillage. However, the greater weed population in reduced tillage requires implementation of effective weed control strategies. Row sowing improved teff yields compared with broadcast sowing due to a better tillering capacity, and efficient resource utilization (water, light and nutrients). However, the high cost of labor for line making, sowing, and weeding in row planting calls for provision of small-scale labor-reduction technologies. The impact of soil compaction was found to be insignificant in teff production rather it is costly, and we suggest avoiding this practice from teff cultivation system.

Overall, we conclude that reduced tillage, row sowing, without soil compaction are promising alternative practices for improving teff productivity by reducing the cost of production in erosion-prone areas. However, the benefits from reduced tillage-based systems can be maximized if properly integrated with crop residue management and mixed-cropping systems (intercropping and crop rotation). As a limitation, the effects of reduced tillage practices in minimizing soil loss, preventing washing of applied fertilizer (nutrients) and consequences on teff yield were not directly quantified in this study despite we indirectly measured their impact on soil parameters such as organic carbon and soil moisture. However, the amount of nutrients washed away together with the soil lost by the runoff (including the one from fertilizer application) should

be experimentally quantified from different tillage and sowing methods to better explain the magnitude of their impacts on soil nutrient contents, teff yield and profitability. Thus, future research is crucial to investigate the long-term impact of agronomic practices including the effects of crop residue management and different cropping systems on soil loss, changes in soil properties, and implications on teff productivity under contrasting teff growing conditions in Ethiopia.

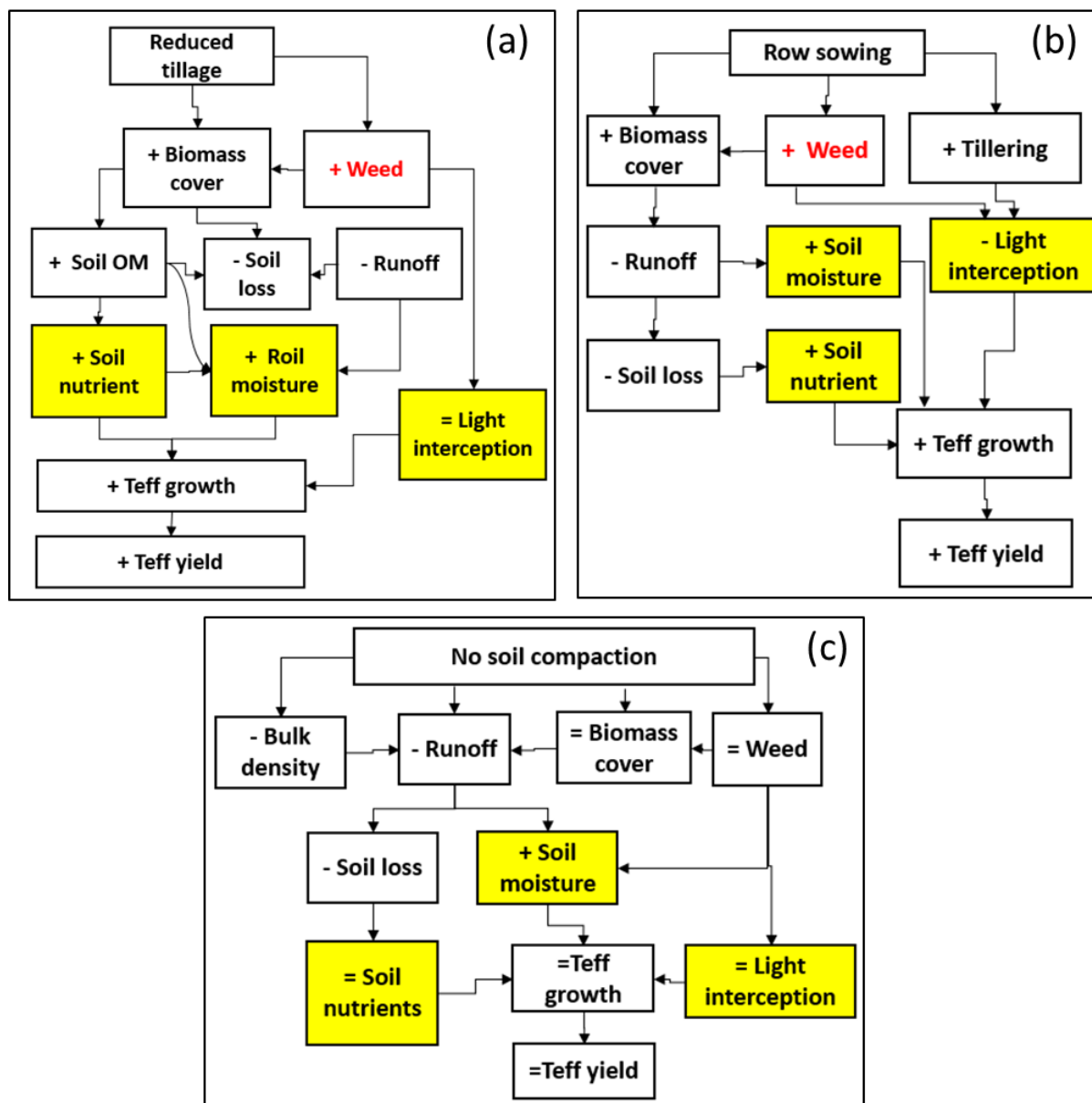


Figure 5-1. Diagram showing how reduced tillage (a), row sowing (b) and avoiding soil compaction (c) influenced teff productivity. The red highlighted parameters indicated potential negative impacts on teff productivity. The yellow box indicates major parameters contributing to teff yield formation processes.

“-“sign indicates reduction; “+” sign indicates increment; “=” sign indicates no difference

SUMMARY

Teff is an important food-security crop that serves as a source of income for millions of smallholder farmers in Ethiopia. Teff flour is used to make a staple flat bread called ‘injera’, as well as pancakes, porridge, and alcoholic beverages. Teff straw is a major source of livestock feed both in Ethiopia and elsewhere. Teff takes the major share of the total crop production in Ethiopia. More than three million hectares of land is cultivated annually with teff in Ethiopia. The demand for teff grain is expanding worldwide owing to its nutritional benefits, mainly as it is gluten free and is rich in lysine, iron, and calcium. Despite it’s a high value crop, the productivity of teff remained very low ($< 1.8 \text{ t ha}^{-1}$) highly constrained by occurrence of lodging, drought, decline in soil fertility and low input application. Moreover, teff-based cultivated lands in Ethiopia are highly degraded and vulnerable to water erosion exacerbated by traditional agronomic practices such as repeated tillage, soil compaction, mono-cropping and complete removal of crop residues. The traditional teff cultivation system is thus the major driver of the high rate of soil erosion that led to the low productivity of teff. Therefore, implementation of improved agronomic practices in the framework of sustainable land management is inevitable to reverse the adverse effects being caused by the traditional agronomic practices would sustainably improve teff productivity in erosion-prone environments in Ethiopia. Therefore, the overall objective of this doctoral research that contains five chapters was to evaluate improved agronomic practices on teff productivity in a water erosion-prone environment.

The first chapter gives a highlight of the traditional teff cultivation system in Ethiopia by focusing on profiling the challenges and opportunities of the existing teff cultivation system. Chapter one further narrates how the low teff productivity is linked with the existing traditional crop management practices. Possible alternative crop management options that could potentially

improve teff productivity by minimizing natural resource degradation were also discussed in chapter one supported with concentrate evidences from previous experiences and studies. Finally, the rationale, objectives and the hypothesis of the doctoral research are formulated in this chapter.

