Norwegian University of Life Sciences
Faculty of Biosciences

Philosophiae Doctor (PhD)
Thesis 2019: 22

Integrated Weed Management in Teff: Case of Tigray, Ethiopia

Integrert ugrasbekjempelse i kornarten Teff, Tigray, Etiopia

Haftamu Gebretsadik Gebrehiwot

Integrated Weed Management in Teff: Case of Tigray, Ethiopia

Integrert ugrasbekjempelse i kornarten Teff, Tigray, Etiopia

Philosophiae Doctor (PhD) Thesis

Haftamu Gebretsadik Gebrehiwot

Norwegian University of Life Sciences
Faculty of Biosciences
Department of Plant Sciences

Ås 2019

Thesis 2019: 22
ISSN: 1894-6402
ISBN: 978-82-575-1552-2

Supervisors

Professor Lars Olav Brandsæter
Norwegian University of Life Sciences, Faculty of Biosciences, Department of Plant Sciences (IPV-NMBU), P.O. Box 5003, NO-1432 Ås, Norway
Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway
E-mail: lars.olav.brandsaeter@nmbu.no / lars.olav.brandsaeter@nibio.no

Researcher Dr. Jan Netland
Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway
E-mail: jan.netland@nibio.no

Professor Jens Bernt Aune
Norwegian University of Life Sciences, Department of International Environment and Development Studies (Noragric-NMBU), P.O. Box 5003, NO-1432 Ås, Norway
E-mail: jens.aune@nmbu.no

Professor Ole Martin Eklo
Norwegian University of Life Sciences, Department of Plant Sciences (IPV-NMBU), P.O. Box 5003, NO-1432 Ås, Norway
Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway
E-mail: olemartin.eklo@nibio.no

Dr. Girmay Tesfay Belay
Mekelle University, College of Dryland Agriculture and Natural Resources, P.O.Box 231, Mekelle, Tigray, Ethiopia
E-mail: girmay.tesfay@mu.edu.et

Evaluating committee

First opponent
Associate Professor Lammert Bastiaans
Crop and Weed Ecology Group, Centre for Crop Systems Analysis, Wageningen University, P.O. Box 430 , 6700 AK Wageningen. The Netherlands. Tel: 31-(0)317 - 484770; Fax: 31-(0)317 - 484892
E-mail: lammert.bastiaans@wur.nl

Second opponent
Senior Scientist Dr. Jukka Salonen
Natural Resources Institute Finland (Luke), Natural Resources Unit, FI-31 600 JOKIOINEN, Finland. Tel. +358 295 326517
E-mail: jukka.salonen@luke.fi

Committee coordinator
Professor Anne-Kjersti Uhlen
Norwegian University of Life Sciences, Faculty of Biosciences, Department of Plant Sciences (IPV-NMBU), P.O. Box 5003, NO-1432 Ås, Norway
E-mail: anne.uhlen@nmbu.no

Dedication

This work is dedicated to my beloved Mother ***Aregash Assefa***, and my brothers ***Berhe Arefayne*** and ***Desalegn Abebe***

ACKNOWLEDGMENTS

This study was financed by "Norwegian Program for Capacity Development in Higher Education and Research for Development (NORHED)" under the project "Research and capacity building in climate smart agriculture in the Horn of Africa".

I have little words to express my deep and grateful appreciation for the unreserved help provided to me from my main supervisor Professor Lars Olav Brandsæter from day one of my study until the end. I am grateful to study under his supervision. His support for the laboratory work in Norwegian Institute of Bioeconomy Research (NIBIO) was marvellously invaluable. Thank you very much for opening your office to me every time I need for your technical and personal advices. I am also indebted and grateful to my co-supervisor Dr. Jan Netland for his personal support during my arrival in Norway and his technical support during the period of my study. I am grateful to thank Professor Ole Martin Eklo for his valuable technical help and sooner feedback during the writing of most of the papers. I am grateful to Dr. Torfinn Torp for his guidance and feedback during data analysis and paper writing. For the laboratory technicians at NIBIO weed science section, thank you very much for your help during bioassay experiment. The guidance during the start of my fieldwork on weed identification and the comments on my first paper provided by Emeritus Professor Kåre Arnstein Lye were really appreciated and invaluable. Thank you professor Kåre.

Thank you very much Professor Jens Bernt Aune for your marvellous support throughout my study period and opened your office every time I need for your personal support. I am deeply grateful for your invitation to dinner at your home and a visit to southern Norway. It was a pleasant and unforgettable exposure to me during my stay in Norway. I am really indebted and grateful to the support of Anna Holm from NORAGRIC in relation to financial matters during my stay at NMBU. I thank Anders Dysvik, IT expert at NORAGRIC, for his personal commitment during purchase of materials required for my study and repair of my laptop throughout my study period. The technical support from Leif Åge of IPV was also highly appreciated and thankful.

For the smooth and successful fieldwork implementation in Tigray, Ethiopia, the help from Dr. Girmay Tesfay Belay was so invaluable and very grateful. It would not be easy to accomplish the experiments and collecting data without his guidance and unreserved and heartily support. Thank you very much Dr. Addis Abraha, Dr. Alemtsehay Tsegay, Dr. Emiru Birhane and Dr. Nigusse Abadi for your personal advices and encouragements. The assistance from staffs of Department of Dryland Crop and Horticultural Sciences, and finance and administrative staff of the College of Dryland Agriculture and Natural Resources during implementation of my experiments was amazing and grateful. Thank you for the field workers at Axum and Mekelle research sites.

I have received heartfelt advices, encouragement and shared delightful moments from and with my friends Kidanemariam Abreha, Kahsay Gebremariam Nirea and his wife Rewina Tadelle, Girmay Berhe, Girmay Kahsay, Dawit Gebreezgabher and his family, Tsedal Asres, Girmanesh Abreha, Haile Welearegay and Dawit Kahsay to mention some. Thank you friends!

I am deeply, heartily and proudly grateful to have a lovely mother Aregash Assefa who is a stepping-stone, strong base and a key to my progressive success in every walk of my life. Thank you very much my mom. I am also so grateful to have my brothers and at the same time my close friends, Berhe Arefayne and Desalegn Abebe, for being corner stones and overall strength in every walk of my life. Thank you very much indeed.

Above all, thank you my almighty GOD!

Haftamu Gebretsadik Gebrehiwot
Ås, Norway
January, 2019

CONTENTS

Abstract

Teff (*Eragrostis tef (*Zucc.*)* Trotter*)* is among the small-grained cereal crops dominantly grown in Ethiopia for its grain and straw. It belongs to the family Poaceae. It is a self-pollinated, annual, warm season C4 grass, adapted to wide agroecological settings with best growth performance in the mid altitudinal ranges, 1500-2300 meters above sea level. As staple crop to more than half of Ethiopian population and highlanders in Eritrea, its demand increases domestically and globally as healthy food from time to time and its production area and volume are on the rise from year to year. However, weeds are the bottleneck during production incurring the farmers' high labour cost and resulting in low productivity of the crop. A number of weed species affect the crop and cause yield loss. The objective of this study was twofold, (i) to provide knowledge about the dominant weeds in teff production, (ii) to develop integrated weed management strategy for teff that enhance and sustain its productivity while reducing its production costs. To achieve this objective, a field survey and field experiments were conducted in 2015 and 2016 in teff growing areas of Tigray, Ethiopia. All the field experiments were arranged in split plot design with three blocks replicated at locations Axum and Mekelle. Laboratory experiments were conducted at Campus Ås (NMBU/NIBIO).

The survey was conducted to determine the weed species composition, importance and their agroecological distribution. Weed species composition was studied in 128 randomly sampled teff fields of the 26 major teff growing weredas (districts) of Tigray. The fields were situated at three altitudes: lowland (<1500 m a.s.l.), midlands (1500–2500 m a.s.l.) and highlands (>2500 m a.s.l.). Samples were collected at an average interval of 3–5 km in an inverted W zigzag fashion. Spatial extension of weed density levels were mapped and interpolated for the most frequent weed species to figure out their importance in all the major teff growing areas of Tigray using ARCGIS. From all the major teff growing weredas of Tigray surveyed, 42 weed species were identified. Altitude played a decisive role on number of weed species. The highest average number was from highland (17 species/sample) followed by midland (13.4 species/sample) and lowland (8.2 species/sample). The dominating weed species were *Argomene mexicana*, *Plantago lanceolate, Cyperus esculentus, Erucastrum abyssinicum, Avena abyssinica* and *Galinsoga parviflora*. Of the twelve most frequent weed species, four were perennials and eight were annuals. The weed species with wide spatial extension of higher density levels in most of the major teff growing weredas were *Erucatrum abyssinicum, Plantago lanceolate* and *cyperus esculentus*.

One of the field experiments was conducted to clarify the effects of tillage frequency by ard ploughing, glyphosate application prior to sowing teff and seed rate. In this experiment, the most intensive soil cultivation, compared with the least intensive, increased grain yield by 26%, the use of glyphosate gave 10% higher grain yield and the two highest seed rates, compared with the lowest, increased grain yield by 26%. The following reductions of total weed biomass was found; the most intensive soil tillage, compared with no ard ploughing, gave a 29% reduction, the highest seed rate compared to the lowest, 20% reduction and glyphosate spraying a 13% reduction. Sowing teff immediately after one ard ploughing (minimum tillage), at a seed rate of 15 kg/ha and application of glyphosate significantly reduced weed density, dry weight and cover while enhancing teff vegetative and reproductive performance. Frequent tillage and use of the recommended seed rate (25 kg/ha) had almost similar results.

In another field experiment, data related to teff vegetative and reproductive performance, weed density, biomass, and cover, and time required for hand weeding were collected for 10 teff varieties. The different teff varieties showed variation in their phenology (50% emergence, flowering, and maturity), height, tillering and yield. Between many of the varieties, there were no or minor differences in earliness of emergence, but the varieties ‘Boset' and 'DZ-01-1681' showed, in both sites and years, fewer days to 50% emergence than 'DZ-01-354' and 'DZ CR-358'. The two varieties with earlies emergence were also the two varieties with the lowest plant height. Furthermore, the two varieties with the latest emergence time, 'DZ-01-354' and 'DZ-Cr-358', were also the two varieties with the highest number of tillers. There were significant differences of weed growth in the different varieties, for example, there were 55% less total weed biomass in the two most competitive varieties ('DZ-01-2675' and 'Kora') compared to the two less competitive varieties ('DZ-01-354' and 'DZ-CR-358'). Grain yield of the different varieties varied considerably between locations and years, and often non-significant differences occurred. 'DZ-Cr-387' and 'Local' were the highest yielding varieties while the two varieties with the highest weed infestations ('DZ-01-354' and 'DZ-CR-358') yielded significantly lower than many of the other varieties in 2015. The hypothesis that teff varieties that yield high without weed competition yield low when exposed to weeds due to lack of competitiveness (trade-off) was partially rejected because the variety 'DZ-01-387' on average yielded highest both with and without hand weeding. On the other hand, differences in grain yield with and without weeds ranged from 271 kg ha^{-1} ('Kora') to 472 kg ha^{-1} ('DZ-01-354').

The laboratory experiment was done to determine the potential allelopathic activity (PAA) of teff varieties studied in the field experiment. It was measured as the effect of the varieties on root growth of both dicot and monocot weeds. Ryegrass (*Lolium perenne* cv. Mondiale; cv=cultivar) and radish (*Raphanus sativus* cv. Cherry Belle) were used as model monocot and dicot weeds respectively for the laboratory (bioassay) experiment. The laboratory experiment showed that all the teff varieties had potential allelopathic activity and inhibited early root growth and development of both monocot and dicot model-weeds. In particular, the local variety ('Local') but also other varieties such as 'Boset' and 'DZ-01-2675' were among those with the highest allelopathic potential.

In the study of what traits that explain the difference in competitiveness between varieties, it was the three traits allelopathic potential, time of emergence and biomass production, best explained the differences between the varieties, though height growth and tillering had also visible contribution.

Weed suppressive ability of teff was compared with the most commonly used cover crops in Tigray. Teff suppressed weeds and significantly lowered weed density, biomass and cover, compared to field pea and *Vicia* sp. Such an effect was consistently observed in unweeding plots. However, changing sowing method from broadcasting to row sowing and vice versa did not significantly change teff weed suppressive ability.

Both globally and in Ethiopia, it is important to develop cropping practice that reduce the need for intensive soil cultivation and voracious use of pesticides. In this study, it was clearly demonstrated that less intensive soil tillage resulted in higher weed infestation and greater need for manual weed control later in the growing season. Spraying with glyphosate before sowing of teff reduced weed growth but not to the same extent as the most intensive soil tillage. However, the study showed that the competitiveness of teff can significantly be improved through the use of competitive varieties and high seed rates. We conclude that both variety selection and higher seed rates are important tools for integrated weed management and reduce the need for intensive soil cultivation.

Sammendrag

Teff (*Eragrostis tef* (Zucc.) Trotter) er en småfrøet kornart som hovedsakelig blir dyrket i Etiopia. Både kornavlingen men også halmavlingen er viktig. Teff er en ettårig, selv-pollinert, C4-plante som tilhører grasfamilien (*Poaceae*). Den trives best under relativt varme forhold og det meste av produksjonen i Etiopia foregår i områder som ligger 1500-2300 meter over havet. Teff utgjør en viktig og avgjørende del av kostholdet til mer enn halvparten av befolkningen i Etiopia og i høyereliggende områder av Eritrea. Etterspørselen øker både innenlands og globalt, ikke minst fordi teff i kostholdet blir betraktet som helsemessig gunstig, blant annet fordi den er uten gluten. Dette har forårsaket at både produksjonsareal og -volum øker fra år til år. En av de store flaskehalsene i produksjonen er ugras, både fordi ugraset konkurrer og dermed reduserer avlingene men også fordi det forårsaker mye arbeidskrevende manuell bekjempelse. Dette gir følgelig bøndene høye arbeidskraftkostnader og lav produktivitet.

Målsetningen med dette PhD-studiet har vært to-delt, (i) å fremskaffe kunnskap om hvilke ugrasarter som er dominerende i teff-produksjonen og (ii) å finne metoder for integrert ugrasbekjempelse i teff slik at en kan heve bærekraftig produktivitet og redusere produksjonskostnadene. For å nå disse målsetningene har det blitt gjennomført både kartleggingsstudier og feltforsøk i områder hvor teff dyrkes i Tigray, Etiopia i 2015 og 2016. Alle feltforsøkene ble lagt opp som split-plot forsøk med tre blokker lokalisert til Axum og Mekelle. Laboratorieforsøkene ble utført på Campus Ås (NMBU/NIBIO).

For å fremskaffe kunnskap om hvilke ugrasarter som er vanlig å finne i teff ble det gjennomført en kartlegging av sammensetning og utbredelse av ugrasarter i teff i ulike høydesoner i Tigray. Dette ble utført på til sammen 128 tilfeldig prøveruter fordelt på 26 av de viktigste distriktene for teff-produksjon. Prøverutene ble fordelt innenfor tre høydesoner: (1) < 1500 moh., (2) 1500 – 2500 moh. og (3) > 2500 moh. Prøverutene ble lagt med intervall på ca. 3-5 km i et 'sikksakk' mønster. Utbredelse og tetthet for de ulike ugrasartene ble registrert og framstilt på kart ved hjelp av dataprogrammet ARCGIS for ulike distriktene. På de undersøkte områdene ble 42 ugrasarter identifisert. Høydesone

spilte en avgjørende rolle på antall ugrasarter. Høydesone > 2500 moh. hadde gjennomsnittlig 17 arter, etterfulgt av sone 2 med 13,4 arter og sone 1< 1500 moh. hadde 8,2 arter. De mest dominerende ugrasartene var *Argomene mexicana, Plantago lanceolata, Cyperus esculentus, Erucastrum abyssinicum, Avena abyssinica og Galinsoga parviflora*. Av de tolv vanligste ugrasartene var fire flerårige og åtte ettårige. Ugrasartene med stor romlig utbredelse og høy tetthet var *Erucatrum abyssinicum, Plantago lanceolata og Cyperus esculentus.*

Ett av feltforsøkene ble utført for å se på effekten av jordarbeidingsfrekvensen med ard plog, sprøyting med glyfosat før såing og såfrømengde av teff. I dette forsøket ga den mest intensive jordarbeidinga, sammenlignet med minst intensive, økt kornutbytte med 26 %. Sprøyting med glyfosat ga 10 % høyere kornutbytte og de to høyeste såfrømengdene sammenlignet med den laveste økte kornutbyttet med 26 %. Følgende reduksjoner av den totale ugrasbiomasse ble funnet; Den mest intensive jordbearbeidingen sammenlignet med ingen ard pløying, gav en reduksjon på 29 % av ugraset. Den høyeste såfrømengden sammenlignet med den laveste gav 20 % reduksjon, mens glyfosat sprøyting før såing gav en reduksjon på 13 % av ugraset. Såing av teff umiddelbart etter en ard pløying (minimum jordbearbeiding), en såfrømengde på 15 kg / ha og bruk av glyfosat før såing gav en signifikant reduksjon av ugrastetthet, tørrvekt og dekning, samtidig som det forbedret avlingen av teff både vegetativ vekst og frøproduksjon. Hyppig jordbearbeiding og bruk av anbefalt såfrømengde på 25 kg/ ha hadde nesten like gode resultater.

I et annet feltforsøk ble 10 sorter av teff undersøkt med hensyn på vegetativ vekst og frøavling, samt tilhørende ugrastetthet, biomasse, dekning og tid som kreves for håndluking. De forskjellige teffsortene viste variasjon i deres fenologi (50% spiring, blomstring, modning), høyde, busking og avling. Mellom mange av sortene var det ingen eller mindre forskjeller i tidlighet av spiring, men sortene 'Boset' og 'DZ-01-1681' hadde for begge lokalitetene og forskjellig år, færre dager til 50% spiring enn 'DZ-01-354' og 'DZ CR-358'. De to sortene med tidligst spiring var også de to sortene med lavest plantehøyde. Videre var de to sortene som spirte seinest, 'DZ-01-354' og 'DZ-Cr-358', også de to sortene med høyest antall sideskudd. Det var signifikante forskjeller i ugrasvekst i de forskjellige sortene. For eksempel var det 55% mindre ugrasbiomasse i de to mest konkurransesterke sortene 'DZ-01-2675' og 'Kora' sammenlignet med de to mindre konkurransesterke sortene 'DZ-01-354' og 'DZ-CR-358'. Frøavlingen av de forskjellige sortene varierte betydelig mellom steder og år, men ofte var det ikke-signifikante forskjeller. Imidlertid var 'DZ-Cr-387' og 'Local' de med høyest avling, mens de to sortene med mest ugras var 'DZ-01-354' og 'DZ-CR-358' og gav signifikant lavere frøavling enn mange av de andre sortene i 2015. Hypotesen om at teffsortene som gir stor kornavling uten ugraskonkurranse gir liten avling når de blir utsatt for ugras på grunn av dårlig konkurranseevne ble delvis avvist da sorten 'DZ-01-387' i gjennomsnitt gav høyest kornavling både med og uten håndlukning. På den annen side varierte forskjeller i kornavling med og uten ugras fra 271 kg ha-1 for 'Kora' til 472 kg ha-1 for 'DZ-01-354'.

Laboratorieforsøket ble utført for å bestemme potensiell allelopatisk aktivitet (PAA) fra teffsortene som ble brukt i feltforsøkene i Etiopia og effekter på rotutviklingen hos både tofrøbladete og enfrøbladete ugras. Raigras (*Lolium perenne* cv. Mondiale; cv = cultivar) en enfrøbladet art og reddik (*Raphanus sativus* cv. Cherry Belle) en tofrøbladet art ble brukt som modellugras. Laboratorieforsøket viste at alle de testede teffsortene hadde allelopatisk potensiale og at de hemmet tidlig rotvekst og utvikling hos både det ett- og to-frøbladet model-ugraset. Spesielt den lokale sorten 'Local' men også andre sorter som 'Boset' og 'DZ-01-2675' var blant de med høyest allelopatisk potensiale. I studien av hvilke egenskaper hos teffsorter som forklarer forskjell i konkurranseevne var det de tre egenskapene allelopatisk potensiale, oppspiringstidspunkt og biomasseproduksjon som best forklarte forskjeller mellom sortene, men høydevekst og buskingsevne bidro også.

Som en del av doktorgradsstudiet ble det også utført forsøk hvor dyrking av teff ble sammenlignet med andre kulturvekster for forskjeller på ugrasfremveksten. Disse forsøkene inngår ikke i de fire manuskriptene men noen resultater er vist i avhandlingens innledning. Evnen til teff å hindre ugrasvekst ble sammenlignet med de mest brukte dekkvekstene i Tigray. Teff reduserte signifikant bedre ugras tetthet, biomasse og dekning, sammenlignet med field peas og *Viccia* ssp. En slik effekt ble systematisk observert i ruter som ikke ble luket. Endring av såmetoden, fra breisåing til radsåing, endret ikke teff sin konkurranseevne.

Både globalt og i Etiopia er det viktig å finne dyrkingsmetoder som reduserer behovet for jordarbeiding samtidig som behovet for bruk av plantevernmidler minimeres. Ikke uventet så vi i dette studiet at mindre intensiv jordarbeiding også ga mer ugras og større behov for manuell ugrasbekjempelse senere i vekstsesongen. Sprøyting med glyfosat før såing av teff reduserte ugrasmengden men ikke i samme grad som den mest intensive jordarbeidingen. Studiet viser imidlertid at konkurranseevnen til teff kan forbedres betydelig gjennom bruk av konkurransesterke sorter og større såfrømengder. Vi konkluderer at både sortsvalg og såfrømengde er viktige verktøy både for integrert bekjempelse av ugras og for å redusere behovet for jordarbeiding.

List of papers

Paper I:
G. Haftamu, J.B. Aune, J. Netland, O.M. Eklo and L.O. Brandsæter. Species composition, ecological distribution and importance of weeds in teff fields of Tigray, Northern Ethiopia. Manuscript.

Paper II:
G. Haftamu, J.B. Aune, O.M. Eklo, T. Torp and L.O. Brandsæter. Effect of tillage frequency, seed rate and glyphosate application on teff and weeds in Tigray, Ethiopia. Manuscript.

Paper III:
G. Haftamu, J.B. Aune, J. Netland, T. Torp, O.M. Eklo, and L.O. Brandsæter. Weed competitive ability of teff varieties. Manuscript.

Paper IV:
G. Haftamu, J.B. Aune, O.M. Eklo, T. Torp, and L.O. Brandsæter. Allelopathic potential of teff varieties and their effect on weed growth. Manuscript.

1. INTRODUCTION

1.1. Background

1.1.1. Crop production under Ethiopian agriculture

Ethiopia depends on agrarian economy and practice agriculture since its existence. Agriculture contributes to more than half of its gross domestic product (GDP) and employs more than 80% of its population (CSA 2007; CSA 2016). The country, with its land area of 1,127,127 square kilometres (112.3million hectares), used to depend on the sector for 55 % of its GDP (Getahun 1978). However, agriculture is currently contributing 35.8 % of the GDP (CIA world fact book 2018). Ethiopian agriculture constitutes two systems (1) mixed crop – livestock agriculture in the highland and lowland, and (2) pastoral system mostly in the lowland part of the country (Getahun 1978; CSA 2016). The mixed cropping system is characterized by high labour input, low productivity and use of traditional farm implements and agronomic practices. For food and feed supply, production of crops is routinely practiced in two seasons annually. As one of the components of agriculture, crop production is the source of raw materials for agricultural industries. The country owns wide range of agro-climatic conditions favorable for growing tropical, subtropical and temperate crops. It is also the center of diversity for many crops and hosts large number of livestock.

Crops are produced in both rain-fed and irrigation every year. According to central statistical authority (CSA), the country has about 16 million hectares of arable lands suitable for the production of annual and perennial crops (CSA 2016) with potential to reach up to 55 million hectares (Makombe et al. 2007). Of these arable lands, more than 12.5 million hectares (78.1%) are for rain-fed crop production and 1.8 million hectares (11.3 %) are for irrigation and off-season crop production (CSA 2016). Crops produced on rain-fed and irrigated arable lands are classified as grain crops (cereals, pulses, and oil crops), vegetables and root crops. Grain crops are the most important field crops, occupying around 86 % of the arable land area (CSA 2016) and are main stay of most Ethiopians. Cereals occupy 11.3 million hectares (79 % of the total arable lands), pulses 2.1 million hectares (14.7 %), and oil crops 0.9 million hectares (6.3 %). The principal grain crops are teff, wheat, barley, corn, sorghum, and millet. Teff grows in most agroecological zones of the country. However, vegetables and root crops are produced during the off-season mainly using irrigation and cover 3.02 % and 13.12 %, respectively, of the arable lands.

Crop production under the conventional agriculture in Ethiopia is began by intensive and frequent tillage using the traditional *ard plough (known as 'mahresha or ማሕረሻ* in Tigrigna and '*maresha' or ማረሻ in Amharic)* with an objective to control weeds and characterized by low input use, low productivity and high soil loss by runoff. This has, consequently, resulted in soil and environmental degradation (Araya et al. 2011; Araya et al. 2012; Baudron et al. 2014) and make crop production vulnerable to climate change (Theodor et al. 2012). While sustaining agricultural productivity and maintaining soil resources through soil mulching and reduction of runoff, conservation agriculture (CA) is considered as an alternative to reclaim soil degradation and adapt climate change in Ethiopia. CA includes minimum soil disturbance, increasing organic soil mulch and crop diversification along with the optimum application of agronomic practices (Coughenour 2009; Kassam et al. 2009; Theodor et al. 2012; Baudron et al. 2014; Brouder & Gomez-Macpherson 2014; Farooq & Siddique 2015). CA is globally practiced in more than 125 million hectares in all continents (Theodor et al. 2012). In sub-Saharan Africa including Ethiopia, there is low adoption of CA due to high incidence of weeds (Rockström et al. 2009; Nyssen et al. 2011; Valbuena et al. 2012). Globally, weeds are the bottleneck in CA (Nalewaja 2003; Rockström et al. 2009; Farooq et al. 2011; Chauhan et al. 2012; Trichard et al. 2013; Brouder & Gomez-Macpherson 2014; Eslami, S. V. 2014; Stevenson et al. 2014; Nichols et al. 2015; Singh et al. 2015). However, CA has positive effect on both soil health and crop productivity in Ethiopia along with an efficient control of weeds (Rockström et al. 2009; Araya et al. 2011; Nyssen et al. 2011; Baudron et al. 2014). Unlike to other crops, teff had lower yield with some of the CA practices as it was very sensitive to weeds emerged in response to the reduced tillage on Vertisols in Tigray (Araya et al. 2011).

The biggest challenge to crop production in Ethiopia today are biological threats (weeds, insect pests and diseases), use of traditional farm implements, less use of agricultural technologies, low input use, and population pressure (Getahun 1978; Adenew 2004;

Makombe et al. 2007; Deressa & Hassan 2009; Temesgen & Rashid 2009; Nyssen et al. 2011; Alemayoh et al. 2012; Valbuena et al. 2012; Baudron et al. 2014; Kassie et al. 2014; Stevenson et al. 2014). This becomes more complicated when combined with the negative effects of climate change such as shortage and unevenly distributed rainfall, recurrent drought and long dry spells (Deressa & Hassan 2009; Kassie et al. 2014). Integrated weed management in response to the prevailing climate change is a solution to these challenges as it includes improved agronomic practices and crop varieties that can enhance crop productivity from a unit arable land.

1.1.2. The crop teff

a. Brief description

Teff (*Eragrostis tef (*Zucc*)* Trotter*)* is among the small-grained cereal crops dominantly grown in Ethiopia for its grain and straw. It belongs to the family Poaceae consisting of 350 species from the genus Eragrostis (Costanza 1974; Costanza et al. 1979; Ketema 1997). The genus eragrostis belongs to the tribe *Eragrosteae,* sub family *Eragrostoidae* of the family *Poaceae* (Costanza 1974). The crop has a tiny seeds with size 1–1.7 mm long and 0.6–1 mm in diameter (Habtegebrial et al. 2007b; Baye 2014). Ethiopia is the centre of origin and diversity of teff (Vavilov 1951). It is believed to be originated in between 4000 and 1000 BC with the first seeds discovered in a pyramid in 3359 BC (Vavilov 1951; Costanza 1974). From all of the genus Eragrostis, 43 % originated in Africa, 18 % in South America, 12 % in Asia, 10 % in Australia, 9 % in Central America, 6 % in North America and 2 % in Europe (Costanza 1974). Teff is a self-pollinated, annual, warm season C4 grass produced for its food and feed (Birhanu et al. 2018). It is adapted to wide agroecological settings with best growth performance in the mid altitudinal ranges i.e. 1500-2300 meters above sea level (Ketema 1997; Jackman 1999; Deckers et al. 2001; Adnew et al. 2005; IFPRI 2006; Assefa et al. 2015b). The crop has numerous beneficial traits that are highly preferred by both farmers and consumers. These traits include i) its adaptability and tolerance to extreme environmental conditions, ii) no storage pest that affect seed and grain quality after harvest, iii) nutritious diet rich in protein, slow releasing carbohydrate, gluten free and high iron content and iv) the straw has good quality, nutritious and palatable feed for livestock such as milking cows and oxen (Ketema 1997; Fufa et al. 2001; Rezene & Zerihun 2001;

Haftamu et al. 2010; Assefa et al. 2013; Geremew & Melaku 2013; Kassahun & Tebkew 2013; Baye 2014). Besides to being rich in carbohydrate, the protein content of teff ranges from 8 % to 15 % (on average 10 – 11 %) and used to make a flat, soft, spongy, thin bread called *'Injera'* (Daba 2017; Birhanu et al. 2018). As a gluten free crop, it can be consumed by people with gluten allergy and help prevent suffering from coeliac and other diseases caused by low tolerance to gluten (Birhanu et al. 2018). Nutritionally, the crop supports 60 – 75 % of the Ethiopian population (Daba 2017; Birhanu et al. 2018).

b. Breeding and agronomy

Breeding

Teff was among the most important cereal crops in Ethiopia since the earliest agricultural survey conducted in 1941 (Joyce 1943). The crop has remained the most important cereal crop in Ethiopia because of the dietary and economic values (Daba 2017; Birhanu et al. 2018). Teff research was started in Ethiopia in the 1950s with the objective of improving the crop's productivity through selection of local landraces, and released 24 varieties (Ketema 1993; Assefa et al. 2011). After many years of discovery on flower opening and pollination habits, teff hybridization was began in 1974 (Berhe 1975) and resulted in development of different varieties of the crop. Breeding of teff had also an objective of building knowledge on how to control the agronomic traits of the crop such as lodging, which can cause a yield loss up to 25 % and resulted in the development and release of 32 varieties (Kebebew et al. 2013). Varieties obtained from the breeding process increase genetic grain yield of the crop on average of 0.8 % from their first release in 1970 until 1995 (Kebebew et al. 2013). Currently, there are 42 teff varieties in Ethiopia (Kebebew et al. 2013; Misgana 2018). Nationally, Debrezeit Agricultural Research Center (DzARC) under the Ethiopian Institute of Agricultural Research (EIAR) coordinates teff breeding with the objective of teff agronomic performance enhancement, and develop high yielding and stress tolerant varieties.

Generally, the history of teff breeding in Ethiopia has followed five phases as described in Assefa et al. (2011). The first phase (1956–1974) was characterized by an emphasis on germplasm enhancement (collection/acquisition, characterization and evaluation, systematics and conservation), genetic improvement relying entirely upon mass and/or pure-line selection directly from the existing germplasm and initiation of induced mutation techniques. Second phase (1975–1995) marked by the incorporation of intra-specific hybridization into the already pre-existing breeding methods following the discovery of the chasmogamous floral opening behavior of teff flowers (from about 6:45–7:30 AM) and thereby the artificial crossing technique as described by Berhe (1975). Third phase, (1995–1998) featuring initiation of molecular approaches including development of molecular markers and genetic linkage maps, and analyses of molecular genetic diversity. Fourth phase (1998–2003) marked by further incorporation of in vitro culture techniques and inter-specific hybridization (Tefera et al. 2003) along with re-appraisal of induced mutagenesis particularly for lodging and leaf rust disease resistance. Fifth phase (from 2003 till 2006) featuring introduction of participatory breeding approaches in the pre-existing overall teff genetic improvement ventures (Belay et al. 2006; Belay et al. 2008) and continued extensive molecular and genomic research approaches till present.

Though successful, teff breeding especially through hybridization faces challenges mostly from the natural behaviour of the crop (biological problems). Small seed size, lodging, small flowers that open only at 6:45 – 7:30 am in the morning (Berhe 1975), difficulty of crossing, shattering, pre and post-harvest yield losses, low fertilization after crossing and limited focus are among the challenges of teff breeding in Ethiopia (Ketema 1993; Ketema 1997; Kebebew et al. 2013; Kebebew et al. 2017; Misgana 2018).

Agronomy

Cropping season – from the farmer's perspective

Teff is cultivated in two seasons especially when the volume, coverage and distribution of rainfall is even and uniform. The first season for teff production is from end of April to May for sowing and end of November to early December for harvesting. This season is limited to areas with wider distribution of vertic soils and early onset and high amount of seasonal rainfall. The second and the most common is the season with early July to early August for sowing and late November to mid-December for harvesting. Most of the improved teff varieties are developed based on and produced during the second season. The time of sowing and harvesting varies from one area to another in Ethiopia. Nowadays, the main summer time is shrinking from 5 months (May – September) to fluctuating 2 – 3 months (June – August) (IFPRI 2006; NMA 2017a; NMA 2017b).

Land preparation

Teff fields are ard ploughed more frequently than other crops in order to create a fine seedbed for the tiny seeds and facilitate their germination and to control weeds (Habtegebrial et al. 2007b; Haftamu et al. 2009; Tesfa et al. 2013). Tillage frequency depends on weed type and incidence, soil type, climatic condition, crop type, and availability of oxen. Intensive tillage is required to control perennial weeds (Bergkvist et al. 2017) though there are no scientific studies indicating the link between ard ploughing frequency and perennial weeds in teff. With increasing weed incidence, tillage becomes more intense and frequent. However, the number of passes with the ard plough is variable. Higher tillage frequency is required for vertic soils in high rainfall areas (Tesfa et al. 2013). The average tillage frequency of ard ploughing required for teff in Vertisols reported from researches differently: 3-5 times (Leye 2007), 3 times (Haftamu et al. 2009), 4 times (Nyssen et al. 2000; Habtegebrial et al. 2007a), up to 6 times (Aune et al. 2001), and a maximum of 9-12 times in high and frequent rainfall areas (Tarekegne et al. 1996; Deckers et al. 1998). In areas with less weed incidence, the farmers kept their land undisturbed until the onset of the first rainfall and begin ard ploughing afterwards (Fufa et al. 2001). Generally, the main purpose of frequent ard ploughing is weed control. Not only the number of passes but also the depth of the tillage has a significant role in diminishing weed density and biomass especially perennial weeds (Brandsæter et al. 2011). However, conventional tillage (frequent ard ploughing) fosters soil erosion, reduces soil bulk density, diminish soil water holding capacity and soil water productivity, and aggravates nutrient and water losses from the soil (Nyssen et al. 2000; Habtegebrial et al. 2007b; Leye 2007; Assefa et al. 2008; Tigist et al. 2010; Salem et al. 2015). These authors also reported that conventional tillage enhance teff and maize yields. Such a higher yield was not significant when compared with the yield obtained using conservation tillage (Balesh et al. 2008). Other reports also showed that conservation tillage significantly increase maize yield during medium rainfall season (i.e. 500-800mm) (Mupangwa et al. 2017). However, the negative impact of conservation tillage, according to some reports, overweighs its positive effect mainly attributed to weed effect. It increases soil bulk density and soil water but raised weed density and biomass and reduces crop yield due to competition (Rezene & Zerihun 2001;

Habtegebrial et al. 2007b; Balesh et al. 2008; Temesgen et al. 2009; Tigist et al. 2010; Tesfa et al. 2013; Salem et al. 2015). To utilize its water and nutrient storage advantage, studying the weed control potential of conservation tillage in combination with other agronomic practices such as use of optimum seed rate is of paramount importance in increasing the yield of teff.

Seed rate

The nationally recommended seed rate for teff in Ethiopia is 25-30 kg/ha. Most of the research reports described that teff yield is high at relatively lower seed rate (5 kg/ha) because it facilitated emergence and growth of high number of productive tillers contributing on the final productivity of the crop (Amare & Adane 2015; Bekalu & Arega 2016; Sakatu & Adane 2017). The recommended teff seed rate was determined without considering its effect on weed competitive ability of the crop. Research is required to adjust teff seed rate considering its effect on weeds.

Fertilizer rate

The application of nationally recommended fertilizer rates (Di-Ammonium Phosphate at 100kg DAP/ha, and urea at 100kg Urea/ha) have an economical benefit for the teff farmers in both Vertisol and Cambisol soil types in central zone of Tigray (Teklay & Girmay 2016). Specifically, the recommended fertilizer rates for teff are 60 kg P_2O_5/ha and 60 kg N/ha in Vertisols (black clayey soils) and 40 kg P_2O_5/ha and 40 kg N/ha in sandy soils such as Cambisol, Aridisol and Nitosols (Haftamu et al. 2009; Haftamu et al. 2010).

Traditional weed control methods

The main challenge in teff production, as stated above, is competition from weeds. The crop is relatively less affected by diseases and insect pests as compared to other crops cultivated in Ethiopia (Ketema 1993; Ketema 1997; Tefera et al. 2001; Misgana 2018). The traditional methods for weed control by teff farmers in Ethiopia are frequent tillage and /or the use of post emergence herbicides, such as glyphosate, before sowing teff and hand weeding in the crop. Tillage is described in the land preparation section above. Hand weeding is the removal of weeds manually using hands during vegetative stage of teff. It is considered as the most effective method of weed control, but labor intensive and costly. To make weed control easier, many farmers use glyphosate to control emerging weeds. It is the most widely used broad spectrum, non-selective, efficacious and economic herbicide globally applied post weed emergence to "burn them down" before crop sowing (Nandula, V. et al. 2005; Dill et al. 2008; Powles 2008a; Duke & Powles 2009; Boerboom & Owen 2013). It is commonly used during high weed incidence and in areas where conservation agriculture is widely practiced to control annual and perennial weed species (Nandula, V. et al. 2005; Dill et al. 2008; Powles 2008a; Duke & Powles 2009; Oicha et al. 2010; Teamti & Tesfay 2016; Neli et al. 2017; Seneshaw et al. 2017). In Ethiopia, glyphosate use is increasing from year to year (Seneshaw et al. 2017). Teff smallholder farmers use glyphosate to minimize land preparation and weeding costs as well as to create relatively weed free fields for the crop (Astatke et al. 2003; Assefa et al. 2008; Kassahun & Tebkew 2013; Seneshaw et al. 2017). In Tigray, more than 68 % of the teff farmers use glyphosate to control grass and other perennial weeds in conservation agriculture (Teamti & Tesfay 2016). However, there are glyphosate resistant weed species worldwide, which may have an effect on its efficacy. Those species are adapting the soil environment with glyphosate creating a threat to crop production globally (Heap 1997; Nandula, V. K. et al. 2005; Johnson & Gibson 2006; Powles 2008b; Powles 2008a; Duke & Powles 2009; Boerboom & Owen 2013). *Cyperus esculentus,* in our survey (Paper 1), was the most dominant weed species and is reported as resistant to glyphosate in USA and the monocot weed, *Snowdenia polystachya* found in wheat fields of Oromia region, is reported as resistant to glyphosate in Ethiopia (ISHRW 2013). Besides, a recent report has shown that glyphoshate reduced soil quality due to its effect on soil physical, chemical and biological properties (Neli et al. 2017). According to the report, continuous application of glyphosate under zero tillage condition negatively influenced soil structure stability, nutrient availability and microbial activity.

Harvesting and threshing

Next to hand weeding, the most time consuming and labour-intensive part of teff production is harvesting and threshing. This is conducted manually using sickles by hand after full maturity of the crop. Teff has moderate shattering problem and the farmers do not want to lose even a single seed of the crop. They provide a very high attention to the crop and attentively follow the harvesting time. Such a traditional way of harvesting initiated the establishment of the Agricultural Mechanization Research Centre in Ethiopia through Appropriate Technology for Farmers (ATF) with the objective to create easy and affordable method of teff harvesting and threshing. This centre conducted a formal survey in some selected teff growing regions of the country in 1985 – 1986 (Friew & Lake 2011) and was found that harvesting time for teff (around 210 hr/ha) is more than the time needed to harvest other cereal crops such as sorghum and maize. Currently, Melkassa Agricultural Research Centre under the Ethiopian Institute of Agricultural Research has conducted different studies with regard to development of teff harvesting and threshing machine prototypes and tested some products. According to Friew and Lake (2011), a teff harvester was developed and tested in 2011 and resulted in reduction of harvesting labor by 50% and an increase in yield by 12%. The main challenge according to the report was lodging of teff, which hindered the harvesting. A teff thresher developed by the research centre was not successful due to the small size of teff grains. Some efforts with regard to developing a harvester and thresher prototypes have been made in Tigray Rural Mechanization Research Centre operated under the Tigray Agricultural Research Institute.

c. Its production and constraints

Teff has a broad phenotypic and genetic diversity, which enables it to adapt harsh environments (Ketema 1997; Adnew et al. 2005; Assefa et al. 2015a). Being a staple food to around 3/4 of Ethiopian population, around 3.2 million hectares of the arable land was allocated to teff production and around 45 million quintals was harvested nationally in 2016 (CSA 2016). The area and amount of production steadily increases from year to year.

Ethiopian farmers prefer to grow teff because of the following advantages as described in (Ketema 1993; Ketema 1997):

1. It withstands low moisture conditions better than maize and sorghum. In many areas, maize and sorghum are planted around April; when these crops wilt because of low moisture, the farmers usually re-plough the land in late July or early August

and grow teff. Therefore, teff is a rescue crop that survives and grows with the remaining low moisture in the season as well as the residual soil moisture conditions on Vertisols.

2. It withstands waterlogged and anoxic conditions better than maize, wheat, or sorghum. Farmers grow teff on Vertisols, which is prone to water logging. Maize, wheat or sorghum has difficulties growing on this soil.

3. Cattle prefer teff straw to other straw of cereals crops. In addition, teff straw is an important source of feed during the dry season when feed shortage is acute.

4. Teff has higher market prices than the other cereals, for both its grain and straw.

5. Weevils do not attack teff grain, which means that it has a reduced postharvest loss in storage and requires no pest-controlling storage chemicals. In low moisture stress areas, where more than one sowing is commonly practiced in years of total rain failure, farmers have to store seeds of various crops for a long period. In such situations, teff seed, since it has no storage pests, is the ideal choice.

Constraints

As it is small-seed cereal crop, teff needs fine, moist and well aeriated seedbed for sowing. The seeds are broadcasted on the surface of the soil and appropriate land preparation is needed for successful germination. To achieve ideal sowing bed, teff farmers ard plough the land immediately after harvest until the next sowing period consequently resulting in more frequent tillage than other cereal crops. This makes land preparation labor intensive and time-consuming activity. For teff, weeds remain the main yield-reducing factor. Most small-scale farmers invest to control weeds. When they have to work with conservation agriculture, such a cost increases due to high weed incidence from reduced tillage (Makombe et al. 2007; Nyssen et al. 2011; Valbuena et al. 2012; Baudron et al. 2014; Stevenson et al. 2014). Though tolerant to extreme environmental conditions, teff is poor competitor to weeds especially during extensive infestations and can have a potential yield loss ranging from 35-65 % (Rezene & Zerihun 2001; Kassahun & Tebkew 2013). Not only frequent tillage but also hand weeding is commonly done manually to reduce weed effect on the crop during its growth period. Since the crop is sown by broadcasting, there are no intra row spacing between teff plants to use equipment to control weeds. Another constraint is lodging. During heavy rain, teff plants bend to the ground, which often reduces quality of the grains. Harvesting and threshing are also constraints increasing labor requirements for teff production. Until today, combine harvesters are not used for teff due to its lodging habits obstructing the machine from lifting and cutting the plants during harvesting.

1.1.3. Weeds

a. General description

Weed has been defined from different perspectives. Various definitions of weed are described in Rana and Rana (2016). With crop production perspective, weed is an unwanted plant grown in a crop field during production. It is unwanted because it is not sown and managed by the farmer but emerge and grow by its own. The main reasons for its survival in the crop field, according to Dwight (2017), are (1) produce abundant seeds, (2) rapid emergence and establishment, (3) better seed dormancy, longevity and viability, (4) ability to spread in wide areas, (5) rapid adaptability to new environments, (6) fast reproduction asexually by vegetative reproductive organs and sexually by seeds, and (7) ability to occupy human disturbed areas.

There are about 250,000 plant species in the world, of which 8000 species are considered to be weeds and out of those 200 species are considered to cause high problems to crops and hinder human activity (Thomas et al. 2002; Dwight 2017). Of all the 300 plant families, 12 families contain 68 % of the world's worst weeds and three of these 12 families comprise 43 % of the world's worst weeds with 37 % being classified in Poaceae and Asteraceae (Holm, et al., 1977 as cited in Thomas et al. (2002)). Weeds are classified based on their life cycle, habitat, morphology, and physiology. Details of these classification methods and weed species classified within them can be found in Bunce et al. (2002), Thomas et al. (2002), Robert (2007) and Naidu (2012). Weeds are studied under the field of science called *Weed Science*. These plants are highly linked with the day-to-day activity of human being especially since the beginning of agriculture. They have been mentioned in the arts in the form of poem and theater in early dates, religion (bible) and culture (Robert 2007). As a science, weeds were studied since the beginning of modern agriculture in the 1800's and has become part of agricultural research since 1900's to study their biology, ecology and control methods (Thomas et al. 2002; Robert 2007; Regina & Jodie 2009; Emanuele 2012; Rana & Rana 2016). Though perceived negatively for their effect on crops, weeds can be used as forage to livestock, sources of nectar to honey bees (Miguel et al. 2015), green manure, stabilizes soil structure through enhancement of soil organic matter, can be consumed as leafy vegetables and opens employment opportunity. In Ethiopia, some of the grass weeds especially *C. esculentus* and *C. rotundus* are commonly used as floor ornamentation during coffee ceremony and have aesthetic values when planted at home yards.

b. Impact on crop productivity

Weeds compete with crops for resources such as water, nutrient and sunlight during production. They suppress crop plants by invading and occupy their space. They seriously affect crop growth and development when they utilize the soil water and nutrient from the same root zone as the growing crop plants. Generally, the negative effects of weeds, in addition to crop yield reduction because of competition, according to Dwight (2017), are (1) weeds can serve as a host to disease causing pathogens and insect pest, (2) hinder growth and development of crop plants by emitting toxic substance or root exudates (allelochemicals), (3) reducing crop seed quality by contaminating the produce, (4) late emerging weeds can obstruct harvesting and (5) limit choice of crop rotation sequences and cultural practices. Besides, high incidence of weeds increase labor cost of crop production and reduce total income of the farmer. The effect of weeds is commonly explained in terms of yield reduction. As an instance, weeds can cause potential yield loss of 35-65 % in teff (Rezene & Zerihun 2001; Kassahun & Tebkew 2013).

c. Control

To reduce their negative effect and enhance crop productivity, weeds must be managed. Jensen (2008) summarized the following three potential strategies against weeds: (i) Eradication, all possible efforts are directed against the weed species for elimination. (ii)

Prophylaxis/ Prevention, attempt to avoid crop and revenue loss. (iii) Containment, aims at keeping the weed population at or below a specific level. He linked these strategies the following way. Eradication is mostly against alien weed species, species that is spread to new areas. The second one, prophylaxis / prevention, is an 'insurance strategy', implemented when herbicide costs, or cost of other types of measures, are low. The last strategies, containment, is the one that probably is most linked to modern weed control as integrated weed management where threshold and evaluation of needs for weed control play a crucial role.