The second chapter presents the result of a farm-survey study that was conducted at three contrasting watersheds located in erosion-prone environments of northwestern Ethiopia (Guder, Aba-Gerima and Dibate watersheds representing the highland, midland and lowland agro-ecologies). This chapter examines the characteristics of the teff-based cropping system and explored the key crop management practices and soil fertility factors responsible for teff yield variability. Chapter two indicated that teff production is a low-yielding, less-profitable and resource-intensive enterprise. Soils of the teff-based farming systems were found to be poor in soil fertility and highly vulnerable to water erosion. Poor teff yields were mostly attributed to failure to implement improved agronomic practices and poor soil fertility status. The conventional crop management system was further marked by its' high frequency of tillage, soil compaction, monocropping, and complete removal of crop residues considered as an inherent cause for low teff productivity that emanates from the high soil erosion (losses in soil qualities). Furthermore, this chapter showed the presence of a huge teff yield variability both across and within study sites. Based on this chapter, the observed teff yield variability were partly attributed to differences in crop management practices mainly N and P fertilizer application rates, seeding densities; and soil properties such as soil N and micronutrient content. Moreover, presence of teff yield variability among farmers is an opportunity to raise the low productivity of teff at least by narrowing the yield gap between the low and the high yielders through implementation of improved agronomic practices. This chapter finally proposes the need for evaluation of improved tillage and sowing options for teff production in water erosion-prone environments to counterbalance the problem

posed by the traditional crop management system; as an entry point for the initiation and implementation of the field-based studies presented in chapter three and four.

Chapter three presents the results of the field experiment carried out at one of the representative regional learning watersheds (Aba-Gerima watershed) selected as an erosion-prone teff growing environment. This chapter justified how different tillage and sowing practices influenced soil loss, physio-chemical soil properties, and soil moisture. Reduced tillage practices minimized soil loss by 19% relative to that of conventional tillage, whereas row sowing resulted in a 13% reduction in soil loss over broadcasting. The non-compacted plots showed a 15% reduction in soil loss as compared to compacted ones. As a result, a significant increase in soil total carbon and nitrogen with reduced tillage practices were recorded compared to conventional tillage. Reduced tillage and row sowing practices improved soil moisture content compared to the conventional tillage and broadcast sowing practices. This chapter also highlighted the greater teff growth and yield performance observed under improved agronomic practices (reduced tillage and row sowing) compared with the conventional ones (conventional tillage and broadcasting) was due to the better topsoil conditions and soil moisture favorable for crop growth. Overall, this chapter concludes that the use of reduced tillage, row sowing without soil compaction practices can effectively minimize soil loss leading to an enhanced topsoil conditions that potentially enhances teff growth and yield.

The fourth chapter discusses the details of how different tillage, sowing, and soil compaction practices, and their combinations, impacted teff growth and yield performance. Chapter four clearly showed that reduced tillage improved growth, yield performance and decreased production costs compared with conventional tillage; however, the weed population was substantially larger with reduced tillage than with conventional tillage practices. In the other hand,

row sowing had little or no impacts teff growth and yields, reduced lodging but increased weed population. Again, row sowing reduced seed cost but with higher costs for sowing and weeding compared with broadcast sowing. Despite labor costs being significantly greater with soil compaction than without, little to no differences were observed in teff agronomic and yield performance. Therefore, treatments containing reduced tillage were found to be both high yielding and profitable.

Chapter five synthesized the conclusions from chapter two, three and four. This chapter marked the fact that there is a huge teff yield gap that could be narrowed by implementing improved agronomic practices. The traditional teff cultivation system was the major cause for the low teff productivity in the study areas. The minimum soil disturbance and increased biomass cover in reduced tillage practices resulted in a significant reduction in soil loss that could be lost with the runoff that helps to conserve soil organic matter and soil moisture. This improvement in topsoil conditions contributed to the higher teff productivity observed in reduced tillage than in conventional tillage practices. The reduction in soil loss and better resource utilization (water, nutrients and light) in row sowing leads to a reasonable teff productivity with a minimum soil loss compared with broadcast sowing. This research work also proved that teff productivity was not influenced by soil compaction practices. However, avoiding soil compaction was found to minimize soil loss and reduced cost of production. Based on this study, improved agronomic practices (reducing the number of tillage, row sowing without soil compaction) can be promoted for improving teff productivity if properly integrated with an appropriate weed control and labor-reduction strategies in water erosion-prone areas in Ethiopia.

概要

テフは重要な食料安全保障作物であり、エチオピアの何百万もの零細農家の収入源となっている。テフ粉は、「インジェラ」と呼ばれる主食用の平たいパンのほか、パンケーキ、お粥、アルコール飲料などに使われている。テフのわらは、エチオピアやその他の地域で、家畜の主要な飼料となっている。テフはエチオピアの全作物生産量の中で大きな割合を占めており、年間 300 万ヘクタール以上の土地でテフが栽培されている。テフはグルテンを含まず、リジン、鉄分、カルシウムを豊富に含む栄養的に優れた穀物であるため、世界的に需要が拡大している。高価な作物であるにもかかわらず、テフの生産性は非常に低く（1.5 トン ha⁻¹ 以下）、倒伏、干ばつ、土壌肥沃度の低下、投入量の少なさが大きな制約となっている。さらに、エチオピアのテフ栽培地は劣化が激しく、繰り返しの耕起、家畜による土壌の踏み固め、単作、作物残渣の完全除去などの伝統的な農法により、水食の被害を受けやすい。このように、伝統的なテフ栽培システムは、テフの生産性を低下させる高い土壌侵食率の主要な要因となっている。したがって、持続可能な土地管理の枠組みの中で、改良された農法を実施することは、伝統的な農法によって引き起こされている悪影響を逆転させ、エチオピアの侵食されやすい環境

におけるテフの生産性を持続的に向上させる。そこで、5つの章からなるこの博士論文では、エチオピア北西部の水食被害を受けやすい環境において、様々な耕起・播種方法がテフの生産性に及ぼす比較効果を調査した。

第1章では、テフ栽培システムにおける問題と課題に焦点を当てて、エチオピアの作物生産の概要を説明している。すなわち、テフの生産性の低さが、既存の伝統的な作物管理方法とどのように関連しているかを説明している。天然資源の劣化を最小限に抑えてテフの生産性を向上させる可能性のある、変更可能な作物管理の選択肢についても、これまでの経験や研究から得られた濃厚な証拠をもとに、第1章で論じている。最後に、本章では本論文の理論的根拠、目的、仮説が示されています。

第2章では、エチオピア北西部の侵食されやすい環境にある対照的な3つの流域（高地、中地、低地の農業生態を持つグダー、アバ・ゲリマ、ディバテの各流域）で実施した農場調査の結果を紹介します。本章では、テフをベースとした作付システムの特徴を検証し、テフの収量変動の原因となる主要な作物管理方法と土壌肥沃度の要因を探った。また、第2章では、テフの生産は低収量で収益性が低く、資源集約的であることを示した。テフを栽培している土地は、土壌の肥沃度が低く、水食に対して非常に脆弱であることが分かった。テフの収量が低いのは、改善された農法を実施できなかったこ

とと、土壌の肥沃度が低いことが主な原因である。従来の作物管理システムは、耕起の頻度が高いこと、土壌圧縮、単作、作物残渣の完全除去などの特徴があり、高い土壌侵食（土壌の質の低下）に起因するテフの生産性低下の本質的な原因であると考えられている。さらに、農家間で観察された作物収量のばらつきは、作物管理方法、主に N と P の施肥率、播種密度、土壌 N と微量栄養素の含有量などの土壌パラメータの違いによるものであった。本章では最後に、第 3 章と第 4 章で紹介するフィールドベースの研究の開始と実施のための入口として、このような侵食を受けやすい環境でのテフ生産のための改良された耕起と播種のオプションの評価の必要性を提案する。

第 3 章では、エチオピア北西部の侵食されやすいテフ栽培環境から選ばれた代表的な地域学習流域の 1 つ（アバ・ゲリマ流域）で実施したフィールド実験の結果を紹介する。本章では、テフの耕起・播種方法の違いが、土壌損失、物理化学的な土壌特性、土壌水分にどのような影響を与えるかを明らかにした。減耕法では、従来の耕起法と比較して、土壌損失を 19% 最小化することができたが、条播では、散播と比較して、土壌損失が 13% 減少した。また、非圧縮区画では、圧縮区画に比べて 15% の土壌損失の減少が見られた。その結果、慣行耕うんに比べて、減耕法では土壌の全炭素と窒素が有意に増加した。また、減耕と条播を行うことで、従来の耕作と条播に比べて土壌水分量

が向上しました。本章ではまた、改良型農法（減耕と条播）では、従来型農法（従来型耕耘と散播）に比べてテフの生育と収量が向上したことを強調しているが、これは表土の状態と土壌水分が作物の生育に適していたためである。以上のことから、本章では、土壌圧縮を伴わない条播と減耕を組み合わせることで、土壌損失を効果的に最小限に抑え、テフの生育と収量を向上させるための表土の状態を改善することができると結論づけている。

第4章では、耕耘、播種、土壌圧密の方法の違いやそれらの組み合わせが、テフの農学的・収量的パフォーマンスにどのような影響を与えるかを詳細に説明している。

第4章では、減耕によって、従来の耕うんに比べて生育や収量のパフォーマンスが向上し、生産コストが削減されることが明らかになった。しかし、減耕によって、雑草の数は従来の耕うんに比べて大幅に増加した。一方、条播ではテフの生育と収量が向上し、倒伏も減少したが、雑草の数は増加した。ここでも、条播は種子コストを削減したが、播種と除草にかかるコストは散播よりも高かった。土壌を圧密した場合には、圧密しない場合に比べて労働コストが大幅に増加するにもかかわらず、テフの農学的および収量的パフォーマンスにはほとんど差が見られなかった。したがって、減耕と土壌圧密化な

しの条播を組み合わせることが、侵食されやすい環境でのテフの生産において最も経済的な処理の組み合わせであることが明らかになった。

第5章では、第2章、第3章、第4章の結論をまとめた。この章では、伝統的なテフ栽培システムが、侵食の起こりやすい地域でテフの生産性が低いことの主な原因であるという事実を示した。減耕法では、土壌の攪拌を最小限に抑え、バイオマスの被覆を増やすことで、流出によって失われる可能性のある土壌の損失を大幅に減らすことができ、土壌有機物と土壌水分の保全に役立つ。このように表土の状態が改善されたことで、従来の耕作方法よりも減耕法の方がテフの生産性が高いことが確認された。また、条播では資源（水、養分、光）の利用効率が高いため、散播に比べてテフの生産性が向上した。本研究では、テフの生産性は土壌の圧密方法に影響されないことも証明された。したがって、エチオピアの水食の影響を受けやすい地域において、適切な雑草防除および労働力削減戦略と適切に統合すれば、改善された農法（耕起回数の削減、土壌圧密を伴わない条播）は、テフの生産性を向上させることが示された。

LIST OF PUBLICATIONS

1. Mihretie, F. A., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Ebabu, K., Masunaga, T., Kebede, B., Meshesha, D. T., Tsuji, W., Bayable, M. and Berihun, M. L. Tillage and Crop Management Impacts on Soil Loss and Crop Yields in Northwestern Ethiopia. International Soil and Water Conservation Research (2021). <https://doi.org/10.1016/j.iswcr.2021.04.006>. (available online)

This paper is presented in chapter three

2. Mihretie, F. A., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Masunaga, T., Meshesha, D. T., Ebabu, K. and Bayable, M. Agro-Economic Evaluation of Alternative Crop Management Options for Teff Production in Midland Agro-Ecology, Ethiopia. Agriculture (2021), 11, 298. <https://doi.org/10.3390/agriculture11040298>. (available online)

This paper is presented in chapter four

REFERENCES

- Abebe, G., Tsunekawa, A., Haregeweyn, N., Takeshi, T., Wondie, M., Adgo, E., Masunaga, T., Tsubo, M., Ebabu, K., Berihun, M.L., 2020. Effects of Land Use and Topographic Position on Soil Organic Carbon and Total Nitrogen Stocks in Different Agro-Ecosystems of the Upper Blue Nile Basin. *Sustainability*. 12(6), 2425.
- Abera, M., 2017. Agriculture in the Lake Tana Sub-basin of Ethiopia, in: *Social and Ecological System Dynamics*. Springer, pp. 375-397.
- Abraham, R., 2015. Achieving food security in Ethiopia by promoting productivity of future world food tef: A review. *Adv Plants Agric Res*. 2(2), 00045.
- Adimassu, Z., Alemu, G., Tamene, L., 2019. Effects of tillage and crop residue management on runoff, soil loss and crop yield in the humid highlands of Ethiopia. *Agricultural systems*. 168, 11-18.
- Adimassu, Z., Langan, S., Barron, J., 2018. Highlights of soil and water conservation investments in four regions of Ethiopia. *International Water Management Institute (IWMI)*.
- Adimassu, Z., Mekonnen, K., Yirga, C., Kessler, A., 2014. Effect of soil bunds on runoff, soil and nutrient losses, and crop yield in the central highlands of Ethiopia. *Land Degradation & Development*. 25(6), 554-564.
- Alba, O.S., Syrovyy, L.D., Duddu, H.S., Shirtliffe, S.J., 2020. Increased seeding rate and multiple methods of mechanical weed control reduce weed biomass in a poorly competitive organic crop. *Field Crops Research*. 245, 107648.
- Ali, A.M., 2020. Site-Specific Fertilizer Nitrogen Management in Cereals in South Asia, in: *Sustainable Agriculture Reviews 39*. Springer, pp. 137-178.
- Alskaf, K., Sparkes, D.L., Mooney, S.J., Sjögersten, S., Wilson, P., 2020. The uptake of different tillage practices in England. *Soil Use and Management*. 36(1), 27-44.

- Amare, T., Zeleke, G., Feyisa, T., 2006. Quantifying the impacts of livestock trampling on runoff, soil loss and crop yield under traditional Teff cultivation system. YG Silassie, E. Adgo, Z. Ayalew, A. Abiyu, and B. Tseganeh, Proceedings of the 1st Annual Regional conference on completed Research activities on Natural Resources Management. pp. 44-49.
- Anderson, W., Johansen, C., Siddique, K.H., 2016. Addressing the yield gap in rainfed crops: a review. *Agronomy for sustainable development*. 36(1), 18.
- Araya, A., Keesstra, S., Stroosnijder, L., 2010. Simulating yield response to water of Teff (*Eragrostis tef*) with FAO's AquaCrop model. *Field Crops Research*. 116(1-2), 196-204.
- Araya, T., Cornelis, W., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K.D., Haile, M., 2011. Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. *Soil Use and Management*. 27(3), 404-414.
- Asrat, S., Yesuf, M., Carlsson, F., Wale, E., 2010. Farmers' preferences for crop variety traits: Lessons for on-farm conservation and technology adoption. *Ecological Economics*. 69(12), 2394-2401.
- Assefa, A., Liban, M., Taddese, T., Marye, A., 2006. Determination of optimum rates of Nitrogen and Phosphorus fertilization for tef (*Eragrostis tef*) production in different agro ecological areas of northwestern Ethiopia, Annual Regional Conference in Bahirdar.
- Assefa, K., Cannarozzi, G., Girma, D., Kamies, R., Chanyalew, S., Plaza-Wüthrich, S., Blösch, R., Rindisbacher, A., Rafudeen, S., Tadele, Z., 2015. Genetic diversity in tef [*Eragrostis tef* (Zucc.) Trotter]. *Frontiers in plant science*. 6, 177.
- Assefa, K., Chanyalew, S., 2018. Agronomics of tef. *The Economics of Tef, Exploring Ethiopia's Biggest Cash Crop*. International Food Policy Research Institute (IFPRI), Wasington, DC. 39-70.
- Assefa, K., Chanyalew, S., Tadele, Z., 2017. Tef, *Eragrostis tef* (Zucc.) Trotter. *Millet and Sorghum: Biology and Genetic Improvement*. 226-266.
- Assefa, K., Yu, J.K., Zeid, M., Belay, G., Tefera, H., Sorrells, M., 2011. Breeding tef [*Eragrostis tef* (Zucc.) trotter]: conventional and molecular approaches. *Plant breeding*. 130(1), 1-9.