Different weed control methods are suggested and classified as preventive, cultural, mechanical, biological and chemical control methods (Thomas et al. 2002; Robert 2007; Eslami, S. 2014; Singh et al. 2015; Rana & Rana 2016). Preventive methods include the mechanisms of protecting crop field from weed infestation before, during and after crop production. Before sowing, crop seeds must as much as possible be cleaned from weed seeds mixed with them. Weeds are commonly mowed either using hands or any implements (mowers) before flowering and seed setting. After harvest, the remaining of the crops and weeds are cleaned as preventive action against weed infestation in the next season.

Mechanical weed control by soil tillage is probably the most common control method of weeds. Although the tillage operation can often have other purposes than weed control, it affects the weed flora in some way. Generally, weed seedlings are more sensitive to soil tillage compared to established perennial weed species, and young plants of annual species can be killed largely even by relatively light soil cultivation (Håkansson 2003). Repeated soil cultivation can also decrease weed seed bank inside the soil, but it is then important that weeds through the crop season be prevented from flowering and seed setting. Compared to seedlings, established plants of perennial weeds will in most cases require deep tillage for fragmentation and/or to remove the reproductive parts such as rhizomes and bulbs, as a strategy for starving out the weeds. Many studies (e.g. Ekeberg et al. 1985; Håkansson et al. 1998; Brandsæter et al. 2011) have shown that mouldboard ploughing gives a significant control of perennial weeds. Deepening mouldboard ploughing increases effectiveness (Børresen & Njøs 1994; Brandsæter et al. 2011). Furthermore, the effect of mechanical weed control will differ for different perennial weeds species because of their specific biology (Brandsæter et al. 2017).

Among the cultural methods, crop competition ability with weeds is getting momentum as way of developing nonchemical means of weed management under conservation agriculture. Different crop varieties have a different competitive ability against weeds and Andrew et al. (2015) divided variety competitiveness in two aspects, (i) the ability of the crop to reduce the fitness of a competitor, and (ii) the ability of the crop to withstand the competitive impact of neighbours and resist yield loss. They indicated that these aspects are referred to different terms in the literature, and described, respectively, as 'suppressive ability' and 'tolerance ability' in the same way Hansen et al. (2008) explained. Several traits of a crop plant contribute for its weed competitive ability. Tillering, canopy architecture and belowground biomass may contribute to variety differences in relation to their weed competitive ability (Andrew et al. 2015).

As chemical method of control, the use of post emergence nonselective herbicide is one component during intensive and conventional crop production practices. Glyphosate, is one of the post emergence non-selective herbicide. Biological method can be used as alternative way of weed control but it may need more time to study the impact of the biological agents that can attack a particular weed species.

1.1.4. Integrated weed management

a. Concept

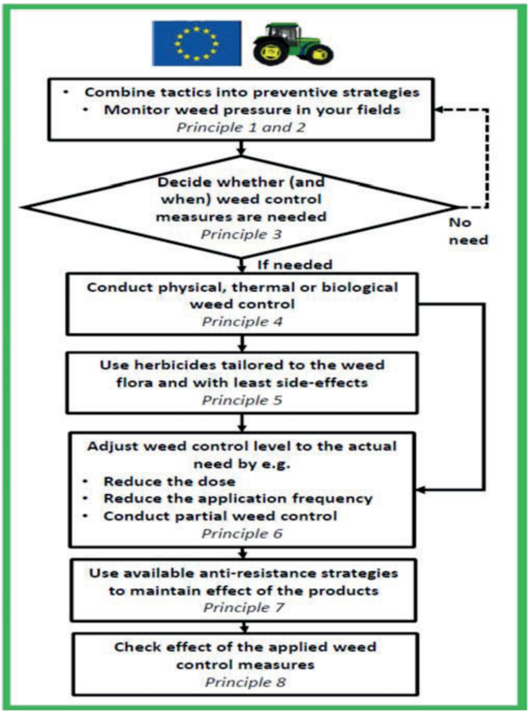

Figure 1. The eight steps/principles of Integrated Weed Management (IWM), adapted from Barzman et al. (2015). Figure made by Therese With Berge, NIBIO, Norway, used with permission.

Integrated Pest Management (IPM) can be defined as the sustained use of all available pest control techniques for keeping the use of pesticides and other interventions to levels that are economically justified, and minimising the risks to human health and the environment. This is the direction of worldwide main pest management, including weed control, Integrated Weed Management (IWM). According to the Directive 2009/128/EC, since 2014, European Union (EU) farmers have been required to follow the principles of IPM as a way to reduce risks of herbicides, fungicides and other pesticides. The principles (1–8) in figure 1 include a cascade of decisions that need to be undertaken to ensure effective weed control, as follows:

1) Before any curative control takes place, possible preventive methods of cultural control need to be considered; 2) Know the weed pressure through monitoring; 3) Monitor weed pressure for a decision about the necessity of control; 4) Decide when proper non-chemical measures should be preferred, also in conventional farming; 5) Restrict application of herbicide ingredients, with least side-effects, to those species requiring control; 6) Make case-specific reductions of herbicides dose and application frequency in combination with the use of site-specific weed management; 7) Establish anti-resistance strategies to maintain effect of the products. 8) Check the effect of applied weed control measures (EU

Directive 2009). These principles are highly relevant worldwide when modified to local circumstances.

Linked to the definition of IPM mentioned above, IWM is defined as a weed management system that can keep the weed infestation level below economic threshold by combining different weed control methods (Emanuele 2012; Harker & O'Donovan 2013; Singh 2013; Rana & Rana 2016; Timothy et al. 2016). It is a holistic approach to weed management that provides the crop an advantage over the weeds growing with it (Harker & O'Donovan 2013). It is developed in response to the need for effective weed control methods that can enhance crop yield with minimum effect on the agroecosystem. In conventional agriculture, frequent tillage and applying herbicides negatively affect soil properties and the biological diversity of the agroecosystem. This calls for the development of sustainable, environmentally friendly and well-integrated weed management strategies to reduce the weed infestation below the levels that do not cause significant crop yield loss while avoiding devastative effect on the environment and biological diversity of the agroecosystem. The concern on the intensive use of herbicides on human health and the environment, challenges linked to a sufficient weed control, the emergence of herbicide resistant weed species and the need for sustainably higher crop yield to feed the ever increasing human population are the main drivers for the development and adoption of Integrated Weed Management (IWM) (Swanton & Weise 1991; Thomas et al. 2002; Robert 2007; Chauhan et al. 2012; Emanuele 2012; Harker & O'Donovan 2013; Singh 2013; Eslami, S. V. 2014; Chauhan et al. 2015; Rana & Rana 2016). According to Rana and Rana (2016), IWM includes two basic decision making processes: (1) the appropriate time to apply the control method (s) that can reduce weed infestation levels far below the economic threshold, and (2) the best combination of the control measures (methods) that can provide high advantage to the crop over weeds, resulting in higher crop yield and maximum profit. To achieve these processes, an intensive research is necessary to study weeds and their management methods. Generally, weed research conducted to develop IWM should include components with regard to ecological principles, use of plant interference and crop – weed competition, weed importance and ecological distribution, crop agronomy and breeding and limited use of non-selective herbicides (Eslami, S. V. 2014; Chauhan et al. 2015; Farooq & Siddique

2015; Nichols et al. 2015; Singh et al. 2015; Rana & Rana 2016; Timothy et al. 2016). In both conventional and conservation agriculture, IWM targets weed community during its development and weed population consisting of the most important weed species during its implementation.

b. Role in crop productivity

Different factors influence crop productivity. These factors are both biotic and abiotic components of the ecosystem. Weeds, as part of the biotic components of the ecosystem, can cause considerable change in crop productivity during production. Oerke (2006) specified a global potential loss of 34% because of weeds. IWM incorporates different agronomic practices from land preparation to harvesting and storage that have a direct effect on crop productivity. These agronomic practices can enhance the advantage of the crop over the weeds during their competition for water, nutrients, sunlight and space (Harker & O'Donovan 2013; Rana & Rana 2016; Dwight 2017). In most cases, weeds are the result of crop production and largely to our management decisions (Preston 2003). Therefore, our choice of the components of IWM may determine weed incidence and crop yield. Generally, crops with an available water, nutrients, sunlight and space obtained as the result of IWM have higher productivity while minimizing threats to the environment, human health and overall agroecosystem.

c. Limitations

According to Rana and Rana (2016), continuous use of control measures targeting annual weeds helps buildup of less important perennial weeds and makes them dominant and difficult to control. Most components of IWM are site and time specific, which makes the management decisions both site and time dependent (Buhler 2002). All components of IWM vary with crop types, crop ecology, weed species importance and ecological distributions, weed biology, agricultural practices (e.g. conventional vs conservation) and farmer's crop preferences (Buhler 2002). IWM may not work with number of crops adapting to similar climatic conditions. Under IWM for CA, reduced tillage do not sufficiently expose weed seeds to intensive sunlight and weaken their germination and aggravates their emergence, seed setting, build-up of seed bank inside the soil and make them difficult to control (Nalewaja 2003; Farooq et al. 2011; Müller-Schärer & Collins 2012; Eslami, S. V. 2014; Nichols et al. 2015). This undermines the expected results from the IWM. Most of the components of current IWM lacks incorporation of the weed competitive ability of crop variety, which is, nowadays, considered as important method to combat herbicide resistant weeds both in conventional and in CA.

1.1.5. Influence of cover crops on weeds

Cover crops, based on their specific uses, are called 'green manure', 'smother crop', 'living mulch' and 'catch crops' (Teasdale et al. 2007). Another term, 'subsidiary crops', is also used more or less synonymously to 'cover crop' (e.g. Schmidt et al. 2017). A cover crop is a crop plant grown purposely or on its own for both its agricultural and/or ecological benefits. Ecologically, cover crops can intercept incoming light radiation; alter temperature and biological activity at different trophic levels in the leaf canopy and underlying soils (Teasdale et al. 2007). In agriculture, cover crops are used to manage soil fertility, soil erosion, soil quality, water, weeds, insect pests, diseases, biodiversity and wildlife in the agroecosystem (Lu et al. 2000).

Cover crops suppress weeds when used as living mulch and/or a residue left on the field to cover the soil. Their influence on weeds become more stronger when used as live mulching than residue (Teasdale et al. 2007). Live cover crops may successfully compete weeds for light and intercept the incoming radiation (Teasdale et al. 2007; Kruidhof et al. 2008), use it for their photosynthesis to produce high biomass and suppress emerging weed plants (Kruidhof et al. 2008). Cover crops affected weed density and species composition in both wheat and bean fields (Shrestha et al. 2002). They have also allelopathic effect on weeds and interfere their growth and development. They successfully inhibited early emergence of weeds (Creamer et al. 1996). Use of annual legume cover crops, before planting cereal crops during the main season, can supress weeds and can reduce up to 78 % of weed density and 80 % of dry weight (Fisk et al. 2001).

1.1.6. Climate change in Ethiopia

a. Overview and Impact

Climate change is the long-term fluctuation in the earth's climate components including temperature, precipitation, wind and sunshine (Zerga & Mengesha 2016). The increase or decrease in the earth's temperature and long lasting fluctuation of seasonal precipitation are considered as indicators of climate change (IPCC 2007). The earth's temperature is increasing from time to time, as an instance, by 1.3 °C from 1960 to 2006 (USAID 2012). This resulted in seasonal rainfall variability in most of the negatively affected countries causing alternatively occurring drought and flooding (IPCC 2007; USAID 2016). In a continental level, Africa will be warmer at the end of this century and the temperature is rising consistently due to anthropogenic climate change (climate change induced due to human activity) in the last 50 – 100 years (Niang et al. 2014). They also reported that the change in temperature in Africa is faster than any other places in the world. It increases by an average annual temperature of 2 °C and there will be an increase in precipitation in eastern Africa particularly highlands of Ethiopia and a shift in species of plants will occur in the ecosystem due to the rise in CO_2 concentration (Niang et al. 2014). Some researchers reported a decreased amount of precipitation in the Sub Saran Africa specifically east Africa due the warmth in the Indian Ocean (Funk et al. 2008). Generally, climate change causes threats in relation to food security, health, water availability and biodiversity in Africa (Bryan et al. 2009; Niang et al. 2014).

Ethiopia, like any other country in the world, is affected by climate change and causes negative impact on its agriculture, food security, human health, water supply and mainly its economic development (Zenebe et al. 2011; Emerta 2013; Mwendera 2013; Zenebe et al. 2014; USAID 2016; Zerga & Mengesha 2016). It directly affects the small-scale farmers. Unless adaptation measures are implemented, the effect will be a threat for the future (Bryan et al. 2009; Emerta 2013; USAID 2016). As 85% of its population are dependent on agriculture, which contributes to around 36 % of its GDP, the impact of climate change burdens the economy of the country. Such an effect of climate change is expected to cause about 10 % reduction in Ethiopia's GDP in the next 30 – 40 years (Zenebe et al. 2011; Zenebe et al. 2014; USAID 2016).

b. Effect on weed management

Climate change causes and will cause losses in biodiversity due to intervention and disturbances in the natural ecosystem because of environmental pollution, intensive use of specific species, introduction of non-native species, water pollution and urbanization (IPCC 2002). The shifts in plant species in Ethiopia due to climate change affects the species composition, importance and ecological distribution of weeds in the farmlands. As an abiotic factor of the ecosystem, climate, which is strongly linked to the altitudinal position of the crop field, has a paramount impact on the composition of weed species (Peerzada et al. 2017; Shekhawat et al. 2017; Singh et al. 2017; Stenchly et al. 2017; van der Meulen & Chauhan 2017). The seasonal change in temperature and precipitation has a huge impact on the variability of the state and structure of the plant community in the ecosystem in general and on weed communities in the agroecosystem in particular (Shahid et al. 1999). With increasing temperature, the rate of photosynthesis increases in C_4 weed species and infestation increases sharply and may shift the competition advantage from the crop to the weed species (Chandrasena 2009; Ramesh et al. 2017). During moist and humid seasons, a limited number of dominant weed species will take advantage (Hyvönen et al. 2003; Amedie 2013; Valerio et al. 2013; Smith et al. 2014; Houngbédji et al. 2016). Additionally, higher CO_2 concentration from the greenhouse gas emission around agricultural microclimate promotes robust weed growth, productivity and enhance diversity of these species (Tubiello et al. 2007). Such weeds diminish crop overall performance, reduce yield and escalate cost of production. This will be accompanied by unpredictable intense rainfall and flooding along with long dry spells in the highlands and elevating temperature in the lowlands of Ethiopia due to climate change (USAID 2016). Such short-lasting intense rainfall in the highlands causes flooding and soil erosion resulting in soil degradation in the highlands. This creates discrepancies in weed species composition of both lands. As indicator, Kassie et al. (2014) reported that there is an increase intensity per rainfall event in Ethiopia causing loss in soil and nutrients due to flooding and there is an increase in length of dry spell by 0.8 days per decade in the country due to shrinkage of rainy days during the main season. This calls for development of an integrated weed management that consider the weed dynamics due to climate change in Ethiopia.

Introduction of crop varieties that can adapt to the changing climate is considered as component of climate change adaptation strategies in Ethiopia (Bryan et al. 2009; USAID 2012; Zerga & Mengesha 2016). To cope with long lasting changes in the temperature and precipitation and to improve their tolerance to weed pressure, crop breeding must enhance weed competitiveness and adaptation to moisture stress. Within the different varieties of any crops, there are agronomic traits that can enhance their weed competitive ability such as emergence, maturity, plant height, tiller number per plant, biomass yield and allelopathy (Andrew et al. 2015). However, the varieties, which were competitive to a particular weed species at some time, may not be competent enough to another weed species, which may be appeared due to the prevailing climate change. This is because weeds not only have a shift in their species composition but also in their traits that can have both ecological and agronomic implications (Peters et al. 2014). This means invasive weeds may emerge and the crop may not compete it sufficiently during production. However, the cycle of the change in the weed species composition may have wide time gap and slow. Therefore, in addition to the development and introduction of crop varieties, improving the availability of soil moisture and enhancing soil fertility through suppressing weeds using cover crops have an important contribution on the overall success of integrated weed management and strengthening weed competitive ability of the crop under the prevailing climate change in Ethiopia.

1.2. Problem justification

Teff is produced with attentive follow up and care than other cereal crops in Ethiopia. Farmers consider teff yield maximization as their main objective because it is highly demanding crop and generates income from its grain and straw. They allocate fertile land for its production, frequently till the land up to 12 times to control weeds, allow soil moisture storages, sow the seeds in a well prepared seedbed free from clods and stumps, apply relatively the highest amount of available fertilizers, trample the soil to foster its emergence, carefully hand weed 2 – 3 times, and carefully plan and implement its harvesting and threshing. Most often, teff farmers use other cereals such as maize and sorghum for their domestic or household consumption while selling teff grain and straw in the market to generate income. Due to weeds, however, teff productivity is still lower frustrating farmers and urgently in need of solution to satisfy the ever-increasing demand of the crop both in the rural and urban areas of Ethiopia.

During its production, teff faces fierce competition from weeds at its vegetative and reproductive stage. It is less competitor to weeds and potentially loose its yields from 35-65 % (Rezene & Zerihun 2001; Kassahun & Tebkew 2013). The traditional weed control methods used by teff farmers are applied randomly and do not have focused target on any of the most important weed species. Among factors, not taken enough into account is potential occurrence of herbicide resistant weeds and/or how tolerant certain weed species may be against soil cultivation. In other words, farmers apply those methods in unintegrated manner, poorly linked to the eight steps of integrated weed management (Barzman et al. 2015), in every season of teff production. In most cases, they are less effective weed control methods as the farmers experience weed pressure every year and incur more costs to control them but harvest low yield and deprive the expected income from the crop. Studies in relation to teff agronomy and breeding focus on yield maximization of teff and their outputs are evaluated based on their role on the productivity of the crop. Those outputs do not stay sustainably because they do not thoroughly consider weed effect on crop productivity. The limited studies on weeds in teff mainly focus on tillage frequencies and herbicide application and less often on the effect of seed rate and hand weeding. The outputs from almost all the weed researches are dispersed and less consistent in time and space. Generally, there is no developed guidelines or practice for integrated weed management for teff in Ethiopia.

Therefore, an integrated weed management approach considering identification of the most important weed species along with their defined ecological distribution, optimum tillage frequency, seed rate and appropriate sowing method, and effect-based application of herbicides (such as glyphosate), using teff varieties with the most weed competitive and suppressive ability has paramount impact on sustainable enhancement of teff productivity and household income. At the same time, this may help farmers produce teff with less exposure to negative climate change impacts, as it will include some components of adaptation strategies. Besides, as this weed management includes control methods that can reduce reliance on herbicides, it will also have an agroecological, economic and environmental benefits.

1.3. Objectives and hypotheses

The main objective of this study was to develop tools connected to some selected principles of an integrated weed management for teff in Tigray, Ethiopia.

Specific objectives and hypotheses of this study are described as follows:

i. **Paper I:** Species composition, ecological distribution and importance of weeds in teff fields of Tigray, Northern Ethiopia

Objectives

- Identify and describe weed species and their composition in teff fields
- Clarify the altitudinal variability and ecological distribution of the weed species
- Map spatial extension of weed density levels in major teff growing areas of Tigray.

ii. **Paper II:** Effect of tillage frequency, seed rate and glyphosate application on teff and weeds in Tigray, Ethiopia

Hypotheses

- Frequent tillage reduces weed incidence and enhances teff vegetative and reproductive performance
- Higher seed rate reduces weed incidence and enhances teff vegetative and reproductive performance
- Applying glyphosate before teff sowing reduces weed incidence and enhances teff vegetative and reproductive performance
- There is a synergy among the effects of tillage frequency, seed rate and glyphosate application

iii. **Paper III:** Weed competitive ability of teff varieties

Hypotheses

- There are differences between teff varieties for traits commonly considered as important for variety competitiveness in other cereal species
- Weeds respond to various teff varieties differently
- There is a trade-off between yield potential and weed competitiveness in teff varieties
- Variety competitiveness influence weeding time of teff.

iv. **Paper IV:** Allelopathic potential of teff varieties and their effect on weed growth

The objectives of this study were to uncover new knowledge about (i) allelopathic activity of teff varieties and (ii) identify the most important agronomic trait (s) of teff contributing on the weed competitive ability of the crop.

Based on the objectives, the following hypotheses were raised:

- There are differences in allelopathic activity between teff varieties
- Emergence and allelopathic activity are the two most important traits for teff weed competitive ability

v. To evaluate weed suppressive ability of teff by comparing it with commonly used cover crops

2. MATERIALS AND METHODS

2.1. Weed sampling, identification and mapping

Tigray is located at 14^{0}08’12”N 38^{0}18’34”E bordered by Eritrea in the north, Amhara in the south, Sudan in the west and Afar region in the East. It has seven zones constituting 12 urban and 35 rural *weredas* (districts) (Table 1 and figure 2). The zones include Southern Zone, Southeastern Zone, Mekele special Zone, Eastern Zone, Central Zone, Northwestern Zone and Western Zone. Except in the Western Zone, teff is growing in all zones and is the most important crop in terms of its economic and nutritional values (Ketema 1997; Baye 2014; CSA 2016). Of the 35 rural weredas, 26 are the major teff growing areas.

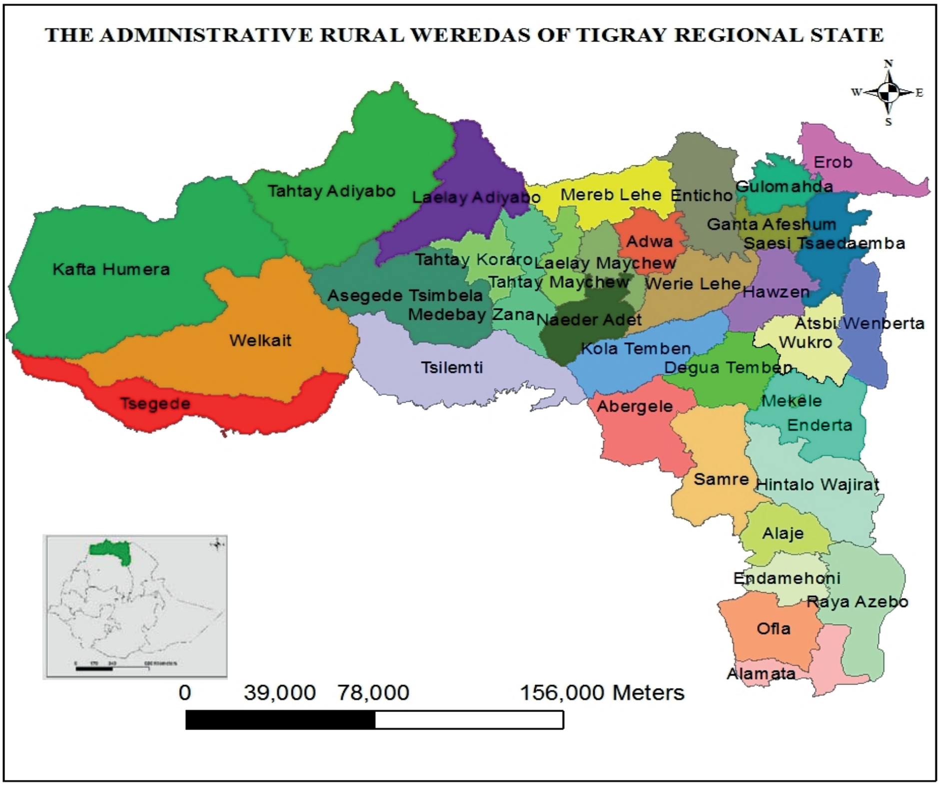

Figure 2. The 35 rural administrative weredas of Tigray, Ethiopia

Table 1. Tigray administrative zones and its major teff growing weredas

Southern Zone	South-eastern Zone	Eastern Zone	Central Zone	Northwestern Zone	Western Zone	Mekelle Zone
Alaje Raya azebo Ofla Endamekhoni Raya alamata	Saharti samre Degua tembien Enderta Hentalo wajirat	Ganta afeshum Saesi'e tsaedaemba Wukro kilteawla'elo Hawzen Atsbi wenberta Erob Gulomekeda	Mereb lekhe Naeder adiet Tahtay maichew Laelay maichew Geter adwa Ahferom (enticho) Wer'e lekhe Kola tembien Tanqua abergele	Tahtay koraro Medebay zana Laelay adyabo Asgede tsibla	Kafta humera Tahtay adyabo Tsegede Welkait Tselemti	Mekelle

Weed sampling

Teff needs a very smooth seedbed. Before sowing at the end of June to the beginning of July, on average, tillage is carried out 4 – 5 times. Especially in fields with vertic soil types and during onset of seasonal rainfall, frequent tillage is important. This type of soil is very heavy and difficult to till during off-season using the traditional Ethiopian *ard* plough. For this reason, farmers plough their land continuously to form fine seedbeds for teff. Teff farmers apply 100 kg/ha DAP (Di-ammonium Phosphate) at sowing and 100 kg/ha urea in split 50 kg/ha at emergence and 50 kg/ha before tillering or after first hand weeding or 30–45 days after sowing.

Most of the teff fields selected were "hot spot" areas, well known for their continuous teff production. Sampling of weeds was done with the consent of teff farmers and selected based on their frequency of teff production. On these sampling fields, the farmers had been growing teff for at least four years and at most eight years. Weed sampling was done before the first hand weeding and herbicide application.

During the two survey seasons (2015 and 2016), a total of N=128 teff fields were randomly sampled. Half of these were sampled in 2015, during the period 5–31 August, and the remaining in 2016, during the period 15 August to 10 September. The small shift in days of the sampling periods in 2016 is owing to the late onset of seasonal rainfall and late sowing of teff in most growing areas surveyed. The samples were stratified in lowlands (less than 1500 m a.s.l.) (N=21), midlands (1500–2500 m a.s.l.) (N=84) and highlands (above 2500 m a.s.l.) (N=23). The highest number of fields sampled in the midlands is the result of the highest area coverage of teff in this altitudinal range.

Two types of weed assessments were carried out: (1) A big quadrate (1 m^2) was used to record the presence, plus or minus, of each weed species, and (2) A rectangular frame measuring 0.1 m^2 (25 cm x 40 cm) put in one of the sides of the bigger quadrate (1 m^2) was used to count and collect the different weed species. A single rectangular frame (0.1 m^2) was taken from each sample at the centre of a farmer's teff fields. The weed sampling assessments used in this study was identical to the method used in Salonen et al. (2011), however, modified by the method used in Esayas et al. (2012). Quadrates were separated at an interval of 3–5 km (Esayas et al. 2012). Because of the rugged topography, some sampling fields were up to 8 km away from each other. After counting, certain weed species, which were not easily identifiable in the field were pressed, mounted and sent to Addis Ababa University National Herbarium for identification.

Altitudinal distribution of these weed-sampling fields has been analysed using Digital Elevation Model (DEM) of Ethiopia.

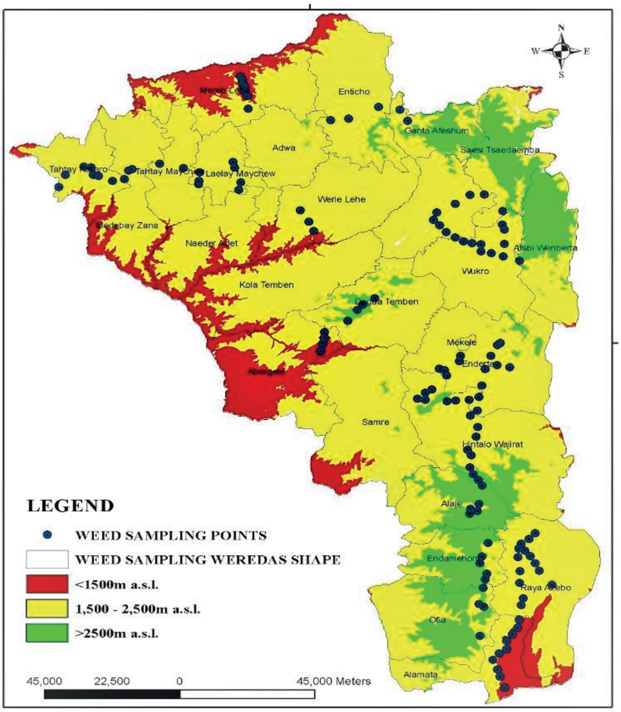

Figure 3. Altitudinal distribution of the sampling fields in all 26 teff growing areas of Tigray

In Tigray in general, and in the sampling fields in particular, the highest rainfall is recorded in July and August. The warmest months are April, May and June (Table 2).

Table 2. Average annual rainfall, minimum and maximum temperature

Location	Year	Av. Annual Rainfall (mm)	Av. Annual Min – T^0	Av. Annual Max – T^0
Axum	2015	725	11	27
	2016	675	11	27
Mekelle	2015	580	11	28
	2016	560	11	28
Tigray	2015	800	13	27
	2016	880	13	27

Source: (NMA 2017b)

Data Analysis

Weed species composition and importance analysis

Weed species composition and importance were analysed using frequency (F), abundance (A), dominance (D), and similarity index (SI) (Jaccard 1912; Taye & Yohanes 1998; Esayas et al. 2013; Assefa et al. 2016)

Frequency or prevalence: Percentage of sampling plots on which a particular weed species is found. It describes how often a particular weed species occurs in the survey area. Frequency is calculated for all weed species as follows:

Frequency: $F = X/N \times 100$

Where, F = frequency,
X = number of occurrences of a weed species,
N = sample number.

Abundance: Population density of a weed species expressed as the number of individuals of weed plants per unit area.

Abundance: $A = \Sigma W/N$

Where, A = abundance,
W = number of individuals of a weed species,
N = sample number.

Dominance: Abundance of an individual weed species in relation to the total weed abundance i.e. infestation level.

Dominance: $D = A/\Sigma A \times 100$

Where, D = dominance,
ΣA = total abundance of all species.

Similarity index (community index): Describes similarity of weed communities in different locations.

$$SI = (Epg)/(Epg + Epa + Epb) \times 100$$

Where, SI= similarity index;
Epg = number of weed species found in all locations;
Epa = number of species only in location a
Epb = number of species only in location b.

Interpolating spatial extension of density levels of weed species

Interpolation considers the XY coordinates to bind an area inside which spatial extension of the density levels of the weed species was estimated (Figure 4). The area of the colour on the maps (Figures 4–6 in **paper I**) refers to the spatial extension of a specific density range, with deep green being low density and deep red colour being high density. ArcGIS using spatial analyst tool automatically calculated spatial extension within the boundary of the sampling points crossing the major teff growing areas (Figure 4). This tool interpolates the spatial extension through natural neighbour, which connects the coordinates with the same magnitude of density levels. The interpolation of spatial extension of density levels was done for the 12 most frequent weed species including the weed species *Eragrostis cilianensis*, as it is the wild relative of teff (Ann & Chris 1989).

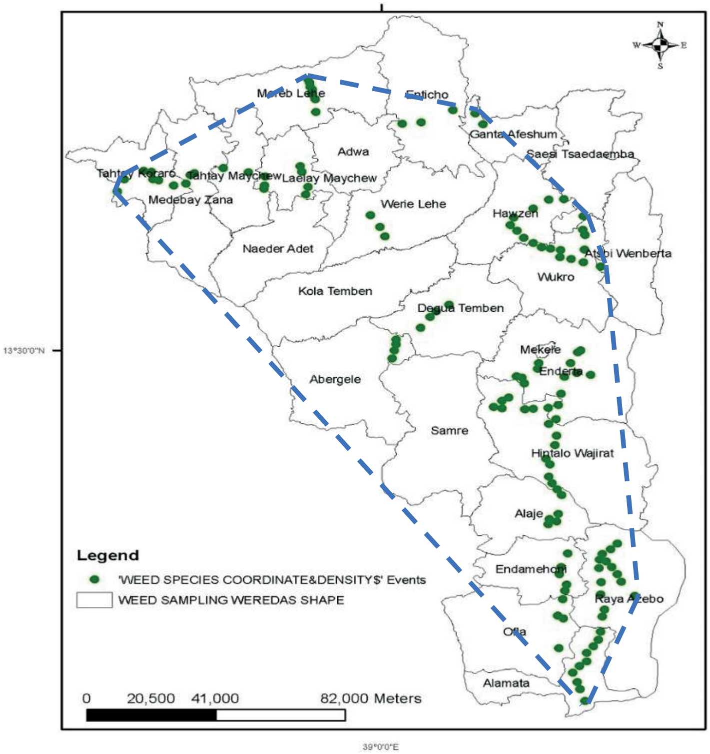

Figure 4. Delineated areas of interpolation based on XY coordinates of the surveyed fields of the major teff growing areas of Tigray, Ethiopia

2.2. Field experiments and data analysis

Three designed experiments were conducted in two locations namely *Axum* and *Mekelle* during 2015 and 2016 production seasons in Tigray, Ethiopia.

Description of the study areas

Axum research site

Axum is located 245 km northwest of Mekelle (capital of Tigray region). The research site is located 4 km east of Axum town and the experiments were laid on deep black vertic soils with small patches of Cambisol (soil description was made based on WRB 2014 as in FAO (2015)). The experimental fields were located on 14°07'37"N and 38°45'51"E at an altitude of 2098 m a.s.l. It has tepid to cool sub-moist mid-highlands agroecological classification with an annual rainfall ranging from 401-800 mm, temperature ranges from 15 – 28 °C.

Mekelle research site

This site was at the Mekelle University main Campus. It is located at 13°28′48″N and 39°29′25″E at an altitude of 2224 m a.s.l. The soil at the site is characterized as Cambisol dominated by sandy loam texture with patches of Vertisols (soil description was made based on WRB 2014 as in FAO (2015)). It has a moderate temperature with annual minimum temperature of 12 °C and maximum temperature of 30 °C where its average temperature is around 20 °C. The site receives an annual rainfall ranging from 400 mm to 600 mm (NMA 2017a).

Climate in 2015 and 2016

In both *Axum* and *Mekelle*, the highest rainfall is commonly recorded in July and August. The warmest months are April, May and June.

Table 3. Rainfall, minimum temperature and maximum temperature in Axum and Mekelle during 2015 and 2016

Location	Year	Rainfall (mm)	Min. Temperature (°C)	Max. Temperature (°C)
Axum	2015	725	11	27
	2016	675	11	27
Mekelle	2015	580	11	28
	2016	560	11	28

Source: (NMA 2017b).

Field experimental design and treatments

Experiment 1: Effect of tillage frequency, seed rate and glyphosate application on teff and weeds in Tigray, Ethiopia **(Paper II)**

The experiment had a split plot design arranged in three blocks with three levels of tillage (zero, minimum and conventional) on the main plots and combination of seed rate with three levels (5 kg/ha, 15 kg/ha and 25 kg/ha) and glyphosate with two levels (with and without) as sub plot treatments. The plot sizes were 2 m by 2 m for sub plot and 7 m by 17 m for the main plot. There were 1 m space between the subplots, 1 m between main plots within blocks and 1.5 m between blocks to control border effect. Glyphosate was applied at a recommended rate of 4 liters/ha (1440 g a.i./ha) 7-10 days before teff sowing.

Experiment 2: Weed competitive ability of teff varieties ***(Paper III)***

The experiment had a split plot design with two levels of hand weeding (with and without) on the main plots and ten teff varieties (Table 4) as sub plot treatments arranged in three blocks. The plot sizes were 2 m by 3 m for sub plot and 2 m by 39 m for the main plot. There were a distance of 1 m space between the subplots, 1 m between main plots within block and 1.5 m between blocks to control border effect.

Experiment 3: Agronomic evaluation of teff weed suppressive ability as compaerd to cover crops ***(not included in papers)***

The experiment had a split plot design with two sowing method (broadcasting and row sowing) on the main plots and combination of hand weeding (with and without) and cover crop species (Fieldpea, Grasspea, Lentil, Teff and Vicia sp.) as sub plot treatments arranged in three blocks. Teff was sown in rows at inter-row spacing of 20 cm. The plot sizes were 3 m by 3 m for sub plot and 3 m by 39 m for the main plot. There were a distance of 1 m space between the subplots, 1 m between main plots within blocks and 1.5 m between blocks to control border effect.

Data collection and analysis

Data collection

Data related to teff traits, weed responses and weeding time were recorded from all the three experiments by locations and years. Crop traits include days to emergence, heading, maturity, plant height, tiller number per plant, biomass and grain yields. Weed responses include weed density, biomass and cover organized by weed type (monocot and dicot), locations and years. Weeding time refers to the time required to hand weed a hectar of land and calculated based on the time (in minutes) recorded from each plots of the experiments.

Data analysis

Combined analysis of the experiments was done by locations and years. The MIXED procedure of SAS (SAS version 9.4) was used. The crop data included hand weeding, varieties, tillage frequency, seed rate, glyphosate application, sowing method, cover crop species, locations and years as factors. All factors in the experiments from both crop and weed data were considered as fixed. Weed assessment was taken in a successive two years and three weeding times. A repeated measurement mixed model was used during weed data analysis to account for a correlation among the assessments from the same plot recorded in the different times. For the correlation analysis, unstructured (un) and first-order autoregressive (ar(1)) covariance structures were used. The final model for the analysis was chosen based on the Akaike information criterion (AIC) and Schwarz Bayesian Information criterion (BIC). The model with the lowest AIC and BIC value was considered as a final model for analysis. Model assumptions in the split plot model, potential outliers etc were checked with usual residual plots. The least square means of different groups were compared using the Tukey-Kramer multiple comparison method at 5% levels of significance. For graphing, Microsoft Excel 2016 was used.

2.3. Bioassay experiment and data analysis

This part includes materials and methods used to determine the potential allelopathic activity of teff varieties and identify their important agronomic traits contributing to their weed competitive ability (**Paper IV)**.

Plant materials

Ten teff varieties were used for the bioassay experiment (Table 4). Nine of them were improved, highly productive, adaptive and widely used varieties and one local landraces widely grown in middle altitude of Ethiopia. These varieties were selected based on their importance and preference by most teff farmers of Ethiopia.

Table 4. General description of the teff varieties used for the experiment

R. No.	Varieties	Year of Release	Seed colour	Maturity (Days)	Height (cm)	On-Station Yield (kg/ha)	On-farm Yield (kg/ha)	Yield Gap (kg/ha)
1	Boset	2012	Very White	75-86	75-90	1800 - 2000	1400 - 1800	0 - 400
2	DZ-01-1681	2002	Dark Brown	84-93	74-85	2500	1600 - 2000	500 - 900
3	DZ-01-2675	2004	Pale White	112-123	47-91	1800 - 2800	1600 - 2000	200 - 800
4	DZ-Cr-387	2005	White	86-151	72-104	2500 - 2700	1600 - 2000	700 - 900
5	DZ-01-974	1995	White	76-138	84-123	2400 - 3400	2000 - 2500	400 - 900
6	DZ-Cr-385	2009	White	65-88	82-90	1600	1000	0 - 600
7	DZ-01-354	1970	Pale White	85-130	53-115	1800 - 2800	1800 - 2200	0 - 600
8	DZ-Cr-358	1995	White	76-138	70-109	2100 - 3600	1800 - 2400	3000 - 1200
9	Kora	2012	White	88-95	90-110	2400 - 3400	2000 - 2500	400 - 900
10	Local	A land race with no known phenotypic and genetic description and commonly sown by the farmers in the experimental sites						

Source: (EMAaRD 2014)

Ryegrass (*Lolium perenne cv. Mondiale; cv=cultivar*) was used as model weed in Bertholdsson (2005) and radish (*Raphanus sativus* cv Cherry Belle) on Campbell et al. (2009) and Dennis et al. (2016). Ryegrass represent grass (monocot) weeds whereas radish represent broadleaved (dicot) weeds.

Detecting allelopathic activity of teff varieties (bioassay experiment)

In the bioassay experiment, the varieties were tested for their allelopathic potential. Randomized complete block design (RCBD) with four blocks replicated in time was used during the testing period. An agar-based bioassay was conducted using ryegrass and radish as model weeds. The laboratory methods used during the period of the experiment were almost thoroughly adopted from Bertholdsson (2005) and Wu et al. (2000). The whole process of the experiment had three major steps.

i. Seed germination of teff varieties and model weeds

Seed germination of teff and the model weeds (ryegrass and radish) were performed in weed laboratory (NIBIO, Ås, Norway) in a dark condition (Figure 5). Petri dishes with litmus paper (grade 1 with 8.5 cm size Whatman litmus paper) was used to germinate the seeds and 2 ml water was applied. Seeds of both teff and weed species were germinated in darkness at room temperature of 20 °C for three days for teff and ryegrass, and two days for radish. All seeds were very clean and less vulnerable to contamination and hence seed sterilization was not necessary. All the seeds of teff and model weeds were germinated and immediately become ready for transplanting into a water agar.

Figure 5. Germination of teff, ryegrass and radish seeds

ii. Transplanting of seedlings of teff and model weeds into water agar and their stay at the growth chamber (bioassay)

In the final bioassay, plastic tissue culture vials (Phytotech, 300 mL) were filled with 30 mL 1.5 % water Agar (agar bacto) (Figure 6). Twelve pre-germinated teff seedlings planted in a circle 1 cm away from the vial wall in to which six pre-germinated perennial ryegrass or six radish seedlings were transplanted in to the center of the vial and 1 cm away from the teff seedlings (Figure 6). After completing transplanting, the agar vials were sealed and immediately placed in a growth chamber with a light/dark cycle of 12/12 hr, at a temperature of 20 ˚C during the day and 15 ˚C during the night and inflorescent light of around 50 μmol m^{-2} s^{-1} (Bertholdsson 2005). This low light level was used to protect the roots of seedlings from the effect of high light intensity.

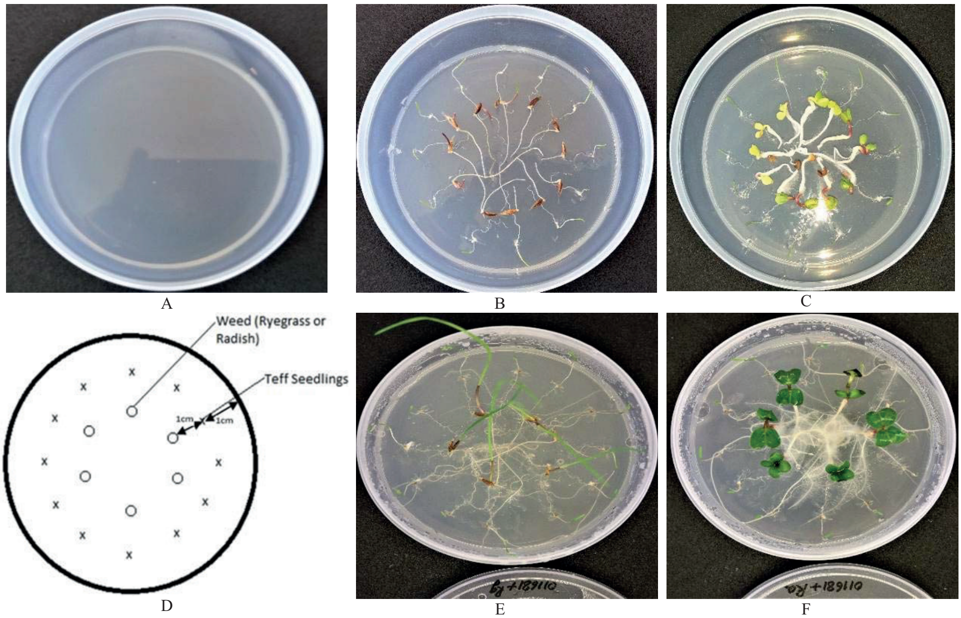

Figure 6. Seedling transplanting and growth of teff and model weeds in water agar
(A)Plastic tissue culture vials filled with 30 ml water agar; (B) Teff (DZ-01-1681) and ryegrass transplanted into water agar; (C) Teff (DZ-01-1681) and radish transplanted into water agar;(D) Transplanting design for teff and model weeds; (E) Teff (DZ-01-1681) and ryegrass after their stay at the growth chamber for 7 days; (F) Teff (DZ-01-1681) and radish after their stay at the growth chamber for 7 days

iii. Root analysis and dry weight measurements

After 7 days, the agar vials along with the teff, ryegrass and radish seedlings were taken out of the growth chamber. The roots of the model weeds were carefully withdrawn from the agar manually and scanned to measure their area, length, volume and diameter using an image analyzer (WINRHIZO ARABIDO 2013) (Figure 7). Vials with only the weed species were used as controls.

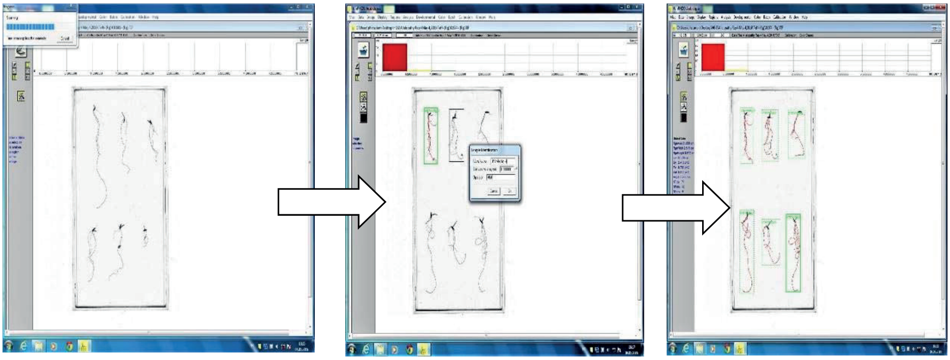

Figure 7. Model weed root scanning and analysis using WINRHIZO ARABIDO 2013

Roots of ryegrass and radish were dried at 60 ^{o}C for 48 hours and dry weight was measured after removal of emerging shoots.