- Aune, J.B., Bussa, M.T., Asfaw, F.G., Ayele, A.A., 2001. The ox ploughing system in Ethiopia: can it be sustained? *Outlook on Agriculture*. 30(4), 275-280.
- Bahrani, M., Raufat, M., Ghadiri, H., 2007. Influence of wheat residue management on irrigated corn grain production in a reduced tillage system. *Soil and Tillage Research*. 94(2), 305-309.
- Bai, Z., Caspari, T., Gonzalez, M.R., Batjes, N.H., Mäder, P., Bünemann, E.K., de Goede, R., Brussaard, L., Xu, M., Ferreira, C.S.S., 2018. Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. *Agriculture, ecosystems & environment*. 265, 1-7.
- Bakken, L., Børresen, T., Njøs, A., 1987. Effect of soil compaction by tractor traffic on soil structure, denitrification, and yield of wheat (*Triticum aestivum* L.). *Journal of Soil Science*. 38(3), 541-552.
- Balemi, T., Negisho, K., 2012. Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. *Journal of soil science and plant nutrition*. 12(3), 547-562.
- Ball, B., 1986. Cereal production with broadcast seed and reduced tillage: a review of recent experimental and farming experience. *Journal of Agricultural Engineering Research*. 35(2), 71-95.
- Barretto, R., Buenavista, R.M., Rivera, J.L., Wang, S., Prasad, P.V., Siliveru, K., 2020. Teff (*Eragrostis tef*) processing, utilization and future opportunities: a review. *International Journal of Food Science & Technology*.
- Basso, B., Liu, L., 2019. Seasonal crop yield forecast: Methods, applications, and accuracies, in: *advances in agronomy*. Elsevier, pp. 201-255.
- Bavec, F., Bavec, M., 2002. Effects of plant population on leaf area index, cob characteristics and grain yield of early maturing maize cultivars (FAO 100–400). *European Journal of Agronomy*. 16(2), 151-159.
- Bayable, M., Tsunekawa, A., Haregeweyn, N., Ishii, T., Alemayehu, G., Tsubo, M., Adgo, E., Tassew, A., Tsuji, W., Asaregew, F., 2020. Biomechanical properties and agro-morphological traits for

- improved lodging resistance in Ethiopian teff (*Eragrostis tef* (Zucc.) Trotter) accessions. *Agronomy*. 10(7), 1012.
- Baye, T.G., 2017. Poverty, peasantry and agriculture in Ethiopia. *Annals of Agrarian Science*. 15(3), 420-430.
- Bayu, W., Rethman, N., Hammes, P., Alemu, G., 2006. Application of farmyard manure improved the chemical and physical properties of the soil in a semi-arid area in Ethiopia. *Biological agriculture & horticulture*. 24(3), 293-300.
- Ben-Zeev, S., Rabinovitz, O., Orlov-Levin, V., Chen, A., Graff, N., Goldwasser, Y., Saranga, Y., 2020. Less is more: lower sowing rate of irrigated tef (*Eragrostis tef*) alters plant morphology and reduces lodging. *Agronomy*. 10(4), 570.
- Berhanu, Y., Angassa, A., Aune, J.B., 2021. A system analysis to assess the effect of low-cost agricultural technologies on productivity, income and GHG emissions in mixed farming systems in southern Ethiopia. *Agricultural Systems*. 187, 102988.
- Berhe, T., Gebretsadik, Z., Edwards, S., Araya, H., 2011. Boosting tef productivity using improved agronomic practices and appropriate fertilizer, Achievements and prospects of Tef improvement. *Proceedings of the second International Workshop*. pp. 133-140.
- Berihun, M.L., Tsunekawa, A., Haregeweyn, N., Dile, Y.T., Tsubo, M., Fenta, A.A., Meshesha, D.T., Ebabu, K., Sultan, D., Srinivasan, R., 2020. Evaluating runoff and sediment responses to soil and water conservation practices by employing alternative modeling approaches. *Science of The Total Environment*. 141118.
- Berihun, M.L., Tsunekawa, A., Haregeweyn, N., Meshesha, D.T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A.A., Sultan, D., Yibeltal, M., 2019. Exploring land use/land cover changes, drivers and their implications in contrasting agro-ecological environments of Ethiopia. *Land Use Policy*. 87, 104052.
- Berner, A., Hildermann, I., Fliessbach, A., Pfiffner, L., Niggli, U., Mäder, P., 2008. Crop yield and soil fertility response to reduced tillage under organic management. *Soil and Tillage Research*. 101(1-2), 89-96.

- Bescansa, P., Imaz, M., Virto, I., Enrique, A., Hoogmoed, W., 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. *Soil and Tillage Research*. 87(1), 19-27.
- Beza, E., Silva, J.V., Kooistra, L., Reidsma, P., 2017. Review of yield gap explaining factors and opportunities for alternative data collection approaches. *European Journal of Agronomy*. 82, 206-222.
- Blackshaw, R.E., Semach, G., Janzen, H.H., 2002. Fertilizer application method affects nitrogen uptake in weeds and wheat. *Weed Science*. 50(5), 634-641.
- Blanco-Canqui, H., Wortmann, C.S., 2020. Does occasional tillage undo the ecosystem services gained with no-till? A review. *Soil and Tillage Research*. 198, 104534.
- Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analyses of soils 1. *Agronomy journal*. 54(5), 464-465.
- Bremner, J., Mulvaney, C., 1996. Nitrogen-Total. *Methods of Soil Analysis, Part 2*. Soil Science Society of America Book Series. 5, 1085-1121.
- Brenner, C., Strohmeier, S., Ziadat, F., Klik, A., 2013. Soil conservation measures in the Ethiopian Highlands: The effectiveness of stone bunds on soil erosion processes. *EGUGA*. EGU2013-5392.
- Büchi, L., Wendling, M., Amossé, C., Jeangros, B., Sinaj, S., Charles, R., 2017. Long and short term changes in crop yield and soil properties induced by the reduction of soil tillage in a long term experiment in Switzerland. *Soil and Tillage Research*. 174, 120-129.
- Burayu, W., Chinawong, S., Suwanketnikom, R., Mala, T., Juntakool, S., 2006. Tillage System and fertilizer rate effects on sorghum productivity in the Central Rift Valley of Oromiya, Ethiopia. *Agriculture and Natural Resources*. 40(1), 1-10.
- Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research*. 3(2), 119-129.
- Cannell, R., 1985. Reduced tillage in north-west Europe—a review. *Soil and Tillage Research*. 5(2), 129-177.

- Carter, M., 1992. Influence of reduced tillage systems on organic matter, microbial biomass, macro-aggregate distribution and structural stability of the surface soil in a humid climate. *Soil and Tillage Research*. 23(4), 361-372.
- Chai, J., Yu, X., Xu, C., Xiao, H., Zhang, J., Yang, H., Pan, T., 2019. Effects of yak and Tibetan sheep trampling on soil properties in the northeastern Qinghai-Tibetan Plateau. *Applied Soil Ecology*. 144, 147-154.
- Chanyalew, S., Ferede, S., Damte, T., Fikre, T., Genet, Y., Kebede, W., Tolossa, K., Tadele, Z., Assefa, K., 2019. Significance and prospects of an orphan crop tef. *Planta*. 250(3), 753-767.
- Chapman, H., 1965. Cation-exchange capacity. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*. 9, 891-901.
- Chen, H., Zhang, X., Abia, M., Lü, D., Yan, R., Ren, Q., Ren, Z., Yang, Y., Zhao, W., Lin, P., 2018. Effects of vegetation and rainfall types on surface runoff and soil erosion on steep slopes on the Loess Plateau, China. *Catena*. 170, 141-149.
- Cooper, R.J., Hama-Aziz, Z., Hiscock, K.M., Lovett, A.A., Dugdale, S.J., Sünnerberg, G., Noble, L., Beamish, J., Hovesen, P., 2017. Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment. *Agriculture, Ecosystems & Environment*. 237, 181-193.
- Cottenie, A., 1980. Soil and plant testing as a basis of fertilizer recommendations.
- CSA, 2018. Crop production and area coverage, Addis Ababa, Ethiopia.
- De Cárcer, P.S., Sinaj, S., Santonja, M., Fossati, D., Jeangros, B., 2019. Long-term effects of crop succession, soil tillage and climate on wheat yield and soil properties. *Soil and Tillage Research*. 190, 209-219.
- Degefa, K., Jaleta, M., Legesse, B., 2017. Economic efficiency of smallholder farmers in maize production in Bako Tibe district, Ethiopia. *Developing Country Studies*. 7(2), 80-86.