Data Analysis

Backward multiple regression and correlation analysis of the data from both bioassay and field experiments were done using SAS 9.4. Model weed responses from bioassay experiment were correlated and regressed with PAA (Potential Allelopathic Activity) and SPAA (Specific Potential Allelopathic Activity) to identify the variable that contribute significantly to the variance of the allelopathic effect of the varieties. PAA and SPAA together with other agronomic traits were correlated and regressed with weed responses from field experiments to identify the important teff traits contributing on weed competitive ability of the crop. Correlation analysis among the model weed responses from bioassay experiment and agronomic traits from field experiments was done to see the relationships among the responses and traits. PAA was calculated based on the formula stated in Bertholdsson (2005) as PAA = (1- A1/A2)*100 with A1 = weed root area in presence of teff varieties and A2 = weed root area without teff varieties. Based on PAA, specific potential allelopathic activity (SPAA) was calculated as SPAA = PAA/weed root dry weight (this is the root dry weight of the model weed mixed with the specific teff variety based on which SPAA is calculated). PAA values can be positive or negative. Its values are positive when the weed root area is lower in the presence of teff varieties than in their absence and negative when the weed root area is higher in the presence of teff varieties. Positive PAA values indicate that teff has allelopathic effect on the model weeds and vice versa.

3. MAIN RESULTS AND DISCUSSION

3.1. Weeds in teff fields

3.1.1. Species composition

From all 128 fields sampled, 42 weed species were identified (Table 3 in **Paper I**). These 42 weed species belong to 16 families. The families with highest number of species were *Poaceae* (15 species), *Asteraceae* (7 species), and *Fabaceae* (3 species). The families *Commelinaceae*, *Cyperaceae*, *Amaranthaceae* and *Polygonaceae* were consisting of two species. The remaining families consisting of only one species were *Plantagonaceae*, *Apiaceae*, *Brassicaceae*, *Solonaceae*, *Lamiaceae*, *Papaveraceae*, *Rubiaceae*, *Nyctaginaceae* and *Convolvulaceae*.

The mean weed species richness (no. of species/sample) from each sample unit was 8.2 from the lowlands, 13.4 from the midlands and 17 from the highlands. Of the 42 weed species, 15 were monocots and 27 were dicots (Table 3 in **Paper I**). When classified by life cycle, these identified teff weeds include 31 annual and 11 perennial species (Table 3 in **Paper I**).

3.1.2. Importance

The most frequent weed species were *Erucastrum abyssinicum* (68.8 %), *Cyperus esculentus* (68 %), *Cynadon dactylon* (64.8 %) and *Avena abyssinica* (64.1 %) (Table 3 in **Paper I**). The next most common weed species in all the major teff growing areas of Tigray included *Argomone Mexicana* (57.8 %), *Brachiara eruciformis* (54.7 %), *Setaria pumila* (53.1 %), *Plantago lanceolate* (50 %), *Cyperus rotundus* (49.2 %), *Medicago polymorpha.* (49.2 %), and *Datura stramonium* (41.4 %) (Table 3 in **Paper I**). *Cyperus rotundus* is also common in upland rice of western Ethiopia (Assefa et al. 2016).

The dominance of the weeds was calculated based on their abundance. The most dominant teff weed species were *Argomene Mexicana* (9.5 %), *Plantago lanceolate* (8.7 %), *Cyperus esculentus* (7.8 %), *Erucastrum abyssinicum* (6.9 %), *Avena abyssinica* (6.9 %) and *Galinsoga parviflora* (6.0 %) (Table 3 in **Paper I**). Dominance indicates the infestation level of the weed species in all teff growing areas of Tigray. These weed species were responsible for

45.8 % of the total infestation level of all the identified teff weed species. These six weed species were the most important in terms of their infestation level.

3.1.3. Temporal and ecological distribution

Looking at the altitudinal distribution, there were weed species found only in the (i) lowlands, (ii) low to midlands and (iii) mid to highlands, and also (iv) weed species found in all altitudinal classes, i.e. low to highlands but no weed species specific to highlands (Table 3 in **Paper I**).

The spatial extension of the density levels of the 12 most common weeds species were different in different teff fields (Figures 4-6 in **Paper I**). Spatial extension of the density levels of the four most frequent weed species, *Erucastrum abyssinicum*, *Cyperus esculentus*, *Cynodon dactylon* and *Avena abyssinica,* are presented in the following maps (Figure 8).

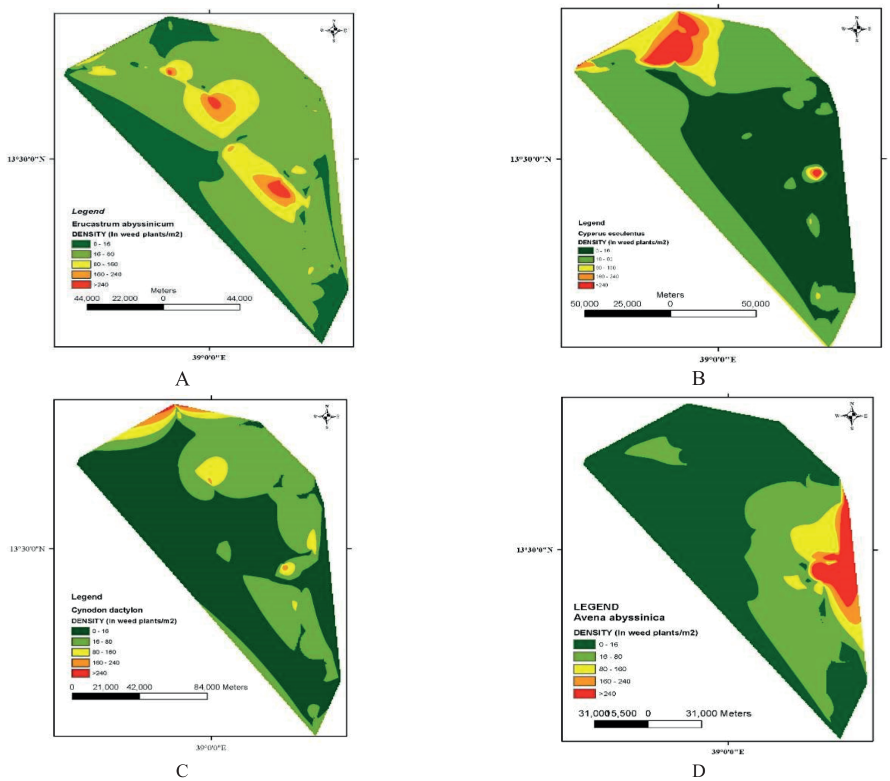

Figure 8. Spatial extension of density level of the four most frequent weed species in major teff growing areas of Tigray: (A) *Erucastrum abyssinicum,* (B) *Cyperus esculentus*, (C) *Cynodon dactylon,* (D) *Avena abyssinica,*

Similarity index was computed for both year of collection and altitudinal ranges of the teff fields under study. The similarity index between 2015 and 2016 was 93.3% showing very high similarity in teff weed species between these production seasons. The similarity index between lowland and midland was 58.3 %, lowland and highland 0 % because there were no common weed species between them, and midland and highland 87.5 %. There was a higher similarity in teff weed species between midland and highland than between lowland and midland. Among the identified weed species, 22 were common in all altitudinal ranges (Table 3 in **Paper I**).

3.2. Effects of tillage frequency, seed rate and glyphosate

The main effect of the three factors (tillage frequency, seed rate and glyphosate) on days to emergence, flowering, maturity, plant height, tiller number per plant, biomass and grain yields, weed density, weed dry weight and weed cover was significant (Table 3 and 6 in **Paper II**). There was no significant interaction effect of all the factors on both teff and weeds (Table 3 and 6 in **Paper II).** All factors had stable effect on weeds in all locations and years under study.

3.2.1. On teff vegetative and reproductive performance

Teff phenology[1] was not influenced by tillage frequency (Table 3 in **Paper II**). The small-sized teff seeds were broadcasted in the upper surface of a moist soil and water was not a constraint for germination and emergence of the crop. This may result in similar days to emergence among plots with the different ard ploughing frequencies. This is in consistent with reports from other parts of Ethiopia as the crop is produced following almost the same agronomic procedures (Fufa et al. 2001; Tesfa et al. 2013). No significant variation in tiller number per plant was observed among the different ard ploughing frequencies. However, tillage frequency had significant effect on plant height, biomass and grain yields. The tallest and highest yielding teff plants were observed under conventional tillage. Zero tillage reduced crop biomass yield by 14.6 % compared to minimum tillage and 26.3 % compared to conventional tillage (Table 4 in **Paper II**). Grain yield in zero tillage was 9 % less than

---

[1] Teff phenology refers to Days to 50% emergence, 50% heading and 50% maturity of teff altogether.

the grain yield from minimum tillage and 20.7 % lower than the grain yield from conventional tillage (Table 4 in **Paper II**). The variation in plant height, biomass and grain yield due to the difference in tillage frequency may be attributed to differences in weed infestation and changes in soil physical, chemical and biological properties (Habtegebrial et al. 2007b; Leye 2007; Haftamu et al. 2009; Salem et al. 2015; Tesfahunegn 2015). A lower yield in zero and reduced tillage compared to conventional tillage have been reported in other studies conducted on teff and other cereal crops in Ethiopia (Assefa et al. 2008; Balesh et al. 2008; Sime et al. 2015).

The difference in teff seed rate significantly affected all the agronomic traits of the crop (Table 3 in **Paper II). ** This is consistent with the results obtained from Bekalu and Arega (2016) and Amare and Adane (2015). Sowing teff at the lowest seed rate (5 kg/ha) delayed its emergence, flowering and maturity (Table 4 in **Paper II**). However, this seed rate enabled teff to grow taller plants with higher tiller number per plant. This might be the result of less intra-species competition among teff plants for space allowing them to use soil water and nutrients efficiently to grow taller plants and emerge new tillers. Besides, this low seed rate reduced biomass yield by 22.3 % compared to 15 kg/ha seed rate and by 26 % compared to the 25 kg/ha seed rate. It also reduced grain yield by around 21 % compared to the highest seed rates. However, there were no significant differences between 15 kg/ha and 25 kg/ha seed rates due to their effect on all agronomic traits of teff.

Application of glyphosate did not change teff phenology and tiller number per plant significantly but increased biomass yield from 5316 kg/ha to 5854 kg/ha (by 538 kg/ha) and grain yield from 1203 kg/ha to 1318 kg/ha (by 115 kg/ha) (Tables 3 and 4 in **Paper II**) . In other words, it enhanced teff yields by about 10 %. Such an increase in yield was less compared to other studies reporting that higher yield could be achieved from using glyphosate (Brookes et al. 2017).

3.2.2. On weed density, dry weight and cover

All the three factors (tillage frequency, seed rate and glyphosate application) had significant main effects on weed density, dry weight and cover (Table 6 in **Paper II**). No interaction effect was observed on most of the weed responses.

There was no significant difference between conventional and minimum tillage practices in weed density, biomass, and cover (Tables 6 and 7 in **Paper II**). However, both of them had significant difference from zero tillage. The highest total weed density[2] (219 weeds/m^2), total dry weight[3] (147 g/m^2) and weed cover (15 %) was recorded from plots with zero tillage (Table 7 in **Paper II**). This result is consistent with other reports stating that weed incidence and infestation were higher in zero tillage (Assefa et al. 2008; Balesh et al. 2008; Sime et al. 2015). Conventional tillage diminished total weed density, total weed dry weight and weed cover by 19.4 %, 29 % and 37 % respectively as compared to zero tillage and by 12.6 %, 15.4 % and 8.7 % as compared to minimum tillage. Comparing the two weed types under different tillage frequencies, monocot weeds had a higher density and dry weight than dicot weeds (Table 7 in **Paper II**), which may be attributed to their tolerance to tillage. Weed species such as *Cyperus esculentus* and *Setaria pumila* in *Axum* and *Avena abyssinica* in *Mekelle* regenerated after frequent ard ploughing in the conventional tillage (Personal Obs.). Other studies also showed that these were among the species showing tolerance to frequent tillage (Swanton et al. 1993; Kaleb et al. 2003; Santín Montanyá & Catalán 2006; Nichols et al. 2015; Santín-Montanyá et al. 2018).

Seed rate influenced weed density, dry weight and cover significantly (Table 6 in **Paper II**). The highest total weed density (221 weeds/m^2), total weed dry weight (137 g/m^2) and weed cover (13 %) were recorded from plots with the 5 kg/ha seed rate (Table 7 in **Paper II**). Though there were a higher number of tillers per plant in the 5 kg/ha than the other seed rates (15 kg/ha and 25 kg/ha), they could not cover their space to sufficiently suppress the weed species. To achieve a comparable plot cover as of the higher seed rates, the number of tillers per plant from the lowest seed rate should have been significantly higher and estimated to be 3-5 times. However, the number of tillers from the lowest teff plant density (8 tillers/plant) was higher by only 2.8 tillers (54.5 %) than the tillers from 15 kg/ha (5.2 tillers) and only 3.7 tillers (87 %) than the tillers from a seed rate of 25 kg/ha (4.3 tillers/plant). This opened space for the weeds to grow and thereby increased weed

---

[2] The sum of the density of monocot and dicot weeds
[3] The sum of the dry weight of monocot and dicot weeds

density, dry weight and cover in the lowest teff plant population. The result is consistent with studies on pulses (e.g. Fieldpea) and cereal crops (e.g. winter and spring wheat) showing that increasing seed rate enhanced their weed suppression and competition ability, which resulted in reduction of weed above ground dry weight (Townley-Smith & Wright 1994; Korres & Froud-Williams 2002; Kristensen et al. 2008).

There was a significant difference in weed dry weight and cover due to glyphosate application (Table 6 in **Paper II**). Such an effect was not observed on weed density. Therefore, the effect of the herbicide was more on weed dry weight and weed cover than on weed density. Late emerging weed species may have reduced the effect of glyphosate on weed density. There were weed species, *Plantago lanceolate* and *Cyperus esculentus* (Powles 2008b; ISHRW 2013), found to be glyphosate resistant in other places, emerged after spraying the herbicide in both years and locations. No reference was found whether these weed species were resistant in the study areas. However, it was successful in weakening the ability of the weeds to utilize soil water and nutrients efficiently and hinder them from accumulating biomass (dry weight). This resulted in significant reduction of dry weight and cover of weeds. Generally, the application of glyphosate significantly reduced monocot dry weight by 20.5 %, total dry weight by 14.2 % and cover by 15.8 % as compared to plots without glyphosate (Table 7 in **Paper II**).

3.2.3. On weeding time

Frequent tillage, higher seed rate and application of glyphosate reduced the time required for hand weeding (Figure 4 in **Paper II**). The average weeding time with conventional, minimum and zero tillage was 3109 hrs/ha, 3355.3 hrs/ha and 3743.2 hrs/ha respectively. Zero tillage increased weeding time by 10.4 % as compared to minimum tillage and by 17 % as compared to conventional tillage. Weeding time with the different seed rates of 5 kg/ha, 15 kg/ha and 25 kg/ha was 3352 hrs/ha, 3439 hrs/ha and 3547 hrs/ha respectively. Lower seed rate increased weeding time by 3 % as compared to 15 kg/ha seed rate and by 5.5 % as compared to the 25 kg/ha seed rate. Glyphosate application (3536 hr/ha) reduced weeding time by 7.5 % compared to plots without application (3270 hr/ha).

3.3. Weed competitive ability of teff varieties

3.3.1. Genotypic effect

The genotypic effect (effect of varietal difference) of teff on weed competitive ability was studied by considering the agronomic performance of ten teff varieties in the presence and absence of hand weeding as described in **paper III**.

Traits of teff varieties

There was significant difference among the teff varieties in most of their agronomic traits (Table 4 in **Paper III**). They showed significant difference in days to emergence, maturity, plant height, tiller number per plant, biomass yield and grain yield.

Among the varieties, '*DZ-Cr-358'* and *'DZ-01-354'* were late to emerge and mature with the highest number of tillers per plant where as the variety '*Boset'* was significanlty earlier in emergence and maturity. The earlier variety ('*Boset'*) took on average 5.7 days to emerge and 90 days to mature where as the later variety ('*DZ-Cr-358'*) took on average 16 days to emerge and 113.5 days to mature. This result is consistent with the characteristics of these varieties described in the Ethiopian Crop Varieties annual bulletin (EMAaRD 2014). The trend in the phenology showed that those emerged early matured early and vise versa. Though distinct in their genetic makeup, the early emerging varieties might have early access to water, nutrients and sunlight for their vegetative and reproductive growth and development. Many early vigor traits like early emerging, early coverage, early biomass and early height are among plant properties frequently mentioned to be important for competition ability in other cereal crops such as wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare L.*) and oats (*Avena sativa* L.) as reviewed by Andrew et al. (2015). In addition to genetic difference, hand weeding of these teff varieties delayed their maturity. Early maturity of the teff varieties was observed in unweeded plots taking an average of 106.5 days compared to 109 days in weeded plots.

Plant height is among the crop agronomic traits contributing on weed competitive ability of cereal crops (Asif et al. 2014; Andrew et al. 2015). In this study, there was significant height differences among the varieties (Table 4 in **Paper III**). The varieties '*DZ-Cr-387'* and

‘*DZ-01-974’* had taller plants with an average value of 97 cm. The varieties had significantly taller plants in unweeded plots (on average 93 cm) than on weeded plots (on average 89 cm) (Table 4 and Figure 1 in **Paper III**). This may be in response to competition of the varieties with weeds for sunlight. Similar trend was observed on tillers per plant. The varieties ‘*DZ-Cr-358’* and *‘DZ-01-354’* had the highest tillers per plant with average values of 5.82 and 4.48 respectively (Figure 2 in **Paper III**). Weeding the varities also significantly increased their tiller number per plant from an average of 3.3 tillers/plant in unweeded plots to 4.5 tillers/plant in weeded plots. The increment was 28.3 %. In other cereal crops such as wheat, tillering increased with decreased weed density (Khan et al. 2012; Asif et al. 2014). Besides, Andrew et al. (2015) stated that rate of tiller production is plastic and density dependent. Inter and intraspecific competition may contribute on the reduction of the tiller number/plant of the varieties in the absence of hand weeding.

Biomass and grain yields of the teff varieties were significantly different (Table 4 in **Paper III**). The average biomass yields of ‘*DZ-Cr-358’* i.e. 4223.6 kg/ha and ‘*DZ-01-354’* i.e. 5286.8 kg/ha were 48 % and 35 % respectively lower than the highest yielding variety ‘*Kora’* having an average biomass yield of 8118.1 kg/ha (Figure 3 in **Paper III**). Similarly, the average grain yield of ‘*DZ-Cr-358’* (813.2kg/ha) and ‘*DZ-01-354’* (1001kg/ha) were 40.4 % and 26.6 % respectively lower than the variety ‘*Kora’* having an average grain yield of 1364.1 kg/ha (Figure 3 in **Paper III**). In Ethiopia, the variety ‘*Kora’* is the highest yielder followed by *DZ-Cr-387* (Kebebew et al. 2011; Kebebew et al. 2017). The late emerging varieties i.e. *DZ-Cr-358* and *DZ-01-354* had the least yield because those varieties had not only emerged late but also matured late. Late maturity means that the varieties require more water for their seed filling and physiological maturity. Therefore, this low yield may be attributed to the competition among the tillers at the end of the production season especially for water necessary for their maturity. The other possible reason for the low yield may be due to the suppression of late emerging plants of the varieties by early emerging weeds. However, weeding significantly enhanced biomass and grain yields of all the varieties tested (Table 4 in **Paper III**). Average biomass yield of the varieties from weeded plots, 7295 kg/ha, was 15.3 % higher than the yield obtained from unweeded plots (6327.4 kg/ha). Average grain yield of the varieties, 1448 kg/ha, from weeded plots, was 32 %

higher than that obtained from unweeded plots (1096 kg/ha). The higher yield of the teff varieties achieved by hand weeding may be attributed to the less competition from weeds.

Since the interaction of the different varieties and hand weeding was not significant for most of the agronomic traits especially grain and biomass yields even by location and year(Table 4 in **Paper III**), the difference among the varieties is stable in all locations and years under study and in plots with and without hand weeding.

Influence of the teff varieties on weeds

The genotypic difference among teff varieties resulted in significant variation in weed density, dry weight and cover (Table 6 in **Paper III**). Significant effect of the varieties was observed in weed density, weed dry weight and cover (Table 7 in **Paper III**). The highest weed density had been recorded from plots with the variety *DZ-Cr-358 (*349 shoots/m^2) and *DZ-01-354* (328 shoots/m^2) while the least was from plots with *DZ-Cr-387* (263 shoots/m^2) and *DZ-Cr-385* (262 shoots/m^2) (Table 7 in **Paper III**). The highest weed dry weight was recorded from the plots with the variety *DZ-01-354* and *DZ-Cr-358* with an average value of 347.2 g/m^2 and 356.4 g/m^2 respectively (Table 7 in **Paper III**). The least amount of weed dry weight was obtained from plots with *DZ-01-2675* with an average value of 150.1 g/m^2 (Table 7 in **Paper III**). The later was not significantly different from the weed dry weight obtained from plots with the varieties *DZ-Cr-387* and *DZ-Cr-385.* The weed cover in plots with the varieties *'Kora'* and *'DZ-Cr-387'* was 13.7 % with the highest cover being observed from plots with *DZ-01-354* (22.2 %) and *DZ-Cr-358* (23.4 %) (Table 7 in **Paper III**). In other words, the high yielding varieties reduced the weed cover by 38.3 % when compared to *'DZ-01-354'*and by 41.8 % when compared to *'DZ-Cr-358'*.

The effect of the varieties on weeds was consistent by locations and years under study. Based on weed classes, the genotypic difference in teff had an effect on monocots than dicots. Such an effect of the varieties was not significant when compared by locations and years. Hand weeding of the varieties significantly reduced weed density, dry weight and cover (Table 7 in **Paper III**). It reduced weed density by 23 %, dry weight by 40 % and cover by 37 % but it did not have singnificant effect spatiotemporally and hence its effects are consistent in both locations and years under study.

There was a trade-off between the teff varietys' yield potentail and weed competitiveness. The teff varieties '*Kora'* and *'DZ-Cr-387'*compete strongly with weeds as seen as their effect on weed density, dry weight and cover while they had higher yields at the end of the production seasons than other varieties. However, they sacrifice some of their yields during their competition with both monocot and dicot weeds. For instance, the variety '*Kora'* lost as much as 6 % of its biomass yield and 18 % of its grain yield (Figure 5 in **Paper III**). Similarly, the variety *'DZ-Cr-387'* lost as much as 17 % of its biomass yield and 21 % of its grain yield (Figure 5 in **Paper III**). As comparison, the variety *'DZ-01-354'* lost 29 % of its grain yield and 38 % of its biomass yield and the variety *'DZ-Cr-358'* lost 30 % of its grain yield and 28 % of its biomass yield due to weed competition. According to Andrew et al. (2015), there is a trade-off between yield potential and competitive ability of crop varieties when they lose less yield in cost of their competition with weeds though competitiveness can be result of the performance of multiple crop traits. Such a trade-off was observed in '*Kora'* and *'DZ-Cr-387'*as they lost less amount of their biomass and grain yields than other varieties in cost of their competitiveness with weeds as they significantly reduced weed density, dry weight and cover.

The competitive ability of the teff variety *'DZ-Cr-387'* resulted in reduction of on average 52.5 % of the weeding time in both locations, which may be considered as a compensation to the yield reduction of the variety due to competition with weeds (Figure 4 in **Paper III**).

3.3.2. Allelopathic effect

Allelopathic effect of teff varieties was studied using two model weed species namely ryegrass (*Lolium perenne cv. Mondiale; cv=cultivar*) and radish (*Raphanus sativus* cv. Cherry Belle). Allelopathic effect was explained in terms of potential allelopathic activity (PAA) and specific potential allelopathic activity (SPAA) of the varieties. Mixture of the different teff varieties affected the root length, root area and root dry weight of both model weeds. All the teff varieties showed differences in their potential allelopathic effect on weeds.

Allelopathic effect on ryegrass

Highest root length and root area and among the highest root dry weight, were observed in the teff variety *'DZ-Cr-387'* when mixed with ryegrass with average values of 19.4 cm, 0.53 cm^2 and 13.6 mg respectively (Figure 9). A much lower root length, root area and root dry weight of ryegrass were observed when mixed with the teff variety *'DZ-01-2675'* with average values of 17.3 cm, 0.5 cm^2 and 12.7 mg and local landrace with an average values of 16.7 cm, 0.47 cm^2 and 12.5 mg, followed by *'DZ-Cr-358'* and *Boset* (Figure 9). Teff varieties resulting in lower root diameter, root dry weight, root area and root length of ryegrass have higher PAA and SPAA. The highest average potential allelopathic activity was recorded from local land race with an average values of PAA 11.77 % and SPAA 1.21 %/mg and *'DZ-01-2675'* with *PAA 10.89 % and SPAA 1.14 %/mg.* The least was from *'DZ-Cr-387'* with an average values of *PAA 0.19 % and SPAA 0.11 %/mg*.

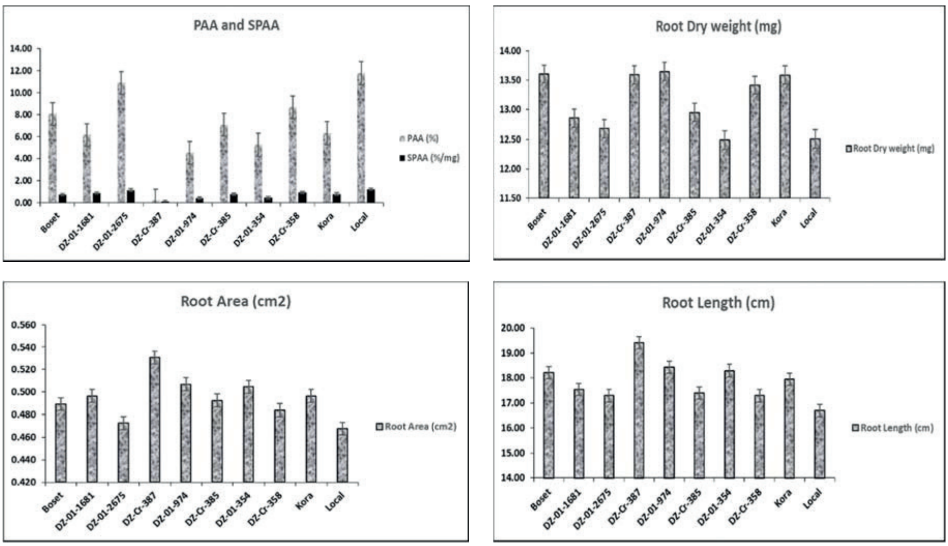

Figure 9. Potential allelopathic activity of different teff varieties and their effect on root growth of ryegrass***.*** *Root area, root length and root dry weight of ryegrass without teff varieties (control) were 0.61 cm^2, 20.6 cm and 15.2 mg*

There was significant and strong negative correlation between PAA and SPAA of teff varieties and root length, root area, root dry weight and root volume of ryegrass (Table 2 in **Paper IV**). There was also correlation among most of the response of ryegrass (Table 1 in Appendix A in **Paper IV**). Significant strong positive correlation was observed among root length, root area and root volume but root diameter and root dry weight did not show correlation between each other and with the other responses. Backward multiple regression analysis indicated that root length, root area and root dry weight of ryegrass significantly contributed to 99.94 % of the variability of PAA of teff varieties (Table 3 in **Paper IV**). The analysis also showed that only root area and root diameter of ryegrass contributed to 97.02 % of the variability of SPAA of teff varieties. However, root volume, did not show significant contribution on their variability (Table 2 and 3 in **Paper IV**).

Allelopathic effect on radish

The highest radish root length, 28.5 cm, was recorded from *'DZ-Cr-387'* followed by *'DZ-01-1681'* with 25.3 cm and *'DZ-01-354'* with 25.2 cm (Figure 10). Similarly the highest value of root area was found in *'DZ-Cr-387'* (1.1 cm^2) followed by *'DZ-01-1681'* (1.05 cm^2) and *'DZ-01-974'* (1.02 cm^2) (Figure 10). The highest radish root dry weight was recorded for *'DZ-01-1681'* (12 mg) followed by *'DZ-Cr-358'* (11.1 mg) and Local landrace (10.7 mg). Relatively lower root length (24.2 cm), root area (0.98 cm^2) and root dry weight (9.7 mg) were recorded from *'DZ-01-2675'* (Figure 10).

The different teff varieties showed variable PAA and SPAA on radish (Figure 10). When comparing the PAA of the teff varieties, *Boset* had recorded the highest PAA with 16.3 % followed by *'DZ-01-2675'* with 12.6 % and *'Kora'* with 12 %. The least PAA values was from *'DZ-Cr-387'* with a value of 1.8 %. The teff varieties had also variability in SPAA where the highest value 1.53 %/mg was observed from *'Boset'* followed by *'Kora'* and *'DZ-Cr-385'* both having an average value of 1.56 %/mg. The least SPAA value, 0.237 %/mg, was from the variety *'DZ-Cr-387'*.

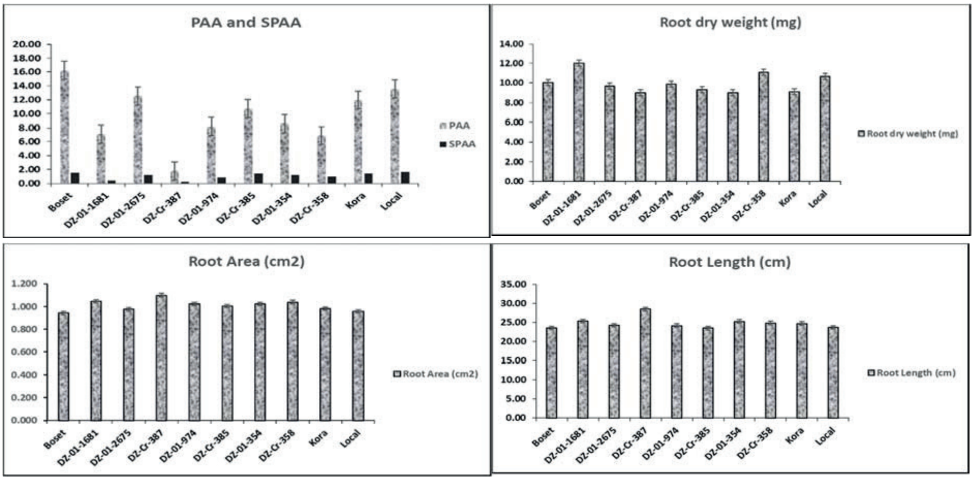

Figure 10. Potential allelopathic activity of different teff varieties and their effect on root growth of radish. Root area, root length and root dry weight of ryegrass without teff varieties (control) were 1.4 cm^2, 31.4 cm and 14.3 mg

The variety *'DZ-Cr-387'* has shown consistent low allelopathic effect on both ryegrass and radish, which means this variety has lower allelopathic effect than the other teff varieties.

There was significant and strong negative correlation between PAA and SPAA of teff varieties and root length, root area and root volume of radish (Table 2 in **Paper IV**). There was also correlation among most of the response of radish (Table 2 in Appendix A in **Paper IV**). Significant strong positive correlation was observed between root length and root area and significant strong negative correlation between root length and root diameter. There was also significant strong positive correlation between root area and root volume. However, root dry weight did not show significant correlation with the other responses of radish. Backward multiple regression analysis showed that root area significantly explained 98.8 % of the variability of PAA and root length, root area and root diameter significantly explained 98.2 % of the variability of SPAA of teff varieties on radish (Table 3 in **Paper IV**).

3.3.3. Important contributing traits

There is little knowledge on differences in weed competitiveness of the varieties of teff and traits explaining such differences are not well understood. In **paper III**, the influence of the teff varieties on weeds was studied and found out that the weed biomass (DW) differed from 150.11 g/m^2 to 356.37 g/m^2, in unweeded plots, between the most and less (plus 137%) competitive teff varieties. What traits of the teff varieties caused such differences in weed responses was not addressed. This part will explain and identify the important contributing traits to weed competitive ability of teff.

Backward multiple regression analysis indicated that teff agronomic traits including days to emergence, heading, maturity, plant height, tiller number per plant, biomass yield and potential allelopathic activity significantly contributed for 39.2 % - 99.7 % of the variation in weed biomass, cover and density in both *Axum* and *Mekelle* during 2015 and 2016 (Tables 5 and 6 in **Paper IV**). Most of the traits had more of a combined effect on the variability of the weed responses. The contribution of teff emergence and biomass on the variance of the weed responses was significant in both locations and years and accounted for 92 % and 77.2 % respectively of the variance in weed biomass, 63 % and 62 % respectively of the variance in weed density and 66.4 % and 74.5 % respectively of the variance in weed cover in *Axum*. They did not have significant contribution on the variance of the weed responses in *Mekelle*. Heading, maturity and tiller number per plant significantly contributed on the overall variability of the weed responses in all the experimental locations. The variance of such responses due the difference in plant height of teff varieties was not consistent in all locations and years. Tiller number per plant explained 12.2 % of the variance in weed biomass, 29 % of the variance in weed density and 27.7 % of the variance in weed cover in both *Axum* and *Mekelle*. Potential allelopathic activity of teff varieties had significant contribution on the variance of weed biomass, cover and density (Tables 5 and 6 in **Paper IV**). PAA contributed from 21.5 % to 28.2 % of the variance in weed biomass, cover and density in both locations and years.

3.4. Weed suppression ability of teff as compared to cover crops

Among the cover crops, teff was successful in reducing weed density, dry weight and cover next to Grasspea (Figure 11). The highest weed density, dry weight and cover was recorded from plots with Fieldpea followed by *Vicia sp.* (Figure 11). Teff reduced weed density, dry weight and cover by 33.3 %, 55.6 % and 27 % respectively as compared to Fieldpea and by 23 %, 53.8 % and 11.6 % as compared to *Vicia villosa* (Figure 11). Sowing method did not have significant effect on weed density, dry weight and cover and weed responses did not show significant differences whether teff is broadcasted or drilled in rows (Table 5). However, hand weeding significantly reduced weed density, dry weight and cover by 17 %, 29.5 % and 27.7 % respectively (Table 5). Teff lowered weed density, dry weight and cover even in the absence of hand weeding more than other cover crop species studied (Figure 12).

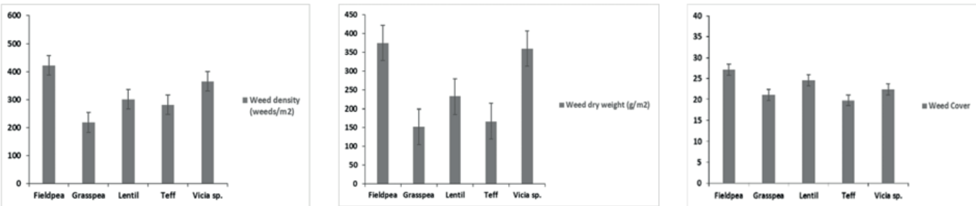

Figure 11. Effect of cover crop species on weed density, dry weight and cover

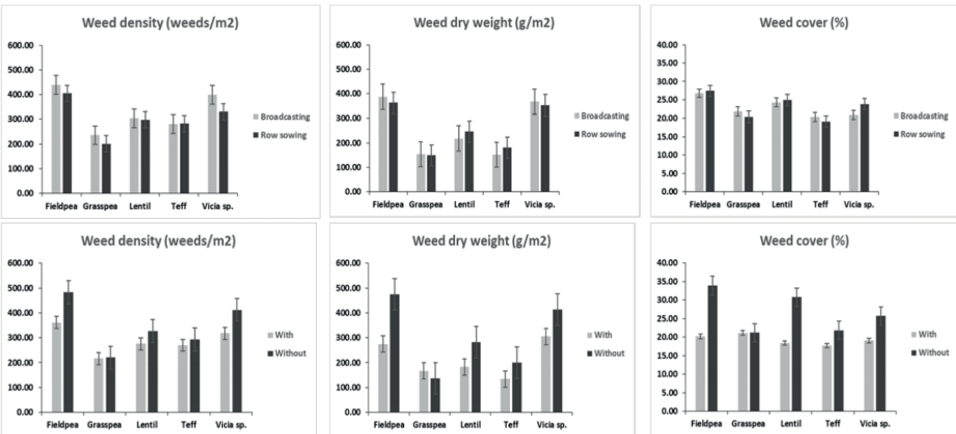

Figure 12. Effects of cover crop species, sowing methods and hand weeding on weed density, dry weight and cover

Table 5. Sowing method and hand weeding effects on weed density, dry weight and cover

Factors	Weed Density (weeds/m^2)	Weed Dry weight (g/m^2)	Cover (%)
Sowing Method			
Broadcasting	331.48	255.98	22.8389
Row Planting	303.55	258.16	23.139
Hand weeding			
With	288.1b	212.6b	19.3b
without	347a	301.6a	26.7a

4. CONCLUSION AND PRACTICAL RECOMMENDATIONS

4.1. Conclusion

The major teff growing areas of Tigray showed variation in weed species composition and richness. These species also showed variability in ecological distribution and adaptation. Altitude had determinant influence on such variability. Based on frequency and dominance, the most important weed species in teff fields were *Plantago lanceolate, Erucastrum abyssinicum, Setari pumila, Cynodon dactylon, Cyperus esculentus, Cyperus rotundus, Avena, abyssinica, Argomone mexicana, and Medicago polymorpha.*

Intensive soil tillage by ard ploughing reduced weed biomass significantly (29% reduction compared with no ard ploughing), clearly more than glyphosate spraying (13% reduction compared with no use). High seed rate also decreased weed biomass significantly (20% reduction compared to the lowest). Combining the factors, reduced tillage (ard ploughing once), the use 15 kg/ha seed rate and application of glyphosate especially when there is high incidence of monocot weeds minimized weed incidence and infestation while enhanced teff vegetative and reproductive performances. Similar results can be obtained by frequent tillage and using the highest seed rate (25 kg/ha).

Since the varieties showed variation in their agronomic traits, weeds respond differently to different teff varieties. All the teff varieties showed differences in potential allelopathic activity (PAA) and had inhibited early root growth and development of both monocot and dicot weeds. Allelopathic effect of teff had conspicuous role in affecting weeds during their late stages and were able to affect their density, biomass, and cover. The teff varieties '*Kora'* and *'DZ-Cr-387'* significantly lowered weed density, dry weight and cover and hence were more competitive to weeds but the varieties '*DZ-Cr-358'* and '*DZ-01-354'* were the least competitive. Generally, teff varieties affected more of monocot than dicot weeds. The competitive ability of the teff variety *'DZ-Cr-387'* shortened weeding time. PAA, days to emergence and biomass yield were the agronomic traits of teff significantly contributing on weed competitive ability of teff. However, there was trade-off between the yield potential and weed competitiveness in most of the varieties specially '*Kora'* and *'DZ-Cr-387'* as they lost less amount of their yields while significantly reducing weed infestation. Teff had weed suppressive ability comparable with the most commonly used cover crops in Tigray. In other words, teff can be an alternative cover crop during crop production in Ethiopia.

The outputs from the weed survey satisfied principle 1 of the IWM as described in figure 1 above. Besides, information from research reports showing that weeds cause high teff yield loss was used as an input to decide further studies on the principles 4 – 8 of the IWM in the context of teff production. The research outputs from both field and laboratory experiments satisfied principles 4 – 6. Further studies on response of the identified dominant weed species to glyphosate and checking the outputs of the studies described above under the farmer's condition will satisfy the remaining principles 7 and 8.

4.2. Practical recommendations

The identification of dominant weed species in the teff fields of Tigray and the knowledge about their ecological distribution is an 'eye-opener' to the farming community producing teff. The existence of these dominant weed species in all the field experiments, the altitude where the field experiments were conducted and the research areas consisting the favourable soil types for teff asserted the practical implication of the research output of this study and its wider use in the country. Understanding the most important weed species in teff fields help farmers to have weed management specific to weed species, saves time and labor cost, enhance teff weed competitive ability and increase its yield, and raise household income from teff production.

Teff farmers in Tigray can use integrated weed management for teff developed in this study by combining minimum tillage (ard ploughing once) at both Vertisol and Cambisol soil types along with manual removal of the uprooted weeds, application of glyphosate especially during high weed incidence, the teff variety '*DZ-Cr-387' or 'Kora'* sown at 20 cm between rows with seed rate of 15 kg/ha, and hand weeding with special focus on the identified dominant weed species. On Vertisols, farmers can alternately use frequent and minimum tillage at planned seasonal interval based on weed incidence and infestation.

5. REFERENCE

Adenew, B. (2004). The food security role of agriculture in Ethiopia. *Journal of Agricultural and Development Economics*, 1 (1): 138-153.

Adnew, T., Ketema, S., Tefera, H. & Sridhara, H. (2005). Genetic Diversity in Tef [Eragrostis tef (Zucc.) Trotter] Germplasm. *Genetic Resources and Crop Evolution*, 52 (7): 891-902.

Alemayoh, S. T., Dorosh, P. & Gemessa, S. A. (2012). Crop production in Ethiopia: regional patterns and trends. In Paul, D. & Shahidur, R. (eds) vol. 74 *Food and agriculture in Ethiopia: Progress and policy challenges*, p. 53. Philadelphia, Pennysylvania: University of Pennysylvania press.

Amare, A. & Adane, L. (2015). Determination of Seed Rate and Variety on the Growth and Yield of Teff in Eastern Amhara Region, Ethiopia. *Journal of Biology, Agriculture and Healthcare*, 5 (5): 27-33.

Amedie, F. A. (2013). *Impacts of Climate Change on Plant Growth, Ecosystem Services, Biodiversity, and Potential Adaptation Measure*. Gothenburg, Sweden: University of Gothenburg, Biological and Environmental Sciences. 61 pp.

Andrew, I. K. S., Storkey, J. & Sparkes, D. L. (2015). A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research*, 55 (3): 239-248.

Ann, S. & Chris, P. (1989). *A weed identification guide for Ethiopia*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). 280 pp.

Araya, T., Cornelis, W. M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K. D., Haile, M., et al. (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.

Araya, T., Cornelis, W. M., Nyssen, J., Govaerts, B., Getnet, F., Bauer, H., Amare, K., Raes, D., Haile, M. & Deckers, J. (2012). Medium-term effects of conservation agriculture based cropping systems for sustainable soil and water management and crop productivity in the Ethiopian highlands. *Field Crops Research*, 132: 53-62.

Asif, M., Iqbal, M., Randhawa, H. & Spaner, D. (2014). Crop Competitiveness. In *Managing and Breeding Wheat for Organic Systems*: Springer, Cham.

Assefa, A., Liben, M., Tadesse, T. & Yeshalem, B. (2008). The effect of tillage frequency and weed control on yield of tef (Eragrostis tef) in Yielmana-Densa Area, northwestern Ethiopia. *East African Journal of Science*, 2 (1): 35-40.

Assefa, G., Theodrose, T. & Alemu, D. (2016). Quantitative Determination of Weed Occurrence on Upland Rice of Bambasi, Ethiopia. *Ecology and Evolutionary Biology*, 1 (3): 53-56.

Assefa, K., Yu, J. K., Zeid, M., Belay, G., Tefera, H. & Sorrells, M. E. (2011). Breeding tef [Eragrostis tef (Zucc.) trotter]: conventional and molecular approaches. *Plant Breeding*, 130 (1): 1-9.

Assefa, K., Tadele, Z., Chanyalew, S., Ethiopian Institute of Agric. Research, D. Z. C. & Pflanzenwissenschaften, U. B. I. f. (2013). *Achievements and Prospects of Tef Improvement: Proceedings of the Second International Workshop, November 7-9, 2011, Debre Zeit, Ethiopia*: Universität Bern.

Assefa, K., Cannarozzi, G., Girma, D., Kamies, R., Chanyalew, S., Plaza-Wüthrich, S., Blösch, R., Rindisbacher, A., Rafudeen, S. & Tadele, Z. (2015a). Genetic diversity in tef [Eragrostis tef (Zucc.) Trotter]. *Frontiers in plant science*, 6.

Assefa, K., Cannarozzi, G., Girma, D., Kamies, R., Chanyalew, S., Plaza-Wüthrich, S., Blösch, R., Rindisbacher, A., Rafudeen, S. & Tadele, Z. (2015b). Genetic diversity in tef [Eragrostis tef (Zucc.) Trotter]. *Frontiers in Plant Science*, 6: 177.

Astatke, A., Jabbar, M. & Tanner, D. (2003). Participatory conservation tillage research: an experience with minimum tillage on an Ethiopian highland Vertisol. *Agriculture, Ecosystems & Environment*, 95 (2): 401-415.

Aune, J., B., Matewos, T. B., Fenta, G. A. & Abyie, A. A. (2001). The OX Ploughing System in Ethiopia: Can it be Sustained? *Outlook on Agriculture*, 30 (4): 275-280.

Balesh, T., Aune, J. B., Johnsen, F. H. & Vanlauwe, B. (2008). The prospects of reduced tillage in tef (Eragrostis tef Zucca) in Gare Arera, West Shawa Zone of Oromiya, Ethiopia. *Soil and Tillage Research*, 99 (1): 58-65.

Barzman, M, Bàrberi, P., Birch, A.N.E., Boonekamp, P., Dachbrodt-Saavdeh, S., Graf, B., Hommel, B., Jensen, J.E., Kiss, J., Kudsk, P., Lamichhane, J.R.,Messean, A., Moonen, A-C., Ratnadass, A., Ricci, P., Sarah, J-L., & Sattin, M. (2015). Eight principles of integrated pest management. Agronomy for Sustainable Development 35: 1199-1215.

Baudron, F., Jaleta, M., Okitoi, O. & Tegegn, A. (2014). Conservation agriculture in African mixed crop-livestock systems: Expanding the niche. *Agriculture, Ecosystems & Environment*, 187: 171-182.

Baye, K. (2014). *Teff: nutrient composition and health benefits*: International Food Policy Research Institute (IFPRI).

Bekalu, A. & Arega, A. (2016). Effect of Seed Rate on Yield and YieldComponents of Tef (Eragrostic tef) Trotter) at Shebedino, Southern Ethiopia. *Journal of Natural Sciences Research*, 6 (21): 6-11.

Belay, G., Tefera, H., Tadesse, B., Metaferia, G., Jarra, D. & Tadesse, T. (2006). Participatory variety selection in the Ethiopian cereal Tef (*Eragrostis tef*). *Experimental Agriculture*, 42 (1): 91-101.

Belay, G., Hailu, T., Anteneh, G., Kebebew, A. & Gizaw, M. (2008). Highly client-oriented breeding with farmer participation in the Ethiopian cereal tef [Eragrostis tef (Zucc.) Trotter]. *African Journal of Agricultural Research*, 3 (1): 022-028.