- Delmotte, S., Titttonell, P., Mouret, J.-C., Hammond, R., Lopez-Ridaura, S., 2011. On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. *European Journal of Agronomy*. 35(4), 223-236.
- Desta, B.T., Gezahegn, A.M., Tesema, S.E., 2021. Impacts of tillage practice on the productivity of durum wheat in Ethiopia. *Cogent Food & Agriculture*. 7(1), 1869382.
- Di Falco, S., Bezabih, M., Yesuf, M., 2010. Seeds for livelihood: crop biodiversity and food production in Ethiopia. *Ecological Economics*. 69(8), 1695-1702.
- Donkor, E., Owusu-Sekyere, E., Owusu, V., Jordaan, H., 2016. Impact of row-planting adoption on productivity of rice farming in Northern Ghana. *Review of Agricultural and Applied Economics (RAAE)*. 19(395-2016-24360), 19-28.
- Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A.A., 2019. Effects of land use and sustainable land management practices on runoff and soil loss in the Upper Blue Nile basin, Ethiopia. *Science of the total environment*. 648, 1462-1475.
- Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A.A., 2020. Exploring the variability of soil properties as influenced by land use and management practices: A case study in the Upper Blue Nile basin, Ethiopia. *Soil and Tillage Research*. 200, 104614.
- Endale, B.W., Simphiwe, E.M., Yimer, A.A., 2020. Trends in climate extremes at local farming calendar timescale: evidence from Merti District, Ethiopia. *Modeling Earth Systems and Environment*. 1-11.
- Erkossa, T., Stahr, K., Gaiser, T., 2006. Soil tillage and crop productivity on a Vertisol in Ethiopian highlands. *Soil and Tillage Research*. 85(1-2), 200-211.
- Eshetu, G., Johansson, T., Garedew, W., Yisahak, T., 2020. Determinants of smallholder farmers' adaptation options to climate change in a coffee-based farming system of Southwest Ethiopia. *Climate and Development*. 1-8.

- Eyob, T., Kibebew, K., Tekalign, M., Hailu, S., 2015. Assessment and mapping of some soil micronutrients status in agricultural land of Alichu-Woriro Woreda, Siltie Zone, Southern Ethiopia. *American Journal of Plant Nutrition and Fertilization Technology*. 5(1), 16-25.
- Ferede, S., Yirga, C., Kehaliew, A., Agegnehu, G., Alemu, T., 2020. Farming Systems Characterization and Analysis in East Gojjam Zone: Implications for research and development (R&D) interventions. Ethiopian Institute of Agricultural Research.
- Fikadu, A., Wedu, T.D., Derseh, E., 2019. Review on economics of teff in Ethiopia. *Open Access Biostatistics & Bioinformatics*. 2, 1-8.
- Fikadu, Z., 2020. Pesticides use, practice and its effect on honeybee in Ethiopia: a review. *International Journal of Tropical Insect Science*. 1-9.
- Fischer, R., Ramos, O.M., Monasterio, I.O., Sayre, K., 2019. Yield response to plant density, row spacing and raised beds in low latitude spring wheat with ample soil resources: an update. *Field crops research*. 232, 95-105.
- Folberth, C., Yang, H., Gaiser, T., Abbaspour, K.C., Schulin, R., 2013. Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. *Agricultural Systems*. 119, 22-34.
- Foy, C.D., 1992. Soil chemical factors limiting plant root growth, in: *Limitations to plant root growth*. Springer, pp. 97-149.
- Fufa, H., Tesfa, B., Hailu, T., Kibebew, A., Tiruneh, K., Aberra, D., Seyfu, K., 2000. Agronomy research in tef, Narrowing the Rift. Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, Debre Zeit, Ethiopia. pp. 16-19.
- Gashaw, T., Tulu, T., Argaw, M., 2018. Erosion risk assessment for prioritization of conservation measures in Geleda watershed, Blue Nile basin, Ethiopia. *Environmental Systems Research*. 6(1), 1.
- Gebrehiwot, H.G., Aune, J.B., Netland, J., Eklo, O.M., Torp, T., Brandsæter, L.O., 2020. Weed-Competitive Ability of Teff (*Eragrostis tef* (Zucc.) Trotter) Varieties. *Agronomy*. 10(1), 108.

- Gebretsadik, H., Haile, M., Yamoah, C.F., 2009. Tillage frequency, soil compaction and N-fertilizer rate effects on yield of teff (*Eragrostis tef* (Zucc) Trotter) in central zone of Tigray, Northern Ethiopia. *Momona Ethiopian journal of science*. 1(1).
- Gelaw, A.M., Qureshi, A.S., 2020. Tef (*Eragrostis tef*): A superfood grain from Ethiopia with great potential as an alternative crop for marginal environments, in: *Emerging Research in Alternative Crops*. Springer, pp. 265-278.
- Gezahegn, A.M., Desta, B.T., Takele, A., Eshetu, S., 2019. Productivity of tef [*Eragrostis tef*] under conservation tillage practices in central Ethiopia. *Cogent Food & Agriculture*. 5(1), 1707038.
- Ghimire, R., Lamichhane, S., Acharya, B.S., Bista, P., Sainju, U.M., 2017. Tillage, crop residue, and nutrient management effects on soil organic carbon in rice-based cropping systems: A review. *Journal of integrative agriculture*. 16(1), 1-15.
- Gomez, K.A., Gomez, A.A., 1984. *Statistical procedures for agricultural research*. John Wiley & Sons.
- Habte Werede, M., Smith, J.U., Boke Ambaye, S., 2018. Integrated soil fertility management for sustainable teff (*Eragrostistef*) production in Halaba, Southern Ethiopia. *Cogent Food & Agriculture*. 4(1), 1519008.
- Haile, G., Fetene, M., 2012. Assessment of soil erosion hazard in Kilie catchment, East Shoa, Ethiopia. *Land Degradation & Development*. 23(3), 293-306.
- Haileselassie, B., Stomph, T.-J., Hoffland, E., 2011. Teff (*Eragrostis tef*) production constraints on Vertisols in Ethiopia: farmers' perceptions and evaluation of low soil zinc as yield-limiting factor. *Soil Science and Plant Nutrition*. 57(4), 587-596.
- Haileselassie, H., Araya, A., Habtu, S., Meles, K.G., Gebru, G., Kisekka, I., Girma, A., Hadgu, K.M., Foster, A., 2016. Exploring optimal farm resources management strategy for Quncho-teff (*Eragrostis tef* (Zucc.) Trotter) using AquaCrop model. *Agricultural Water Management*. 178, 148-158.
- Hailu, G., Weersink, A., Minten, B., 2017. Determinants of the productivity of teff in Ethiopia. *The European Journal of Development Research*. 29(4), 866-892.

- Hailu, H., Mamo, T., Keskinen, R., Karlun, E., Gebrekidan, H., Bekele, T., 2015. Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. *Agriculture & Food Security*. 4(1), 1-10.
- Hailu, T., Seyfu, K., 2000. Production and importance of tef in Ethiopia Agriculture. Hailu Tefera, Getachew Belay and Mark Sorrels (Eds) *Narrowing the Rift: Tef research and development- Proceedings of the international Tef Genetics and improvement*. 16-19.
- Haregeweyn, N., Tsunekawa, A., Nyssen, J., Poesen, J., Tsubo, M., Tsegaye Meshesha, D., Schütt, B., Adgo, E., Tegegne, F., 2015. Soil erosion and conservation in Ethiopia: a review. *Progress in Physical Geography*. 39(6), 750-774.
- Haregeweyn, N., Tsunekawa, A., Poesen, J., Tsubo, M., Meshesha, D.T., Fenta, A.A., Nyssen, J., Adgo, E., 2017. Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River. *Science of the Total Environment*. 574, 95-108.
- Hassen, I.W., Regassa, M.D., Berhane, G., Minten, B., Taffesse, A.S., 2018. Teff and its role in the agricultural and food economy. *The economics of Tef, exploring Ethiopia's Biggest Cash Crop*. International Food Policy Research Institute (IFPRI), Washington DC. 11-37.
- Hendershot, W., Lalonde, H., Duquette, M., 1993. Soil reaction and exchangeable acidity. *Soil sampling and methods of analysis*. 2.
- Herweg, K., Ludi, E., 1999. The performance of selected soil and water conservation measures—case studies from Ethiopia and Eritrea. *Catena*. 36(1-2), 99-114.
- Hobbs, P.R., Giri, G.S., 1997. Reduced and zero-tillage options for establishment of wheat after rice in South Asia, in: *Wheat: prospects for global improvement*. Springer, pp. 455-465.
- Hofmeijer, M.A., Krauss, M., Berner, A., Peigné, J., Mäder, P., Armengot, L., 2019. Effects of reduced tillage on weed pressure, nitrogen availability and winter wheat yields under organic management. *Agronomy*. 9(4), 180.
- Horst, W., Abdou, M., Wiesler, F., 1993. Genotypic differences in phosphorus efficiency of wheat. *Plant and Soil*. 155(1), 293-296.