Bergkvist, G., Ringselle, B., Magnuski, E., Mangerud, K. & Brandsæter, L. O. (2017). Control of Elymus repens by rhizome fragmentation and repeated mowing in a newly established white clover sward. *Weed Research*, 57 (3): 172-181.

Berhe, T. (1975). A breakthrough in tef-breeding technique. *Information Bulletin on Cereal Improvement and Production Project (FAO)*, 12: 11-13.

Bertholdsson, N. O. (2005). Early vigour and allelopathy – two useful traits for enhanced barley and wheat competitiveness against weeds. *Weed Research*, 45: 94-102.

Birhanu, G., Zerihun, T., Genene, T., Endegena, A., Endeshaw, A. & Getasew, A. (2018). Traditional Knowledge on Teff (Eragrostistef) Farming Practice and Role of Crop Rotation to Enrich Plant Growth Promoting Microbes for Soil Fertility in East Showa: Ethiopia. *Agri Res & Tech*, 16 (5): 1-17.

Boerboom, C. & Owen, M. (2013). Glyphosate-Resistant Weeds. In GWC (ed.) *The Glyphosate, Weeds, and Crops Series*, p. 8.

Brandsæter, L. O., Bakken, A. K., Mangerud, K., Riley, H., Eltun, R. & Fykse, H. (2011). Effects of tractor weight, wheel placement and depth of ploughing on the infestation of perennial weeds in organically farmed cereals. *European Journal of Agronomy*, 34 (4): 239-246.

Brandsæter, L.O., K. Mangerud, M. Helgheim & T.W. Berge. (2017). Control of perennial weeds in spring cereals through stubble cultivation and mouldboard ploughing during autumn or spring. Crop Protection 98: 16-23.

Brookes, G., Taheripour, F. & Tyner, W. E. (2017). The contribution of glyphosate to agriculture and potential impact of restrictions on use at the global level. *GM crops & food*, 8 (4): 216-228.

Brouder, S. M. & Gomez-Macpherson, H. (2014). The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. *Agriculture, Ecosystems & Environment*, 187: 11-32.

Bryan, E., Deressa, T. T., Gbetibouo, G. A. & Ringler, C. (2009). Adaptation to climate change in Ethiopia and South Africa: options and constraints. *Environmental Science & Policy*, 12 (4): 413-426.

Buhler, D. D. (2002). Challenges and opportunities for integrated weed management. *Weed Science*, 50 (3): 273-280.

Bunce, J. A., Charudattan, R., Martinez, A. M., Parker, C., Press, M. C. & Riches, C. R. (2002). *The world's worst weeds*, vol. 44. 55-58 pp.

Børresen, T. and Njøs, A. (1994). The effect of mouldboard ploughing depth and seedbed preparation on crop yields, weed infestation and soil properties from 1940 to 1990 on loam soil in south eastern Norway. Soil Till. Res. 32, 21-39.

Campbell, L. G., Snow, A. A., Sweeney, P. M. & Ketner, J. M. (2009). Rapid evolution in crop-weed hybrids under artificial selection for divergent life histories. *Evolutionary Applications*, 2 (2): 172-186.

Chandrasena, N. (2009). How will weed management change under climate change? Some perspectives. *Journal of Crop and Weed*, 5 (2): 95-105.

Chauhan, B. S., Singh, R. G. & Mahajan, G. (2012). Ecology and management of weeds under conservation agriculture: A review. *Crop Protection*, 38: 57-65.

Chauhan, B. S., Ahmed, S., Awan, T. H., Jabran, K. & Manalil, S. (2015). Integrated weed management approach to improve weed control efficiencies for sustainable rice production in dry-seeded systems. *Crop Protection*, 71: 19-24.

CIA world fact book. (2018). *Ethiopian Economy 2018*. USA: theodora.com. Available at: https://theodora.com/wfbcurrent/ethiopia/ethiopia_economy.html (accessed: 10 September, 2018).

Costanza, S. H. (1974). *Literature and Numerical Taxonomy of Teff (Eragrostis Tef)*. Urbana, Illinois, USA: Cornel University.

Costanza, S. H., Dewet, J. M. J. & Harlan, J. R. (1979). Literature review and numerical taxonomy ofEragrostis tef (T'ef). *Economic Botany*, 33 (4): 413-424.

Coughenour, C. M. (2009). Innovating Conservation Agriculture: The Case of No-Till Cropping. *Rural Sociology*, 68 (2): 278-304.

Creamer, N. G., Bennett, M. A., Stinner, B. R., Cardina, J. & Regnier, E. E. (1996). Mechanisms of weed suppression in cover crop-based production systems. *HortScience*, 31 (3): 410-413.

CSA. (2007). *Population and Housing Census*. Addis Ababa, Ethiopia: Central Statistical Agency.

CSA. (2016). *Agricutlrual Sample Survey 2015/2016 (2008E.C): Report on Area, Production and Farm Management Practice on Belg Season Crops for Private Peasant Holdings*, vol. V (5). Addis Ababa, Ethiopia: CENTRAL STATISTICAL AGENCY. 131 pp.

Daba, T. (2017). Nutritional and Soio-Cultural Values of Teff (Eragrostis tef) in Ethiopia. *International Journal of Food Science and Nutrition*, 2 (3): 50-57.

Deckers, J., Driessen, P., Nachtergaele, F. & Spaargaren, O. (2001). World reference base for soil resources–in a nutshell. *Soil Classification*: 173-181.

Deckers, J. A., Nachtergaele, F. O. & Spaargaren, O. C. (eds). (1998). *World Reference Base for Soil Resource: Introduction.* Acco Leuven/Amersfoort. Belgium. 165 pp.

Dennis, C. O., Jose, V. F. & Nikol, H. (2016). Weed Control and Radish (Raphanus sativus) Response to S-metolachlor on Organic Soils. *HortScience*, 51 (1): 79-83.

Deressa, T. T. & Hassan, R. M. (2009). Economic impact of climate change on crop production in Ethiopia: evidence from cross-section measures. *Journal of African economies*, 18 (4): 529-554.

Dill, G. M., CaJacob, C. A. & Padgette, S. R. (2008). Glyphosate-resistant crops: adoption, use and future considerations. *Pest Management Science*, 64 (4): 326-331.

Duke, O. S. & Powles, B. S. (2009). Glyphosate-resistant crops and weeds: now and in the future. *AgBioForum*, 12 (3&4): 346-357.

Dwight, D. L. (2017). *Introduction to weeds: what are weeds and why do we care?* Pennsylvania, USA: Penn state University. Available at: https://extension.psu.edu/introduction-to-weeds-what-are-weeds-and-why-do-we-care (accessed: August 1, 2018).

Ekeberg, E., Riley, H., Njøs, A. (1985). Plogfri jordarbeiding til vårkorn: I. Avling og kveke. Fors. Forsk. Landbr. 36, 45-51. (In Norwegian).

EMAaRD. (2014). *Crop Variety Issue No.12: Summary of Released/Registered Varieties of Crops*, vol. 12. Addis Ababa: Ethiopian Ministry of Agriculture and Rural Development.

Emanuele, R. (2012). *Ecological weed management*. PhD Thesis. Viterbo (VT): Tuscia University Environmental Sciences. 185 pp.

Emerta, A. A. (2013). *Climate change, growth and poverity in Ethiopia*. Working paper No. 3, vol. 03. Texas, USA: The robert s.strauss center for international security and law.

Esayas, T., Abraham, G. H. & Mashila, D. (2012). Quantitative and Qualitative Determination of Weeds in Cotton-Growing Areas of Humera and Metema, Northwestern Ethiopia. *Ethiop. J. Appl. Sci. Technol.*, 3 (1): 57-69.

Esayas, T., Abraham, G. H. & Mashila, D. (2013). Weed Interference in Cotton (Gossypium hirsutum L.) in the Middle Awash, Ethiopia. *Ethio. J. Appl. Sci. Technol.*, 4: 41-49.

Eslami, S. (2014). *Weed Management in Conservation Agriculture Systems*. 87-124 pp.

Eslami, S. V. (2014). Weed Management in Conservation Agriculture Systems. In Chauhan, B. S. & Mahajan, G. (eds) *Recent Advances in Weed Management*, pp. 87-124. New York, NY: Springer New York.

EU Directive. (2009). Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009: Establishing a framework for Community action to achieve the sustainable use of pesticides. *Official Journal of the European Union*: 71-86.

FAO. (2015). *World reference base for soil resources 2014: International soil classification system for naming soils and creating legends for soil maps*. World soil resources reports, vol. 106. Rome, Italy: Food and Agriculture Organization of the United Nations. 203 pp.

Farooq, M., Flower, K. C., Jabran, K., Wahid, A. & Siddique, K. H. M. (2011). Crop yield and weed management in rainfed conservation agriculture. *Soil and Tillage Research*, 117: 172-183.

Farooq, M. & Siddique, K. H. M. (2015). Conservation Agriculture: Concepts, Brief History, and Impacts on Agricultural Systems. In Farooq, M. & Siddique, K. H. M. (eds) *Conservation Agriculture*, pp. 3-17. Cham: Springer International Publishing.

Fisk, J. W., Hesterman, O. B., Shrestha, A., Kells, J. J., Harwood, R. R., Squire, J. M. & Sheaffer, C. C. (2001). Weed Suppression by Annual Legume Cover Crops in No-Tillage Corn This research was partially supported by North Central SARE project LNC 93-58. *Agronomy Journal*, 93 (2): 319-325.

Friew, K. & Lake, K. (2011). Some Experiences on Tef Mechanization. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement*, p. 379. Debre Zeit, Ethiopia: Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center and University of Bern, Institute of Plant Sciences, Switzerland.

Fufa, H., Tesfa, B., Hailu, T., Kebebew, A., Tiruneh, K., Aberra, D. & Seyfu, K. (2001). Agronomy research in tef. In Hailu, T., Getachew, B. & Mark, E. S. (eds) *Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement*, pp. 167-176. DebreZeit, Ethiopia: DebreZeit Agricultural Research Center.

Funk, C., Dettinger, M. D., Michaelsen, J. C., Verdin, J. P., Brown, M. E., Barlow, M. & Hoell, A. (2008). Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proceedings of the National Academy of Sciences*, 105 (32): 11081.

Geremew, B. & Melaku, U. (2013). Food Science and Human Nutrition Research. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement*, p. 379.

Stämpfli AG, 3001 Bern, Switzerland: Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; Institute of Plant Sciences, University of Bern, Switzerland.
Getahun, A. (1978). Agricultural systems in Ethiopia. *Agricultural Systems*, 3 (4): 281-293.
Habtegebrial, K., Singh, B. & Haile, M. (2007a). Impact of tillage and nitrogen fertilization on yield, nitrogen use efficiency of tef (Eragrostis tef (Zucc.) Trotter) and soil properties. *Soil and Tillage Research*, 94 (1): 55-63.
Habtegebrial, k., Singh, B. R. & Haile, M. (2007b). Impact of tillage and nitrogen fertilization on yield, nitrogen use efficiency of tef (Eragrostis tef (Zucc.) Trotter) and soil properties. *Soil and Tillage Research*, 94 (1): 55-63.
Haftamu, G., Mitiku, H. & 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 Sciences*, 1 (1): 82-94.
Haftamu, G., Mitiku, H. & Yamoah, C. F. (2010). Plowing Frequency, Soil Compaction and N-Fertilizer Rate Effect on the N uptake, N use efficiency and CP content of Teff (Eragrostis tef (Zucc.) Trotter) on Vertisols of Central Zone of Tigray, Northern Ethiopia. *Journal of Drylands*, 3 (1): 79-90.
Håkansson, I., Stenberg, M., and Rydberg, T. (1998). Long-term experiments with different depths of mouldboard ploughing in Sweden. Soil Till. Res. 46, 209-223.
Håkansson, S. (2003). Weeds and weed management on arable land: an ecological approach. CABI Publishing, Wallingford, Oxon, UK. 274 pp.
Hansen, P. K., Kristensen, K. & Willas, J. (2008). A weed suppressive index for spring barley (Hordeum vulgare) varieties. *Weed Research*, 48 (3): 225-236.
Harker, K. N. & O'Donovan, J. T. (2013). Recent Weed Control, Weed Management, and Integrated Weed Management. *Weed Technology*, 27 (1): 1-11.
Heap, I. M. (1997). The occurrence of herbicide-resistant weeds worldwide. *Pest Management Science*, 51 (3): 235-243.
Houngbédji, T., Dessaint, F., Nicolardot, B., Shykoff, J. A. & Gibot-Leclerc, S. (2016). Weed communities of rain-fed lowland rice vary with infestation by Rhamphicarpa fistulosa. *Acta Oecologica*, 77: 85-90.
Hyvönen, T., Ketoja, E., Salonen, J., Jalli, H. & Tiainen, J. (2003). Weed species diversity and community composition in organic and conventional cropping of spring cereals. *Agriculture, Ecosystems & Environment*, 97 (1): 131-149.
IFPRI. (2006). *Atlas of the Ethiopian Rural Economy*. Addis Ababa, Ethiopia: International Food Policy Research Institute and Central Statistical Agency. 1-108 pp.
IPCC. (2002). Climate change and biodiversity. In Habiba, G., Avelino, S. & Robert, T. W. (eds) *IPCC Technical Paper V*, p. 86. Geneva, Swizerland: WMO and UNEP.
IPCC. (2007). *Climate Change; Fourth Assessment report of the*
Intergovernmental Panel on Climate Change: Cambridge University Press.
ISHRW. (2013). *Herbicide Resistant Yellow Nutsedge (Cyperus esculentus)*. USA, Arkansas: International Survey of Herbicide Resistant Weeds. Available at: http://www.weedscience.org/Details/Case.aspx?ResistID=6752 (accessed: December 25, at 1:00AM).
Jaccard, P. (1912). The distribution of the flora in the alpine zone. *New phytologist*, 11 (2): 37-50.
Jackman, N. D. (1999). *Tef and Finger Millet: Archaeobotanical Studies of Two Indigenous East African Cereals*. Canada: Simon Fraser University, Archaeology. 170 pp.
Jensen, J.E. (2008). Weed control thresholds. In: weed science Compendium 2009 (Eds. Streibig, J.C. & Andreasen, C.). Department of Agriculture and Ecology. Taastrup, Denmark. 340 p.
Johnson, W. G. & Gibson, K. D. (2006). Glyphosate-Resistant Weeds and Resistance Management Strategies: An Indiana Grower Perspective. *Weed Technology*, 20 (3): 768-772.

Joyce, F. d. V. (1943). Notes on agriculture in Ethiopia. *East African Agricultural And Forestry Journal*, 8: 176-181.
Kaleb, B. H., Johnson, W. G. & Massey, R. E. (2003). Weed Management and Economic Returns in No-Tillage Herbicide-Resistant Corn (Zea mays). *Weed Technology*, 17 (2): 239-248.
Kassahun, Z. & Tebkew, D. (2013). Weed Research in Tef. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement*, p. 379. Stämpfli AG, 3001 Bern, Switzerland: Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; Institute of Plant Sciences, University of Bern, Switzerland.
Kassam, A., Friedrich, T., Shaxson, F. & Pretty, J. (2009). The spread of Conservation Agriculture: justification, sustainability and uptake. *International Journal of Agricultural Sustainability*, 7 (4): 292-320.
Kassie, B. T., RÖTter, R. P., Hengsdijk, H., Asseng, S., Van Ittersum, M. K., Kahiluoto, H. & Van Keulen, H. (2014). Climate variability and change in the Central Rift Valley of Ethiopia: challenges for rainfed crop production. *The Journal of Agricultural Science*, 152 (1): 58-74.
Kebebew, A., Sherif, A., Getachew, B., Gizaw, M., Hailu, T. & Mark, E. S. (2011). Quncho: the first popular tef variety in Ethiopia. *International Journal of Agricultural Sustainability*, 9 (1): 25-34.
Kebebew, A., Solomon, C. & Gizaw, M. (2013). Conventional and Molecular Tef Breeding. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement*, p. 379. Addis Ababa, Ethiopia: Ethiopian Institute of Agricultural Research.
Kebebew, A., Solomon, C., Yazachew, G., Mitiku, A., Tsion, F., Jifar, H., Nigussu, H., Mihireteab, H. S., Girma, C. & Molalign, A. (2017). Tef (Eragrostis tef) Variety Kora. *Ethiop. J. Agric. Sci.* , 27 (2): 137-140.
Ketema, S. (1993). *Tef {Eragrostis tef): breeding, genetic resources, agronomy, utilizaton and role in Ethiopian agriculture*. Addis Ababa, Ethiopia: Institute of Agricultural Research.
Ketema, S. (1997). *Tef (Eragrostis tef (Zucc.) Trotter): Promoting the conservation and use of underutilized and neglected crops*, vol. 12: Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute.
Khan, I. A., Hassan, G., Khan, S. A. & Shah, S. (2012). Wheat-wild oats interactions at varying densities and proportions. *Pak J Bot*, 44: 1053-1057.
Korres, N. E. & Froud-Williams, R. J. (2002). Effects of winter wheat cultivars and seed rate on the biological characteristics of naturally occurring weed flora. *Weed Research*, 42 (6): 417-428.
Kristensen, L., Olsen, J. & Weiner, J. (2008). Crop Density, Sowing Pattern, and Nitrogen Fertilization Effects on Weed Suppression and Yield in Spring Wheat. *Weed Science*, 56 (1): 97-102.
Kruidhof, H. M., Bastiaans, L. & Kropff, M. J. (2008). Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. *Weed Research*, 48 (6): 492-502.
Leye, M. T. (2007). *Conservation Tillage Systems and Water Productivity-Implications for Smallholder Farmers in Semi-Arid Ethiopia: PhD, UNESCO-IHE Institute for Water Education, Delft, The Netherlands*: CRC Press.
Lu, Y.-C., Watkins, K. B., Teasdale, J. R. & Abdul-Baki, A. A. (2000). Cover crops in sustainable food production. *Food Reviews International*, 16 (2): 121-157.
Makombe, G., Kelemework, D. & Aredo, D. (2007). A comparative analysis of rainfed and irrigated agricultural production in Ethiopia. *Irrigation and Drainage Systems*, 21 (1): 35-44.
Miguel, A. A., Clara, I. N., Mark, G., Ben, W., Steve, W., Gualbert, G. & Barbara, G.-H. (2015). *Crops, weeds and pollinators: Understanding ecological interaction for better management*. Rome, Italy: Food and Agriculture Organization (FAO) of the United Nations.
Misgana, M. (2018). Progress, Achievements and Challenges of Tef Breeding in Ethiopia. *Journal of Agricultural Science and Food Research*, 9 (1): 204-2012.

Müller-Schärer, H. & Collins, A. R. (2012). Integrated weed management. *Encyclopedia of environmental management. Taylor and Francis, New York*: 1-7.

Mupangwa, W., Mutenje, M., Thierfelder, C. & Nyagumbo, I. (2017). Are conservation agriculture (CA) systems productive and profitable options for smallholder farmers in different agro-ecoregions of Zimbabwe? *Renewable Agriculture and Food Systems*, 32 (1): 87-103.

Mwendera, E. (2013, June 25-26, 2013). *Climate Change Impacts on Water, Agriculture and Food Security*. CN+ Expert Workshop on Climate Change, Food Security & Water Resources, AU commission, Addis Ababa, Ethiopia. Addis Ababa, Ethiopia: AU commision.

Naidu, V. S. G. R. (2012). *Hand Book on Weed Identification*. Jabalpur, India: Directorate of Weed Science Research.

Nalewaja, J. D. (2003). Weeds and Conservation Agriculture. In García-Torres, L., Benites, J., Martínez-Vilela, A. & Holgado-Cabrera, A. (eds) *Conservation Agriculture: Environment, Farmers Experiences, Innovations, Socio-economy, Policy*, pp. 201-210. Dordrecht: Springer Netherlands.

Nandula, V., N. Reddy, K., Duke, S. & H. Poston, D. (2005). *Glyphosate-Resistant Weeds: Current Status and Future Outlook*, vol. 16. 183-187 pp.

Nandula, V. K., Reddy, K. N., Duke, S. O. & Poston, D. H. (2005). Glyphosate-resistant weeds: Current status and future outlook. *Outlooks on Pest Management*, 16 (4): 183.

Neli, R.-A., María, J. A. & Verónica, B. R. (2017). Effect of glyphosate application on soil quality and health under natural and zero tillage field conditions. *Soil Environ.*, 36 (2): 141-154.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014). Africa. In Barros, V. R., Field, C. B., Dokken, D. J., Mastrandrea, M. D., Mach, K. J., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., et al. (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on limate Change*, pp. 1199-1265. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Nichols, V., Verhulst, N., Cox, R. & Govaerts, B. (2015). Weed dynamics and conservation agriculture principles: A review. *Field Crops Research*, 183: 56-68.

NMA. (2017a). Agromet Bega Assessment and Belg 2017 Outlook. *Agromet: National Meteorological Agency of Ethiopia*.

NMA. (2017b). *Annual Weather Report* Addis Ababa, Ethiopia: National Meteorological Agency

Nyssen, J., Poesen, J., Haile, M., Moeyersons, J. & Deckers, J. (2000). Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. *Soil and Tillage Research*, 57 (3): 115-127.

Nyssen, J., Govaerts, B., Araya, T., Cornelis, W. M., Bauer, H., Haile, M., Sayre, K. & Deckers, J. (2011). The use of the marasha ard plough for conservation agriculture in Northern Ethiopia. *Agronomy for Sustainable Development*, 31 (2): 287-297.

Oerke, E.C. (2006). Crop Losses to Pests. Journal of Agricultural Science, 144, 31-43.

Oicha, T., Cornelis, W. M., Verplancke, H., Nyssen, J., Govaerts, B., Behailu, M., Haile, M. & Deckers, J. (2010). 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.

Peerzada, A. M., Ali, H. H. & Chauhan, B. S. (2017). Weed management in sorghum [Sorghum bicolor (L.) Moench] using crop competition: A review. *Crop Protection*, 95: 74-80.

Peters, K., Breitsameter, L. & Gerowitt, B. (2014). Impact of climate change on weeds in agriculture: a review. *Agronomy for Sustainable Development*, 34 (4): 707-721.

Powles, S. B. (2008a). Evolution in action: glyphosate-resistant weeds threaten world crops. *Outlooks on Pest Management*, 19 (6): 256-259.

Powles, S. B. (2008b). Evolved glyphosate-resistant weeds around the world: lessons to be learnt. *Pest Management Science*, 64 (4): 360-365.

Preston, S. (2003). Principles of sustainable weed management for croplands. *NCAT*: 15.
Ramesh, K., Matloob, A., Aslam, F., Florentine, S. K. & Chauhan, B. S. (2017). Weeds in a Changing Climate: Vulnerabilities, Consequences, and Implications for Future Weed Management. *Frontiers in Plant Science*, 8: 95.
Rana, S. & Rana, M. C. (2016). *Principles and Practices of Weed Management*. India: Department of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur.
Regina, S. B. & Jodie, S. H. (2009). Weeds of agricultural importance: bridging the gap between evolutionary ecology and crop and weed science. *New phytologist*, 184: 741-743.
Rezene, F. & Zerihun, T. (2001). Weed Research in Tef. In Hailu, T., Getachew, B. & Mark, E. S. (eds) *Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on tef Genetics and Improvement*, pp. 201-213. DebreZeit, Ethiopia: DebreZeit Agricultural Research Center.
Robert, L. Z. (2007). *Fundamentals of Weed Science*. London, British: Elsevier Inc., Academic Press (AP).
Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A. W., 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.
Sakatu, H. & Adane, B. (2017). Evaluation of Fertilizer and Seed Rate Effect on Yield and Yield Component of Tef [Eragrostis tef (Zucc.) Trotter] on Vertisols in Central high-lands of Ethiopia. *Journal of Natural Sciences Research*, 7 (11): 25-31.
Salem, H. M., Valero, C., Muñoz, M. Á., Rodríguez, M. G. & Silva, L. L. (2015). Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. *Geoderma*, 237-238 (Supplement C): 60-70.
Salonen, J., Hyvönen, T. & Jalli, H. (2011). Composition of weed flora in spring cereals in Finland - a fourth survey. *Agricultural and Food Science*, 20 (3): 245-261.
Santín-Montanyá, M., Catalán, G., Tenorio, J. L. & M. García-Baudín, J. (2018). *Effect of the tillage systems on weed flora composition*, vol. 69.
Santín Montanyá, I. & Catalán, G. (2006). Effect of the tillage systems on weed flora composition. In Cantero-Martínez, C. & Arrue Ugarte, J. L. (eds) Options Méditerranéennes : Série A. Séminaires Méditerranéens, vol. 69 *Troisièmes rencontres méditerranéennes du semis direct*, pp. 143-147: Zaragoza : CIHEAM.
Schmidt, H.H., Bergkvist, G. , Campiglia, E., Radicetti, E., Wittwer, R.A., Finckh, M.R. & Hallmann, J. (2017). Effect of tillage, subsidiary crops and fertilisation on plant-parasitic nematodes in a range of agro-environmental conditions within Europe. *Ann Appl Biol*, 171: 477–489
Seneshaw, T., Minten, B., Alemu, D. & Bachewe, F. (2017). The Rapid Expansion of Herbicide Use in Smallholder Agriculture in Ethiopia: Patterns, Drivers, and Implications. *The European Journal of Development Research*, 29 (3): 628-647.
Shahid, N., Chair, F. S., Chapin, I., Robert, C., Paul, R. E., Frank, B. G., David, U. H., Lawton, J. H., Robert, V. O. N., Harold, A. M., et al. (1999). *Biodiversity and Ecosystem Functioning: Maintaining Natural Life Support Processes*. Issues in Ecology. Wahington DC,USA: Ecology Society of America. 14 pp.
Shekhawat, K., Rathore, S. S., Dass, A., Das, T. K., Mahajan, G. & Chauhan, B. S. (2017). Weed menace and management strategies for enhancing oilseed brassicas production in the Indian sub-continent: A review. *Crop Protection*, 96: 245-257.
Shrestha, A., Knezevic, S. Z., Roy, R. C., Ball-Coelho, B. R. & Swanton, C. J. (2002). Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. *Weed Research*, 42 (1): 76-87.

Sime, G., Aune, J. B. & Mohammed, H. (2015). Agronomic and economic response of tillage and water conservation management in maize, central rift valley in Ethiopia. *Soil and Tillage Research*, 148: 20-30.

Singh, M., Bhullar, M. S. & Chauhan, B. S. (2017). Relative time of weed and crop emergence is crucial for managing weed seed production: A study under an aerobic rice system. *Crop Protection*, 99: 33-38.

Singh, P. K. (2013). *Introduction to Weed Science and Challenges*. Jabalpur (M.P.): Directorate of Weed Science Research (ICAR).

Singh, V. P., Barman, K. K., Singh, R. & Sharma, A. R. (2015). Weed Management in Conservation Agriculture Systems. In Farooq, M. & Siddique, K. H. M. (eds) *Conservation Agriculture*, pp. 39-77. Cham: Springer International Publishing.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J., Jafari, M., et al. (2014). *Agriculture, Forestry and Other Land Use (AFOLU)*. IPCC (ed.). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press. p. 112.

Stenchly, K., Lippmann, S., Waongo, A., Nyarko, G. & Buerkert, A. (2017). Weed species structural and functional composition of okra fields and field periphery under different management intensities along the rural-urban gradient of two West African cities. *Agriculture, Ecosystems & Environment*, 237: 213-223.

Stevenson, J. R., Serraj, R. & Cassman, K. G. (2014). Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia. *Agriculture, Ecosystems & Environment*, 187: 1-10.

Swanton, C. J. & Weise, S. F. (1991). Integrated Weed Management: The Rationale and Approach. *Weed Technology*, 5 (3): 657-663.

Swanton, C. J., David, R. C. & Douglas, A. D. (1993). Weed Succession under Conservation Tillage: A Hierarchical Framework for Research and Management. *Weed Technology*, 7 (2): 286-297.

Tarekegne, A., Gebre, A., Tanner, D. G. & Mandefro, C. (1996). Effect of Tillage Systems and Fertilizer Levels on Continous Wheat Production in Central Ethiopia. In Tanner, D. G., Payne, T. S. & Abdalla, O. S. (eds) *Proceeding of the The Ninth Regional Wheat Workshop for Eastern, Central and Southern Africa*, pp. 56-63. Addis Ababa, Ethiopia: CIMMYT.

Taye, T. & Yohanes, L. (1998). Qualitative and quantitative determination of weeds in tef in West Shewa Zone. *Arem (Ethiopia)*.

Teamti, T. & Tesfay, A. (2016). Farmers' Perception on Glyphosate Application in Conservation Agriculture System of Northern Ethiopia. *International Journal of African and Asian Studies*, 17: 31-35.

Teasdale, J., Brandsaeter, L., Calegari, A., Neto, F. S., Upadhyaya, M. & Blackshaw, R. (2007). Cover crops and weed management. In Upadhyaya, M. & Blackshaw, R. (eds) *Non-chemical weed management: Principles, concepts and technology*, pp. 49-64: CAB International.

Tefera, H., Belay, G. & Sorrells, M. E. (2001). *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.

Tefera, H., Assefa, K. & Belay, G. (2003). Evaluation of interspecific recombinant inbred lines of Eragrostis tef x E. pilosa [Ethiopia]. *Journal of Genetics and Breeding* 57: 21-30.

Teklay, T. & Girmay, G. (2016). Agronomic and economic evaluations of compound fertilizer applications under different planting methods and seed rates of tef [eragrostis tef (zucc.) trotter] in northern ethiopia. *Journal of the Drylands*, 6 (1): 409-422.

Temesgen, M., Hoogmoed, W. B., Rockstrom, J. & Savenije, H. H. G. (2009). Conservation tillage implements and systems for smallholder farmers in semi-arid Ethiopia. *Soil and Tillage Research*, 104 (1): 185-191.

Temesgen, T. D. & Rashid, M. H. (2009). Economic Impact of Climate Change on Crop Production in Ethiopia: Evidence from Cross-section Measures. *Journal of African Economies*, 18 (4): 529-554.

Tesfa, B., Solomon, J., Yifru, A., Minale, L. & Waga, M. (2013). Crop Management Research for Tef. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement: Proceedings of the Second International Workshop, November 7-9, 2011, Debre Zeit, Ethiopia*, p. 379. Stämpfli AG, 3001 Bern, Switzerland: Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; Institute of Plant Sciences, University of Bern, Switzerland.

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 (Supplement C): 241-249.

Theodor, F., Rolf, D. & Amir, K. (2012). Overview of the Global Spread of Conservation Agriculture. *Field Actions Science Reports [Online]*, Special Issue (6): 1-8.

Thomas, J. M., Stephen, C. W. & Floyd, M. A. (2002). *Weed Science: Principles and Practices*. Fourth edition ed. New York, USA: John Wiley & Sons, Inc.

Tigist, O., Cornelis, W. M., Verplancke, H., Nyssen, J., Govaerts, B., Behailu, M., Haile, M. & Deckers, J. (2010). 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.

Timothy, J. K., Kamrun, N., Shafiq, I., Arshadul, M. H., Apurba, R., Virender, K., Israil, H., Khaled, H., Sumona, S., Mahesh, K. G., et al. (2016). *Integrated weed management: Experiential learning modules for sustainable intensification and agricultural service provision*. Book 2. Mexico, D.F.: CIMMYT.

Townley-Smith, L. & Wright, A. T. (1994). Field pea cultivar and weed response to crop seed rate in western Canada. *Canadian Journal of Plant Science*, 74 (2): 387-393.

Trichard, A., Alignier, A., Chauvel, B. & Petit, S. (2013). Identification of weed community traits response to conservation agriculture. *Agriculture, Ecosystems & Environment*, 179: 179-186.

Tubiello, Francesco, N., Soussana, Jean-François, Howden & Mark, S. (2007). Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences*, 104 (50): 19686-19690.

USAID. (2012). *Climate change adaptation in Ethiopia*. Washington DC, USA: USAID.

USAID. (2016). Climate change risk profile, Ethiopia. *Country Fact Sheet*: 5.

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A. J., Gérard, B., Rufino, M. C., Teufel, N., van Rooyen, A., et al. (2012). Conservation Agriculture in mixed crop–livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research*, 132: 175-184.

Valerio, M., Tomecek, M., Lovelli, S. & Ziska, L. (2013). Assessing the impact of increasing carbon dioxide and temperature on crop-weed interactions for tomato and a C3 and C4 weed species. *European Journal of Agronomy*, 50: 60-65.

van der Meulen, A. & Chauhan, B. S. (2017). A review of weed management in wheat using crop competition. *Crop Protection*, 95: 38-44.

Vavilov, N. I. (1951). The Origin, Variation, Immunity and Breeding of Cultivated Plants. *Soil Science*, 72 (6): 482.

Wu, H., Pratley, J., Lemerle, D. & Haig, T. (2000). Evaluation of seedling allelopathy in 453 wheat (Triticum aestivum) accessions against annual ryegrass (Lolium rigidum) by the equal-compartment-agar method. *Australian Journal of Agricultural Research*, 51: 937-944.

Zenebe, G., Jesper, S., Alemu, M. & Atlaw, A. (2011). *Climate Change and the Ethiopian Economy: A Computable General Equilibrium Analysis*. Discussion Paper Series. University of Gothenburg in Sweden and Resources for the future in Washington DC, USA: Environment for Development.

Zenebe, G., Alemu, M., Rahel, D., Samuel, A. & Meseret, M. K. (2014). *Climate change can have significant negative impacts on Ethiopia's agriculture*. Discussion paper series. Ethiopia: Environment for Development, Research brief. 1-3 pp.

Zerga, B. & Mengesha, G. (2016). *Climate Change in Ethiopia Variability, Impact, Mitigation, and Adaptation*, vol. 2. 19 pp.

PAPERS

PAPER I:

G. Haftamu, J.B. Aune, J. Netland, O.M. Eklo, and L.O. Brandsæter. Species composition, ecological distribution and importance of weeds in teff fields of Tigray, Ethiopia. Manuscript.

Species composition, ecological distribution and importance of weeds in teff fields of Tigray, Ethiopia

G. Haftamu[ab], J. B. Aune[c], J. Netland[d], O. M. Eklo [bd] and L. O. Brandsæter[bd]

[a] *Mekelle University, College of Dryland Agriculture and Natural Resources*
[b] *Norwegian University of Life Sciences, Department of Plant Sciences (IPV-NMBU)*
[c] *Norwegian University of Life Sciences, Department of International Environment and Development Studies (Noragric-NMBU)*
[d] *Norwegian Institute of Bio-economy Research (NIBIO)*

Abstract

Teff (Eragrostis tef (Zucc.) Trotter) is highly vulnerable to weed competition. A number of weed species affect the crop and cause yield loss. In spite of this, there are no studies on their composition, ecological distribution and economic importance. This has halted the development of integrated and economically feasible management systems under both conventional and conservation agriculture in major growing areas of teff. A survey was conducted during 2015 and 2016 to determine the species composition, abundance and their agroecological distribution. Weed species composition was studied in 128 randomly sampled teff fields of the 26 major teff growing weredas *(districts) of Tigray in both years. The fields were situated at three altitudes: lowland (<1500 m a.s.l.), midlands (1500–2500 m a.s.l.) and highlands (>2500 m a.s.l.). Samples were collected at an average interval of 3–5 km in an inverted W zigzag fashion. Spatial extension of weed density levels were mapped and interpolated for the most frequent weed species in order to figure out their importance in all the major teff growing areas of Tigray using ARCGIS. In all, 42 weed species were identified. Altitude played a decisive role on number of weed species. The highest average number was from highlands (16.96 species/sample) followed by midland (13.36 species/sample) and lowland (8.19 species/sample). All the weed species represented 16 families, where the most diverse families were Poaceae (15 species) and Asteraceae (7 species). Among the most frequent weed species were Erucastrum abyssinicum, Cyperus esculentus, Cynadon dactylon and Avena abyssinica. The most dominant weed species were Argomene mexicana, Plantago lanceolate, Cyperus esculentus, Erucastrum abyssinicum, Avena abyssinica and Galinsoga parviflora. The weed species with wide spatial extension of dense population in most of the major teff growing areas were Erucatrum abyssinicum, Plantago lanceolata and cyperus esculentus.*

Key words: *Teff, Weed, Species composition, Importance of weed species, Ecological distribution*

Introduction

In natural ecosystems, the different plant species are intermingled and compete with each other for resources (Pyšek et al. 2005). In agriculture, farmers put a great deal of effort into reducing or eliminating yield losses due to weed competition, but control inefficiency is common, which in turn results in crop loss from weed competition (Oerke 2006). The growth of weeds in the crop field degrades soil resources such as nutrients and water. Weeds affect crop production mainly through reduction in the availability of nutrients, water and light for crop plants. When uprooted and removed from the crop field, they drain a huge amount of nutrients from the soil and hence can aggravate soil nutrient contents (Dumanski et al. 2006; Reicosky 2015).

Weed species composition has both temporal and spatial variability caused by biotic factors such as competition, and abiotic factors of the ecosystem (Theodore & Harold 1997; Shahid et al. 1999; Renton & Chauhan 2017). Among the abiotic factors, climate which is strongly linked to the altitudinal position of the crop field, has a paramount impact on the composition of weed species (Peerzada et al. 2017; Shekhawat et al. 2017; Singh et al. 2017; Stenchly et al. 2017; van der Meulen & Chauhan 2017). The seasonal change in temperature and precipitation has a huge impact on the variability of the state and structure of the plant community in the ecosystem in general and on weed communities in the agroecosystem in particular (Shahid et al. 1999). With increasing temperature, the rate of photosynthesis increases and hence weed infestation increases sharply. Especially during moist and humid seasons, a limited number of dominant weed species will take advantage (Amedie 2013; Houngbédji et al. 2016; Hyvönen et al. 2003; Smith et al. 2014; Valerio et al. 2013). Additionally, higher CO_2 concentration from the greenhouse gas emission around agricultural microclimate promotes robust weed growth, productivity and enhance diversity of these species (Tubiello et al. 2007). Such weeds diminish crop overall performance and escalate cost of production. The next paramount factor is the biotic (crop–weed) component of the agroecosystem. This component describes the interaction between crop and weeds in the field. This is highly influenced by the weed management practices implemented to enhance crop yield. Scandinavian agriculture demonstrates the close relationship between crops and weeds with different life cycles, clearly showing that the relationships of weeds with crops largely depends on times and types of tillage (Håkansson 2003). The frequency of mechanical weeding also influences the crop–weed interaction. Reduced tillage promotes weed infestation and causes crop yield loss (Amir Kassam et al. 2009; Giller et al. 2009; Hobbs et al. 2008). Access to effective control measures, both chemical and non-chemical, also significantly affects the crop–weed component. Generally, the agroecosystem components influence the weed flora, which can result in changes of the weed species and their economic importance.

Different weed species affect teff and result in its yield loss. Young, newly emerged cereal plants in particular, are known to be sensitive to weed competition (Håkansson 2003). Teff plants, at low density, create good conditions for growth of weeds, and becoming vulnerable to their competitive advantage (Ketema 1997). The teff crop needs well aerated, fertile, and proper seedbed preparation for favourable sowing and crop development conditions (Haftamu et al. 2009). Weeds in teff are traditionally controlled by frequent soil tillage before sowing, and hand weeding during the growing season, and the intensity of both tillage and hand weeding is related to weed species, density and developmental stage (Haftamu et al. 2009). Although they have an impact on weeds, these agronomic practices are not the sole components of an effective weed management system. Systematic integration of proper preventive and direct control measures reduces weed incidence and enhances crop productivity (Crop Life International 2012; Local Land Services 2016).

Integrated Pest Management (IPM) can be defined as the sustained use of all available pest control techniques for keeping the use of pesticides and other interventions to levels that are economically justified, and minimising the risks to human health and the environment. This is the direction of worldwide main pest management, including weed control. According to the Directive 2009/128/EC, since 2014, European Union (EU) farmers have been required to follow the principles of IPM as a way to reduce risks of herbicides, fungicides and other pesticides. The principles (1–8) include a cascade of decisions that need to be undertaken to ensure effective weed control, as follows: 1) Before any curative control takes place, possible preventive methods of cultural control need to be considered; 2) Know the weed pressure through monitoring; 3) Monitor weed pressure for a decision about the necessity of control; 4) Decide when proper non-chemical measures should be preferred, also in conventional farming; 5) Restrict application of herbicide ingredients, with least side-effects, to those species requiring control; 6) Make case-specific reductions of herbicides dose and application frequency in combination with the use of site-specific weed management; 7) Establish anti-resistance strategies to maintain effect of the products. 8) Check the effect of applied weed control measures (EU Directive 2009). These principles are highly relevant worldwide when modified to local circumstances.

The present study concerning the knowledge of weed species present and their density in the crop field, is relevant to most of the principles above, especially principles 2 and 3 concerning weed pressure and decision support on the need for control. Generally, weed surveys aim at record the actual and present weed species and their density, as well as the shifts in the weed flora composition over time, in response to interacting factors related to the environment, field properties and cropping (Salonen et al. 2013). Several weed flora exist in Ethiopia and teff, as the most economically important crop in the country, is facing huge yield losses both temporally and spatially, due to weeds (Ketema 1997). In Ethiopia, teff is grown from the extreme lowlands to the extreme highlands i.e. 0–5 m a.s.l. to as high as 3200 m a.s.l., the major growers being limited to an altitudinal range from around 1500 m a.s.l. to as high as 2300 m a.s.l. (IFPRI 2006). The weed flora is closely related to the altitude and agroecological setting of the crop field (Lososová et al. 2004). Weed surveys have been conducted on cotton in other parts of Ethiopia (Esayas et al. 2013) but no surveys of weeds in teff have been carried out in Ethiopia; the need for knowledge about weed composition and level is crucial. For effective, economical and environmentally friendly integrated weed management, there is a need to know about the weed species present and their density in the teff field and their variability with altitude. Our study is the first weed survey in teff and can be referred to as a baseline study for later surveys to decide on shifts in flora.

Therefore, the objectives of this study are to:

1) Identify and describe the weed species and their composition in teff fields
2) Elucidate the altitudinal variability and ecological distribution of the weed species
3) Map spatial extension of weed density levels in major teff growing areas of Tigray

Materials and methods

Description of the study areas

Tigray, where the survey was carried out, is one of the nine regional states of Ethiopia. It is located at $14^0 08'12''$N $38^0 18'34''$E bordered by Eritrea in the north, Amhara in the south, Sudan in the west and Afar region in the East. It has seven zones constituting 12 urban and 35 rural *weredas* (districts) (Table 1). The zones include Southern Zone, Southeastern Zone, Mekele special Zone, Eastern Zone, Central Zone, Northwestern Zone and Western Zone. Except in the Western Zone, teff is growing in all zones of Tigray and is the most important crop in terms of its economic and nutritional values (Baye 2014; CSA 2016; Ketema 1997). Of the 35 rural weredas, 26 are important teff growing areas and are the major teff growing weredas of the region.

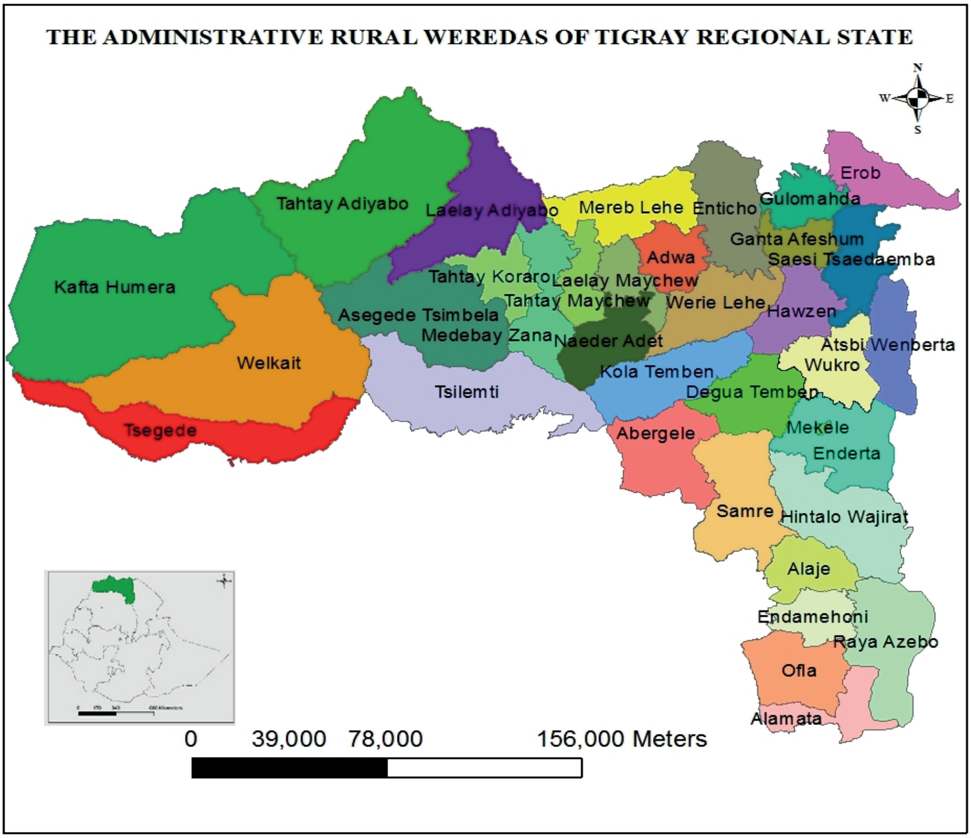

Fig. 1. The 35 rural administrative weredas of Tigray, Northern Ethiopia

Table 1. Tigray administrative zones and major teff growing weredas

Southern Zone	South-eastern Zone	Eastern Zone	Central Zone	Northwestern Zone	Western Zone	Mekelle Zone
Alaje Raya azebo Ofla Endamekhoni Raya alamata	Saharti samre Degua tembien Enderta Hentalo wajirat	Ganta afeshum Saesi'e tsaedaemba Wukro kilteawla'elo Hawzen Atsbi wenberta Erob Gulomekeda	Mereb lekhe Naeder adiet Tahtay maichew Laelay maichew Geter adwa Ahferom (enticho) Wer'e lekhe Kola tembien Tanqua abergele	Tahtay koraro Medebay zana Laelay adyabo Asgede tsibla	Kafta humera Tahtay adyabo Tsegede Welkait Tselemti	Mekelle

Weed sampling

Teff needs a very smooth seedbed. Before sowing at the end of June to the beginning of July, on average, tillage is carried out 4–5 times. Especially in fields with vertic soil types and during onset of seasonal rainfall, frequent tillage is important. This type of soil is very heavy and difficult to till during off season using the traditional plough (*Mahresha*). For this reason, farmers plough their land continuously to form fine seedbeds for teff. Teff farmers apply DAP (Di-ammonium Phosphate) at sowing and Urea at both emergence and before tillering or after first hand-weeding. The first hand-weeding is carried out 30–45 days after sowing but before tillering.

Most of the teff fields selected were "hot spot" areas, well known for their season-to-season teff production. Sampling of weeds was done in those fields with the consent of teff farmers and selected based on their frequency of teff production. Most of these fields grow teff for at least four years, and at most, eight years according to the farmers' information. Weed sampling was done before the first hand-weeding and herbicide application.

During the two survey seasons (2015 and 2016), a total of N=128 teff fields were randomly sampled. Half of these were sampled in 2015, during the period 5–31 August, and the remaining in 2016, during the period 15 August to 10 September. The small shift in days of the sampling periods in 2016 is owing to the late onset of seasonal rainfall and late sowing of teff in most growing areas surveyed. The samples were stratified in lowlands (less than 1500 m a.s.l.) (N=21), midlands (1500–2500 m a.s.l.) (N=84) and highlands (above 2500 m a.s.l.) (N=23). The highest number of fields sampled in the midlands is the result of the highest area coverage of teff in this altitudinal range.

Two types of weed assessments were carried out: (1) A big quadrate (1 m^2) was used to record the presence, plus or minus, of each weed species, and (2) A rectangular frame measuring 0.1 m^2 (25 cm x 40 cm) put in one of the sides of the bigger quadrate (1 m^2) was used to count and collect the different weed species. A single rectangular frame (0.1 m^2) was taken from each sample from the centre of a farmer's teff fields. The weed sampling assessments used in our study was identical to the method used in Salonen et al. (2011), however, modified by the method used in Esayas et al. (2012). Quadrates were separated at an interval of 3–5 km (Esayas et al. 2012). However, because of the rugged topography, some sampling fields were up to 8 km away from each other. After counting, certain weed species which we were not able to identify in the field were pressed, mounted and sent to Addis Ababa University's National Herbarium for identification. Altitudinal distribution of these weed-sampling fields has been analysed using Digital Elevation Model (DEM) of Ethiopia.

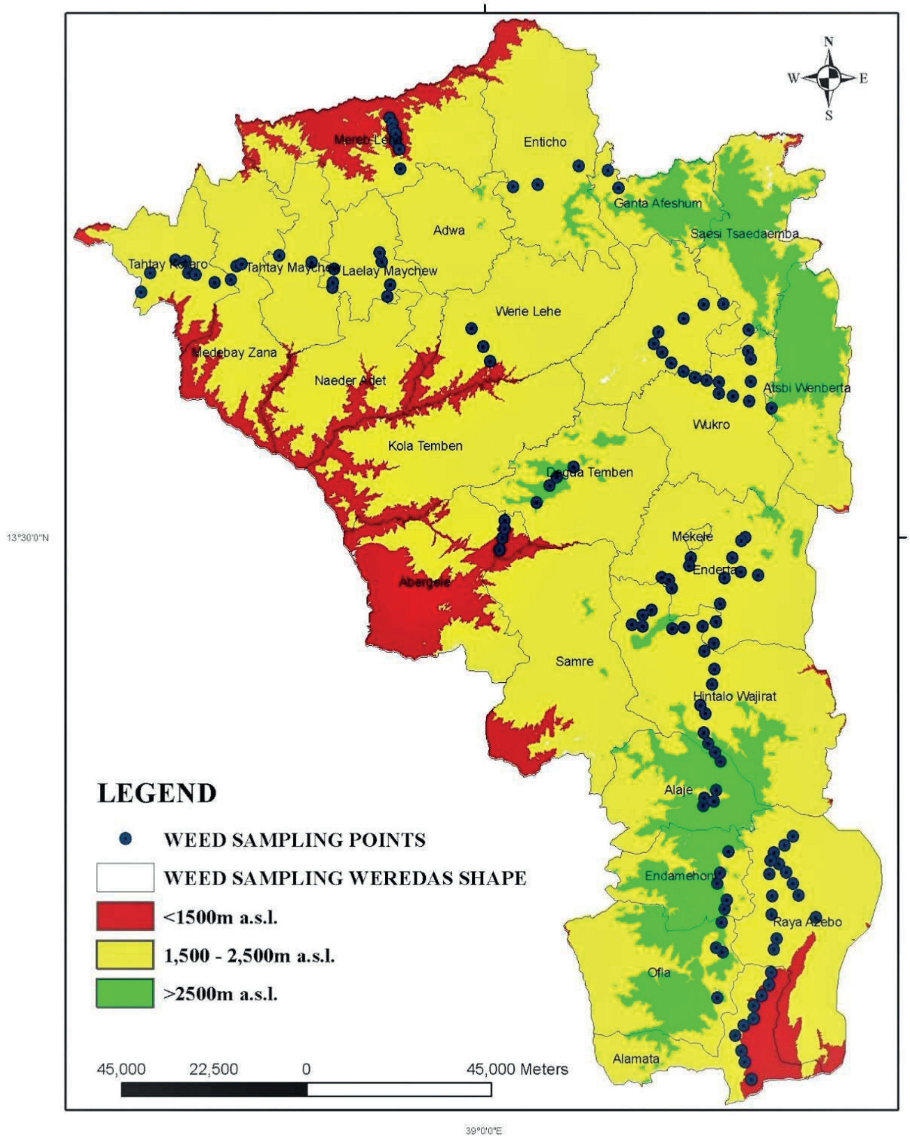

Fig. 2. Altitudinal distribution of the sampling fields in all 26 teff growing areas of Tigray

In Tigray in general, and in the sampling fields in particular, the highest rainfall is recorded in July and August. The warmest months are April, May and June (Table 2).

Table 2. Average annual rainfall, minimum and maximum temperature

Location	Year	Av. Annual Rainfall (mm)	Av. Annual Min – T^0	Av. Annual Max – T^0
Axum	2015	725	11	27
	2016	675	11	27
Mekelle	2015	580	11	28
	2016	560	11	28
Tigray	2015	800	13	27
	2016	880	13	27

Source: (NMA 2017)

Data analysis

Weed species composition and importance analysis

Weed species composition was analysed by frequency (F), abundance (A), dominance (D), and similarity index (SI) (Assefa et al. 2016; Esayas et al. 2013; Jaccard 1912; Taye & Yohanes 1998)

Frequency or prevalence: Percentage of sampling plots on which a particular weed species is found. It describes how often a particular weed species occurs in the survey area. Frequency is calculated for all weed species as follows:

Frequency: F = X/N x 100

Where, F = frequency,

X = number of occurrences of a weed species,

N = sample number.

Abundance: Population density of a weed species expressed as the number of individuals of weed plants per unit area.

Abundance: A = ΣW/N

Where, A = abundance,

W = number of individuals of a weed species,

N = sample number.

Dominance: Abundance of an individual weed species in relation to the total weed abundance i.e. infestation level.

Dominance: D = A/ΣAx100

Where, D = dominance,

ΣA = total abundance of all species.

Similarity index (community index): Describes similarity of weed communities in different locations.

SI = (Epg)/(Epg + Epa +Epb)x100

Where, SI= similarity index;

Epg = number of weed species found in all locations;

Epa = number of species only in location a

Epb = number of species only in location b.

Interpolating spatial extension of density levels of weed species in teff fields

Interpolation considers the XY coordinates to bind an area inside which spatial extension of the density levels of the weed species was estimated. Therefore, the area of the colour on the maps (Figs. 4–6) refers to the spatial extension of a specific density range, with deep green being low density and deep red colour being high density. ArcGIS using spatial analyst tool automatically calculated spatial extension within the boundary of the sampling points crossing the major teff growing areas. This tool interpolates the spatial extension through natural neighbour, which connects the coordinates with the same magnitude of density levels. The interpolation of spatial extension of density levels was done for the 12 most frequent weed species, except the weed species *Eragrostis cilianensis*, as it is the wild relative of teff (Ann & Chris 1989).

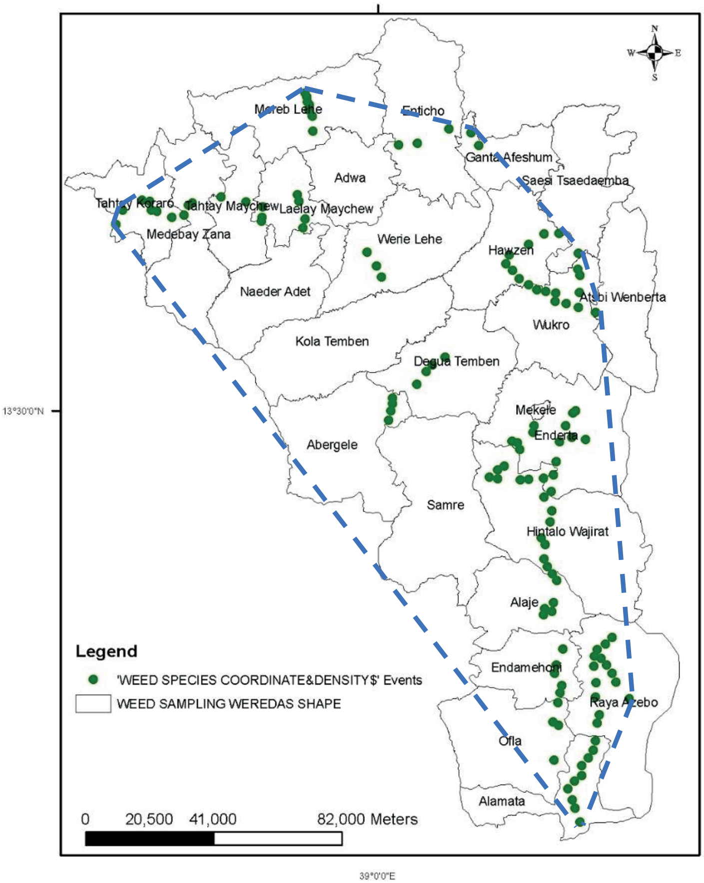

Fig. 3. Delineated areas of interpolation based on XY coordinates of the surveyed fields of the major teff growing areas of Tigray, Ethiopia

Results

Species composition

From all 128 fields sampled, 42 weed species (Table 3) were collected. These 42 weed species belong to 16 families. The families with highest number of species were *Poaceae* (15 species), *Asteraceae* (7 species), *Fabaceae* (3 species). *Commelinaceae*, *Cyperaceae*, *Amaranthaceae* and *Polygonaceae* each with two species, and *Plantagonaceae*, *Apiaceae*, *Brassicaceae*, *Solonaceae*, *Lamiaceae*, *Papaveraceae*, *Rubiaceae*, *Nyctaginaceae* and *Convolvulaceae* each consisting of one species, were the other weed species families. Looking at the altitudinal distribution, there were weed species only found in the (i) lowlands, (ii) low to midlands and (iii) mid to highlands, and also (iv) weed species found in all altitudinal classes, i.e. low to highlands but no weed species specific to highlands (Table 3).

The average weed species richness (no. of species/sample) from each sample unit was 8.19 from the lowlands, 13.36 from the midlands and 16.96 from the highlands. Of the 42 weed species, 15 were monocots and 27 were dicots (Table 3). When classified by life cycle, these identified teff weeds include 31 annual and 11 perennial species (Table 3).

Weed species frequency, dominance and similarity index

The most frequent weed species were *Erucastrum abyssinicum* (68.8%), *Cyperus esculentus* (68%), *Cynadon dactylon* (64.8%) and *Avena abyssinica (64.1%)* (Table 3). The next most common weed species in all the major teff growing areas of Tigray included *Argomone Mexicana* (57.8%), *Brachiara eruciformis* (54.7%), *Setaria pumila* (53.1%), *Plantago lanceolate* (50%), *Cyperus rotundus* (49.2%), *Medicago polymorpha.* (49.2%), and *Datura stramonium* (41.4%) (Table 3). Of these, *Cyperus rotundus* is also common in upland rice of western Ethiopia (Assefa et al. 2016). The spatial extension of the density levels of these most common weeds species in teff fields were interpolated using ARCGIS based on their geographical coordinates (Figs. 4–6).

The dominance of the teff weeds was also calculated based on their abundance. The most dominant teff weed species were *Argomene Mexican* (9.5%), *Plantago lanceolate* (8.7%), *Cyperus esculentus* (7.8%), *Erucastrum abyssinicum* (6.9%), *Avena abyssinica* (6.9%) and *Galinsoga parviflora* (6.0%) (Table 3). Dominance indicates the infestation level of the weed species in all major teff growing areas of Tigray. These weed species are responsible for 45.8% of the total infestation level of all the identified teff weed species. These six weed species can be considered as the most important in terms of their infestation level, though some of them have site-specific effects as they were less frequent in the major teff growing areas surveyed.

Similarity index was computed for both year of collection and altitudinal ranges of the teff fields under study. The similarity index between 2015 and 2016 was 93.3% and there was very high similarity in teff weed species between these production seasons. The similarity index between lowland and midland was 58.3%, lowland and highland 0% (no common weed species between them), and midland and highland 87.5%. There was a higher similarity in teff weed species between midland and highland than that between lowland and midland. From the 42 weed species, 22 were common in all altitudinal ranges (Table 3).

Table 3. Importance and altitudinal classes of the identified weed species collected from teff major growing areas of Tigray, Ethiopia in 2015 and 2016 production seasons

R.No	Life Cycle	Weed Types Mono-cots	Di-cots	Weed Family	Weed Species	Total Density	Freq. (%)	Freq. Rank	Domi-nance	Abundance	Alt. Class
1	Annual		*x*	*Brassicaceae*	*Erucastrum abyssinicum (A. Rich.)*	381	68.8	1	7.0	3.0	L-H
2	Perennial[1]	*x*		*Poaceae*	*Cyperus esculentus*	429	68.0	2	7.8	3.4	L-H
3	Perennial[2]	*x*		*Poaceae*	*Cynodon dactylon (L.) Pers.*	214	64.8	3	3.9	1.7	L-H
4	Annual	*x*		*Poaceae*	*Avena abyssinica Hochst.*	376	64.1	4	6.9	2.9	L-H
5	Annual		*x*	*Papaveraceae*	*Argemone mexicana L.*	520	57.8	5	9.5	4.2	L-H
6	Annual		*x*	*Lamiaceae*	*Leucas deflexa Hook.f*	187	54.7	6	3.4	1.5	L-H
7	Annual	*x*		*Poaceae*	*Brachiaria eruciformis (J.E.Sm.)Griseb*	140	54.7	6	2.6	1.1	L-H
8	Annual	*x*		*Poaceae*	*Setaria pumila (Poir.)Roem.&Schult*	179	53.1	7	3.3	1.4	L-H
9	Perennial[1]		*x*	*Plantaginaceae*	*Plantago lanceolata L.*	479	50.0	8	8.7	3.7	M-H
10	Perennial[1]	*x*		*Poaceae*	*Cyperus rotundus L.*	122	49.2	9	2.2	1.0	L-H
11	Annual		*x*	*Fabaceae*	*Medicago polymorpha.*	192	49.2	9	3.5	1.5	M-H
12	Annual		*x*	*Solanaceae*	*Datura stramonium L.*	64	41.4	10	1.2	0.5	L-H
13	Annual		*x*	*Asteraceae*	*Galinsoga parviflora Cav.*	330	39.8	11	6.0	2.6	M-H
14	Annual		*x*	*Asteraceae*	*Xanthium strumarium L.*	68	39.1	12	1.2	0.5	L-H
15	Perennial[2]		*x*	*Commelinaceae*	*Commelina reptans Brenan*	269	38.3	13	4.9	2.1	L-H
16	Perennial[1]	*x*		*Poaceae*	*Digitaria abyssinica (A.Rich)Stapf*	135	37.5	14	2.5	1.1	L-H
17	Annual		*x*	*Polygonaceae*	*Oxygonum sinuatum (Meisn.) Dammer*	92	35.9	15	1.7	0.7	L-H
18	Annual		*x*	*Asteraceae*	*Xanthium spinosum L.*	54	35.9	15	1.0	0.4	L-H
19	Annual	*x*		*Commelinaceae*	*Commelina diffusa Burm.f*	52	35.9	15	1.0	0.4	M-H
20	Annual		*x*	*Amaranthaceae*	*Amaranthus hybridus L.*	108	35.2	16	2.0	0.8	M-H
21	Annual		*x*	*Asteraceae*	*Lactuca sp.*	46	33.6	17	0.8	0.4	L
22	Annual	*x*		*Poaceae*	*Eragrostis cilianensis (AlL.) Vign. ex Janchen*	66	32.0	18	1.2	0.5	L-H
23	Annual		*x*	*Amaranthaceae*	*Amaranthus spinosus L.*	79	29.7	19	1.4	0.6	M-H

According to IFPRI (2006): Lowland (L): less than 1500 metres above sea level and characterised by warm temperature and represents lowland teff weeds
Mid – Highlands (M-H): >1500 metres above sea level and represents weeds adapted to moderately warm areas
Low – highland (L-H): altitude of weeds crossing all the altitudinal ranges and adapted to both warm and cold temperatures
Low – midlands (L-M): altitude of weed species adapted to warm to moderately warm areas of Tigray
N.B. [1]= refers to stationary perennial weeds and [2] = refers to creeping perennial weeds

Table 3 Continued ...

R.No.	Life Cycle	Weed Types Mono-cots	Weed Types Di-cots	Weed Family	Weed Species	Total Density	Freq. (%)	Freq. Rank	Domi-nance	Abundance	Alt. Class
24	Perennial[1]		x	*Polygonaceae*	*Rumex nepalensis Spreng.*	47	28.9	20	0.9	0.4	M-H
25	Annual		x	*Apiaceae*	*Agrocharis melanantha Hochst.)*	234	28.1	21	4.3	1.8	M-H
26	Annual		x	*Asteraceae*	*Bidens pilosa L.*	41	27.3	22	0.8	0.3	L-H
27	Annual		x	*Asteraceae*	*Guizotia scabra (Vis.) Chiov.*	81	26.6	23	1.5	0.6	L-H
28	Perennial[2]	x		*Poaceae*	*Urochloa sp.*	171	18.8	24	3.1	1.3	L-M
29	Perennial	x		*Poaceae*	*Digitaria milanjiana (Rendle) Stapf*	21	15.6	25	0.4	0.2	L-H
30	Annual	x		*Poaceae*	*Echinochloa colona (L.) Link*	20	14.1	26	0.4	0.2	M-H
31	Annual		x	*Convolvulaceae*	*Ipomea sp.*	22	13.3	27	0.4	0.2	M-H
32	Annual		x	*Fabaceae*	*Trifolium schimperi A.Rich*	28	12.5	28	0.5	0.2	L-H
33	Annual		x	*Asteraceae*	*Acanthospermum hispidum DC.*	22	11.7	29	0.4	0.2	L
34	Annual		x	*Rubiaceae*	*Spermacoce sphaerostigma (A. Rich.) Vatke*	102	10.2	30	1.9	0.8	L-H
35	Annual	x		*Poaceae*	*Dactyloctenium aegyptium (L.) Willd.*	11	8.6	31	0.2	0.1	L-M
36	Annual	x		*Poaceae*	*Pennisetum spp.*	13	7.8	32	0.2	0.1	M-H
37	Perennial[2]	x		*Poaceae*	*Urochloa trichopus (Hochst.) Stapf*	9	7.0	33	0.2	0.1	L-M
38	Perennial[1]	x		*Poaceae*	*Cyperus sesquiflorus (Torr.) Mattf & Kiik.*	76	7.0	33	1.4	0.6	L-M
39	Annual		x	*Fabaceae*	*Senna sp.*	5	2.3	34	0.1	0.04	L-M
40	Perennial[2]		x	*Fabaceae*	*Glycine sp.*	3	1.6	35	0.1	0.02	L
41	Annual		x	*Nyctaginaceae*	*Boerhavia coccinea Mill.*	3	0.8	36	0.1	0.02	L
42	Annual	x		*Poaceae*	*Echinochloa sp.*	1	0.8	36	0.02	0.01	L-H

According to IFPRI (2006): Lowland (L): less than 1500 metres above sea level and characterised by warm temperature and represents lowland teff weeds **Mid – Highlands (M-H):** >1500 metres above sea level and represents weeds adapted to moderately warm areas / **Low – highland (L-H):** altitude of weeds crossing all the altitudinal ranges and adapted to both warm and cold temperatures / **Low – midlands (L-M):** altitude of weed species adapted to warm to moderately warm areas of Tigray. *N.B. [1]= refers to stationary perennial weeds and [2] = refers to creeping perennial weeds*

Spatial extension of density levels of Teff Weed Species

The 12 weed species (Table 3) with the highest frequency were selected for spatial analysis using ArcGIS. From these 12 most frequent weed species, four were perennials and eight were annuals (Table 3). The following maps depict the spatial extension of density level of the 12 most common weed species in the experimental locations.

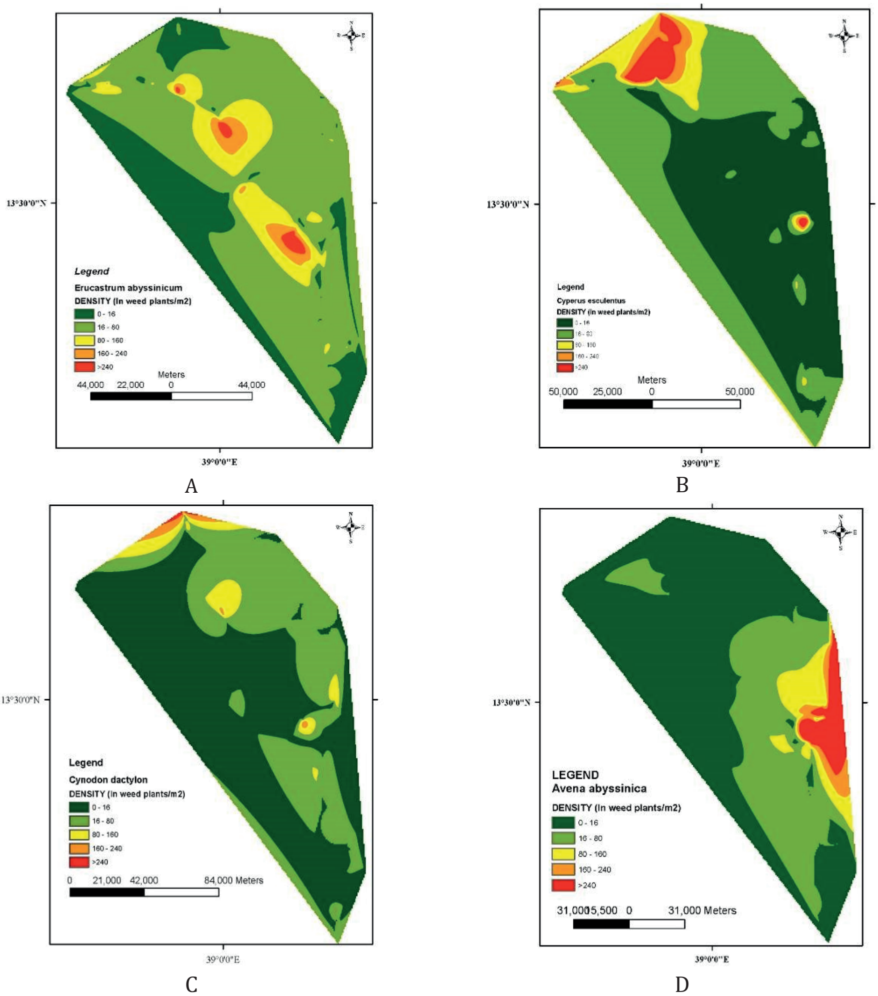

Fig. 4. Spatial extension of density level of weed species in major teff growing areas of Tigray: (A) *Erucastrum abyssinicum,* (B) *Cyperus esculentus*, (C) *Cynodon dactylon,* (D) *Avena abyssinica,*

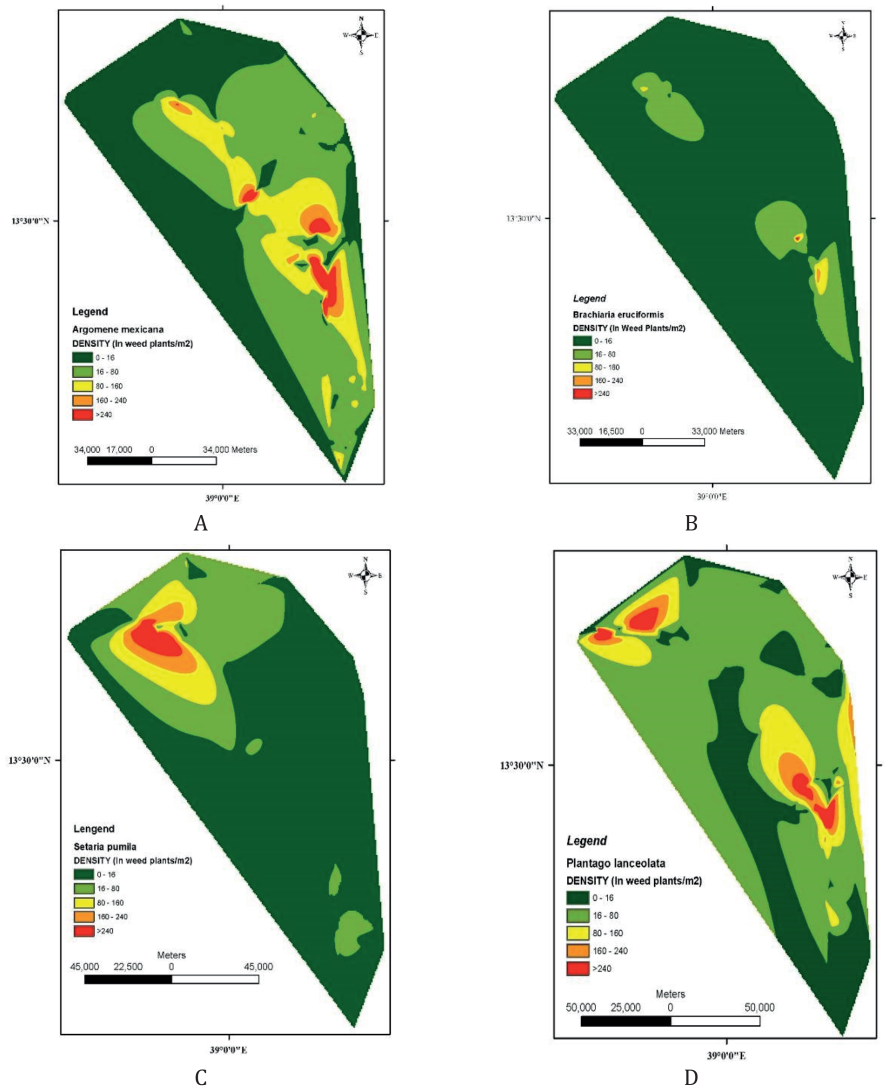

Fig. 5. Spatial extension of density level of weed species in major Teff growing areas Tigray: (A) *Argomene mexicana L,* (B) *Brachiaria eruciformis,* (C) *Setaria pumila,* (D) *Plantago lanceolate,*

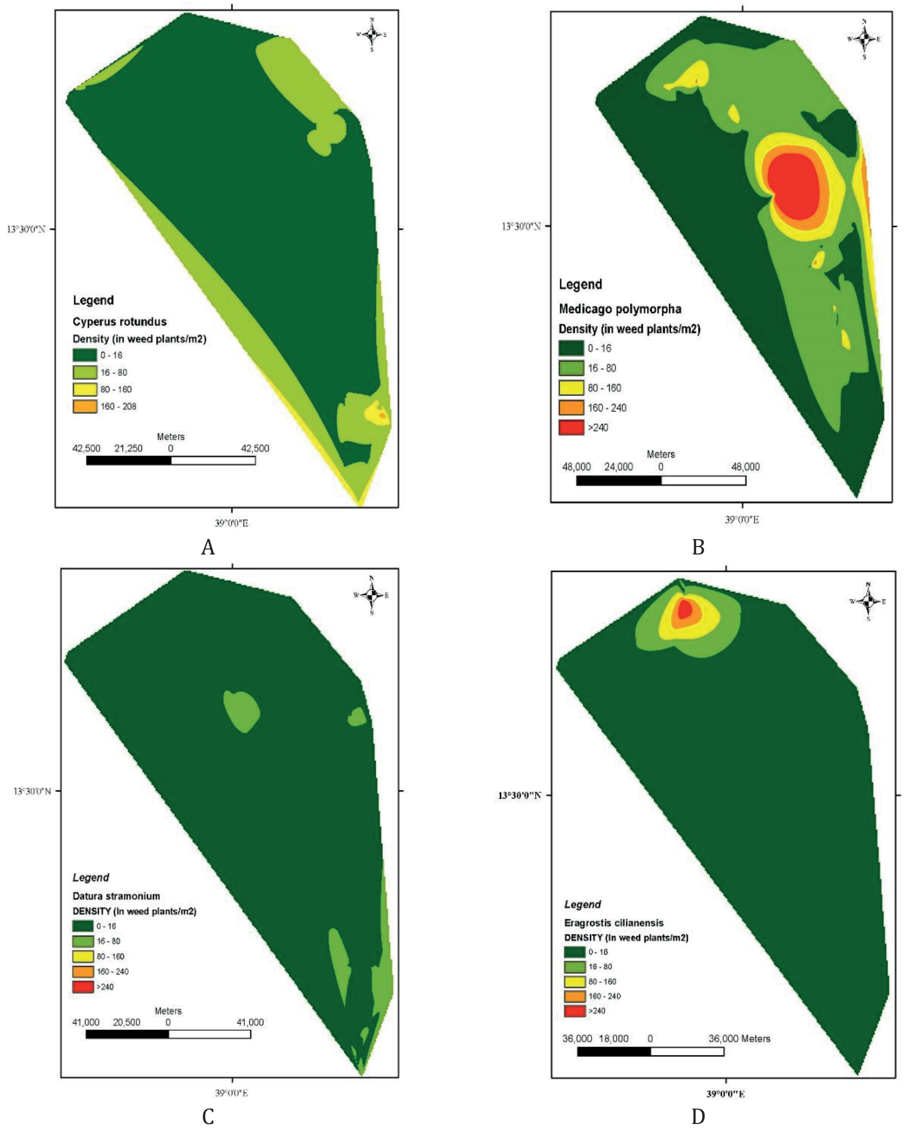

Fig. 6. Spatial extension of density level of weed species in major Teff growing areas Tigray: (A) *Cyperus rotundus,* (B) *Medicago polymorpha,* (C) *Datura stramonium,* (D) *Eragrostis cilianensis,* (Wild relative of Teff (Ann & Chris 1989)).

Discussion

According to Esayas et al. 2012 and Taye & Yohanes 1998, any family having greater than five weed species from all fields under study is considered as diverse. The Poaceae and Asteraceae families were the most diverse because each of them had more than five weed species. Most of the broadleaved weeds (Dicots) were sensitive to tillage when established as seedlings (Håkansson 2003) and can be eliminated by first hand-weeding; hence, most of their families were less diverse. However, most of the grass weeds (Monocots) especially those with actively regenerative parts upon cutting by plough (e.g. *Cynodon dactylon)* are more tolerant to tillage and resistant to herbicides (e.g. *Cyperus esculentus*) (ISHRW 2013), and were consequently the most diverse and important weeds in the major teff growing areas of Tigray. Most of the weed species were annuals, therefore their infestation can be minimised easily by crop management practices. Some of the annuals emerged even after the first weeding. If there is continuous rainfall during the production season, their competitive ability towards teff can be higher. That is why most farmers hand-weed twice or three times in a production season. The perennials have a fast regenerative potential due to their trailing internodes of some creeping species and rhizomes of some stationary species, which may escalate their infestation in the teff field. This is because during hand-weeding, the size of the perennial weeds, especially perennial monocot weeds, is small and may not be uprooted completely. This fosters the spread of fast regenerative rhizomes and internodes. These types of weeds are commonly part of the two most diverse families i.e. Poaceae and Asteraceae. Most of the teff farmers in almost all areas of Tigray need mechanisms to control these perennial weeds, though they have their own traditional mechanisms such as frequent tillage, frequent hand-weeding, and use of early maturing teff varieties. Of course some of the annual and perennial grass weeds such as *Pennisetum spp., C.esculentus, D.abyssinica, C.rotundus, S.pumila, B.eruciformis, C.dactylon*, *E.cilianensis* and *A.abyssinica* are economically important and used as livestock forage. Some of these grass species are also harvested and sold in nearby markets during weekends and holidays because they are used by the town/urban residents as a floor decorating component during Ethiopian traditional coffee ceremonies.

Most of the weed species were obtained from 65% (84 out of 128) of the total fields studied and located at mid altitude (1500–2500 metres above sea level) where teff production is more frequent and intensive. The difference in weed species richness among the altitudes is attributed to both environmental and management factors. Cropping systems and management practices are the most important factors contributing to the variability of weed species richness and composition in the crop field (Fried et al. 2008; Johnson & Kent 2002). Cropping history can also affect weed species richness and composition (Fried et al. 2008). Among the environmental factors affecting weeds in agro-climatic conditions, altitude has the most determinant effect on species composition, importance and infestation levels (Michaela et al. 2015; Pal et al. 2013). Teff grows in 17 of the 49 agroecologies (ecologies of cultivated fields) of Ethiopia (IFPRI 2006). As a C_4 plant, it needs high radiation intensity, relatively high supply of nutrients and water for its vegetative growth (Assefa et al. 2015; Ketema 1997). The highlands are characterised by low intensity of radiation, high soil moisture (water logging conditions) and high loss of nutrients by leaching, which result in low vegetative performance of teff. Such conditions, with a low competitive crop, create a favourable environment for different weed species to grow. Håkansson (2003) for example, indicates that improved crop stand reduces weed populations including species richness. Those factors may therefore explain why the weed species richness is higher in the highlands than in the lowlands and midlands. The low richness in the lowlands is attributed to the warm agro-climatic conditions that foster robust growth of weeds, especially during good water and nutrient supply, which cover the ground easily and suppress other weak species, and favour competitiveness of a restricted number of successful weed species (Amedie 2013; Houngbédji et al. 2016; Hyvönen et al. 2003; Smith et al. 2014; Valerio et al. 2013). The agro-climatic variability along the altitudinal gradient of the crop land and the adaptation of the weeds to it resulted in those species specific to (i) lowlands, (ii) low to midlands and (iii) mid to highlands. This was highly reflected in the output of this study. The last group of distribution (iv), which included more than 52% (22 of the 42) identified weed species, had wider adaptation as they had been found in all altitudinal ranges of the major teff growing areas of Tigray. Among these, we may find the most important, successful and highly competitive weeds in teff fields.

A study in western Shewa (Oromia Region, Central Ethiopia) found that the species *M.polymorpha, G.scabra, P.lanceolata, G.parviflora, S.pumila, and Cyperus spp.* are the most frequent and dominant teff weed species in the area (Taye & Yohanes 1998). Except *G.scabra*, all of these species were also the most frequent and dominant teff weed species in this study. This shows that most of the weed species identified in major teff growing areas of Tigray are not specific to this region. Teff has fibrous and shorter roots than other cereal crops and uses nutrients and water available in the upper part of the soil profile (Ketema 1997). Such a shallow root zone may leave the lower parts of the profile open to other plants, i.e weed species with longer roots and deeper root zones. This may be the reason for some of the weed species being frequent and dominant in the teff field under study.

To see the persistency of the teff weed species both temporally and spatially, a similarity index (in %) has been determined. This considers the weed species richness in the teff fields. There were similarities among weed species between 2015 and 2016 production seasons. When we observe spatially along the altitudinal gradient, there was similarity in weed species between lowland and midland, and midland and highland. Dissimilarity among teff weed species was observed between lowland and highland altitudinal ranges, in that the teff weed species in lowlands were totally different from those in the highlands because there were no weed species specific to highlands. If the similarity proportion between two sampling fields or any sampling component is greater than or equal to 60%, they are considered to be highly similar (Taye & Yohanes 1998). Not only similarity index but also frequency, abundance and dominance are important weed species parameters. Frequency shows commonness of the weed species whereas dominance indicates infestation levels of the species. The most frequent weed species may or may not be dominant and vice versa. Such a behaviour of the weed species was also reflected in this study. The most common weed species were not dominant, though some species were both frequent and dominant. The most dominant weed species are the most important and can result in higher yield loss of teff. Spatial extension of the density levels of the frequent teff weed species were interpolated using ARCGIS, and were mapped based on their density recorded during the study period. This generally showed that the most frequent weed species had different density levels spatially in different teff growing areas of Tigray. Besides, the most common weed species had wider influences in more than half of the teff growing weredas of Tigray.

Conclusion

- ✓ The different teff growing areas showed wider variation in weed species composition. They also have high differences in teff weed species richness.

- ✓ Based on frequency and dominance, the most important weed species in the different teff growing areas of Tigray are *Plantago lanceolate, Erucastrum abyssinicum, Setari pumila, Cynodon dactylon, Cyperus esculentus, Cyperus rotundus, Avena, abyssinica, Argomone mexicana, and Medicago polymorpha.*

- ✓ All the species showed variability in ecological distribution and adaptation. Altitude has a determinant influence on weed species richness and overall ecological distribution. Highlands have higher weed species richness and the lowlands have lower weed species richness. However, most of the weed species had similar ecological distribution and adaptation.

- ✓ Mid altitude (1500–2500 m a.s.l.) is a favourable altitudinal range to develop integrated teff weed management, as it constitutes all types of weed species found in both lowlands and highlands.

Acknowledgements

Technicians in Mekelle University, college of dryland agriculture and natural resources, department of crop and horticultural sciences contributed substantially to the fieldwork. We thank teff farmers in Tigray, Northern Ethiopia for their heartfelt cooperation during data collection. The study received financial support from NORHED through the project 'Research and capacity building in the Horn of Africa' and NIBIO. We would like to thank Professor Emeritus Kåre Arnstein Lye (NMBU) both for some advice before starting up and for looking through the paper and giving important comments. The authors thank anonymous referees for valuable comments on earlier versions of the paper.

References

Amedie, F. A. (2013). *Impacts of Climate Change on Plant Growth, Ecosystem Services, Biodiversity, and Potential Adaptation Measure*. Gothenburg, Sweden: University of Gothenburg, Biological and Environmental Sciences. 61 pp.

Amir Kassam, Theodor Friedrich, Shaxson, F. & Pretty, J. (2009). The spread of Conservation Agriculture: justification, sustainability and uptake. *International Journal of Agricultural Sustainability*, 7 (4): 292-320.

Ann, S. & Chris, P. (1989). *A weed identification guide for Ethiopia*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). 280 pp.

Assefa, G., Theodrose, T. & Alemu, D. (2016). Quantitative Determination of Weed Occurrence on Upland Rice of Bambasi, Ethiopia. *Ecology and Evolutionary Biology*, 1 (3): 53-56.

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 teff [Eragrostis tef (Zucc.) Trotter]. *Frontiers in Plant Science*, 6: 177.

Baye, K. (2014). *Teff: nutrient composition and health benefits*: International Food Policy Research Institute (IFPRI).

Crop Life International. (2012). *Implementing Integrated Weed Management for Herbicide Tolerant Crops*. Brussels, Belgium: Crop Life International. 62 pp.

CSA. (2016). *Agricutlrual Sample Survey 2015/2016 (2008E.C): Report on Area, Production and Farm Management Practice on Belg Season Crops for Private Peasant Holdings*, vol. V (5). Addis Ababa, Ethiopia: CENTRAL STATISTICAL AGENCY. 131 pp.

Dumanski, J., Peiretti, R., Benites, J., McGarry, D. & Pieri, C. (2006). *The Paradigm of Conservation Agriculture*. World Association of Soil and Water Conservation: World Association of Soil and Water Conservation. 58-64 pp.

Esayas, T., Abraham, G. H. & Mashila, D. (2012). Quantitative and Qualitative Determination of Weeds in Cotton-Growing Areas of Humera and Metema, Northwestern Ethiopia. *Ethiop. J. Appl. Sci. Technol.*, 3 (1): 57-69.

Esayas, T., Abraham, G. H. & Mashila, D. (2013). Weed Interference in Cotton (Gossypium hirsutum L.) in the Middle Awash, Ethiopia. *Ethio. J. Appl. Sci. Technol.*, 4: 41-49.

EU Directive. (2009). Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009: Establishing a framework for Community action to achieve the sustainable use of pesticides. *Official Journal of the European Union*: 71-86.

Fried, G., Norton, L. R. & Reboud, X. (2008). Environmental and management factors determining weed species composition and diversity in France. *Agriculture, Ecosystems & Environment*, 128 (1–2): 68-76.

Giller, K. E., Witter, E., Corbeels, M. & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research*, 114 (1): 23-34.

Haftamu, G., Mitiku, H. & 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 Sciences*, 1 (1): 82-94.

Håkansson, S. (2003). *Weeds and Weed Management on Arable Lands: An Ecological Approach*. Wallingford, Oxon, UK: CABI Publishing. 274 pp.

Hobbs, P. R., Sayre, K. & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Phil. Trans. R. Soc. B*, 363: 543-555.

Houngbédji, T., Dessaint, F., Nicolardot, B., Shykoff, J. A. & Gibot-Leclerc, S. (2016). Weed communities of rain-fed lowland rice vary with infestation by Rhamphicarpa fistulosa. *Acta Oecologica*, 77: 85-90.

Hyvönen, T., Ketoja, E., Salonen, J., Jalli, H. & Tiainen, J. (2003). Weed species diversity and community composition in organic and conventional cropping of spring cereals. *Agriculture, Ecosystems & Environment*, 97 (1): 131-149.

IFPRI. (2006). *Atlas of the Ethiopian Rural Economy*. Addis Ababa, Ethiopia: International Food Policy Research Institute and Central Statistical Agency. 1-108 pp.

ISHRW. (2013). *Herbicide Resistant Yellow Nutsedge (Cyperus esculentus)*. USA, Arkansas: International Survey of Herbicide Resistant Weeds. Available at: http://www.weedscience.org/Details/Case.aspx?ResistID=6752 (accessed: December 25, at 1:00AM).

Jaccard, P. (1912). The distribution of the flora in the alpine zone. *New phytologist*, 11 (2): 37-50.

Johnson, D. E. & Kent, R. J. (2002). The impact of cropping on weed species composition in rice after fallow across a hydrological gradient in west Africa. *Weed Research*, 42: 89-99.

Ketema, S. (1997). *Tef (Eragrostis tef (Zucc.) Trotter): Promoting the conservation and use of underutilized and neglected crops*. Rome, Italy: 12. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute.

Local Land Services. (2016). *Preparing a Whole of Property Weed Management Plan*. The Wales, British: Local Land Services. 24 pp.

Lososová, Z., Chytrý, M., Cimalová, Š., Kropáč, Z., Otýpková, Z., Pyšek, P., Tichý, L. & Bakker, J. P. (2004). Weed vegetation of arable land in Central Europe: Gradients of diversity and species composition. *Journal of Vegetation Science*, 15 (3): 415-422.

Michaela, K., Luděk, T. & Josef, S. (2015). Weed species diversity in the czech republic under different farming and site conditions. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis,*, 63: 741-749.

NMA. (2017). *Annual Weather Report* Addis Ababa, Ethiopia: National Meteorological Agency

Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science*, 144 (1): 31-43.

Pal, R. W., Pinke, G., Botta-Dukát, Z., Campetella, G., Bartha, S., Kalocsai, R. & Lengyel, A. (2013). Can management intensity be more important than environmental factors? A case study along an extreme elevation gradient from central Italian cereal fields. *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology*, 147 (2): 343-353.

Peerzada, A. M., Ali, H. H. & Chauhan, B. S. (2017). Weed management in sorghum [Sorghum bicolor (L.) Moench] using crop competition: A review. *Crop Protection*, 95: 74-80.

Pyšek, P., Jarošík, V., Kropáč, Z., Chytrý, M., Wild, J. & Tichý, L. (2005). Effects of abiotic factors on species richness and cover in Central European weed communities. *Agriculture, Ecosystems & Environment*, 109 (1): 1-8.

Reicosky, D. C. (2015). Conservation tillage is not conservation agriculture. *JOURNAL OF SOIL AND WATER CONSERVATION*, 70 (5): 103A-108A.

Renton, M. & Chauhan, B. S. (2017). Modelling crop-weed competition: Why, what, how and what lies ahead? *Crop Protection*, 95: 101-108.

Salonen, J., Hyvönen, T. & Jalli, H. (2011). Composition of weed flora in spring cereals in Finland - a fourth survey. *Agricultural and Food Science*, 20 (3): 245-261.

Salonen, J., Hyvönen, T., Kaseva, J. & Jalli, H. (2013). Impact of changed cropping practices on weed occurrence in spring cereals in Finland – a comparison of surveys in 1997–1999 and 2007–2009. *Weed Research*, 53 (2): 110-120.
Shahid, N., Chair, F. S., Chapin, I., Robert, C., Paul, R. E., Frank, B. G., David, U. H., Lawton, J. H., Robert, V. O. N., Harold, A. M., et al. (1999). *Biodiversity and Ecosystem Functioning: Maintaining Natural Life Support Processes*. Issues in Ecology. Wahington DC,USA: Ecology Society of America. 14 pp.
Shekhawat, K., Rathore, S. S., Dass, A., Das, T. K., Mahajan, G. & Chauhan, B. S. (2017). Weed menace and management strategies for enhancing oilseed brassicas production in the Indian sub-continent: A review. *Crop Protection*, 96: 245-257.
Singh, M., Bhullar, M. S. & Chauhan, B. S. (2017). Relative time of weed and crop emergence is crucial for managing weed seed production: A study under an aerobic rice system. *Crop Protection*, 99: 33-38.
Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J., Jafari, M., et al. (2014). *Agriculture, Forestry and Other Land Use (AFOLU)*. IPCC (ed.). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press. p. 112.
Stenchly, K., Lippmann, S., Waongo, A., Nyarko, G. & Buerkert, A. (2017). Weed species structural and functional composition of okra fields and field periphery under different management intensities along the rural-urban gradient of two West African cities. *Agriculture, Ecosystems & Environment*, 237: 213-223.
Taye, T. & Yohanes, L. (1998). Qualitative and quantitative determination of weeds in tef in West Shewa Zone. *Arem (Ethiopia)*.
Theodore, M. W. & Harold, D. C. (1997). Changes in the Weed Species Composition of the Southern United States: 1974 to 1995. *Weed Technology*, 11 (2): 308-317.
Theodore, M. W. & Harold, D. C. (1997). Changes in the Weed Species Composition of the Southern United States: 1974 to 1995. *Weed Technology*, 11 (2): 308-317.
Tubiello, Francesco, N., Soussana, Jean-François, Howden & Mark, S. (2007). Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences*, 104 (50): 19686-19690.
Valerio, M., Tomecek, M., Lovelli, S. & Ziska, L. (2013). Assessing the impact of increasing carbon dioxide and temperature on crop-weed interactions for tomato and a C3 and C4 weed species. *European Journal of Agronomy*, 50: 60-65.
van der Meulen, A. & Chauhan, B. S. (2017). A review of weed management in wheat using crop competition. *Crop Protection*, 95: 38-44.