- Hudson, N., 1993. Field measurement of soil erosion and runoff. Food & Agriculture Org.
- Hundera, F., Tefera, H., Asefa, K., Kefyalew, T., Bogale, T., Debelo, A., Ketema, S., 2001. Agronomy research in tef.
- Hurni, H., 1983. Soil erosion and soil formation in agricultural ecosystems: Ethiopia and Northern Thailand. Mountain research and development. 131-142.
- Hurni, H., 1993. Land degradation, famine, and land resource scenarios in Ethiopia.
- Hussain, M., Khan, M., Mehmood, Z., Zia, A., Jabran, K., Farooq, M., 2013. Optimizing row spacing in wheat cultivars differing in tillering and stature for higher productivity. Archives of Agronomy and Soil Science. 59(11), 1457-1470.
- Hussain, M., Mehmood, Z., Khan, M.B., Farooq, S., Dong-Jin, L., Farooq, M., 2012. Narrow row spacing ensures higher productivity of low tillering wheat cultivars. International Journal of Agriculture and Biology. 14(3).
- Joshi, A., Chand, R., Arun, B., Singh, R., Ortiz, R., 2007. Breeding crops for reduced-tillage management in the intensive, rice–wheat systems of South Asia. Euphytica. 153(1-2), 135-151.
- Karlun, E., Lemenih, M., Tolera, M., 2013. COMPARING FARMERS' PERCEPTION OF SOIL FERTILITY CHANGE WITH SOIL PROPERTIES AND CROP PERFORMANCE IN BESEKU, ETHIOPIA. Land Degradation & Development. 24(3), 228-235.
- Kebebew, A., Sherif, A., Getachew, B., Gizaw, M., Tefera, H., Sorrells, M., 2011. Quncho: the first popular tef variety in Ethiopia. International journal of agricultural sustainability. 9(1), 25-34.
- Khorami, S.S., Kazemeini, S.A., Afzalnia, S., Gathala, M.K., 2018. Changes in soil properties and productivity under different tillage practices and wheat genotypes: a short-term study in Iran. Sustainability. 10(9), 3273.
- Kidane, D., Alemu, B., 2015. The effect of upstream land use practices on soil erosion and sedimentation in the Upper Blue Nile Basin, Ethiopia. Research Journal of Agriculture and Environmental Management. 4(2), 55-68.

- Kitchen, N., Sudduth, K., Drummond, S., 1999. Soil electrical conductivity as a crop productivity measure for claypan soils. *Journal of Production Agriculture*. 12(4), 607-617.
- Klik, A., Rosner, J., 2020. Long-term experience with conservation tillage practices in Austria: Impacts on soil erosion processes. *Soil and Tillage Research*. 203, 104669.
- Kort, J., Collins, M., Ditsch, D., 1998. A review of soil erosion potential associated with biomass crops. *Biomass and Bioenergy*. 14(4), 351-359.
- Kurothe, R., Kumar, G., Singh, R., Singh, H., Tiwari, S., Vishwakarma, A., Sena, D., Pande, V., 2014. Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. *Soil and Tillage Research*. 140, 126-134.
- Lal, R., 1995. Biophysical factors in the choice of tillage systems for sloping lands. *El Uso Sostenible del Suelo en Zonas de Ladera: El Papel Esencial de los Sistemas de Labranza Conservacionista*. RELACO, III Reunia Bienal de la Red Latinoamericana de Labranza Conservacionista, Diciembre 4-8, 1995, San Jose, Costa Rica. 52-58.
- Landon, J., Manual, B.T.S., 1991. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Hong Kong: Longman Scientific and Technical Group Ltd.
- Lark, R., Stafford, J., 1997. Classification as a first step in the interpretation of temporal and spatial variation of crop yield. *Annals of Applied Biology*. 130(1), 111-121.
- Larney, F., Bullock, M., 1994. Influence of soil wetness at time of tillage and tillage implement on soil properties affecting wind erosion. *Soil and Tillage Research*. 29(1), 83-95.
- Liang, J., Karamanos, R., 1993. DTPA-extractable Fe, Mn, Cu and Zn. Soil sampling and methods of analysis. 87-90.
- Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. *Soil and Tillage research*. 89(2), 210-220.
- Liu, T., Song, F., 2012. Maize photosynthesis and microclimate within the canopies at grain-filling stage in response to narrow-wide row planting patterns. *Photosynthetica*. 50(2), 215-222.

- Mäder, P., Berner, A., 2012. Development of reduced tillage systems in organic farming in Europe. *Renewable Agriculture and Food Systems*. 27(1), 7-11.
- Mann, M.L., Warner, J.M., 2017. Ethiopian wheat yield and yield gap estimation: A spatially explicit small area integrated data approach. *Field crops research*. 201, 60-74.
- Mariye, M., Mariyo, M., Changming, Y., Lakew Teffera, Z., Weldegebrial, B., 2020. Effects of land use and land cover change on soil erosion potential in Berhe district: A case study of Legedadi watershed, Ethiopia. *International Journal of River Basin Management*. (just-accepted), 1-31.
- Marwat, K.B., Khan, M.A., Hashim, S., Nawab, K., Khattak, A.M., 2011. Integrated weed management in wheat. *Pak. J. Bot.* 43(1), 625-633.
- Matsuyama, H., Ookawa, T., 2020. The effects of seeding rate on yield, lodging resistance and culm strength in wheat. *Plant Production Science*. 23(3), 322-332.
- Mekonen, G., 2016. Soil characterization, classification, and mapping of three twin watersheds in the Upper Blue Nile basin (Aba Gerima, Guder and Dibate) Amhara Design and Supervision Works Enterprise, Final project report, Bahir Dar, Ethiopia.
- Mesene, M., 2017. Extent and impact of land degradation and rehabilitation strategies: Ethiopian Highlands. *Journal of Environment and Earth Science*. 7(11), 22-32.
- Mihretie, F., Tsunekawa, A., Bitew, Y., Chakelie, G., Derebe, B., Getahun, W., Beshir, O., Tadesse, Z., Asfaw, M., 2020. Teff [*Eragrostis tef* (Zucc.)] rainfed yield response to planting method, seeding density, and row spacing. *Agronomy Journal*.
- Mihretie, F., Tsunekawa, A., Bitew, Y., Chakelie, G., Derebe, B., Getahun, W., Beshir, O., Tadesse, Z., Asfaw, M., 2021a. Teff [*Eragrostis tef* (Zucc.)] rainfed yield response to planting method, seeding density, and row spacing. *Agronomy Journal*. 113(1), 111-122.
- Mihretie, F.A., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Masunaga, T., Meshesha, D.T., Tsuji, W., Ebabu, K., Tassew, A., 2021b. Tillage and sowing options for enhancing productivity and profitability of teff in a sub-tropical highland environment. *Field Crops Research*. 263, 108050.

- Minella, J.P., Merten, G.H., Barros, C.A., Ramon, R., Schlesner, A., Clarke, R.T., Moro, M., Dalbianco, L., 2018. Long-term sediment yield from a small catchment in southern Brazil affected by land use and soil management changes. *Hydrological Processes*. 32(2), 200-211.
- MoA, 2001. Soil and water conservation field manual. MoA: Addis Ababa.
- Mousavi, S.R., Shahsavari, M., Rezaei, M., 2011. A general overview on manganese (Mn) importance for crops production. *Australian Journal of Basic and Applied Sciences*. 5(9), 1799-1803.
- Muche, H., Yimer, F., Temesgen, M., 2014. Effects of conservation tillage integrated with ‘Fanya Juus’ structures on soil loss in Northern Ethiopia. *Global Journal of Science Frontier Research*. 14(7), 1-12.
- Murphy, S.D., Yakubu, Y., Weise, S.F., Swanton, C.J., 1996. Effect of planting patterns and inter-row cultivation on competition between corn (*Zea mays*) and late emerging weeds. *Weed science*. 865-870.
- Myers, J., Waggoner, M., 1996. Runoff and sediment loss from three tillage systems under simulated rainfall. *Soil and Tillage Research*. 39(1-2), 115-129.
- Ndoli, A., Baudron, F., Sida, T.S., Schut, A.G., van Heerwaarden, J., Giller, K.E., 2018. Conservation agriculture with trees amplifies negative effects of reduced tillage on maize performance in East Africa. *Field Crops Research*. 221, 238-244.
- Negatu, B., Kromhout, H., Mekonnen, Y., Vermeulen, R., 2016. Use of chemical pesticides in Ethiopia: a cross-sectional comparative study on knowledge, attitude and practice of farmers and farm workers in three farming systems. *The Annals of occupational hygiene*. 60(5), 551-566.
- Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 3 Chemical methods*. 5, 961-1010.
- Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Adgo, E., Cochrane, L., Floquet, A., Abele, S., 2018. Applying Ostrom’s institutional analysis and development framework to soil and water conservation activities in north-western Ethiopia. *Land use policy*. 71, 1-10.
- Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Ayalew, Z., Abele, S., 2020a. Economic and financial sustainability of an *Acacia decurrens*-based Taungya system for farmers in the Upper Blue Nile Basin, Ethiopia. *Land Use Policy*. 90, 104331.

- Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Tsubo, M., Adgo, E., Ayalew, Z., Abele, S., 2020b. The impacts of *Acacia decurrens* plantations on livelihoods in rural Ethiopia. *Land Use Policy*. 100, 104928.
- Oicha, T., Cornelis, W., Verplancke, H., Nyssen, J., Govaerts, B., Behailu, M., Haile, M., Deckers, J., 2010a. Short-term effects of conservation tillage on soil (Vertisol) and crop (teff, *Eragrostis tef*) attributes in the orthern Ethiopian highlands, *Proceedings of the 19th World Congress of Soil Science, Soil Solutions for a Changing World*. pp. 149-152.
- Oicha, T., Cornelis, W., Verplancke, H., Nyssen, J., Govaerts, B., Behailu, M., Hailu, M., Deckers, J., 2010b. Short-term effects of conservation tillage on soil (Vertisol) and crop (teff, *Eragrostis tef*) attributes in the northern Ethiopian highlands, *19th World congress of Soil Science: Soil solutions for a changing world. International Union of Soil Sciences (IUSS)*, pp. 149-152.
- Oicha, T., Cornelis, W.M., Verplancke, H., Nyssen, J., Govaerts, B., Behailu, M., Haile, M., Deckers, J., 2010c. Short-term effects of conservation agriculture on Vertisols under tef (*Eragrostis tef* (Zucc.) Trotter) in the northern Ethiopian highlands. *Soil and Tillage Research*. 106(2), 294-302.
- Olsen, S., Cole, C., Watambe, F., Dean, L., 1954. Estimation of available phosphorus in soil by extraction with NaHCO_3 , USDA Ciraza (Quoted from, *Method of soil Analysis*, CA Black 2nd ed.) 1165 Am. Soc. Agron., Inc. Medision Wisconsin, USA.
- Olson, R.A., Kurtz, L., 1982. Crop nitrogen requirements, utilization, and fertilization. *Nitrogen in agricultural soils*. 22, 567-604.
- Ouedraogo, Y., Taonda, J.B.S., Sermé, I., Tychon, B., Biielders, C.L., 2020. Factors driving cereal response to fertilizer microdosing in sub-Saharan Africa: A meta-analysis. *Agronomy Journal*.
- Paff, K., Asseng, S., 2018. A review of tef physiology for developing a tef crop model. *European Journal of Agronomy*. 94, 54-66.
- Peech, M., 1965. Hydrogen-ion activity. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*. 9, 914-926.

- Raclot, D., Le Bissonnais, Y., Louchart, X., Andrieux, P., Moussa, R., Voltz, M., 2009. Soil tillage and scale effects on erosion from fields to catchment in a Mediterranean vineyard area. *Agriculture, ecosystems & environment*. 134(3-4), 201-210.
- Renard, K.G., 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). United States Government Printing.
- Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A., Temesgen, M., Mawenya, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research. *Soil and Tillage Research*. 103(1), 23-32.
- Rurinda, J., Zingore, S., Jibrin, J.M., Balemi, T., Masuki, K., Andersson, J.A., Pampolino, M.F., Mohammed, I., Mutegi, J., Kamara, A.Y., 2020. Science-based decision support for formulating crop fertilizer recommendations in sub-Saharan Africa. *Agricultural Systems*. 180, 102790.
- Rusinamhodzi, L., Corbeels, M., Van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for sustainable development*. 31(4), 657.
- Sankaranarayanan, S., Zhang, Y., Carney, J., Nigussie, Y., Esayas, B., Simane, B., Zaitchik, B., Siddiqui, S., 2020. What Are the Domestic and Regional Impacts From Ethiopia's Policy on the Export Ban of Teff? *Frontiers in Sustainable Food Systems*. 4, 4.
- Savabi, M.R., Giffor, G.F., 1987. APPLICATION OF SELECTED SOIL LOSS EQUATIONS TO TRAMPLED SOIL CONDITIONS 1. *JAWRA Journal of the American Water Resources Association*. 23(4), 709-716.
- Schlegel, A.J., Assefa, Y., Haag, L.A., Thompson, C.R., Stone, L.R., 2018. Long-term tillage on yield and water use of grain sorghum and winter wheat. *Agronomy Journal*. 110(1), 269-280.
- Schütz, L., Gattinger, A., Meier, M., Müller, A., Boller, T., Mäder, P., Mathimaran, N., 2018. Improving crop yield and nutrient use efficiency via biofertilization—A global meta-analysis. *Frontiers in Plant Science*. 8, 2204.

- Scopel, E., Triomphe, B., Affholder, F., Da Silva, F.A.M., Corbeels, M., Xavier, J.H.V., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E., 2013. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. *Agronomy for Sustainable Development*. 33(1), 113-130.
- Seyfu, K., 1997. Teff (*Eragrostis tef* (Zucc.) Trotter): promoting the conservation and use of underutilized and neglected crops. Institute of Plant Genetics and Crop Plant Research. 12.
- Shapiro, S.S., Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). *Biometrika*. 52(3/4), 591-611.
- Sharma, B., Chaudhary, T., 1983. Wheat root growth, grain yield and water uptake as influenced by soil water regime and depth of nitrogen placement in a loamy sand soil. *Agricultural Water Management*. 6(4), 365-373.
- Shatar, T., McBratney, A., 2004. Boundary-line analysis of field-scale yield response to soil properties. *The Journal of Agricultural Science*. 142, 553.
- Shelton, D.P., Jasa, P.J., Dickey, E.C., 1986. Soil erosion from tillage and planting systems used in soybean residue: part I-influences of row spacing. *Transactions of the ASAE*. 29(3), 756-0760.
- Sileshi, G., Akinnifesi, F.K., Debusho, L.K., Beedy, T., Ajayi, O.C., Mong'omba, S., 2010. Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. *Field Crops Research*. 116(1-2), 1-13.
- Sims, J.T., 2000. Soil test phosphorus: Bray and Kurtz P-1. *Methods of phosphorus analysis for soils, sediments, residuals, and waters*. 13-14.
- Sinclair, T.R., Vadez, V., 2002. Physiological traits for crop yield improvement in low N and P environments. *Plant and Soil*. 245(1), 1-15.
- Smith, D., Owens, P., Leytem, A., Warnemuende, E., 2007. Nutrient losses from manure and fertilizer applications as impacted by time to first runoff event. *Environmental Pollution*. 147(1), 131-137.