PAPER II:

G. Haftamu, J.B. Aune, O.M. Eklo, T. Torp and L.O. Brandsæter. Effect of tillage frequency, seed rate and glyphosate application on teff and weeds in Tigray, Ethiopia. Manuscript.

Effect of tillage frequency, seed rate and glyphosate application on teff and weeds in Tigray, Ethiopia

G. Haftamu [ab], J. B. Aune[c], O.M. Eklo[bd], T. Torp[d] and L.O. Brandsæter[bd]

[a] *Mekelle University, College of Dryland Agriculture and Natural Resources, P.O.Box 231, Mekelle, Tigray, Ethiopia*
[b] *Norwegian University of Life Sciences, Department of Plant Sciences (IPV-NMBU), P.O. Box 5003, NO-1432 Ås, Norway*
[c] *Norwegian University of Life Sciences, Department of International Environment and Development Studies (Noragric-NMBU), P.O. Box 5003, NO-1432 Ås, Norway*
[d] *Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway*

Abstract

Teff is a major part of the daily diet and an important livestock feed in Ethiopia. It is a poor competitor to weeds and can suffer yield losses ranging from 35 to 65 %. Field experiments were conducted in 2015 and 2016 to study effect of tillage frequency, seed rate and glyphosate on teff and weeds. The experiments were arranged in split plot design with three blocks consisting of tillage frequency (conventional, minimum and zero tillage) as main plot and the combination of seed rate (5 kg/ha, 15 kg/ha and 25 kg/ha) and glyphosate (with and without) as subplots. Results showed that zero tillage reduced teff biomass yield by 15 % as compared to minimum tillage and 26 % as compared to the conventional tillage. It also diminished grain yield by 9 % as compared to minimum tillage and 21 % as compared to conventional tillage. Lowering the seed rate to 5 kg/ha reduced biomass yield by 22 % as compared to 15 kg/ha and 26 % as compared to 25 kg/ha. It also reduced the grain yield by around 21 % as compared to the 15 kg/ha and 25 kg/ha seed rates. Conventional tillage significantly diminished weed density, dry weight and cover by 19 %, 29 % and 37 % respectively as compared to zero tillage and by 13 %, 15 % and 9 % as compared to minimum tillage. The highest seed rate (25kg/ha) significantly reduced total weed density, dry weight and cover by 18 %, 19 % and 15 % respectively as compared to the 5 kg/ha seed rate. Glyphosate application significantly affected weed dry weight and cover but not weed density. Its application reduced weed dry weight by 14 % and cover by 16 %. Generally, minimum tillage along with the seed rate of 15 kg/ha enhanced teff productivity and minimized weed effect. Application of glyphosate was more effective on monocot than on dicot weeds. The study shows that minimum tillage combined with a moderate seed rate and application of glyphosate can be an option for teff farmers to control weeds.

Key words: Teff, Weed, Tillage frequency, Seed rate, Glyphosate application

Introduction

Teff (*Eragrostis tef (*Zucc) Trotter*)* is a small-grained cereal crop grown in Ethiopia for its grain and straw. It has a wide agro-ecological adaptation and grows best in the mid altitudinal ranges i.e. 1500-2300 m a.s.l. (Ketema 1997; IFPRI 2006). Ethiopian farmers have a long history of teff production. The crop is a major part of the daily source of diet and an important livestock feed in the country. The area and amount of production steadily increases from year to year. In 2016, around 3.2 million hectares of land or 27.4 % of the total cereal area was under teff production and around 4.5 million tons or 18 % of the cereal production was harvested nationally in Ethiopia (CSA 2016).

Though tolerant to extreme environmental conditions, teff is poor competitor to weeds and can suffer yield losses ranging from 35 to 65 % (Rezene & Zerihun 2001; Kassahun & Tebkew 2013). Its fields are ploughed more frequently than other cereal crops in order to create a fine seedbed that allow the tiny seeds to germinate and to control weeds (Haftamu et al. 2009; Tesfa et al. 2013). Furthermore, tillage frequency depends on weed type and weed infestation, soil type, climatic condition, and availability of oxen. If no use of herbicides, intensive tillage is required to control perennial weeds (Bergkvist et al. 2017) and with increasing weed infestation, more frequent tillage is needed. Tillage intensity also depend on soil type. Higher tillage frequency is required for vertic soils in high rainfall areas because of its clayey nature, which needs more pulverization to create a fine seedbed for teff (Tesfa et al. 2013). Studies report different tillage frequencies: 3 times (Haftamu et al. 2009), 3 to 6 (Leye 2007), 4 times (Nyssen et al. 2000; Habtegebrial et al. 2007a), and up to 6 times (Aune et al. 2001). In high rainfall areas up to 9-12 times tilling have been reported to control severe weed infestation (Tarekegne et al. 1996; Deckers et al. 1998). In areas with less weed incidence, the farmers keep their land undisturbed until the onset of the rain (Fufa et al. 2001). Generally, the main reason for frequent ard ploughing is weed control. Not only the number of passes but also the depth of the tillage has a significant role in diminishing weed density and biomass especially for perennial weeds (Brandsæter et al. 2011). However, increasing ard ploughing intensity increase soil erosion, reduces soil bulk density, diminish soil water holding capacity and soil water productivity, and aggravates nutrient and water losses from the soil (Nyssen et al. 2000; Habtegebrial et al. 2007b; Leye 2007; Assefa et al. 2008; Tigist et al. 2010; Salem et al. 2015). These authors also showed that conventional tillage resulted in higher teff and maize yields. In some instances, such a higher yield is not significant when compared with conservation tillage in both Vertisol and Nitosol soil types (Balesh et al. 2008). Conservation tillage also significantly increased maize yield especially during medium rainfall season with an amount ranging from 500 to 800mm (Mupangwa et al. 2017). However, it increases weed density and exposes the crops to weed competition (Habtegebrial et al. 2007a; Balesh et al. 2008; Tigist et al. 2010; Salem et al. 2015). To utilize its water and nutrient storage advantage, studying the potential of preventive and direct weed control measures is therefore crucial for increasing teff yield in Ethiopia in both conventional and conservation agricultures. Improving the crop competitiveness by using varieties that are more competitive with higher seed rates are among the actual preventive measures.

Most of the research reports found that teff yield is high at relatively low seed rate (5kg/ha) though the recommended rate is 25-30kg/ha. A low seed rate can be used because it fosters teff tillering ability (Amare & Adane 2015; Bekalu & Arega 2016; Sakatu & Adane 2017). Such a seed rate together with the fertilizer application at the recommended rates of DAP (Di-Ammonium Phosphate) and Urea had plausible yield benefits for the teff farmers in both Vertisol and Cambisol soil types in central zone of Tigray (Teklay & Girmay 2016).

Glyphosate is among the most common herbicides used in Ethiopia to control early emerging weeds before crop sowing and its demand is increasing from year to year (Seneshaw et al. 2017). Teff smallholder farmers use glyphosate to minimize land preparation and weeding costs as well as to create relatively weed free fields for the crop (Astatke et al. 2003; Assefa et al. 2008; Kassahun & Tebkew 2013; Seneshaw et al. 2017). In Tigray, more than 68% of the teff farmers use glyphosate to control grass and other perennial weeds in conservation agriculture (Teamti & Tesfay 2016). However, there are weed species resistant to glyphosate reported globally posing a threat to the continued use of glyphosate (Heap 1997; Nandula et al. 2005; Johnson & Gibson 2006; Powles 2008b; Powles 2008a; Duke & Powles 2009; Boerboom & Owen 2013). Among the teff weed species, *Cyperus esculentus* is registered as resistant to glyphosate in USA and the monocot weed, *Snowdenia polystachya,* is resistant to glyphosate in Ethiopia in wheat fields of Oromia region (ISHRW 2013). Besides, a recent report has shown that glyphoshate affected soil physical, chemical and biological properties and may reduce soil quality (Neli et al. 2017). Therefore, it is important to study the effect of glyphoshate application on teff and weeds.

The hypotheses for our study were the following:

i. Frequent tillage reduces weed incidence and enhances teff vegetative and reproductive performance
ii. Higher seed rate reduces weed incidence and enhances teff vegetative and reproductive performance
iii. Applying glyphosate before teff sowing reduces weed incidence and enhances teff vegetative and reproductive performance
iv. There is a synergy among the effects of tillage frequency, seed rate and glyphosate application

Materials and methods

Description of the study areas

The study was located at two sites, Axum and Mekelle, in Tigray, Ethiopia

Axum Research Site

Axum is located 245 km northwest of Mekelle, which is the capital city of Tigray region. The research site is located 4 km east of Axum town. The experiment was laid out on deep black vertic soil with small patches of Cambisol with sandy clay texture (soil description was made based on WRB 2014 as in FAO (2015)). The experimental fields were located on 14°07'37"N and 38°45'51"E at an altitude of 2098 m a.s.l. It has tepid to cool sub-moist mid-highlands agroecological classification with an annual rainfall ranging from 401-800 mm, temperature ranges from 15 – 28 °C.

Mekelle Research Site

This site was at Mekelle University main campus. It is located at 13°28′48″N and 39°29′25″E at an altitude of 2224 m a.s.l. The soil at the site is characterized as Cambisol dominated by sandy loam texture with patches of Vertisols (soil description was made based on WRB 2014 as in FAO (2015). It has a moderate temperature with annual minimum temperature of 12 °C and maximum temperature of 30 °C where its average temperature is around 20 °C. The site receives an annual rainfall ranging from 400 mm to 600 mm (NMA 2017a).

Climate in 2015 and 2016

In both *Axum* and *Mekelle*, the highest rainfall is commonly recorded in July and August. The warmest months are April, May and June.

Table 1. Rainfall, minimum temperature and maximum temperature in Axum and Mekelle during 2015 and 2016

Location	Year	Rainfall (mm)	Min. Temperature (°C)	Max. Temperature (°C)
Axum	2015	725	11	27
	2016	675	11	27
Mekelle	2015	580	11	28
	2016	560	11	28

Source: (NMA 2017b)

Field experimental design and treatments

The experiment was laid in a split plot design arranged in three blocks with three levels of tillage (zero, minimum and conventional) on the main plots and combination of seed rate with three levels (5 kg/ha, 15 kg/ha and 25 kg/ha) and glyphosate with two levels (with and without) was used as sub plot treatments. Conventional tillage refers to the number of ard ploughings (3 times in *Mekelle* and 4 times in *Axum*) done by the farmers in the experimental sites using the traditional Ethiopian *ard plough* (Figure 1). Minimum tillage refers to ard ploughing only once and zero tillage refers to shallow light disturbance of the soil using a hoe. The plot sizes were 7 m by 17 m for the main plot and 2 m by 2 m for sub plot. There were 1 m (border) space between the subplots, 1 m between main plots within blocks and 1.5 m between blocks to control border effect. Glyphosate was applied at a recommended rate of 4 L/ha (1440 g a.i./ha) 7-10 days before teff sowing.

Figure 1. Ethiopian traditional *ard plough* in use by a farmer in '*Axum'* in 2015

The teff variety *DZ-Cr-387* or *'Quncho'* was used during the experiment. The details on teff and weed management and assessment operations are presented in table 2 and these dates correspond well with farmers' time of farm operations.

Table 2. Description of crop and weed management and assessment operations in the two experimental sites

Operations	2015	2016
Axum Research Site		
First ard ploughing	13-May	16-May
Second ard ploughing	6-Jun	3-Jun
Third ard ploughing	3-Jul	30-Jun
Fourth ard ploughing	21-Jul	19-Jul
Seed bed preparation and field designing	21-Jul	19-Jul
Field fertilizing* and sowing**	21-Jul	19-Jul
Crop assessment	27 July - 21 Nov.	25 July - 29 Nov.
Weed assessment		
First weeding	19 Aug.	22 Aug.
Second weeding	01 Oct.	03 Oct.
Third weeding	19 Nov.	26 Nov.
Crop harvesting	22 Nov.	30 Nov.
Crop and weed biomass measurement	06 Dec.	13 Dec.
Crop threshing and grain weighing	06-10 Dec.	14 - 17 Dec.
Mekelle Research Site		
First ard ploughing	24-May	26-May
Second ard ploughing	23-Jun	27-Jun
Third ard ploughing	28-Jul	30-Jul
Seed bed preparation and field designing	27-Jul	01-Aug
Field fertilizing* and sowing**	27-Jul	01-Aug
Crop assessment	03 Aug - 07 Dec.	08 Aug. -09 Dec.
Weed assessment		
First weeding	03Sep.	05 Sep.
Second weeding	29Sep.	05 Oct.
Third weeding	27 Nov.	26 Nov.
Crop harvesting	01 Dec.	28 Nov.
Crop and weed biomass measurement	14 Dec.	5 Dec.
Crop threshing and grain weighing	14-19 Dec.	05 - 11 Dec.

**Fertilizing of field was done by applying DAP and Urea at a rate of 60 kgN/ha and 60 kgP_2O_5 for Vertisol and 40 kgN/ha and 40 kgP_2O_5 for light sandy loam soils. Axum has Vertisol and Mekelle has Cambisol; **Sowing was done at a nationally recommended seed rate (25 kg/ha)*

Data collection

The collected data can be classified within three classes (i) crop data, (ii) weed data and (iii) weeding time data.

i) Crop data

The crop data includes days to emergence, heading, maturity, tiller number /plant, plant height, biomass yield, and grain yield. The teff phenology, days to emergence, heading, and maturity, was recorded by registering the dates for crop covering 50 % of the plot area are emerged, flowered and matured. Tiller number/plant and plant height were measured by taking 10 teff plants randomly from each plot. Tiller number/plant was recorded by counting the number of tillers in a single teff plant. Plant height, which is height of the teff plant from node separating root and shoot until the tip of the panicle were measured using a *meter*. Biomass yield is the sum of the straw and grain yield of the crop.

ii) Weed data

Density, biomass and cover for monocot and dicot weeds

Weed shoot density and aboveground weed biomass were assessed three times before harvest in one randomly placed quadrate (25 cm * 25 cm) per plot.

Weed density or infestation was estimated visually (coverage) by weeding time (first, second and third weeding). The space occupied by the crop and weeds on all small plots was expressed as percentage ground coverage. The area covered by crop, weeds and bare soil was summed up to 100 %. The biomass samples were dried at 65 °C for 48 h to determine the dry weight.

Identification of dominant weed species

Weed species were taken randomly using 50 cm x 50 cm quadrate before sowing. There were 12 samples per experimental field. The weed species were identified and counted for each sample**.** Six weed species from *Axum* and five weed species from *Mekelle* were identified and their frequency, abundance and dominance were calculated based on the most commonly used procedures (Jaccard 1912; Taye & Yohanes 1998; Esayas et al. 2013; Assefa et al. 2016). The first three weed species from each location having the highest values of frequency, abundance and dominance were considered as the dominant weed species in the experimental areas of both locations.

iii) Time used for hand weeding and competitiveness on teff

Estimation of time used for hand weeding

This estimation was based on the weeding time of a single person required to hand weed the 4 m^2 subplots. This is recorded as minutes/person/plot and is averaged over all blocks and weeding times of the experiment in each location. This average value of the weeding time was converted into hours/ha.

Data analysis procedures

Combined analysis of the teff tillage experiments was done by year and location. The MIXED procedure of SAS (SAS version 9.4) was used. The crop data included tillage frequency, seed rate, glyphosate, year and location as factors. All factors from both data groups were considered as fixed. Weed assessment was taken in a successive two years and three weeding times. A repeated measurement mixed model was used for weed data analysis to account for correlation among the assessments from the same plot recorded at the different times. For the correlation analysis, unstructured (un) and first-order autoregressive (ar(1)) covariance structures were used. The final model for the analysis was chosen based on the Akaike information criterion (AIC) and Schwarz Bayesian Information criterion (BIC). The model with the lowest AIC and BIC value was considered as a final model for analysis. Model assumptions were checked with usual residual plots. The least square means of different groups were compared using the Tukey-Kramer multiple comparison method at 5 % levels of significance.

Result

Tillage frequency and application of glyphosate did not show significant interaction effect with locations and years on teff and weeds (Table 3 and Table 6). Unlike to other factors, seed rate had a significant interaction effect with locations and years on teff vegetative and reproductive performance (Table 3). Only significant main effect of seed rate was observed on weed density, biomass, and cover. Generally, there was no significant synergistic effects between the three factors on teff and weeds (Table 3 and Table 6).

Effects of tillage frequency, seed rate and application of glyphosate on teff

Tillage frequency did not significantly influence days to emergence, heading, maturity, and tiller number per plant of teff (Table 3). However, it significantly influenced plant height, biomass yield and grain yield. The tallest and highest yielding teff plants were observed under conventional tillage. Zero tillage reduced crop biomass yield by 14.6 % compared to minimum tillage and 26.3 % compared to yield from conventional tillage (Table 4). Grain yield in zero tillage was 9 % less than that from minimum tillage and 20.7 % lower than the grain yield from conventional tillage (Table 4).

Seed rate significantly influenced all agronomic traits (Table 3). The 5 kg/ha seed rate caused late emergence, heading and maturity, but resulted in the tallest plants with the highest tiller number per plant (Table 4). This low seed rate reduced biomass yield by 22.3 % compared to 15 kg/ha seed rate and by 26 % compared to the 25 kg/ha seed rate. Low seed rate also reduced the grain yield by around 21 % compared to both highest seed rates. There were no significant differences for agronomic traits between 15 kg/ha and 25 kg/ha seed rates (Table 3).

Application of glyphosate significantly affected plant height, biomass yield and grain yields, but did not have an effect on phenology and tiller number per plant of teff (Table 3). With glyphosate, teff had significantly taller plants and higher biomass and grain yields. It increased plant height by 5 %, biomass yield by 10.1 % and grain yield by 9.6 % (Table 4).

Table 3. ANOVA table with P-values for the main and interaction effect of factors on agronomic traits of teff

Factor effects	Days to 50% Emergence	Days to 50% Heading	Days to 50% Maturity	Plant Height (cm)	Total Tiller No./Plant	Biomass Yield (kg/ha)	Grain Yield (kg/ha)
Tillage frequency (TF)	0.195	0.0773	0.7023	**0.0018**	0.8369	**<.0001**	**<.0001**
Seed rate (kg/ha) (SR)	**<.0001**	**<.0001**	**<.0001**	**0.0201**	**<.0001**	**<.0001**	**<.0001**
TF*SR	0.5173	0.8457	0.566	0.3139	0.6703	0.5386	0.2325
Glyphosate (Gp)	0.5533	0.4508	0.9609	**<.0001**	0.8252	**0.0184**	**0.0236**
TF*Gp	0.7505	0.9947	0.4107	**0.0297**	0.1643	0.4175	0.2276
SR*Gp	0.1155	0.2407	0.7693	0.8214	0.7873	0.909	0.6331
TF*SR*Gp	0.1398	0.0064	0.2317	0.2964	0.4311	0.5276	0.7851
Year (Yr)	0.0811	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
TF*Yr	0.1306	0.1994	0.9614	**0.0074**	0.3506	0.4204	0.8782
SR*Yr	**0.001**	0.1472	**0.0179**	0.741	**<.0001**	0.2989	0.2766
TF*SR*Yr	0.4468	0.4976	0.381	0.4006	0.4628	0.8954	0.8143
Gp*Yr	0.4342	0.7828	0.8205	**0.0012**	0.5103	0.5238	0.6528
TF*Gp*Yr	0.6293	0.7608	0.4429	0.1845	0.3674	0.9034	0.9638
SR*Gp*Yr	0.0693	0.2217	0.8182	0.6898	0.355	0.7771	0.4471
TF*SR*Gp*Yr	0.071	0.1556	**0.0007**	0.4106	0.8833	0.172	0.0845
Location (Loc)	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.012**	0.4403	**0.0269**
TF*Loc	0.195	0.0773	0.5153	0.1601	0.8588	0.6846	0.4151
SR*Loc	**<.0001**	**<.000**1	0.4868	0.2127	**0.0004**	**0.0021**	**0.0116**
TF*SR*Loc	0.5173	0.8457	0.2116	0.7495	0.9678	0.6314	0.6615
Gp*Loc	0.5533	0.4508	0.8066	0.2567	0.0829	**0.0253**	0.075
TF*Gp*Loc	0.7505	0.9947	0.9279	0.4831	0.2445	0.8228	0.4786
SR*Gp*Loc	0.1155	0.2407	0.6293	0.1192	0.2275	0.9037	0.9322
TF*SR*Gp*Loc	0.1398	0.0065	**0.0165**	0.6695	0.4048	0.874	0.6514
Yr*Loc	**<.0001**	**<.0001**	**<.0001**	**0.0094**	0.1478	**<.0001**	**<.0001**
TF*Yr*Loc	0.1306	0.1994	0.8597	0.1068	0.4872	0.1356	0.5848
SR*Yr*Loc	**0.001**	0.1472	**<.0001**	0.2445	**0.0002**	0.1086	**0.0182**
TF*SR*Yr*Loc	0.4468	0.4976	0.6313	**0.0438**	**0.033**	**0.0432**	**0.0129**
Gp*Yr*Loc	0.4342	0.7828	0.9638	0.6121	0.0764	0.4713	0.782
TF*Gp*Yr*Loc	0.6293	0.7608	0.9614	0.438	0.8644	0.3192	0.1394
SR*Gp*Yr*Loc	0.0693	0.2217	0.8813	0.9773	0.3595	0.9552	0.7452
TF*SR*Gp*Yr*Loc	0.071	0.1556	0.2408	0.0836	0.6015	0.9056	0.6302
Transformation	-	-	-	-	-	-	-
Type[a]	Ar(1)	Ar(1)	Ar(1)	un	un	Ar(1)	Ar(1)

[a] Among the commonly used serial structures used for correlations, "unstructured" (un, in SAS) was used. This was used during analysis because it resulted in models with lower values of Akaike Information Criterion (AIC) and Schwarz Bayesian Information Criterion (BIC)

Table 4. Tillage frequency, seed rate and glyphosate main effects on agronomic traits of teff

Fixed Factors	Days to 50% emergence	Days to 50% heading	Days to 50% maturity	Plant height (cm)	Tiller number /Plant	Biomass yield (kg/ha)	Grain yield (kg/ha)
Tillage Frequency							
Zero	10.4	69.3	118.7	89.2b	5.8	4750c	1126b
Minimum	10.2	69.1	118.6	92.8a	5.8	5559b	1236b
Conventional	10	68.7	118.5	93.5a	5.6	6445a	1419a
Seed Rate							
5 kg/ha	11.3a	70a	119.7a	93.7a	8a	4608b	1074b
15 kg/ha	9.5b	68.8b	118.3b	91.6ab	5b	5928a	1357a
25 kg/ha	9.7b	68.3b	117.8b	90.2b	4b	6218a	1349a
Glyphosate							
Without	10.2	68.9	118.60	89.63b	5.8	5316b	1203b
With	10.1	69.1	118.59	94.02a	5.7	5854a	1318a

Means connected by the same letter and those not connected by any letters are not significantly different using Tukey's multiple comparison method at 5 % level

Interaction effects of seed rate, location and year on teff

In both years and locations, there was no significant effect of tillage frequency and application of glyphosate on agronomic traits of teff (Table 3). In other words, their effects were consistent and the same in both Axum and Mekelle research sites.

The interaction effects between seed rate and location and between seed rate, location and year were significant for most the teff responses (Table 3). The results of the seed rate was therefore separated and presented for both locations and years (Table 5; Figure 2; Figure 3). Although not always significant, many of the comparisons showed that teff had earlier emergence, flowering and maturity at the two highest seed rates (15 kg/ha and 25 kg/ha) (Figure 2). In some cases, the highest seed rate (25 kg/ha) gave earlier development than the 15 kg/ha seed rate. Teff needed longer time to emergence, flowering and maturity in plots receiving seed rate of 5 kg/ha.

Seed rate caused significant difference in plant height of teff in Mekelle in both years. The lowest seed rate resulted in the tallest teff plants in both locations and years with the highest average value of 118.1 cm (Figure 3). Different seed rates resulted in a significant difference in teff biomass and grain yields in both locations and years (Table 5 and Figure 3). The highest biomass and grain yields were recorded in Axum in 2015.

Table 5. ANOVA table with P-values for the effect of seed rate on teff analyzed separately for locations and years

Teff agronomic traits	Axum		Mekelle	
	2015	2016	2015	2016
Days to 50% emergence	**<.0001**	**0.0049**	**<.0001**	**<.0001**
Days to 50% heading	**<.0001**	**0.0037**	**0.0002**	**<.0001**
Days to 50% maturity	**<.0001**	**0.004**	**0.0005**	**<.0001**
Plant Height (cm)	0.2238	0.5322	**0.0043**	**0.0474**
Total tiller No./Plant	**<.0001**	**0.0206**	**0.0117**	**0.0023**
Crop biomass (kg ha^{-1})	**<.0001**	**<.0001**	0.4397	**0.0185**
Grain Yield (kg/ha)	**0.0015**	**<.0001**	0.2597	**0.0187**

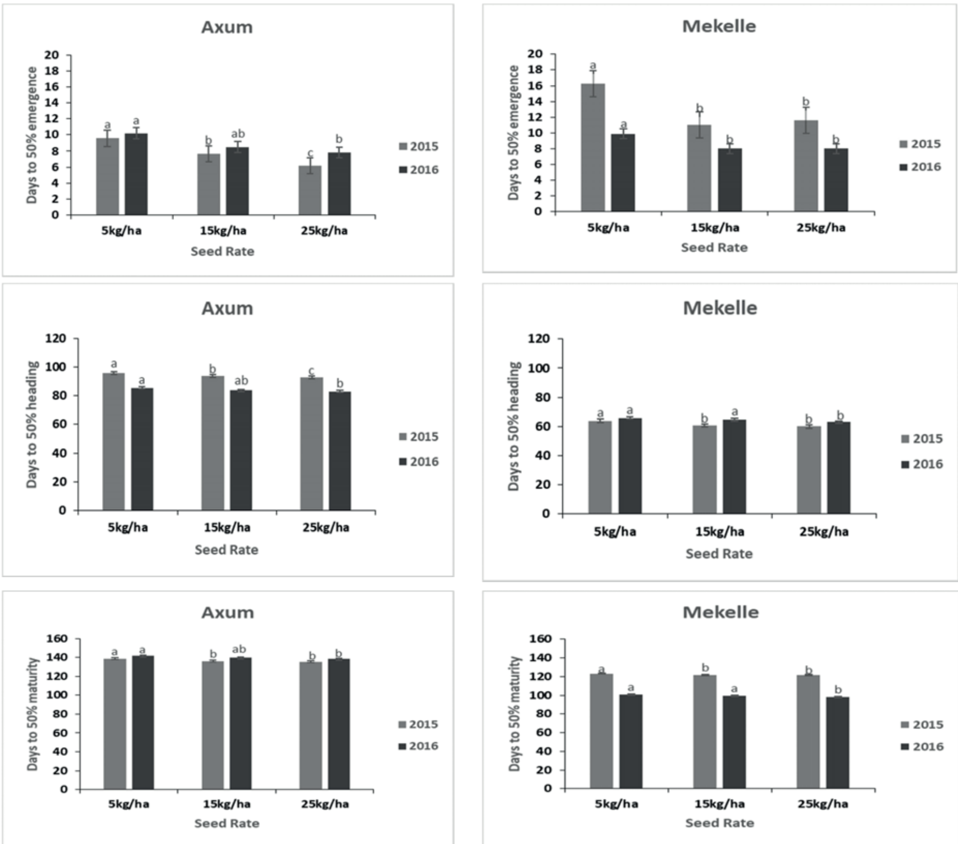

Figure 2. Effect of seed rate on days to 50% emergence, heading and maturity by year and location. Values with same letters within sub-figure and within year are not significantly different using Tukey multiple comparison method at 5 % level.

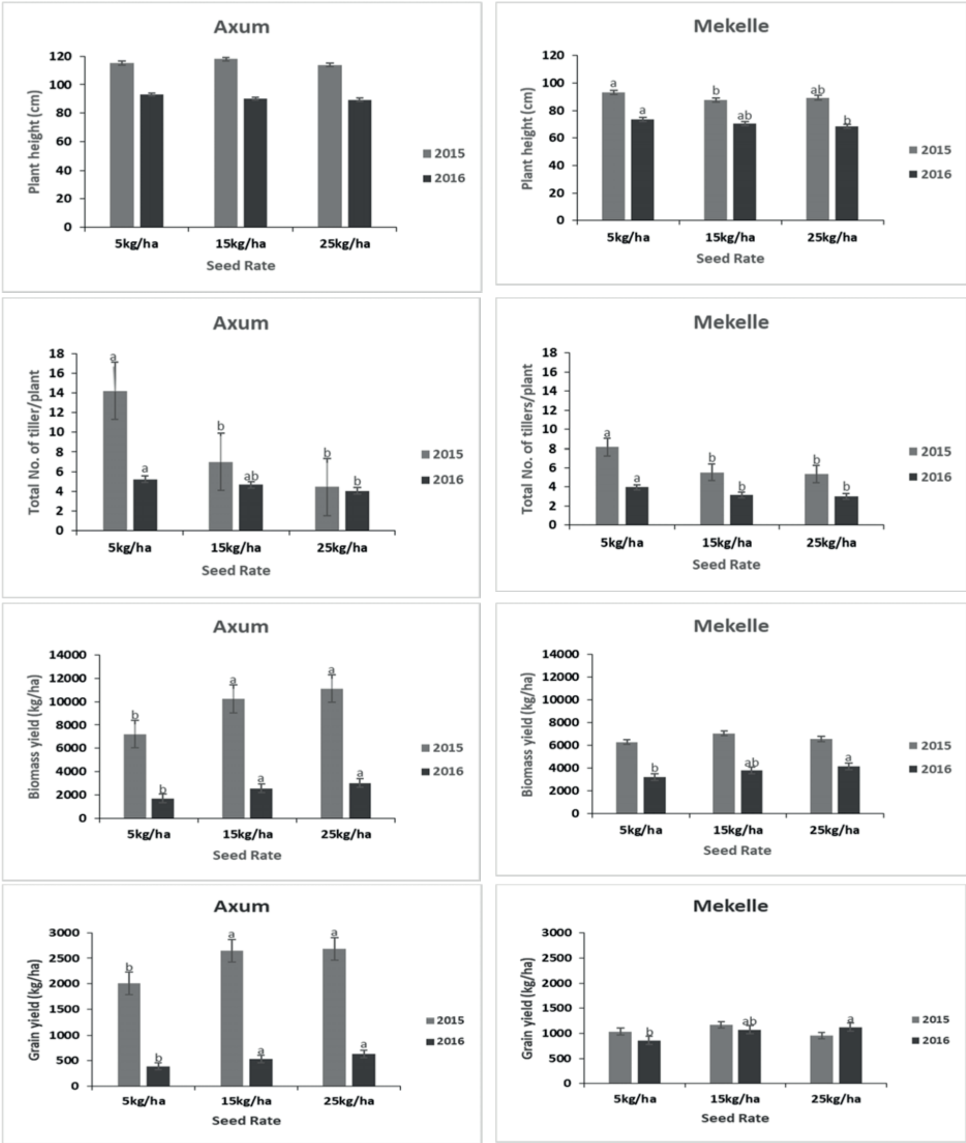

Figure 3. Effect of seed rate on yield and yield components of teff by year and location. Values with same letters within sub-figure and within year are not significantly different using Tukey multiple comparison method at the 5 % level.

Effects of tillage frequency, seed rate and application of glyphosate on weeds

In general there was a significant effect of tillage frequency, seed rate and application of glyphosate on weeds (Table 6) and very few of the interactions were significant. Hence, the presentation focus on effect of the main factors, and not the interactions.

Tillage frequency significantly affected weed density, dry weight and cover (Table 6). However, for dicot weeds, there was no effect of tillage frequency (Table 7). There was no significant difference between conventional and minimum tillage practices in overall weed density, biomass, and cover. Conventional tillage diminished total density, total dry weight and cover by 19.4 %, 29 % and 37 % respectively as compared to zero tillage and by 12.6 %, 15.4 % and 8.7 % as compared to minimum tillage. Tillage had stronger effect on monocot than on dicot weeds. Conventional tillage reduced monocot density by 19.6 % of the monocot density and monocot dry weight by 35.3 % compared to reduced tillage. It diminished dicot density by 19.2 % and dicot dry weight by 13.1 % compared to minimum tillage.

Seed rates significantly influenced weed density, dry weight and cover (Table 6). They also affected density of monocot weeds and dry weight of all types of weeds (Table 7). There was no significant difference between 15 kg/ha and 25 kg/ha seed rates on their effects on weed density, dry weight and cover. The highest seed rate (25 kg/ha) significantly reduced total weed density, total dry weight and cover by 17.5 %, 19.2 % and 15.04 % respectively as compared to the 5 kg/ha seed rate. Similarly, it decreased monocot and dicot weed dry weights by 18.1 % and 21.4 % respectively compared to the lowest seed rate.

Though it had a significant effect on weed cover, application of glyphosate did not significantly affect weed density (Table 6). However, the use of the herbicide significantly reduced monocot dry weight by 20.5 %, total dry weight by 14.2 % and cover by 15.8 % as compared with plots without glyphosate (Table 7).

Table 6. ANOVA table with P-values for the main and interaction effects on weeds

Factor Effect	Monocot Density (No./ m²)	Dicot Density (No./m²)	Total Density (No./m²)	Monocot Dry Weight (g/m²)	Dicot Dry Weight (g/m²)	Total Dry Weight (g/m²)	Weed Cover (%)
Tillage frequency (TF)	**0.0244**	**0.0474**	**0.0156**	**0.0416**	0.1382	**0.0437**	**<.0001**
Seed rate (kg/ha) (SR)	**0.0005**	0.0787	**0.0002**	**0.0495**	**0.0006**	**0.0306**	**0.0018**
TF*SR	0.1526	0.8219	0.3463	0.6657	0.929	0.815	0.6117
Glyphosate (Gp)	0.4051	0.2421	0.9783	**0.0113**	0.7496	**0.0195**	**<.0001**
TF*Gp	0.8774	0.6984	0.7746	0.1523	0.756	0.1394	**0.0008**
SR*Gp	0.9862	0.8023	0.918	0.1209	0.4954	0.135	0.9237
TF*SR*Gp	0.1232	0.3588	0.1877	0.2116	0.4317	0.2404	0.6636
Year (Yr)	**<.0001**	**0.0002**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
TF*Yr	0.0753	0.1275	0.1519	0.1529	**0.0499**	0.0563	0.7812
SR*Yr	0.0769	0.4865	0.0568	0.3198	0.0626	0.1079	0.8795
TF*SR*Yr	0.1834	0.2129	0.6696	0.5409	0.9368	0.5646	0.7234
Gp*Yr	0.9939	0.8569	0.9221	0.38	0.4673	0.2909	0.4267
TF*Gp*Yr	0.9275	0.9581	0.9674	0.4469	0.3607	0.693	0.346
SR*Gp*Yr	0.054	0.7309	0.2407	0.3874	0.7203	0.3185	0.2511
TF*SR*Gp*Yr	0.4945	0.4388	0.4044	**0.0155**	0.4647	**0.0445**	0.9951
Location (Loc)	**0.0007**	**<.0001**	**<.0001**	**0.0012**	**<.0001**	**0.0475**	**0.0013**
TF*Loc	0.3517	0.8527	0.3318	0.1942	0.4748	0.2839	**0.0002**
SR*Loc	0.9108	0.9955	0.9182	0.0623	**0.0017**	**0.0095**	0.1522
TF*SR*Loc	0.2071	0.6812	0.3211	**0.0294**	0.8568	**0.0286**	0.5448
Gp*Loc	0.5041	0.0863	0.1123	0.1512	0.5213	0.1306	**<.0001**
TF*Gp*Loc	0.7657	0.7835	0.6619	**0.0447**	0.1869	**0.0372**	0.1762
SR*Gp*Loc	0.8965	0.181	0.339	0.5362	0.8222	0.5651	0.5272
TF*SR*Gp*Loc	0.1146	0.5308	0.1838	0.6684	0.6769	0.5265	0.7083
Yr*Loc	**<.0001**	**<.0001**	**<.0001**	0.1768	**<.0001**	0.3996	**0.0158**
TF*Yr*Loc	0.209	0.2475	0.1557	0.5756	0.7027	0.6008	0.3584
SR*Yr*Loc	0.5201	0.1755	0.1993	0.2982	**0.0312**	0.0832	0.8676
TF*SR*Yr*Loc	**0.0429**	0.3019	0.1389	0.1211	0.7599	0.2074	0.1474
Gp*Yr*Loc	0.6524	0.494	0.4794	0.7145	0.9606	0.7101	0.4564
TF*Gp*Yr*Loc	0.5607	0.9804	0.6609	0.9926	0.2634	0.9224	0.2638
SR*Gp*Yr*Loc	0.2247	0.5608	0.1592	0.6896	0.6923	0.7943	0.9094
TF*SR*Gp*Yr*Loc	0.5371	0.8948	0.7608	0.4176	0.6843	0.3114	0.8757
Transformation	-	-	-	-	-	-	-
Types[a]	un	Ar(1)	un	un	un	Ar(1)	un

[a] *Among the commonly used serial structures used for correlations, "unstructured" (un, in SAS) was used. This was used during analysis because it resulted in models with lower values of Akaike Information Criterion (AIC) and Schwarz Bayesian Information Criterion (BIC)*

Table 7. Tillage frequency, seed rate and glyphosate main effects on weeds

Fixed Factors	Monocot Density (No./m²)	Dicot Density (No./m²)	Total Density (No./m²)	Monocot Dry Weight (g/m²)	Dicot Dry Weight (g/m²)	Total Dry Weight (g/m²)	Weed Cover (%)
Tillage Frequency							
Zero	128a	91a	219a	105a	42	147a	15a
Minimum	122ab	79ab	201ab	86ab	38	124ab	11b
Conventional	103b	73b	176b	68b	36	104b	10b
Seed Rate							
5kg/ha	135a	86	221a	93a	44a	137a	13a
15kg/ha	110b	84	194b	90ab	37b	127ab	12b
25kg/ha	108b	74	182b	76b	34b	110b	11b
Glyphosate							
Without	120	79	208	96a	38	134a	13a
With	115	84	199	77b	39	116b	11b

Means connected by the same letter and those not connected by any letters are not significantly different using Tukey's multiple comparison method with 5 % level

Time used for hand weeding

Weeding time was reduced by frequent tillage, high seed rate and application of glyphosate (Figure 4). The average weeding time with conventional, minimum and zero tillage was 3109 hrs/ha, 3355.3 hrs/ha and 3743.2 hrs/ha respectively. Zero tillage increased weeding time by 10.4 % as compared to minimum tillage and by 17 % as compared to conventional tillage. Weeding time with the different seed rates of 5, 15 and 25 kg/ha was 3352 hrs/ha, 3439 hrs/ha and 3547 hrs/ha respectively. Lower seed rate increased weeding time by 3 % as compared to 15 kg/ha seed rate and by 5.5 % as compared to the 25 kg/ha seed rate. Glyphosate application (3536 hr/ha) reduced weeding time by 7.5 % compared to plots without application (3270 hr/ha).

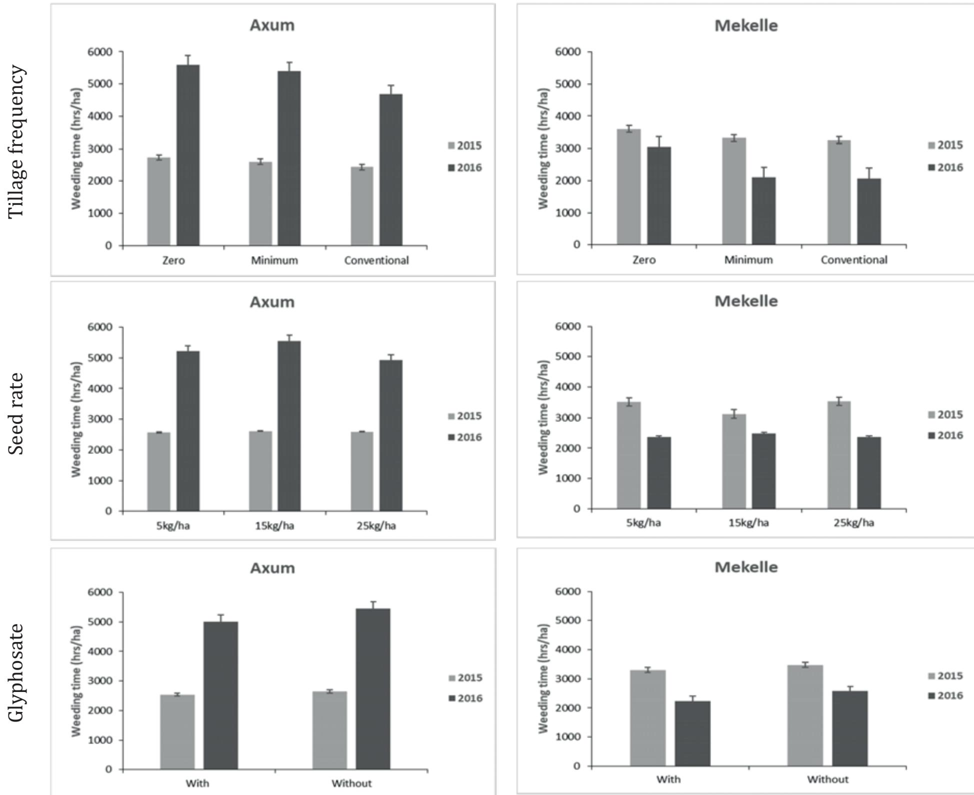

Figure 4. Effect of tillage frequency, seed rate and glyphosate on weeding time in two locations and seasons

Dominant Weeds

The most dominant weeds identified in the research sites were *Plantago lanceolate* L*. (dicot), Cyperus esculentus (monocot)* and *Setaria pumila* (poir.)Roem.&Schult (monocot) in *Axum* and *Avena abyssinica* Hochst (monocot)*, Galinsoga parviflora Ca (dicot)* and *Plantago lanceolate* L (dicot)*.* in *Mekelle*.

Discussion

Effects of tillage frequency, seed rate and application of glyphosate on teff

Teff phenology, days to 50% emergence, heading and maturity, was not influenced by tillage frequency. The small sized teff seeds are sown in the upper surface of the soil and one might expect that more intensive tillage made the seed bed drier and thus cause reduced or delayed seed germination. The seeds in our study, however, were broadcasted in a moist soil and water was not a constraint for germination and emergence. This is also probably the normal conditions for farmers sowing teff seeds in this region. This is in consistent with reports from other parts of Ethiopia as the crop is produced following almost the same agronomic procedures (Fufa et al. 2001; Tesfa et al. 2013).

Higher plant height, biomass yield and grain yield was obtained in conventional tillage most likely because of less weed infestation compared to less tillage frequency. Tillage intensity can, however, also influence soil physical, chemical and biological properties and hence can affect plant height, biomass yield and grain yield (Habtegebrial et al. 2007b; Leye 2007; Haftamu et al. 2009; Salem et al. 2015; Tesfahunegn 2015). A lower yield in zero and reduced tillage compared to traditional tillage have been reported in other studies conducted on teff and other cereal crops in Ethiopia (Assefa et al. 2008; Balesh et al. 2008; Sime et al. 2015).

The difference in teff seed rate significantly affected all crop traits including grain yield**.** This is in consistent with the results obtained from Bekalu and Arega (2016) and Amare and Adane (2015). From our study, the use of the lowest seed rate delayed teff emergence, flowering and maturity. However, there were taller plants with higher tiller number in plots with 5 kg/ha seed rate. This might be the result of less intra-species competition among teff plants for space allowing them to use soil water and nutrients efficiently. Faster germination at higher seed rates may be explained by greater strength to break through the soil surface crust when there is higher number of emerging shoots. As far as we know, there have been no previous experiments with different seed rates of teff and effects on weeds. A research group at the University of Copenhagen, however, have performed many studies of seed rates and different sowing pattern in other cereal species like wheat (Olsen et al. 2005; Olsen & Weiner 2007; Kristensen et al. 2008; Olsen et al. 2012). In their studies both increased seed rates and the use of uniform sowing patterns significantly increased grain yield and reduced weed growth.

Application of glyphosate did not change teff phenology, days to emergence, heading and maturity, and tiller number per plant significantly but increased biomass yield by 538 kg/ha and grain yield by 115.1 kg/ha, most likely due to less weeds in plots treated with glyphosate. In other words, it enhanced teff yields by about 10 %. Such an increase in yield was less compared to other studies stating that higher yield could be achieved from using the herbicide as described in Brookes et al. (2017)

Effects of tillage frequency, seed rate and application of glyphosate on weeds

All measured effects, except for dicot weed dry weight, showed more weeds at zero tillage compared to conventional tillage. This result is consistent with a huge number of other reports stating that weed incidence and infestation are higher in zero and minimum tillage (Assefa et al. 2008; Balesh et al. 2008; Sime et al. 2015) compared to more frequent soil tillage. Comparing the two weed classes, monocot weeds had a higher density and dry weight than dicot weeds, which may be connected to their general higher tolerance to soil tillage. Tørresen et al. (2003) found that the monocots, *Elymus repens* and *Poa annua,* as troublesome weeds in reduced tillage. Weed species such as *Cyperus esculentus* and *Setaria pumila* in Axum and *Avena abyssinica* in Mekelle regenerated after frequent ard ploughing in the conventional tillage. Studies have shown that these species are tolerant to frequent tillage (Swanton et al. 1993; Kaleb et al. 2003; Santín Montanyá & Catalán 2006; Nichols et al. 2015; Santín-Montanyá et al. 2018).

Seed rate influenced weed density, dry weight and cover significantly. The highest weed density, dry weight and cover were recorded from plots with the lowest seed rate, 5 kg/ha. Though there were a higher number of tillers per plant in the 5 kg/ha than the other seed rates (15 kg/ha and 25 kg/ha), they could not cover their space to sufficiently suppress the weed species. To achieve a comparable plot cover as of the higher seed rates, the number of tillers per plant from the lowest seed rate should have been significantly higher, and estimated to be 3-5 times. However, the number of tillers from the lowest teff plant density (8 tillers/plant) was higher by only 2.8 tillers (54.5 %) than the tillers from 15 kg/ha (5.2 tillers/plant) and only 3.7 tillers (87 %) than the tillers from a seed rate of 25 kg/ha (4.3 tillers/plant). This opened space for the weeds to grow and thereby increased weed density, dry weight and cover in the lowest teff plant population. Our result was consistent with studies on other pulse (Fieldpea) and cereal crops (winter and spring wheat) showing that increasing seed rate enhance their weed suppression and competition ability, which resulted in reduction of weed above ground dry weight (Townley-Smith & Wright 1994; Korres & Froud-Williams 2002; Kristensen et al. 2008).