- Soinne, H., Keskinen, R., Rätty, M., Kanerva, S., Turtola, E., Kaseva, J., Nuutinen, V., Simojoki, A., Salo, T., 2020. Soil organic carbon and clay content as deciding factors for net nitrogen mineralization and cereal yields in boreal mineral soils. *European Journal of Soil Science*.
- Streit, B., Rieger, S.B., Stamp, P., Richner, W., 2002. The effect of tillage intensity and time of herbicide application on weed communities and populations in maize in central Europe. *Agriculture, ecosystems & environment*. 92(2-3), 211-224.
- Stroosnijder, L., 2005. Measurement of erosion: is it possible? *Catena*. 64(2-3), 162-173.
- Taddese, G., 2001. Land degradation: a challenge to Ethiopia. *Environmental management*. 27(6), 815-824.
- Tadesse, L., Suryabhadgavan, K., Sridhar, G., Legesse, G., 2017. Land use and land cover changes and Soil erosion in Yezat Watershed, North Western Ethiopia. *International soil and water conservation research*. 5(2), 85-94.
- Taffesse, A.S., Dorosh, P., Gemessa, S.A., 2012. Crop production in Ethiopia: Regional patterns and trends. *Food and agriculture in Ethiopia: Progress and policy challenges*. 53-83.
- Tanaka, A., Diagne, M., Saito, K., 2015. Causes of yield stagnation in irrigated lowland rice systems in the Senegal River Valley: Application of dichotomous decision tree analysis. *Field Crops Research*. 176, 99-107.
- Team, R.C., 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. .
- Tebebu, T.Y., Bayabil, H.K., Stoof, C.R., Giri, S.K., Gessess, A.A., Tilahun, S.A., Steenhuis, T.S., 2017. Characterization of degraded soils in the humid Ethiopian highlands. *Land Degradation & Development*. 28(7), 1891-1901.
- Tefera, H., Belay, G., Sorrells, M., 2001a. Narrowing the Rift. Tef research and development.
- Tefera, H., Belay, G., Sorrells, M., 2001b. Narrowing the Rift: Tef Research and Development: Proceedings of the " International Workshop on Tef Genetics and Improvement", Debre Zeit, Ethiopia, 16-19 October, 2000. Ethiopian Agricultural Research Organization.

- Teklewold, H., Mekonnen, A., 2017. The tilling of land in a changing climate: Empirical evidence from the Nile Basin of Ethiopia. *Land Use Policy*. 67, 449-459.
- Teklu, Y., Tefera, H., 2005. Genetic improvement in grain yield potential and associated agronomic traits of tef (*Eragrostis tef*). *Euphytica*. 141(3), 247-254.
- Temesgen, M., Hoogmoed, W., Rockstrom, J., Savenije, H., 2009. Conservation tillage implements and systems for smallholder farmers in semi-arid Ethiopia. *Soil and Tillage Research*. 104(1), 185-191.
- Temesgen, M., Rockstrom, J., Savenije, H., Hoogmoed, W., Alemu, D., 2008. Determinants of tillage frequency among smallholder farmers in two semi-arid areas in Ethiopia. *Physics and chemistry of the earth, parts A/B/C*. 33(1-2), 183-191.
- Tesfahunegn, G.B., 2015. Short-term effects of tillage practices on soil properties under Tef [*Eragrostis tef* (Zucc. Trotter)] crop in northern Ethiopia. *Agricultural Water Management*. 148, 241-249.
- Tesfaw, Z., Zemedu, L., Tegegn, B., 2021. Technical efficiency of Teff producer farmers in Raya Kobo district, Amhara National Regional State, Ethiopia. *Cogent Food & Agriculture*. 7(1), 1865594.
- Teshager Abeje, M., Tsunekawa, A., Adgo, E., Haregeweyn, N., Nigussie, Z., Ayalew, Z., Elias, A., Molla, D., Berihun, D., 2019. Exploring drivers of livelihood diversification and its effect on adoption of sustainable land management practices in the Upper Blue Nile Basin, Ethiopia. *Sustainability*. 11(10), 2991.
- Tietel, Z., Simhon, E., Gashu, K., Ananth, D.A., Schwartz, B., Saranga, Y., Yermiyahu, U., 2020. Nitrogen availability and genotype affect major nutritional quality parameters of tef grain grown under irrigation. *Scientific reports*. 10(1), 1-15.
- Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya—An application of classification and regression tree analysis. *Agriculture, ecosystems & environment*. 123(1-3), 137-150.

- Tulema, B., Aune, J.B., Johnsen, F.H., Vanlauwe, B., 2008. The prospects of reduced tillage in teff (*Eragrostis tef* Zucca) in gare arera, West Shawa Zone of Oromiya, Ethiopia. *Soil and Tillage Research*. 99(1), 58-65.
- Unger, P.W., McCalla, T., 1980. Conservation tillage systems, in: *Advances in Agronomy*. Elsevier, pp. 1-58.
- Van Delden, S., Vos, J., Ennos, A., Stomph, T., 2010. Analysing lodging of the panicle bearing cereal teff (*Eragrostis tef*). *New Phytologist*. 186(3), 696-707.
- van der Ploeg, R.R., Böhm, W., Kirkham, M.B., 1999. On the origin of the theory of mineral nutrition of plants and the law of the minimum. *Soil Science Society of America Journal*. 63(5), 1055-1062.
- Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. *Field Crops Research*. 143, 4-17.
- Van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linnquist, B., van Groenigen, K.J., 2013. Climate, duration, and N placement determine N₂O emissions in reduced tillage systems: a meta-analysis. *Global change biology*. 19(1), 33-44.
- Vandecasteele, J., Dereje, M., Minten, B., Taffesse, A.S., 2013. Scaling-up adoption of improved technologies: The impact of the promotion of row planting on farmers' teff yields in Ethiopia. LICOS-Discussion paper series 344/2013. 1-25.
- Vandecasteele, J., Dereje, M., Minten, B., Taffesse, A.S., 2018a. Labour, profitability and gender impacts of adopting row planting in Ethiopia. *European Review of Agricultural Economics*. 45(4), 471-503.
- Vandecasteele, J., Regassa, M.D., Minten, B., Taffesse, A.S., 2014. Perceptions, impacts and rewards of row planting of teff. Available at SSRN 2530422.
- Vandecasteele, J., Regassa, M.D., Minten, B., Taffesse, A.S., 2018b. Perceptions, impacts, and rewards of row planting. *The economics of teff: Exploring Ethiopia's biggest cash crop*.

- Wang, X., Qi, J.-Y., Zhang, X.-Z., Li, S.-S., Virk, A.L., Zhao, X., Xiao, X.-P., Zhang, H.-L., 2019. Effects of tillage and residue management on soil aggregates and associated carbon storage in a double paddy cropping system. *Soil and Tillage Research*. 194, 104339.
- Webb, R., Stephens, D., 1936. Crown and root development in wheat varieties. *J. Agric. Res.* 52, 569-583.
- Williams, L.J., Abdi, H., 2010. Fisher's least significant difference (LSD) test. *Encyclopedia of research design*. 218, 840-853.
- Woldeyohannes, A.B., Accotto, C., Desta, E.A., Kidane, Y.G., Fadda, C., Pè, M.E., Dell'Acqua, M., 2020. Current and projected eco-geographic adaptation and phenotypic diversity of Ethiopian teff (*Eragrostis teff*) across its cultivation range. *Agriculture, Ecosystems & Environment*. 300, 107020.
- Wu, Y.-S., Li, X.-R., Yin, R.-P., Liu, T.-J., 2020. Surface roughness response of biocrust-covered soil to mimicked sheep trampling in the Mu Us sandy Land, northern China. *Geoderma*. 363, 114146.
- Xu, J., Han, H., Ning, T., Li, Z., Lal, R., 2019. Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. *Field Crops Research*. 233, 33-40.
- Zhang, Y., Li, X., Gregorich, E.G., McLaughlin, N.B., Zhang, X., Guo, Y., Gao, Y., Liang, A., 2019. Evaluating storage and pool size of soil organic carbon in degraded soils: Tillage effects when crop residue is returned. *Soil and Tillage Research*. 192, 215-221.
- Zuazo, V.c.H.D., Pleguezuelo, C.R.o.R., 2009. Soil-erosion and runoff prevention by plant covers: a review, in: *Sustainable agriculture*. Springer, pp. 785-811.