There was a significant difference in weed dry weight and cover due to glyphosate application. Such an effect was not observed on weed density. Therefore, the effect of the herbicide was more on dry weight and cover than on weed density. Late emerging weed species probably reduced the effect of glyphosate on weed density. There were weed species, *Plantago lanceolata* and *Cyperus esculentus*, (Powles 2008b; ISHRW 2013) found to be glyphosate resistant in other places, emerged after spraying the herbicide in both years and locations. We, however, are highly unsure that these were resistant in our case. In any case, the herbicide was successful in weakening the ability of the weeds to utilize soil water and nutrients efficiently and hinder them from accumulating biomass (dry weight). This resulted in significant reduction of dry weight and cover of weeds.

Time used for hand weeding

Frequent tillage, higher seed rate and application of glyphosate reduced the time required for weeding. This is a result of more weed infestation in plot with zero tillage, low seed rate and without glyphosate application.

Conclusion

Frequent tillage reduced weed density, dry weight and cover while increased teff performance in terms of its phenology, plant height, tiller number per plant, biomass and grain yields. Hence, this supported the first hypothesis

Higher seed rate reduced weed incidence and enhanced teff vegetative and reproductive performance. Therefore, the second hypothesis was supported.

Applying glyphosate before teff sowing reduced weed incidence and enhanced teff vegetative and reproductive performance. Glyphosate application increased plant height, biomass yield, and grain yield while significantly reducing weed dry weight and cover. This supported the third hypothesis.

There was no synergy among the effects of tillage frequency, seed rate, and glyphosate application because the interaction effect of these three factors did not significantly influence teff and weeds. In this case, the fourth hypothesis was not supported.

Reference

Amare, A. & Adane, L. (2015). Determination of Seed Rate and Variety on the Growth and Yield of Teff in Eastern Amhara Region, Ethiopia. *Journal of Biology, Agriculture and Healthcare*, 5 (5): 27-33.

Assefa, A., Liben, M., Tadesse, T. & Yeshalem, B. (2008). The effect of tillage frequency and weed control on yield of tef (Eragrostis tef) in Yielmana-Densa Area, northwestern Ethiopia. *East African Journal of Science*, 2 (1): 35-40.

Assefa, G., Theodrose, T. & Alemu, D. (2016). Quantitative Determination of Weed Occurrence on Upland Rice of Bambasi, Ethiopia. *Ecology and Evolutionary Biology*, 1 (3): 53-56.

Astatke, A., Jabbar, M. & Tanner, D. (2003). Participatory conservation tillage research: an experience with minimum tillage on an Ethiopian highland Vertisol. *Agriculture, Ecosystems & Environment*, 95 (2): 401-415.

Aune, J., B., Matewos, T. B., Fenta, G. A. & Abyie, A. A. (2001). The OX Ploughing System in Ethiopia: Can it be Sustained? *Outlook on Agriculture*, 30 (4): 275-280.

Balesh, T., Aune, J. B., Johnsen, F. H. & Vanlauwe, B. (2008). The prospects of reduced tillage in tef (Eragrostis tef Zucca) in Gare Arera, West Shawa Zone of Oromiya, Ethiopia. *Soil and Tillage Research*, 99 (1): 58-65.

Bekalu, A. & Arega, A. (2016). Effect of Seed Rate on Yield and YieldComponents of Tef (Eragrostic tef) Trotter) at Shebedino, Southern Ethiopia. *Journal of Natural Sciences Research*, 6 (21): 6-11.

Bergkvist, G., Ringselle, B., Magnuski, E., Mangerud, K. & Brandsæter, L. O. (2017). Control of Elymus repens by rhizome fragmentation and repeated mowing in a newly established white clover sward. *Weed Research*, 57 (3): 172-181.

Boerboom, C. & Owen, M. (2013). Glyphosate-Resistant Weeds. In GWC (ed.) *The Glyphosate, Weeds, and Crops Series*, p. 8.

Brandsæter, L. O., Bakken, A. K., Mangerud, K., Riley, H., Eltun, R. & Fykse, H. (2011). Effects of tractor weight, wheel placement and depth of ploughing on the infestation of perennial weeds in organically farmed cereals. *European Journal of Agronomy*, 34 (4): 239-246.

Brookes, G., Taheripour, F. & Tyner, W. E. (2017). The contribution of glyphosate to agriculture and potential impact of restrictions on use at the global level. *GM crops & food*, 8 (4): 216-228.

CSA. (2016). *Agricutlrual Sample Survey 2015/2016 (2008E.C): Report on Area, Production and Farm Management Practice on Belg Season Crops for Private Peasant Holdings*, vol. V (5). Addis Ababa, Ethiopia: CENTRAL STATISTICAL AGENCY. 131 pp.

Deckers, J. A., Nachtergaele, F. O. & Spaargaren, O. C. (eds). (1998). *World Reference Base for Soil Resource: Introduction.* Acco Leuven/Amersfoort. Belgium. 165 pp.

Duke, O. S. & Powles, B. S. (2009). Glyphosate-resistant crops and weeds: now and in the future. *AgBioForum*, 12 (3&4): 346-357.

Esayas, T., Abraham, G. H. & Mashila, D. (2013). Weed Interference in Cotton (Gossypium hirsutum L.) in the Middle Awash, Ethiopia. *Ethio. J. Appl. Sci. Technol.*, 4: 41-49.

FAO. (2015). *World reference base for soil resources 2014: International soil classification system for naming soils and creating legends for soil maps*. World soil resources reports, vol. 106. Rome, Italy: Food and Agriculture Organization of the United Nations. 203 pp.

Fufa, H., Tesfa, B., Hailu, T., Kebebew, A., Tiruneh, K., Aberra, D. & Seyfu, K. (2001). Agronomy research in tef. In Hailu, T., Getachew, B. & Mark, E. S. (eds) *Narrowing the Rift: Tef*

Research and Development. Proceedings of the International Workshop on Tef Genetics and Improvement, pp. 167-176. DebreZeit, Ethiopia: DebreZeit Agricultural Research Center.
Habtegebrial, K., Singh, B. & Haile, M. (2007a). Impact of tillage and nitrogen fertilization on yield, nitrogen use efficiency of tef (Eragrostis tef (Zucc.) Trotter) and soil properties. *Soil and Tillage Research*, 94 (1): 55-63.
Habtegebrial, k., Singh, B. R. & Haile, M. (2007b). Impact of tillage and nitrogen fertilization on yield, nitrogen use efficiency of tef (Eragrostis tef (Zucc.) Trotter) and soil properties. *Soil and Tillage Research*, 94 (1): 55-63.
Haftamu, G., Mitiku, H. & 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 Sciences*, 1 (1): 82-94.
Heap, I. M. (1997). The occurrence of herbicide-resistant weeds worldwide. *Pest Management Science*, 51 (3): 235-243.
IFPRI. (2006). *Atlas of the Ethiopian Rural Economy*. Addis Ababa, Ethiopia: International Food Policy Research Institute and Central Statistical Agency. 1-108 pp.
ISHRW. (2013). *Herbicide Resistant Yellow Nutsedge (Cyperus esculentus)*. USA, Arkansas: International Survey of Herbicide Resistant Weeds. Available at: http://www.weedscience.org/Details/Case.aspx?ResistID=6752 (accessed: December 25, at 1:00AM).
Jaccard, P. (1912). The distribution of the flora in the alpine zone. *New phytologist*, 11 (2): 37-50.
Johnson, W. G. & Gibson, K. D. (2006). Glyphosate-Resistant Weeds and Resistance Management Strategies: An Indiana Grower Perspective. *Weed Technology*, 20 (3): 768-772.
Kaleb, B. H., Johnson, W. G. & Massey, R. E. (2003). Weed Management and Economic Returns in No-Tillage Herbicide-Resistant Corn (Zea mays). *Weed Technology*, 17 (2): 239-248.
Kassahun, Z. & Tebkew, D. (2013). Weed Research in Tef. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement*, p. 379. Stämpfli AG, 3001 Bern, Switzerland: Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; Institute of Plant Sciences, University of Bern, Switzerland.
Ketema, S. (1997). *Tef (Eragrostis tef (Zucc.) Trotter): Promoting the conservation and use of underutilized and neglected crops*, vol. 12. Rome, Italy: Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute.
Korres, N. E. & Froud-Williams, R. J. (2002). Effects of winter wheat cultivars and seed rate on the biological characteristics of naturally occurring weed flora. *Weed Research*, 42 (6): 417-428.
Kristensen, L., Olsen, J. & Weiner, J. (2008). Crop Density, Sowing Pattern, and Nitrogen Fertilization Effects on Weed Suppression and Yield in Spring Wheat. *Weed Science*, 56 (1): 97-102.
Leye, M. T. (2007). *Conservation Tillage Systems and Water Productivity-Implications for Smallholder Farmers in Semi-Arid Ethiopia: PhD, UNESCO-IHE Institute for Water Education, Delft, The Netherlands*: CRC Press.
Mupangwa, W., Mutenje, M., Thierfelder, C. & Nyagumbo, I. (2017). Are conservation agriculture (CA) systems productive and profitable options for smallholder farmers in

different agro-ecoregions of Zimbabwe? *Renewable Agriculture and Food Systems*, 32 (1): 87-103.

Nandula, V. K., Reddy, K. N., Duke, S. O. & Poston, D. H. (2005). Glyphosate-resistant weeds: Current status and future outlook. *Outlooks on Pest Management*, 16 (4): 183.

Neli, R.-A., María, J. A. & Verónica, B. R. (2017). Effect of glyphosate application on soil quality and health under natural and zero tillage field conditions. *Soil Environ.*, 36 (2): 141-154.

Nichols, V., Verhulst, N., Cox, R. & Govaerts, B. (2015). Weed dynamics and conservation agriculture principles: A review. *Field Crops Research*, 183: 56-68.

NMA. (2017a). Agromet Bega Assessment and Belg 2017 Outlook. *Agromet: National Meteorological Agency of Ethiopia*.

NMA. (2017b). *Annual Weather Report* Addis Ababa, Ethiopia: National Meteorological Agency

Nyssen, J., Poesen, J., Haile, M., Moeyersons, J. & Deckers, J. (2000). Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. *Soil and Tillage Research*, 57 (3): 115-127.

Olsen, J., Kristensen, L., Weiner, J. & Griepentrog, H. W. (2005). Increased density and spatial uniformity increase weed suppression by spring wheat. *Weed Research*, 45 (4): 316-321.

Olsen, J. & Weiner, J. (2007). The influence of Triticum aestivum density, sowing pattern and nitrogen fertilization on leaf area index and its spatial variation. *Basic and Applied Ecology*, 8 (3): 252-257.

Olsen, J. M., Griepentrog, H.-W., Nielsen, J. & Weiner, J. (2012). How Important are Crop Spatial Pattern and Density for Weed Suppression by Spring Wheat? *Weed Science*, 60 (3): 501-509.

Powles, S. B. (2008a). Evolution in action: glyphosate-resistant weeds threaten world crops. *Outlooks on Pest Management*, 19 (6): 256-259.

Powles, S. B. (2008b). Evolved glyphosate-resistant weeds around the world: lessons to be learnt. *Pest Management Science*, 64 (4): 360-365.

Rezene, F. & Zerihun, T. (2001). Weed Research in Tef. In Hailu, T., Getachew, B. & Mark, E. S. (eds) *Narrowing the Rift: Tef Research and Development. Proceedings of the International Workshop on tef Genetics and Improvement*, pp. 201-213. DebreZeit, Ethiopia: DebreZeit Agricultural Research Center.

Sakatu, H. & Adane, B. (2017). Evaluation of Fertilizer and Seed Rate Effect on Yield and Yield Component of Tef [Eragrostis tef (Zucc.) Trotter] on Vertisols in Central high-lands of Ethiopia. *Journal of Natural Sciences Research*, 7 (11): 25-31.

Salem, H. M., Valero, C., Muñoz, M. Á., Rodríguez, M. G. & Silva, L. L. (2015). Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. *Geoderma*, 237-238 (Supplement C): 60-70.

Santín-Montanyá, M., Catalán, G., Tenorio, J. L. & M. García-Baudín, J. (2018). *Effect of the tillage systems on weed flora composition*, vol. 69.

Santín Montanyá, I. & Catalán, G. (2006). Effect of the tillage systems on weed flora composition. In Cantero-Martínez, C. & Arrue Ugarte, J. L. (eds) Options Méditerranéennes : Série A. Séminaires Méditerranéens, vol. 69 *Troisièmes rencontres méditerranéennes du semis direct*, pp. 143-147: Zaragoza : CIHEAM.

Seneshaw, T., Minten, B., Alemu, D. & Bachewe, F. (2017). The Rapid Expansion of Herbicide Use in Smallholder Agriculture in Ethiopia: Patterns, Drivers, and Implications. *The European Journal of Development Research*, 29 (3): 628-647.

Sime, G., Aune, J. B. & Mohammed, H. (2015). Agronomic and economic response of tillage and water conservation management in maize, central rift valley in Ethiopia. *Soil and Tillage Research*, 148: 20-30.

Swanton, C. J., David, R. C. & Douglas, A. D. (1993). Weed Succession under Conservation Tillage: A Hierarchical Framework for Research and Management. *Weed Technology*, 7 (2): 286-297.

Tarekegne, A., Gebre, A., Tanner, D. G. & Mandefro, C. (1996). Effect of Tillage Systems and Fertilizer Levels on Continous Wheat Production in Central Ethiopia. In Tanner, D. G., Payne, T. S. & Abdalla, O. S. (eds) *Proceeding of the The Ninth Regional Wheat Workshop for Eastern, Central and Southern Africa*, pp. 56-63. Addis Ababa, Ethiopia: CIMMYT.

Taye, T. & Yohanes, L. (1998). Qualitative and quantitative determination of weeds in tef in West Shewa Zone. *Arem (Ethiopia)*.

Teamti, T. & Tesfay, A. (2016). Farmers' Perception on Glyphosate Application in Conservation Agriculture System of Northern Ethiopia. *International Journal of African and Asian Studies*, 17: 31-35.

Teklay, T. & Girmay, G. (2016). Agronomic and economic evaluations of compound fertilizer applications under different planting methods and seed rates of tef [eragrostis tef (zucc.) trotter] in northern ethiopia. *Journal of the Drylands*, 6 (1): 409-422.

Tesfa, B., Solomon, J., Yifru, A., Minale, L. & Waga, M. (2013). Crop Management Research for Tef. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement: Proceedings of the Second International Workshop, November 7-9, 2011, Debre Zeit, Ethiopia*, p. 379. Stämpfli AG, 3001 Bern, Switzerland: Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; Institute of Plant Sciences, University of Bern, Switzerland.

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 (Supplement C): 241-249.

Tigist, O., Cornelis, W. M., Verplancke, H., Nyssen, J., Govaerts, B., Behailu, M., Haile, M. & Deckers, J. (2010). 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.

Tørresen, K. S., Skuterud, R., Tandsæther, H. J. & Hagemo, M. B. (2003). Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. *Crop Protection*, 22 (1): 185-200.

Townley-Smith, L. & Wright, A. T. (1994). Field pea cultivar and weed response to crop seed rate in western Canada. *Canadian Journal of Plant Science*, 74 (2): 387-393.

PAPER III:

G. Haftamu, J.B. Aune, J. Netland, O.M. Eklo, T. Torp and L.O. Brandsæter. Weed competitive ability of teff varieties. Manuscript.

Weed competitive ability of teff varieties

G. Haftamu [ab], J.B. Aune[c], J. Netland[d], O.M. Eklo[bd], T. Torp[d] and L.O. Brandsæter[bd]

[a] Mekelle University, College of Dryland Agriculture and Natural Resources, P.O.Box 231, Mekelle, Tigray, Ethiopia
[b] Norwegian University of Life Sciences, Department of Plant Sciences (IPV-NMBU), P.O. Box 5003, NO-1432 Ås, Norway
[c] Norwegian University of Life Sciences, Department of International Environment and Development Studies (Noragric-NMBU), P.O. Box 5003, NO-1432 Ås, Norway
[d] Norwegian Institute of Bio-economy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway

Abstract

Teff adapts to wider climatic and edaphic conditions in Ethiopia. It has vast phenotypic and genotypic diversity. Different teff varieties have been developed, released and used in the country. The crop is challenged by different types of weeds during production. However, the ability of these varieties to compete weeds is not yet known. Experiments were conducted in 2015 and 2016 in two locations, Axum and Mekelle, with a general objective to study the weed competitive ability of different teff varieties. Hand weeding (with and without) and ten teff varieties were considered as factors and arranged in a split plot design with three replications. The design had weeding as main plot and teff varieties as a subplot. Results showed that hand weeding had significant effect on most of teff agronomic traits and weeds. It increased biomass yield by 15 %, grain yield by 32 % and reduced weed density by 22.7 %, dry weight by 39.6 % and cover by 37.4 %. Varietal difference resulted in significant variation in overall teff performance and weed responses. Weed density, dry weight and cover were higher in plots with DZ-Cr-358 and DZ-01-354 and significantly lower in plots with 'Kora' and 'DZ-Cr-387'. Based on the performance of the varieties and weed responses, 'Kora' and 'DZ-Cr-387' were more competitive to weeds while 'DZ-Cr-358' and 'DZ-01-354' were the least competitive varieties. There was yield loss from all varieties during weed competition. The least yield losses were recorded from the varieties 'Kora' (with loss of 6 % in biomass yield and 18 % in grain yield) and 'DZ-Cr-387' (with loss of 17 % in biomass yield and 21 % in grain yield and remained high yielding in unweeded plots while significantly reducing weed density, dry weight and cover. Such a yield loss from 'Kora' and 'DZ-Cr-387' was trade-off between their yields potential and weed competitiveness. Considering the weeding time, the longest time was recorded in Mekelle with an average of 1950 hrs./ha in 2015.

Key words: Teff, Teff varieties, Weeds, Weed competitive ability

Introduction

Teff adapts to a range of climatic and edaphic conditions in Ethiopia. It grows from the sea level to as high as 3300 m a.s.l though it performs best at an altitudinal range from of 1500 to 2300 m a.s.l (IFPRI 2006). The crop has a broad phenotypic and genetic diversity, which enables it to adapt to harsh environments (Ketema 1997; Adnew et al. 2005; Assefa et al. 2015a). Being a staple food to more than 60 % of population in Ethiopia, around 3 million hectares of the arable land (21.4 % of the total area for grain crops and 27.4 % of the total area for cereal crops) is allocated to teff production (CSA 2016).

Teff shows a high diversity at different development stages in morphological, physiological and phenological traits. Most of the varieties differ widely in seed color and seed emergence, panicle type and length, tillering potential, plant height, leaf area, flowering and maturity, lodging potential and overall dry weight (Ketema 1997; Adnew et al. 2005; Assefa et al. 2015a). These traits also enable teff to adapt to various moisture conditions and can perform well under both drought and water logging conditions (Ketema 1997; Assefa et al. 2015a).

Teff varieties adapted to highlands with high moisture and lower temperature mostly have taller straw with longer panicles, higher tillering potential, later emergence and maturity, higher biomass and grain yield (Ketema 1997; Adnew et al. 2005; EMAaRD 2014; Assefa et al. 2015a). On the other hand, teff varieties adapted to arid and semiarid low lands commonly have shorter straw and panicles, lower tillering potential, early emergence and maturity, erect growth habit (low lodging), lower biomass and grain yields (Ketema 1997; Adnew et al. 2005; EMAaRD 2014; Assefa et al. 2015a). However, teff can have a robust vegetative growth with higher tillering potential, early emergence but late maturity, higher lodging, higher biomass and grain yield in humid lowland areas dominantly with irrigated arable lands (Ketema 1997; Kebebew et al. 2011; EMAaRD 2014; Kebebew et al. 2017). Its wide adaptation to different agroecological conditions makes teff exposed and vulnerable to various weed species (Ketema 1997; Teklu & Tefera 2005; IFPRI 2006; Baye 2014; Assefa et al. 2015b; Daniel et al. 2016).

There are many direct and cultural control methods used by farmers to reduce weed competition such as frequent tillage, hand weeding, and use of weeds as forage and thereby increase crop yield and enhance their economic outcome. Some control methods, however, have potential disadvantages. One of them, such as use of herbicides, may not be economically affordable to most small scale farmers and can have health risk to the farming community during and after spray. As a solution to these challenges, there is an increasing interest of integrated non-chemical control options such as the use of competitive varieties. The use of competitive crop varieties offer a cheap option to include in weed management strategies. In contrast to increasing knowledge about the potential for competitive varieties in cereal crops as reviewed by Andrew et al. (2015) in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.), no studies so far have focused on the potential of using competitive teff varieties.

Andrew et al. (2015) divided variety competitiveness in two aspects, (i) the ability of the crop to reduce the fitness of a competitor, and (ii) the ability of the crop to withstand the competitive impact of neighbours and resist yield loss. They indicated that these aspects are referred to different terms in the literature, and described, respectively, as 'suppressive ability' and 'tolerance ability' in the same way Hansen et al. (2008) explained. Similar to the definition used by Violle et al. (2007) and Andrew et al. (2015), we will, in this paper, use the term 'traits', this term being reserved for any feature that is morphological, physiological or phenological characteristics of cereal crops and can be identified and measured at the level of the individual crop plant.

Several traits may explain differences in suppressive or tolerance ability between cereal species (Andrew et al. 2015). The height of the cereal varieties have been included in numerous studies. Wicks et al. (2004) compared winter wheat varieties in their ability to suppress weeds and found a negative correlation between total weed number and plant height. Another finding in their study, however, was that two relatively short varieties suppressed the weeds more than many of the taller varieties. As Andrew et al. (2015) summarized, this was an indication that competitive ability cannot be attributed to a single trait. Another group of traits that frequently explain differences among varieties are different indicator traits of early vigour, including fast germination, early crop height, cover and biomass. Bertholdsson (2005) found that early cover, but also allelopathic potential, explained differences between varieties significantly both in barley and wheat. Tillering, canopy architecture and belowground biomass may contribute to variety differences in relation to their weed competitive ability (Andrew et al. 2015).

Another aspect is the trade-off between yield potential and weed competition. Traits or plant functions that can increase the ability of varieties to suppress weeds persistently need energy allocated from the crop plants during growth and development which would have been required to achieve their final yield potential. Such an energy requirement resulted in decrease of crop yield potential (Olofsdotter et al. 2002; Andrew et al. 2015). As far as we know, no studies have been done clarifying whether this trade-off is also true for teff varieties.

The hypothesis of our study were:

1. There are differences between teff varieties for traits commonly considered as important for variety competitiveness in other cereal species
2. Weeds respond to various teff varieties differently
3. There is a trade-off between yield potential and weed competitiveness in teff varieties
4. Variety competitiveness influence weeding time of teff.

Material and methods

Description of the study areas

Axum Research Site

Axum is located 245 km northwest of the Mekelle (capital of Tigray region). The research site is located 4km east of the Axum town and the experiments were laid on deep black vertic soils with small patches of Cambisol with sandy clay texture (soil description was made based on WRB 2014 as in FAO (2015)). The experimental fields were located on 14°07'37"N and 38°45'51"E at an altitude of 2098 m a.s.l. It has tepid to cool sub-moist mid-highlands agroecological classification with an annual rainfall ranging from 401-800 mm, temperature ranges from 15 – 28 °C.

Mekelle Research Site

This site was at the Mekelle University main Campus. It is located at 13°28′48″N and 39°29′25″E at an altitude of 2224 m a.s.l. The soil at the site is characterized as Cambisol dominated by sandy loam texture with patches of Vertisols (soil description was made based on WRB 2014 as in FAO (2015)). It has a moderate temperature with annual minimum temperature of 12 °C and maximum temperature of 30 °C where its average temperature is around 20 °C. The site receives an annual rainfall ranging from 400 mm to 600 mm (NMA 2017a).

Climate in 2015 and 2016

In both *Axum* and *Mekelle*, the highest rainfall is commonly recorded in July and August. The warmest months are April, May and June.

Table 1. Rainfall, minimum temperature and maximum temperature in Axum and Mekelle during 2015 and 2016

Location	Year	Rainfall (mm)	Min. Temperature (°C)	Max. Temperature (°C)
Axum	2015	725	11	27
	2016	675	11	27
Mekelle	2015	580	11	28
	2016	560	11	28

Source: (NMA 2017b).

Experimental design and treatments

The experiment had a split plot design with two levels of weeding (without weeding and hand weeding) on the main plots and the ten teff varieties as sub plot treatments arranged in three blocks. Both main- and sub-plots were randomized independently. The plot sizes were 2 m by 3 m for sub plot and 2 m by 39 m for the main plot. There were a distance of 1 m space between the subplots, 1 m between main plots within blocks and 1.5 m between blocks to control border effect (avoiding mixture of the seeds from plots each teff varieties).

These teff varieties are commonly used by teff farmers in Ethiopia and are adopted from the lowlands (below 1500 m a.s.l.) to the extreme highlands (as high as 3200 m a.s.l.). The management and assessment operations of these teff varieties are described in table 3. Most of these dates during which the crop and weed management operations conducted were within the range of most of the periods (teff cropping calendar) commonly used by farmers in Tigray, Northern Ethiopia particularly the farmers in the experimental sites. Thorough follow up and management of the experiments had been done by the researchers.

Table 2. General description of the teff varieties used for the experiments

R.No.	Varieties	Year of Release	Seed Color	Maturity (Days)	Height (cm)	On-Station Yield (kg/ha)	On-farm Yield (kg/ha)	Yield Gap (kg/ha)
1	Boset	2012	Very White	75-86	75-90	1800 - 2000	1400 - 1800	0 - 400
2	DZ-01-1681	2002	Dark Brown	84-93	74-85	2500	1600 - 2000	500 - 900
3	DZ-01-2675	2004	Pale White	112-123	47-91	1800 - 2800	1600 - 2000	200 - 800
4	DZ-Cr-387	2005	White	86-151	72-104	2500 - 2700	1600 - 2000	700 - 900
5	DZ-01-974	1995	White	76-138	84-123	2400 - 3400	2000 - 2500	400 - 900
6	DZ-Cr-385	2009	White	65-88	82-90	1600	1000	0 - 600
7	DZ-01-354	1970	Pale White	85-130	53-115	1800 - 2800	1800 - 2200	0 - 600
8	DZ-Cr-358	1995	White	76-138	70-109	2100 - 3600	1800 - 2400	3000 - 1200
9	Kora	2012	White	88-95	90-110	2400 - 3400	2000 - 2500	400 - 900
10	Local	A land race with no known phenotypic and genetic description but commonly sown by the farmers around the experimental sites (used as a control). It is considered as the most adaptable to the condition of the research sites as it is produced by the farmers for more than a decade.						

Source: (EMAaRD 2014)

Table 3. Description of crop and weed management and assessment operations in the two experimental sites

Operations	2015	2016
Axum research site		
First plowing	12-May	15-May
Second plowing	6-Jun	3-Jun
Third plowing	3-Jul	30-Jun
Fourth plowing	20-Jul	18-Jul
Seed bed preparation and field designing	20-Jul	18-Jul
Field fertilizing* and sowing**	20-Jul	18-Jul
Crop assessment	27 July - 21 Nov.	25 July - 29 Nov.
Weed assessment		
First weeding and assessment	18 Aug.	21 Aug.
Second weeding and assessment	30 Sep.	02 Oct.
Third weeding and assessment	18 Nov.	25 Nov.
Crop harvesting	20 Nov.	29 Nov.
Crop and weed biomass measurement	03 Dec.	8 Dec.
Crop threshing and grain weighing	03-05 Dec.	08 - 12 Dec.
Mekelle research site		
First plowing	23-May	25-May
Second plowing	21-Jun	26-Jun
Third plowing	25-Jul	29-Jul
Seed bed preparation and field designing	25-Jul	29-Jul
Field fertilizing* and sowing**	25-Jul	29-Jul
Crop assessment	03 Aug - 07 Dec.	08 Aug. -09 Dec.
Weed assessment		
First weeding and assessment	02 Sep.	04 Sep.
Second weeding and assessment	28 Sep.	04 Oct.
Third weeding and assessment	26 Nov.	25 Nov.
Crop harvesting	30 Nov.	01 Nov.
Crop and weed biomass measurement	07 Dec.	9 Dec.
Crop threshing and grain weighing	07-12 Dec.	09 - 12 Dec.

**Fertilizing of field was done by applying DAP (Di-ammonium Phosphate and Urea at a rate of 60kgN/ha and 60kgP_2O_5 for black Vertic soils and 40kgN/ha and 40kgP_2O_5 for light sandy loam soils. Axum had Vertic black soils and Mekelle has light sandy loam soil type; **Sowing was done at a nationally recommended seed rate i.e. 25kg/ha*

Data collection

The collected data can be classified within three classes i.e. (i) data related to crop traits, (ii) weed data and (ii) data related to weeding time.

i) Data related to crop traits

The crop data includes crop phenology (days to emergence, heading/flowering and maturity), tillering (total tiller number/plant), plant height, biomass yield, and grain yield. The phenology data were obtained by recording the dates when the teff plants covered 50% of the plot area emerged, flowered and matured. Tillering and plant height were measured by taking randomly 10 teff plants from each plot and averaged the values. Tillering was recorded by counting the number of tillers in a single teff plant. Plant height (i.e. height of the teff plant from node separating root and shoot until the tip of the panicle) were measured using *meter* and *centimetre* graduated flexible metal. Biomass yield is the sum of the straw or the vegetative part and the seed/grain or the reproductive part of the crop plant.

ii) Effects of different teff varieties on weeds

Density and biomass

Weed shoot density and aboveground weed biomass were assessed three times before harvest in one randomly placed quadrate (25 cm * 25 cm) per plot.

Weed density or infestation was estimated visually (coverage) by weeding time (first, second and third weeding). The space occupied by the crop and the most abundant weed species on all small plots was expressed as percentage ground coverage. The area covered by crop, weed species and bare soil was summed up to 100%. The biomass samples were dried at 65^0C for 48 h to determine the dry weight.

Identification of Dominant Weed Species

From all part of the experiment fields in both *Axum* and *Mekelle*, 12 samples were taken randomly using 50 cm x 50 cm quadrate before sowing. The weed species were identified and counted from each samples**.** Six weed species from *Axum* and five weed species from *Mekelle* were identified and their frequency, abundance and dominance were calculated based on the most commonly used procedures (Jaccard 1912; Taye & Yohanes 1998; Esayas et al. 2013; Assefa et al. 2016). The first three weed species from each location had the highest values of frequency, abundance and dominance and considered as the dominant weed species in the experimental areas of both locations.

iii) Trade-off between yield potential and weed competitiveness

The concept of trade-off, in our study, had been adopted from Andrew et al. (2015). They stated that there is trade-off between yield potential and weed competitiveness when there is less yield loss from crop varieties incurred as a cost of their competition with weeds. Yield potential of teff varieties, in our study, was referred to the yield obtained from plots with hand weeding and receiving all the recommended teff agronomic practices applied under the prevailing seasonal climatic conditions. Weed competitiveness of varieties was measured in terms their ability to reduce weed density, dry weight and cover in time of weed infestation during production. To observe if there is trade-off between yield potential and weed competitiveness of varieties, yield difference between the weeded and unweeded plots had been calculated for each varieties to determine the loss due to weed competition in those plots without hand weeding. We setup the following formula to calculate the loss in yields of the varieties:

$$Yield\ loss\ (\%) = \frac{\left(Yield\ \left(\frac{kg}{ha}\right) from\ weeded\ plots\right) - \left(yield\ \left(\frac{kg}{ha}\right) from\ unweeded\ plots\right)}{\left(yield\ \frac{kg}{ha}\right) from\ weeded\ plots)} X\ 100$$

The yield loss of each varieties and the weed response had been compared to decide if there was a trade-off between yield potential and weed competitiveness of the varieties.

iv) Weeding time and competitiveness on teff

Estimation of hand weeding time

This estimation was based on the weeding time of a single person required to hand weed the 6 m^2 subplots. This is recorded as minutes/person/plot and is averaged from all replications and weeding times of the experiment in each location. This average value of the weeding time was converted into hours/ha.

Data analysis procedures

Combined analysis of the teff variety experiments was done by year and location. MIXED procedure of SAS (SAS version 9.4) was used. The crop data included hand weeding, variety, year and location as factors. The weed data included in addition – weeding frequency (weeding time – first, second and third). All factors from both data groups were considered as fixed. Weed assessment was taken in a successive two years and three weeding times. A repeated measurement mixed model was used during weed data analysis to observe if there is correlation among the assessments recorded in the different times. For the correlation analysis, two widely known serial structures – unstructured (un) and first-order autoregressive (ar(1)) model structures were used. The final model for the analysis was chosen based on the Akaike information criterion (AIC) and Schwarz Bayesian Information Criterion (BIC). The model with the lowest AIC and BIC value was considered as a final model for analysis. Model assumptions for the split plot analysis (i.e. normal distributed and errors are independent with homogeneous variances) and any outliers within the dataset were checked using standardized residual plots generated during analysis. These plots were composed of normal probability plots and those plots with residuals versus fitted values of the response variables. The least square means of factors were separated using Tukey-Kramer at 5% levels of significance.

Result

Traits of teff varieties

All main factors, hand weeding, variety, year and location, appeared significant for all crop traits with exception of location and the trait grain yield (Table 2). Because the two factor interactions, variety*year, variety*location and year*location, for most crop traits also were significant (Table 4) the analyses afterwards was done separately for locations and years (Table 5). There are results from these analyses, separated in sites and years, which are presented further.

Emergence and maturity

There was variations in days to emergence among the varieties in both locations and years (Table 5). The general picture was that the varieties belonged to two groups, one big group with e.g. '*Boset*' that was early emerging, and the second group of '*DZ-01-354*' and '*DZ-Cr-358*' with late emerging varieties (Figure 1). The least number of days taken to emerge was 5.7 by '*Boset*' in both Axum and Mekelle in 2016, and the highest number of days to emergence was 16 by '*DZ-Cr-358*' in Mekelle in 2015.

Difference among the teff varieties was observed in days to maturity (Table 4). The early emerging variety '*Boset*' matured in most cases significantly earlier than the other teff varieties. '*Boset*' took, on average, 90 days in Axum and Mekelle in 2015 and 2016 (Figure 1). Both '*DZ-01-354*' and '*DZ-Cr-358*' matured later, but not always significantly later than the other varieties. The variety '*DZ-01-354*' took on average of 112 days to maturity, and that of '*DZ-Cr-358*' on average of 113.5 days (Figure 1). Weeding had significant effect on days to maturity of the crop (Table 4). Early maturity of teff was observed in unweeded plots taking an average of 106.5 days compared to 109 days the crop took in weeded plots.

Plant height

The teff varieties differed in plant height (Table 4). The varieties '*Boset*' and '*DZ-01-1681*' had, although not always significantly, the shortest plant height with an average value of 76 cm across locations and seasons (Figure 1). Taller plants were observed from the varieties '*DZ-Cr-387*' and '*DZ-01-974*' having an average value of 97 cm. Teff plants was taller (on average 93 cm) on unweeded plots as compared to 89 cm in plots with hand weeding.

Tiller number per plant

The varieties '*DZ-Cr-358*' and '*DZ-01-354*' had the highest number of tillers per plant with average values of 5.82 and 4.48 respectively, but only '*DZ-Cr-358*' in weeded plots in *Axum* 2015 had significantly more tillers than all the others. Except in 2016 in Mekelle, tillering of the varieties was significantly different in all the locations and seasons (Table 5). The teff varieties '*DZ-Cr-358*' and '*DZ-01-354*' had the highest number of tillers per plant in both Axum and Mekelle in 2015 and 2016 on weeded plots (Figure 2). Hand weeding significantly affected number of tillers per plant (Table 4). Higher number of total tillers per plant was observed in weeded plots with average value of 4.53, which was 28.3 % higher than that from the unweeded ones.

Biomass yield and grain yield

Teff varieties were different in biomass and grain yield (Table 4). They also showed significant difference in Axum and Mekelle in both 2015 and 2016 (Table 5). The varieties '*DZ-Cr-358'* and '*DZ-01-354'* had the least biomass and grain yield (Figure 3). In particular '*DZ-Cr*-358' showed significantly lower biomass and grain yield values compared to most other varieties. The average biomass yields of '*DZ-Cr-358'* i.e. 4223.6 kg/ha and '*DZ-01-354'* i.e. 5286.8 kg/ha were 48 % and 35 % respectively lower than the highest yielding variety '*Kora'* having an average biomass yield of 8118.1kg/ha (Figure 3). Similarly, the average grain yield of '*DZ-Cr-358'* i.e. 813.2kg/ha and '*DZ-01-354'* i.e. 1001kg/ha were 40.4 % and 26.6 % respectively lower than the highest yielding variety '*Kora'* having an average grain yield of 1364.1 kg/ha (Figure 3). Generally, the varieties had higher biomass and grain yields in Axum than in Mekelle (Figure 3). At the same time, they had higher biomass and grain yields in 2015 than in 2016 except in some varieties (Figure 3). Weeding had significant effect on these yields with the highest being recorded from plots with hand weeding. Teff biomass yield harvested from weeded plots, 7295 kg/ha, was 15.3 % higher than the yield obtained from the plots without weeding. Average grain yield i.e.1448 kg/ha from weeded plots, was 32 % higher than that obtained from plots without hand weeding.

Table 4. ANOVA table with P-values for the main factors hand weeding, teff variety, year and location, and their interactions, on different teff traits.

Fixed factors	Teff traits					
	Days to emergence	Days to maturity	Plant Height (cm)	Total tiller No. plant^{-1}	Biomass Yield (kg ha^{-1})	Grain Yield (kg ha^{-1})
Hand weeding[a] (HW)**		0.0256*	<.0001***	<.0001***	<.0001***	<.0001***
Variety (VAR)	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***
HW*VAR		0.6599ns	0.1239ns	0.0001***	0.6068ns	0.3965ns
Year (YR)	<.0001***	<.0001***	<.0001***	<.0001***	0.0007***	0.0797ns
HW*YR		0.2979ns	0.0121*	0.0005***	<.0001***	<.0001***
VAR*YR	<.0001***	<.0001***	0.0049**	<.0001***	<.0001***	<.0001***
HW*VAR*YR		0.8387ns	0.824ns	<.0001***	0.3227ns	0.1585ns
Location (LOC)	<.0001***	0.0012**	<.0001***	<.0001***	<.0001***	0.4654ns
HW*LOC		0.0699ns	0.6995ns	0.0181*	0.9343ns	0.5317ns
VAR*LOC	<.0001***	<.0001***	0.0162*	0.3026ns	0.8262ns	0.7325ns
HW*VAR*LOC		0.6255ns	0.6381ns	0.2726ns	0.6335ns	0.2716ns
YR*LOC	<.0001***	<.0001***	<.0001***	0.4889ns	<.0001***	0.005**
HW*YR*LOC		0.2449ns	0.4912ns	0.7361ns	0.0148*	0.024*
VAR*YR*LOC	<.0001***	<.0001***	0.016*	0.3669ns	0.0131*	0.2639ns
HW*VAR*YR*LOC		0.8457ns	0.3339ns	0.6737ns	0.6299ns	0.8752ns
Transformation of Y	-	-	-	-	-	-
Type[b]	-	un	un	un	un	un

**significant at $P < 0.05$, **significant at $P < 0.01$, ***significant at $P < 0.001$, ns not significant; [a]Hand weeding – refers to uprooting of weeds from the field of the crop (Teff) using hand; **Hand weeding did not have an effect on days to emergence as it was applied after teff sprouting [b] Among the commonly used serial structures used for correlations, "unstructured" (un, in SAS) was used. This was used during analysis because it resulted in models with lower values of Akaike Information Criterion (AIC) and Schwarz Bayesian Information Criterion (BIC)*

Table 5. ANOVA table with P-values for the main factors hand weeding and variety on different teff traits.

Crop (teff) Responses	Fixed Factors											
	Axum						Mekelle					
	2015			2016			2015			2016		
	Hand weeding (HW)	Variety (VAR)	HW x VAR	Hand weeding (HW)	Variety (VAR)	HW x VAR	Hand weeding (HW)	Variety (VAR)	HW x VAR	Hand weeding (HW)	Variety (VAR)	HW x VAR
Days to 50% Emergence		<.0001***			<.0001***			<.0001***			<.0001***	
Days to 50% Maturity	0.0634ns	<.0001***	<.0001***	0.436ns	<.0001***	0.7895ns	0.0056**	<.0001***	0.915ns	0.0574ns	<.0001***	0.4818ns
Plant Height (cm)	0.0002***	<.0001***	0.962ns	0.3788ns	<.0001***	0.5385ns	0.0005***	<.0001***	0.0181*	0.0946ns	<.0001***	0.6292ns
Total tiller No./Plant	0.0005***	<.0001***	<.0001***	0.1181ns	0.004**	0.0244*	<.0001***	0.0003***	0.0245*	<.0001***	0.931ns	0.6258ns
Crop biomass (kg ha-1)	<.0001***	<.0001***	0.4988ns	0.0105*	<.0001***	0.7955ns	<.0001***	<.0001***	0.231ns	0.9559ns	0.1138ns	0.1627ns
Grain Yield (kg/ha)	<.0001***	<.0001***	0.6986ns	0.8003ns	0.2931ns	0.8378ns	0.0149*	<.0001***	0.1626ns	0.2522ns	0.5321ns	0.4654ns

**significant at P < 0.05, **significant at P < 0.01, ***significant at P < 0.001, ns not significant; Hand weeding – refers to uprooting of weeds from the field of the crop (teff) using hand.*

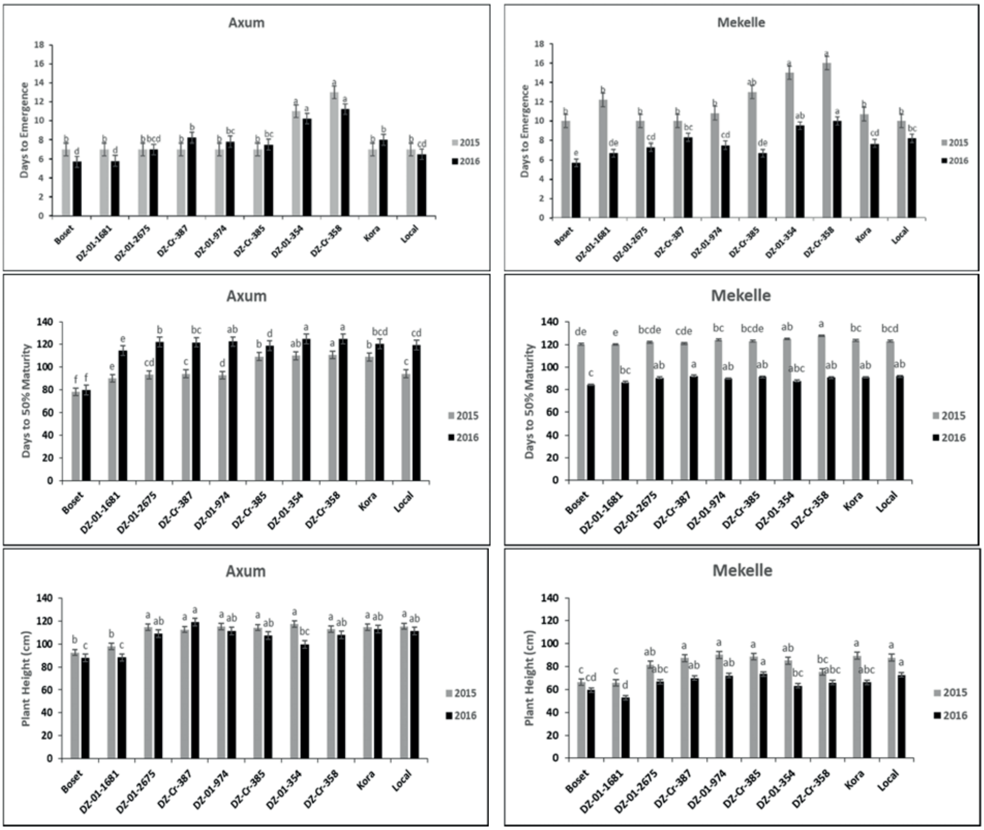

Figure 1. Differences of teff varieties in days to emergence, days to maturity and plant height in *Axum* and *Mekelle* in 2015 and 2016.

**Means of the teff varieties were compared separately within each location and year considering main effect of VAR.*

**Means connected by the same letter are not significantly different*

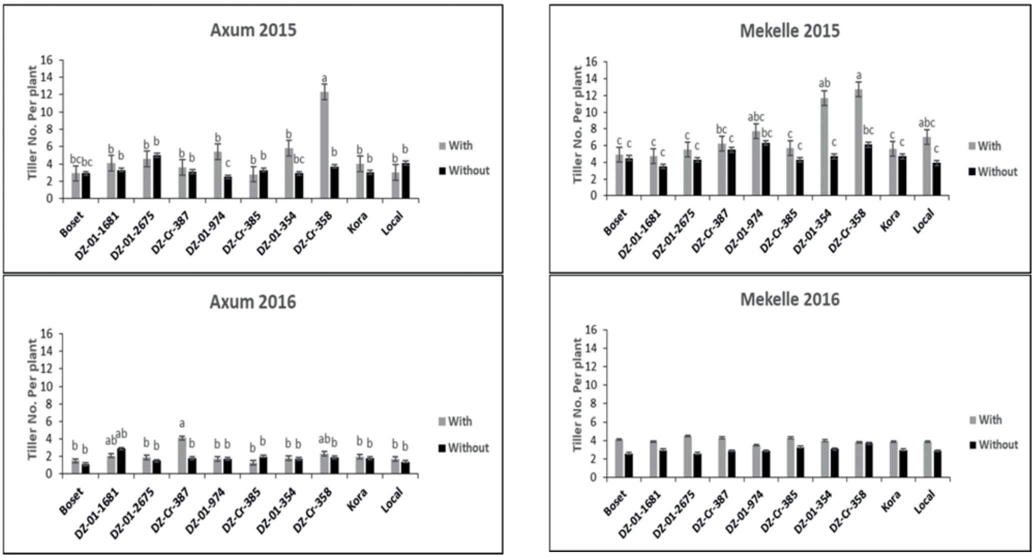

Figure 2. Differences of teff varieties in tiller number per plant in *Axum* and *Mekelle* in 2015 and 2016

**Means of the teff varieties were compared separately within each location and year considering HW*VAR interaction.*
**Means connected by the same letter are not significantly different*

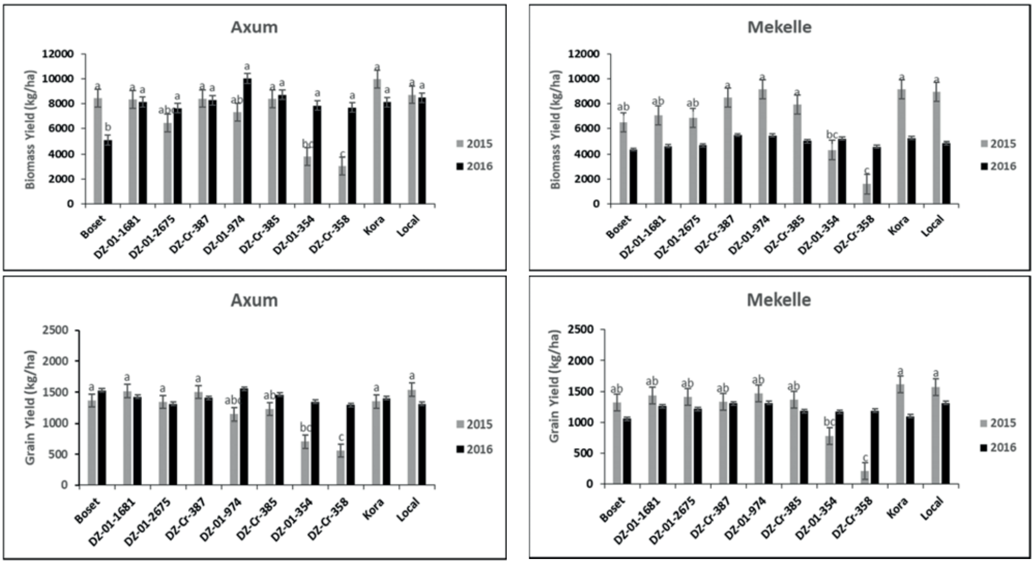

Figure 3. Differences of teff varieties in biomass and grain yields in *Axum* and *Mekelle* in 2015 and 2016.

**Means of the teff varieties were compared separately within each location and year considering main effect of VAR.*
**Means connected by the same letter are not significantly different*

Influence of teff varieties on weeds

In most cases the main factors, hand weeding, variety, year and location, appeared significant for most weed assessments with some few exceptions (Table 6). Because most of the two factor interactions, variety*year, variety*location and year*location, as well as the three and four factor interactions, for weed assessments were not significant (Table 6) and hence the analyses were not further split up.

Weed density

The different teff varieties resulted in significant variation in weed density (Table 6), but only for density of monocot weeds and total weed density. The highest total weed density (sum of the densities of the monocot and dicot weeds) had been recorded from plots with the variety *DZ-Cr-358 (*349 shoots/m^2) and *DZ-01-354* (328 shoots/m^2) while the least was from plots with *DZ-Cr-387* (263 shoots/m^2) and *DZ-Cr-385* (262 shoots/m^2) (Table 7). The later reduced the weed density by 25 % of that recorded from the plot with *DZ-Cr-358*. The effect of the different teff varieties was comparable with the effect of hand weeding. Such an effect of the varieties was not variable spatially and temporally as the interaction of the teff varieties with location and year was not statistically significant in all parameters of weed density (Table 6). Hand weeding had a significant effect on weed density with the highest average value of 364 shoots/m^2 from unweeded plots (Table 7). As compared to the monocot weeds, hand weeding significantly affected the dicots and reduced their density by 29.7 %.

Weed dry weight

The teff varieties affected weed dry weight significantly (Table 6), but again just for monocots and total weed biomass. The highest weight was recorded from the plots with the variety *DZ-01-354* and *DZ-Cr-358* with an average value of 347.2 g/m^2 and 356.4 g/m^2 respectively (Table 7). The least amount of weed dry weight was obtained from plots with *DZ-01-2675* with an average value of 150.1 g/m^2 (Table 7). The later was not significantly different from the weed dry weight obtained from plots with the varieties *DZ-Cr-387* and *DZ-Cr-385.* The varietal difference resulted in significantly reduced dry weight of monocot weeds. Their dry weight from weeded plots (121.64 g/m^2) was higher than that from plots with the varieties *DZ-01-2675* (94.92 g/m^2) and *Kora* (108.1 g/m^2) (Table 7). *DZ-Cr-387 or 'Quncho'* diminished dry weight of dicot weeds (43.72 g/m^2) to the level comparable with weight recorded from hand weeded plots (42.65 g/m^2). Hand weeding had significant effect on the dry weight of weeds (both monocots and dicots) (Table 6). It reduced the dry weight by 39.6 % of the total weeds and, 29.6 % and 57.1 % of the dry weight of monocot and dicot weeds respectively (Table 7).

Weed cover

Like density and dry weight, weed cover was also significantly influenced due to the varietal difference of teff (Tables 6). The varieties *Kora* and *DZ-Cr-387* reduced the weed cover to as low as 13.7 % with the highest cover being observed from plots with *DZ-01-354* (22.24%) and *DZ-Cr-358* (23.4 %) (Table 7). In other words, the high yielding varieties reduced the weed cover by 41.8 % when compared to the cover in plots consisting of *DZ-Cr-358* and by 33.9 % when compared with the cover in unweeded plots. Weeding also significantly affected cover (Table 6) and reduced it from 20.6 % in unweeded plots to 12.89 % in weeded i.e. it reduced weed cover by 59.8 % (Table 7).

Dominant Weeds

The most dominant weeds identified in the research sites were *Plantago lanceolata L., Cyperus esculentus* and *Setaria pumila (poir.) Roem. & Schult* in *Axum* and *Avena abyssinica Hochst, Galinsoga parviflora Ca* and *Plantago lanceolata L* in *Mekelle*.

Trade-off between yield potential and weed competitiveness

Most of the teff varieties showed wide variation in their biomass and grain yields due to hand weeding (Table 8). The highest yield losses due to weed competition in unweeded plots was 36% in biomass yield of the local land race and 38% in grain yield of the variety *'DZ-01-354'* (Figure 5). The least yield losses were recorded from the varieties *'Kora'* (with loss of 6 % in biomass yield and 18 % in grain yield) and '*DZ-Cr-387'* (with loss of 17 % in biomass yield and 21 % in grain yield (Figure 5). On average, the losses in grain yields of the varieties was higher than that of the biomass yields.

Weeding time and competitiveness on teff

The time taken to weed was longer in *Mekelle* than in *Axum* (Figure 4). It was also higher in 2015 than 2016. The longest time was recorded in *Mekelle* with an average of 1950hrs/ha in 2015, which was lowered to 889 hrs./ha in 2016 i.e. reduced by 54.4 %. In *Axum*, the longest time of weeding was 574.1 hrs./ha in 2015 and reduced by 39.5 % to 347.2 hrs./ha in 2016. Such a reduction was attributed to the effect of the different teff varieties on weed density, dry weight and cover. The highest reduction in weeding time, by 50.6 % in *Axum* and by 54.4 % in *Mekelle*, was observed in plots with the teff variety *DZ-Cr-387*. The lowest reduction was observed in *Mekelle*, which was 1.22 % in plots with *DZ-Cr-358* i.e. the weeding time was almost constant in both 2015 and 2016. The average weeding time in plots with *DZ-Cr-358* in *Mekelle* was 1066.7 hrs./ha in 2015 and 1053.7hrs/ha in 2016. There was also 3.76 % increment in weeding time in plots with *DZ-01-354* in *Axum*.

Table 6. ANOVA table with P-values for the main factors hand weeding, teff variety, location and year, and their interactions, on weed assessments.

Fixed factors	Weed assessments						
	Monocots density (Shoots m^{-2})	Dicots density (Shoots m^{-2})	Total density (Shoots m^{-2})	Monocots DW (gm^{-2})	Dicots DW (gm^{-2})	Total DW (gm^{-2})	Weed Cover (%)
Hand weeding (HW)	0.2175ns	0.0197*	0.0306*	0.0195*	0.0004***	<.0001***	<.0001***
Variety (VAR)	0.0108*	0.1665ns	0.0061**	0.0034**	0.2829ns	0.001***	<.0001***
HW*VAR	0.5878ns	0.6069ns	0.7291ns	0.0994ns	0.4166ns	0.0347*	0.0933ns
Year (YR)	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***
HW*YR	0.8377ns	0.5756ns	0.6063ns	0.0492*	0.0022**	0.0007***	0.0006***
VAR*YR	0.0951ns	0.4643ns	0.0533ns	0.0029**	0.262ns	0.001***	<.0001***
HW*VAR*YR	0.0684ns	0.236ns	0.014*	0.0747ns	0.3074ns	0.0204*	0.2295ns
Location (LOC)	<.0001***	0.0028**	0.0003***	<.0001***	0.0012**	<.0001***	0.1635ns
HW*LOC	0.9398ns	0.1464ns	0.5213ns	0.1574ns	0.1746ns	0.7045ns	0.0002***
VAR*LOC	0.0271*	0.645ns	0.2053ns	0.2256ns	0.8689ns	0.5378ns	0.0699ns
HW*VAR*LOC	0.7699ns	0.4824ns	0.7974ns	0.2853ns	0.7797ns	0.7973ns	0.6023ns
YR*LOC	<.0001***	0.0746ns	<.0001***	<.0001***	0.0073**	<.0001***	<.0001***
HW*YR*LOC	0.4346ns	0.2121ns	0.8701ns	0.1359ns	0.2019ns	0.6292ns	0.8513ns
VAR*YR*LOC	0.3921ns	0.4951ns	0.1571ns	0.2075ns	0.8612ns	0.5657ns	0.0364*
HW*VAR*YR*LOC	0.0892ns	0.1316ns	0.008**	0.3467ns	0.7874	0.8529ns	0.6821ns
Transformation of Y	-	-	-	-	-	-	-
Type[b]	un	un	un	un	un	un	un

[*]significant at P < 0.05, [**]significant at P < 0.01, [***]significant at P < 0.001, [ns] not significant; [a]Hand weeding – refers to uprooting of weeds from the field of the crop (teff) using hand; [b]Among the commonly used serial structures used for correlations, "unstructured" (un, in SAS) was used. This was used during analysis because it resulted in models with lower values of Akaike Information Criterion (AIC) and Schwarz Bayesian Information Criterion (BIC)

Table 7. Effects of teff varieties and hand weeding on weed assessments.

Fixed Factors	Monocots density (Shoots m^{-2})	Dicots density (Shoots m^{-2})	Total density (Shoots m^{-2})	Monocots DW (gm^{-2})	Dicots DW (gm^{-2})	Total DW (gm^{-2}) rank	Weed Cover (%)
Variety							
Boset	135.11ab	135.78	270.89ab	131.66ab	56.81	188.48abc 6	15.43b
DZ-01-1681	156ab	131.11	287.11ab	125.93ab	60.33	186.26abc 5	16.65b
DZ-01-2675	138.89ab	132	270.89ab	94.92b	55.19	150.11c 1	16.22b
DZ-Cr-387	136ab	127.11	263.11b	131.48ab	43.72	175.21abc 4	13.61b
DZ-01-974	169.33ab	142.44	311.78ab	134.98ab	61.34	196.32abc 7	15.07b
DZ-Cr-385	116b	146	262.0b	113.39ab	55.12	168.51bc 3	16.24b
DZ-01-354	174.22ab	154.22	328.4ab	247.67ab	99.50	347.17a 9	22.24a
DZ-Cr-358	186.67a	162.22	348.89a	262.27a	94.10	356.37a 10	23.40a
Kora	141.11ab	129.78	270.89b	108.07b	57.08	165.15bc 2	13.79b
Local	140.22ab	124.67	264.89ab	121.39ab	126.24	247.63abc 8	14.74b
Hand weeding							
With	150.71	130.89b	281.6b	121.64b	42.65b	164.29b	12.89b
Without	178	186.18a	364.18a	172.71a	99.24a	271.95a	20.6a

**Means connected by the same letter are not significantly different.*

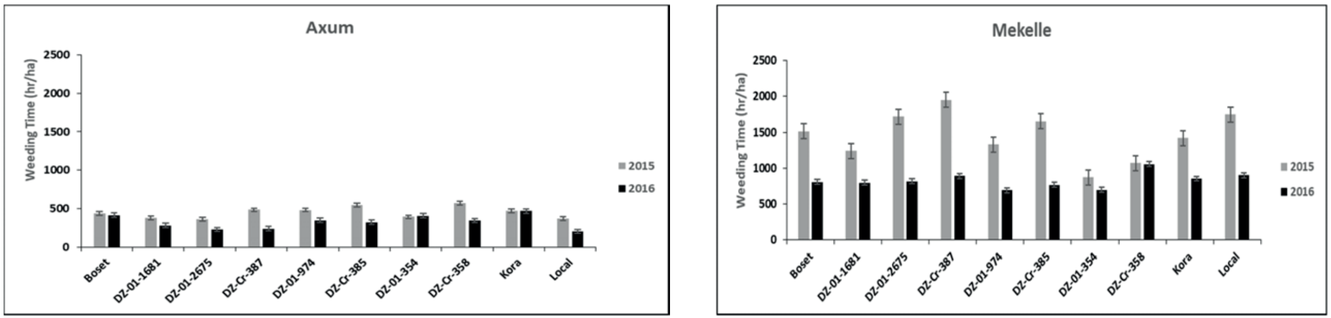

Figure 4. The effect of the different teff varieties on weeding time (hours ha^{-1})

Table 8. Variation in biomass and grain yields of teff varieties due to weeding

Variety	Biomass yield (B.y.) (kg/ha)*		B.y. Difference (kg/ha)	Grain yield (G.y.) (kg/ha)*		G.y. Difference (kg/ha)
	With weeding	Without weeding		With weeding ^{rank}	Without weeding ^{rank}	
Boset	6940.25	5270.86	1669.4	1413.95 ^{8}	1021.6 ^{8}	392.3
DZ-01-1681	7268.03	5126.42	2141.6	1489.16 ^{6}	1029.1 ^{7}	460.1
DZ-01-2675	6459.75	4581.92	1877.8	1444.02 ^{7}	1053.2 ^{6}	390.8
DZ-01-387	8398.58	6940.28	1458.3	1600.85 ^{1}	1270.5 ^{1}	330.3
DZ-01-974	8415.58	6855.61	1560.0	1530.71 ^{3}	1155.5 ^{4}	375.2
DZ-Cr-385	7950.03	6482.45	1467.6	1515.54 ^{4}	1101.2 ^{5}	414.4
DZ-01-354	6180.56	4393.06	1787.5	1236.69 ^{9}	765.12 ^{9}	471.6
DZ-Cr-358	4925	3522.17	1402.8	957.59 ^{10}	668.72 ^{10}	288.9
Kora	8352.81	7883.31	469.5	1499.34 ^{5}	1228.8 ^{2}	270.6
Local	8062.5	5137.5	2925.0	1591.19 ^{2}	1175.6 ^{3}	415.6

N.B. Yield difference = (yield obtained from weeded plots) – (yield obtained from unweeded plots)

** The biomass and grain yield values of teff varieties described in this table were an average from across locations and seasons*

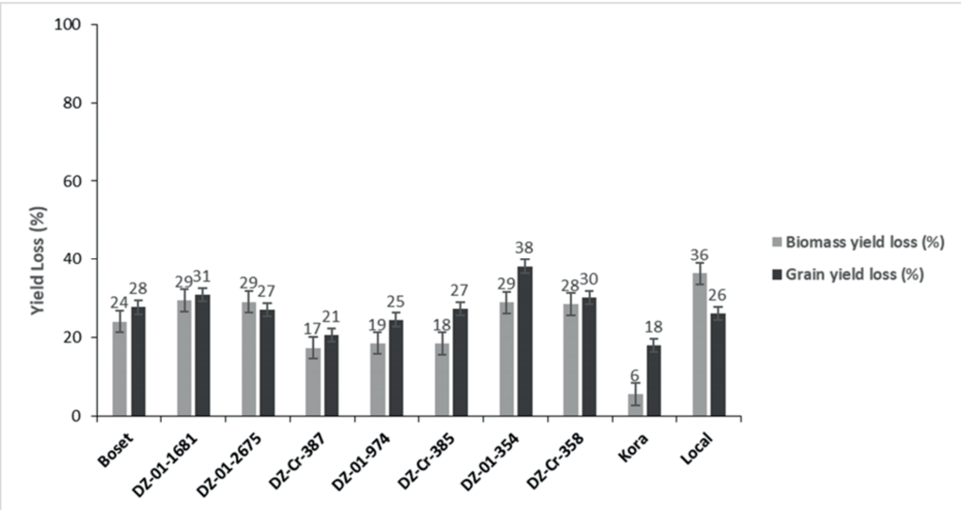

Figure 5. Biomass and grain yield losses of teff varieties due to weed competition in unweeded plots

N.B. Yield loss (%) = % of the yields obtained from weeded plots and lost due to the weed competition in unweeded plots

Discussion

Traits of teff varieties

Emergence and maturity

A huge variation in how quickly the varieties emerge were found, from the early emerging variety *Boset* to late varieties as *DZ-Cr-358* and *DZ-01-354.* This result is consistent with the characteristics of these varieties described in the Ethiopia Crop Varieties annual bulletin (EMAaRD 2014). Rapid emergence, together with early biomass accumulation, belongs to ruderal traits (Didon 2002). Rapid emerging varieties may start the photosynthesis early and such properties are the crucial weed competitive determining factor of cereal crops (Asif et al. 2014). The varieties described above showed the same trend in flowering and maturity as well i.e. *Boset* matured early and *DZ-Cr-358* and *DZ-01-354* matured late. Those emerged early flowered and matured early. Though distinct in their genetic makeup, the early emerging varieties might have early access to water, nutrients and sunlight for their vegetative and reproductive growth and development. This may be the reason why weeding caused delayed maturity of the varieties as it allowed the varieties to use soil resources efficiently with less competition from weeds. On the other hand, early maturity of teff varieties in unweeded plots might be as a mechanism of escaping the stress (due to limited availability of water and nutrients inside the soil) that could occur due to the competition of the crop with the weeds. In most instances, plants allocate the limited water and nutrient to their parts to facilitate their growth and development during stress as survival mechanism (Lambers et al. 2008). Research reports showed that teff varieties differ in their response to water, nutrient, light and heat stress (Dejene & Lemlem 2012; Tesfa et al. 2013; Vos et al. 2013). Many early vigor traits like early emerging, early coverage, early biomass and early height are among plant properties frequently mentioned to be important for competition ability in cereal wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare L.*) and oats (*Avena sativa* L.), as reviewed by Andrew et al. (2015).

Plant height

Plant height is also among the crop agronomic traits contributing on weed competitive ability of cereal crops (Asif et al. 2014; Andrew et al. 2015). In our study there was differences among the varieties in their heights. The early emerging and maturing variety, *Boset,* together with the variety *DZ-01-1681* had shorter plants than other varieties whereas taller plants were observed in *DZ-Cr-387* and *DZ-01-974*. Plant height of a single variety, however, is variable spatiotemporally depending on the availability of water, nutrients and sunlight (EMAaRD 2014) and most commonly in teff production, good supply of water, nutrients and sunlight results in taller plants and longer panicles of a cultivar. It is also very common to observe late maturing varieties having taller plants than early maturing varieties (Ketema 1997; Tefera et al. 2001; Tesfa et al. 2013; EMAaRD 2014; Assefa et al. 2015b). Not only genotypic variability but also agronomic management practices of cereal crops have a conspicuous effect on plant height and panicle length (Asif et al. 2014). In our study, significantly taller teff plants were found in unweeded plots. The taller heights of teff in plots without hand weeding is attributed to the competition of the crop plant with weeds for sunlight. Plants respond to restrict sunlight as a result of weed competition by elongating their stalk (Spitters & Van Ded Bergh 1982; Weiner 1986; Thomas et al. 1993).

Tillering

Weeding teff plots significantly increased tillering as observed in this experiment. This result is in agreement with the finding that tillering of cereal crops such as wheat increased with decreased weed density (Khan et al. 2012; Asif et al. 2014). Besides, Andrew et al. (2015) stated that rate of tiller production is plastic and density dependent and tiller numbers are reduced with increased inter and intraspecific competition. Not only weeding, but also genotypic variance influenced the tillering. Tillering refers to the number of productive and non-productive tiller from a single teff plant. The late emerging, flowering and maturing varieties i.e. *DZ-Cr-358 and DZ-01-354* had significantly higher tillers than other varieties. Interaction of the two factors (hand weeding and variety) had also significant effect on tillering of teff and most of the varieties had higher tillers on weeded plots. The reason is that when weeds are removed from teff plots, they leave a wide space, enabling the crop to get sufficient access to water, nutrients and solar radiation to support itself and its newly emerging tillers from its basal nodes.

Biomass and grain yields

Genotypic variation also resulted in significant difference in biomass and grain yields. Among all the varieties, *Kora* gave the highest biomass yield. This variety is the highest yielder followed by *DZ-Cr-387* (*Quncho)* in other studies (Kebebew et al. 2011; Kebebew et al. 2017). The late emerging varieties i.e. *DZ-Cr-358* and *DZ-01-354* had the least yield because those varieties had not only emerged late but also matured late. This low yield may be attributed to the competition among the tillers at the end of the production season especially for water and hence had shorter time for the productive tiller to reach at the final stage of seed filling and physiological maturity. The other reason for the low yield may be due to the suppression of late emerging varieties by weeds during their early growth stage. The teff yield was significantly higher from the weeded plots. Tillering of teff was higher in plots with hand weeding. This was likely as a result of improved access to water and plant nutrients as well as less competition for radiation. The difference in biomass yield (15.3 %) and grain yield (32 %) from weeded plots as compared to those from plots without hand weeding can be considered as losses as a result of higher weed competition.

As for other cereal species (e.g. Andrew et al. (2015)), there are differences between teff varieties for traits commonly considered as important for variety competitiveness and our <u>hypothesis 1</u> was clearly supported.

Influence of teff varieties on weeds

Weed density, dry weight and cover

In our experiment, hand weeding had a greater effect on dicots compared to monocots, probably because most of the dicots were more easily removable during weeding especially at their early stage. The results showed that weeding significantly reduced density and dry weight of dicots in particular and cover of all weed types in general. Cover was highly related with weed density and it was highly influenced by the removal of weeds, as it was higher in unweeded plots. Weed dry weight is attributed to competitive ability of weeds with crop for water, nutrient and sunlight as it explains weed biomass in the absence of water in the plant tissue.

The differences between varieties was generally huge and comparable with the effect of hand weeding. For instance, the average total weed density from the plot with variety *'DZ-Cr-387' ('Quncho')* (obtained by calculating the mean of weed densities from with and without hand weeded plots consisting of this variety i.e. 263.11 weeds m^{-2}) was 6.7% lower than the average total density from weeded plots (i.e. 281.6 weeds m^{-2}) and 27.8% lower than that from unweeded plots (i.e. 364.18 weeds m^{-2}). Such an effect of the varieties was not variable spatially and temporally as the interaction of the teff varieties with location and year was not significant in all parameters of weed density (Table 4). The high yielding varieties (i.e. biomass and grain yields) reduced the weed cover by 41.8% when compared to the cover in plots consisting of *DZ-Cr-358* and by 33.9% when compared with the cover in unweeded plots. Unlike hand weeding, genotypic difference had significant effect only on monocot density and biomass, not on dicot weeds. Such a variability may be attributed to the difference in emergence, tillering potential, plant height and biomass of the varieties as described in EMAaRD (2014) and Ketema (1997). Crops, with different growth habits such as different root systems, plant height, tillering potential and foliar architecture have different competitive potential to weeds (Mohammadi 2013; Asif et al. 2014; Ali et al. 2017; Sardana et al. 2017; van der Meulen & Chauhan 2017). The late emerging varieties i.e. '*DZ-Cr-358'* and '*DZ-01-354'* allow weed growth and were more infested than other varieties, as the density, dry weight and cover of weeds were higher from plots containing these varieties. The high yielding and the early emerging varieties '*DZ-Cr-387', Kora* and *'DZ-Cr-385'* had a very strong competitive response to weeds because they reduced weed density, dry weight and cover. Those varieties were not only with taller plants but also had the ability to dominate their space through their strong-standing tillers.

There were dominant weed species in both experimental locations. The weed species *Plantago lanceolata* and *Cynodon dactylon* were found in both *Axum* and *Mekelle*. The most common and dominant weed species in *Axum* were *Plantago lanceolata, Cyperus esculentus and Setaria pumila*, and those in *Mekelle* were *Avena abyssinica, Galinsoga parviflora* and *Plantago lanceolata*. Two of the three dominant weed species in *Axum* were monocots and two of the three dominant weed species in *Mekelle* were dicots.

As exemplified above there was huge differences in weed density and biomass between teff varieties and our hypothesis 2, 'Weeds respond to various teff varieties differently', was supported.

Trade-off between yield potential and weed competitiveness

The teff varieties '*Kora'* and *'DZ-Cr-387'*compete strongly with weeds as seen as their effect on weed density, dry weight and cover while they had higher yields at the end of the production seasons than other varieties. However, they sacrifice some of their yields during their competition with both monocot and dicot weeds. For instance, the variety '*Kora'* lost as much as 6 % of its biomass yield and 18 % of its grain yield. Similarly, the variety *'DZ-Cr-387'* lost as much as 17 % of its biomass yield and 21 % of its grain yield. According to Andrew et al. (2015), there is a trade-off between yield potential and competitive ability of crop varieties when they lose less yield in cost of their competition with weeds though competitiveness can be result of the performance of multiple crop traits. Such a trade-off was observed in the teff varieties '*Kora'* and *'DZ-Cr-387'*as they lost less amount of their biomass and grain yields than other varieties in cost of their competitiveness while significantly reducing density, dry weight and cover of weeds.

The hypothesis 3, 'There is a trade-off between yield potential and weed competitiveness in teff varieties', was supported.

Weeding time and competitiveness on teff

The competitive ability of the teff variety *'DZ-Cr-387'* resulted in reduction of 50 – 55% of the weeding time in both locations which can be considered as a compensation to the yield reduction of the variety due to competition with weeds.

Also our fourth hypothesis, 'Variety competitiveness influence weeding time of teff, was supported.

Conclusion

The different teff varieties had different emergence, heading and maturity dates, plant height, tillering and yields.

Weeds respond differently to different teff varieties. The teff varieties '*Kora'* and *'DZ-Cr-387'* significantly lowered weed density, dry weight and cover and hence were more competitive to weeds than e.g. the varieties '*DZ-Cr-358'* and '*DZ-01-354'*. Generally, teff varieties affect more monocot than dicot weeds.

Hand weeding caused delayed flowering and maturity, taller plants, enhanced tillering, reduced weed biomass and enhance yields of teff. It decreased weed density and biomass in both locations and seasons but the efficiency was higher for dicots than monocot weeds.

There was trade-off between the yield potential and weed competitiveness in most of the varieties specially '*Kora'* and *'DZ-Cr-387'* as they lost less amount of their yields while significantly reducing weed infestation.

The competitive ability of the teff variety *'DZ-Cr-387'* resulted in shortened weeding time in both locations.

References

Adnew, T., Ketema, S., Tefera, H. & Sridhara, H. (2005). Genetic Diversity in Tef [Eragrostis tef (Zucc.) Trotter] Germplasm. *Genetic Resources and Crop Evolution*, 52 (7): 891-902.

Ali, H. H., Peerzada, A. M., Hanif, Z., Hashim, S. & Chauhan, B. S. (2017). Weed management using crop competition in Pakistan: A review. *Crop Protection*, 95 (Supplement C): 22-30.

Andrew, I. K. S., Storkey, J. & Sparkes, D. L. (2015). A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research*, 55 (3): 239-248.

Asif, M., Iqbal, M., Randhawa, H. & Spaner, D. (2014). Crop Competitiveness. In *Managing and Breeding Wheat for Organic Systems*: Springer, Cham.

Assefa, G., Theodrose, T. & Alemu, D. (2016). Quantitative Determination of Weed Occurrence on Upland Rice of Bambasi, Ethiopia. *Ecology and Evolutionary Biology*, 1 (3): 53-56.

Assefa, K., Cannarozzi, G., Girma, D., Kamies, R., Chanyalew, S., Plaza-Wüthrich, S., Blösch, R., Rindisbacher, A., Rafudeen, S. & Tadele, Z. (2015a). Genetic diversity in tef [Eragrostis tef (Zucc.) Trotter]. *Frontiers in plant science*, 6.

Assefa, K., Cannarozzi, G., Girma, D., Kamies, R., Chanyalew, S., Plaza-Wüthrich, S., Blösch, R., Rindisbacher, A., Rafudeen, S. & Tadele, Z. (2015b). Genetic diversity in tef [Eragrostis tef (Zucc.) Trotter]. *Frontiers in Plant Science*, 6: 177.

Baye, K. (2014). *Teff: nutrient composition and health benefits*: International Food Policy Research Institute (IFPRI).

Bertholdsson, N. O. (2005). Early vigour and allelopathy – two useful traits for enhanced barley and wheat competitiveness against weeds. *Weed Research*, 45: 94-102.

CSA. (2016). *Agricutlrual Sample Survey 2015/2016 (2008E.C): Report on Area, Production and Farm Management Practice on Belg Season Crops for Private Peasant Holdings*, vol. V (5). Addis Ababa, Ethiopia: CENTRAL STATISTICAL AGENCY. 131 pp.

Daniel, T., Teferi, A. & Tesfaye, W. (2016). Evaluation of Improved Varieties of Teff in West Belessa, Northern Ethiopia. *Review of Plant Sciences*, 3 (1): 1-6.

Dejene, K. M. & Lemlem, S. M. (2012). Integrated Agronomic Crop Managements to Improve Tef Productivity Under Terminal Drought. In Ismail, M. M. R. (ed.) *Water Stress*, p. 300. University Campus STeP Ri, Croatia: Intech - Open Science | Open Minds.

Didon, U. M. E. (2002). Variation Between Barley Cultivars in Early Response to Weed Competition. *Journal of Agronomy and Crop Science*, 188 (3): 176-184.

EMAaRD. (2014). *Crop Variety Issue No.12: Summary of Released/Registered Varieties of Crops*, vol. 12. Addis Ababa: Ethiopian Ministry of Agriculture and Rural Development.

Esayas, T., Abraham, G. H. & Mashila, D. (2013). Weed Interference in Cotton (Gossypium hirsutum L.) in the Middle Awash, Ethiopia. *Ethio. J. Appl. Sci. Technol.*, 4: 41-49.

FAO. (2015). *World reference base for soil resources 2014: International soil classification system for naming soils and creating legends for soil maps*. World soil resources reports, vol. 106. Rome, Italy: Food and Agriculture Organization of the United Nations. 203 pp.

Hansen, P. K., Kristensen, K. & Willas, J. (2008). A weed suppressive index for spring barley (Hordeum vulgare) varieties. *Weed Research*, 48 (3): 225-236.

IFPRI. (2006). *Atlas of the Ethiopian Rural Economy*. Addis Ababa, Ethiopia: International Food Policy Research Institute and Central Statistical Agency. 1-108 pp.

Jaccard, P. (1912). The distribution of the flora in the alpine zone. *New phytologist*, 11 (2): 37-50.

Kebebew, A., Sherif, A., Getachew, B., Gizaw, M., Hailu, T. & Mark, E. S. (2011). Quncho: the first popular tef variety in Ethiopia. *International Journal of Agricultural Sustainability*, 9 (1): 25-34.

Kebebew, A., Solomon, C., Yazachew, G., Mitiku, A., Tsion, F., Jifar, H., Nigussu, H., Mihireteab, H. S., Girma, C. & Molalign, A. (2017). Tef (Eragrostis tef) Variety Kora. *Ethiop. J. Agric. Sci.* , 27 (2): 137-140.

Ketema, S. (1997). *Tef (Eragrostis tef (Zucc.) Trotter): Promoting the conservation and use of underutilized and neglected crops*, vol. 12. Rome, Italy: Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute.

Khan, I. A., Hassan, G., Khan, S. A. & Shah, S. (2012). Wheat-wild oats interactions at varying densities and proportions. *Pak J Bot*, 44: 1053-1057.

Lambers, H., Chapin, F. S. & Pons, T. L. (2008). Growth and Allocation. In Lambers, H., Chapin, F. S. & Pons, T. L. (eds) *Plant Physiological Ecology*, pp. 321-374. New York, NY: Springer New York.

Mohammadi, G. R. (2013). Alternative Weed Control Methods: A Review. In Soloneski, S. & Larramendy, M. (eds) *Weed and Pest Control - Conventional and New Challenges*, p. Ch. 06. Rijeka: InTech.

NMA. (2017a). Agromet Bega Assessment and Belg 2017 Outlook. *Agromet: National Meteorological Agency of Ethiopia*.

NMA. (2017b). *Annual Weather Report* Addis Ababa, Ethiopia: National Meteorological Agency

Olofsdotter, M., Jensen, L. B. & Courtois, B. (2002). Improving crop competitive ability using allelopathy — an example from rice. *Plant Breeding*, 121 (1): 1-9.

Sardana, V., Mahajan, G., Jabran, K. & Chauhan, B. S. (2017). Role of competition in managing weeds: An introduction to the special issue. *Crop Protection*, 95 (Supplement C): 1-7.

Spitters, C. J. T. & Van Ded Bergh, J. P. (1982). *Competition between crop and weeds: A system approach*. Biology and ecology of weeds. The Hague: Dr W. Junk Publishers. 137-148 pp.

Taye, T. & Yohanes, L. (1998). Qualitative and quantitative determination of weeds in tef in West Shewa Zone. *Arem (Ethiopia)*.

Tefera, H., Belay, G. & Sorrells, M. E. (2001). *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.

Teklu, Y. & Tefera, H. (2005). Genetic improvement in grain yield potential and associated agronomic traits of tef (Eragrostis tef). *Euphytica*, 141 (3): 247-254.

Tesfa, B., Solomon, J., Yifru, A., Minale, L. & Waga, M. (2013). Crop Management Research for Tef. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement: Proceedings of the Second International Workshop, November 7-9, 2011, Debre Zeit, Ethiopia*, p. 379. Stämpfli AG, 3001 Bern, Switzerland: Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia; Institute of Plant Sciences, University of Bern, Switzerland.

Thomas, J. B., Schaalje, G. B. & Grant, M. N. (1993). Height, competition and yield potential in winter wheat. *Euphytica*, 74 (1): 9-17.

van der Meulen, A. & Chauhan, B. S. (2017). A review of weed management in wheat using crop competition. *Crop Protection*, 95 (Supplement C): 38-44.

Violle, C., Navas, M.-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I. & Garnier, E. (2007). Let the concept of trait be functional! *Oikos*, 116 (5): 882-892.

Vos, J., Delden, S. H. v. & Stomph, T. J. (2013). Some Ecophysiological Characteristics of Tef, Including Mechanics of Lodging. In Kebebew, A., Solomon, C. & Zerihun, T. (eds) *Achievements and Prospects of Tef Improvement*, p. 379. Stämpfli AG, 3001 Bern, Switzerland: Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia and Institute of Plant Sciences, University of Bern, Switzerland.

Weiner, J. (1986). How Competition for Light and Nutrients Affects Size Variability in Ipomoea Tricolor Populations. *Ecology*, 67 (5): 1425-1427.

Wicks, G. A., Nordquist, P. T., Baenziger, P. S., Klein, R. N., Hammons, R. H. & Watkins, J. E. (2004). Winter Wheat Cultivar Characteristics Affect Annual Weed Suppression. *Weed Technology*, 18 (4): 988-998.

PAPER IV:

G. Haftamu, J.B. Aune, O.M. Eklo, T. Torp and L.O. Brandsæter. Allelopathic potential of teff varieties and their effect on weed growth. Manuscript.

Allelopathic potential of teff varieties and their effect on weed growth

G. Haftamu [ab], J.B. Aune[c], O.M. Eklo[bd], T. Torp[d] and L.O. Brandsæter[bd]

[a] *Mekelle University, College of Dryland Agriculture and Natural Resources, P.O.Box 231, Mekelle, Tigray, Ethiopia*
[b] *Norwegian University of Life Sciences, Department of Plant Sciences (IPV-NMBU), P.O. Box 5003, NO-1432 Ås, Norway*
[c] *Norwegian University of Life Sciences, Department of International Environment and Development Studies (Noragric-NMBU), P.O. Box 5003, NO-1432 Ås, Norway*
[d] *Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway*

Abstract

It is not known whether teff, as cereal crop, has allelopathic effect on weeds. To study the allelopathic potential of teff and its effect on root growth of weeds, both laboratory and field experiments were conducted in Norway (NIBIO weed laboratory in Ås) and in Tigray, Ethiopia (Axum and Mekelle research sites) respectively. Ten commonly grown teff varieties were used for both experiments. In the laboratory experiment, the varieties were tested for their allelopathic potential with an agar based bioassay using ryegrass and radish as model weeds. The field experiments were conducted in Axum and Mekelle research sites during 2015 and 2016 to identify the most important agronomic traits of teff contributing on its weed competitive ability. Randomized complete block design (RCBD) consisting of the ten teff varieties arranged in three blocks was used in both locations. The laboratory experiment containing the mixture of ten teff varieties with the model weeds as a factor and agar petri dishes containing the model weeds without the teff varieties as controls was replicated four times where each block was repeated in time. Results showed that highest average potential allelopathic activity (PAA) and specific potential allelopathic activity (SPAA) was recorded from local land race with PAA average value of 11.77 % and SPAA average value of 1.21 %/mg followed by the variety 'DZ-01-2675' with an average values of 10.89 % and 1.14 %/mg respectively when ryegrass (*Lolium perenne cv. Mondiale; cv=cultivar*) *was used as model weed. The variety 'Boset' had the highest PAA and SPAA with an average values of 16.25 % and 1.53 %/mg respectively when using radish* (*Raphanus sativus* cv Cherry Belle) *as model weed. The least PAA and SPAA were consistently recorded from the variety 'DZ-Cr-387' with an average values of 0.19 % and 0.11 %/mg respectively when mixed with ryegrass and 1.78 % and 0.24 %/mg respectively when mixed with radish. Days to emergence, height, tiller no/plant, biomass yield and PAA of the crop significantly contributed on the variance of the weed biomass, cover and density and hence were the most important agronomic traits enhancing the weed competitive ability of teff.*

Key words: Teff, weed, Ryegrass, Radish, Allelopathy, Potential allelopathic activity, weed root growth

Introduction

Teff is among the oldest cereal crops in the tropical African region and is originated and more diversified in Ethiopia than any other part of the world (Ketema 1997). It is the major cereal crop in Ethiopia both in production and consumption. It is the crop that is consumed by more than 60 % of the country's population on daily basis. Ethiopia owns around 15.2 million hectare of land allocated for grain crops out of which around 11.9 million hectare or around 78 % of the total area allocated for grain crops is for cereals and around 3.3 million hectare or around 21.4 % of the total area for grain crops and 27.4 % of the total area covered by cereals is under teff production (CSA 2016). The crop is not only adaptable to much diversified agro-climatic condition but also has wide genetic variability describing vast agronomic traits (Ketema 1997; Assefa et al. 2015). Such a wide adaptation to different agroecologies exposed it to various weed species (Ketema 1997; Teklu & Tefera 2005; IFPRI 2006; Baye 2014; Assefa et al. 2015; Daniel et al. 2016). It faced challenges from weeds throughout its growing period and caused yield reduction (Assefa et al. 2008; Balesh et al. 2008; Assefa et al. 2013).

There are different cultural methods of weed control most of them are included in agronomic practices of teff. The most common include frequent tillage, hand weeding and to some extent the use of post and pre-emergence herbicides. For largescale farming, herbicide is very commonly used to control weeds but the evolution of herbicide resistant weeds become a bottleneck problem and calling for another alternatives (Powles 2008b; Powles 2008a). Besides, herbicides cause soil quality decline over time especially when using them along with zero tillage explained in terms of water-stable aggregates, particulate organic matter and dehydrogenase activity affecting soil physical, chemical and biological properties (Neli et al. 2017). Additionally, planting design, which includes planting density, row spacing and orientation, can be used as method of weed management as it can enhance crop weed competitive ability (van der Meulen & Chauhan 2017). The use of competitive cultivars is another interesting option both because they do not add any additional costs and because the use of such cultivars have very few, if any, agronomic or environmental concerns. In opposite to the knowledge about the potential for competitive varieties in cereal crops in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.) (Andrew et al. 2015) the knowledge on the potential of using competitive teff varieties is much more restricted. Haftamu et al. (2018), however, studied the weed competitive ability of teff varieties as well as traits, e.g. canopy heights and tillering potential, differences of teff varieties. The link between differences of the traits of teff varieties and competitive ability was however not included in the study of Haftamu et al. (2018).

Resources as different nutrients are commonly limited and plants compete for it throughout their life cycle. According to Andrew et al. (2015), there have been a huge number of studies that illustrate the variation in competitive ability between cultivars of different cereal crops as wheat, oat and barley. They give many examples of traits, e.g. canopy height, early vigor and others that contribute to increased suppressive ability against weeds. There are a range of definitions to the word “competition”, see e.g. in Grace and Tilman (1990). In the present study, however, we will restrict it to include a specific kind of competition, resource competition, but also include another phenomenon of interaction among plants, allelopathy, that include toxins released from plants. Allelopathy is an interference interaction by plant species through release of allelochemicals to hinder the growth and development of another plant species living near to them (Weston & Duke 2003; Willis 2007). Allelochemicals are mostly released by almost all plant species into the soil environment during four important processes; residue decomposition, volatilization, leaching and root exudates which may or may not benefit to other receptor plants (plants which receive allelochemicals during nutrient and water uptake from the soil) (Chou 1999; Weston & Duke 2003). The presence of these allelochemicals halt the proliferation of the roots of susceptible receptor plants and interrupt their life cycle as it blocks their nutrient and water uptake potential. They also hinder weed growth and development during crop production (Qasem & Foy 2001; Singh et al. 2003; Weston & Duke 2003). Cereal crops such as oat, corn, barley and wheat had allelopathic effect on weeds (Wu et al. 2000; Qasem & Foy 2001; Singh et al. 2003; Bertholdsson 2005; Weih et al. 2008). The less considered method of managing weeds is, therefore, the use of the competitive ability of different crop varieties through interference – mainly exudation of allelochemicals that can hider root growth of weeds (Qasem & Foy 2001; Singh et al. 2003; Weih et al. 2008). Bertholdsson (2005) found that early crop biomass and allelopathic activity of barley and wheat were the most important traits significantly contributing for their weed competitiveness.

Therefore, it is of paramount importance to identify teff varieties with the highest allelopathic potential through bioassay and field experiments to find the best components of the integrated teff weed management especially for conventional and conservation agricultural practices in Ethiopia.

The objectives of this study were to uncover new knowledge about (i) allelopathic activity of teff varieties and (ii) identify the most important agronomic trait (s) of teff contributing on the weed competitive ability of the crop. We raised the following hypothesizes:

1. There are differences in allelopathic activity between teff varieties
2. Emergence and allelopathic activity are the two most important traits for teff weed competitive ability

Materials and methods
Plant materials

Ten teff varieties were used for the allelopathic experiment (Table 1). Nine of them were improved, highly productive, adaptive and widely used varieties and one local landraces widely grown in middle altitude of Ethiopia. These varieties were selected based on their importance and preference by most teff farmers of Ethiopia.

Table 1. General description of the teff varieties used for the experiment

R. No.	Varieties	Year of Release	Seed colour	Maturity (Days)	Height (cm)	On-Station Yield (kg/ha)	On-farm Yield (kg/ha)	Yield Gap (kg/ha)
1	Boset	2012	Very White	75-86	75-90	1800 - 2000	1400 - 1800	0 - 400
2	DZ-01-1681	2002	Dark Brown	84-93	74-85	2500	1600 - 2000	500 - 900
3	DZ-01-2675	2004	Pale White	112-123	47-91	1800 - 2800	1600 - 2000	200 - 800
4	DZ-Cr-387	2005	White	86-151	72-104	2500 - 2700	1600 - 2000	700 - 900
5	DZ-01-974	1995	White	76-138	84-123	2400 - 3400	2000 - 2500	400 - 900
6	DZ-Cr-385	2009	White	65-88	82-90	1600	1000	0 - 600
7	DZ-01-354	1970	Pale White	85-130	53-115	1800 - 2800	1800 - 2200	0 - 600
8	DZ-Cr-358	1995	White	76-138	70-109	2100 - 3600	1800 - 2400	3000 - 1200
9	Kora	2012	White	88-95	90-110	2400 - 3400	2000 - 2500	400 - 900
10	Local	A land race with no known phenotypic and genetic description and commonly sown by the farmers in the experimental sites						

Source: (EMAaRD 2014)

Ryegrass (*Lolium perenne cv. Mondiale; cv=cultivar*) was used as reference weed in Bertholdsson (2005) and radish (*Raphanus sativus* cv Cherry Belle) on Campbell et al. (2009) and Dennis et al. (2016). Ryegrass represent grass (monocot) weeds whereas radish represent broadleaved (dicot) weeds.

Part I: Detecting allelopathic activity of teff varieties (bioassay experiment)

In the bioassay experiment, the varieties were tested for their allelopathic potential. Randomized complete block design (RCBD) with four blocks replicated in time was used during the testing period. An agar based bioassay was conducted using ryegrass and radish as model weeds. Our laboratory methods used during the period of the experiment were almost thoroughly adopted from Bertholdsson (2005) and Wu et al. (2000). The whole process of the experiment had three major steps.

i. Seed germination of teff varieties and model weeds

Seed germination of teff and the model weeds (ryegrass and radish) were performed in weed laboratory (NIBIO, Ås, Norway) in a dark condition (Figure 1). Petri dishes with litmus paper (grade 1 with 8.5 cm size Whatman litmus paper) was used to germinate the seeds and 2 ml water was applied. Seeds of both teff and weed species were germinated in darkness at room temperature of 20 °C for three days for teff and ryegrass, and two days for radish. All seeds were very clean and less vulnerable to contamination and hence seed sterilization was not necessary. All the seeds of teff and model weeds were germinated and immediately become ready for transplanting into a water agar.

Figure 1. Germination of teff and model weeds, ryegrass and radish, seeds for bioassay

ii. Transplanting of seedlings of teff and model weeds into water agar and their stay at the growth chamber (bioassay)

In the final bioassay, plastic tissue culture vials (Phytotech, 300 mL) were filled with 30 mL 1.5 % water Agar (Agar Bacto), and twelve pre-germinated teff seedlings planted in a circle 1 cm away from the vial wall with six pre-germinated perennial ryegrass or six radish seedlings, transplanted in the center of the vial and 1 cm away from the teff seedlings (Figure 2). After completing transplanting of the seedlings of the weeds and ten teff varieties, the agar vials were sealed and immediately placed in a growth chamber with a light/dark cycle of 12/12 hr, at a temperature of 20 °C during the day and 15 °C during the night and inflorescent light of around 50 μmol m^{-2} s^{-1} (Bertholdsson 2005). This low light level was used to protect the roots of seedlings from the effect of high light intensity.

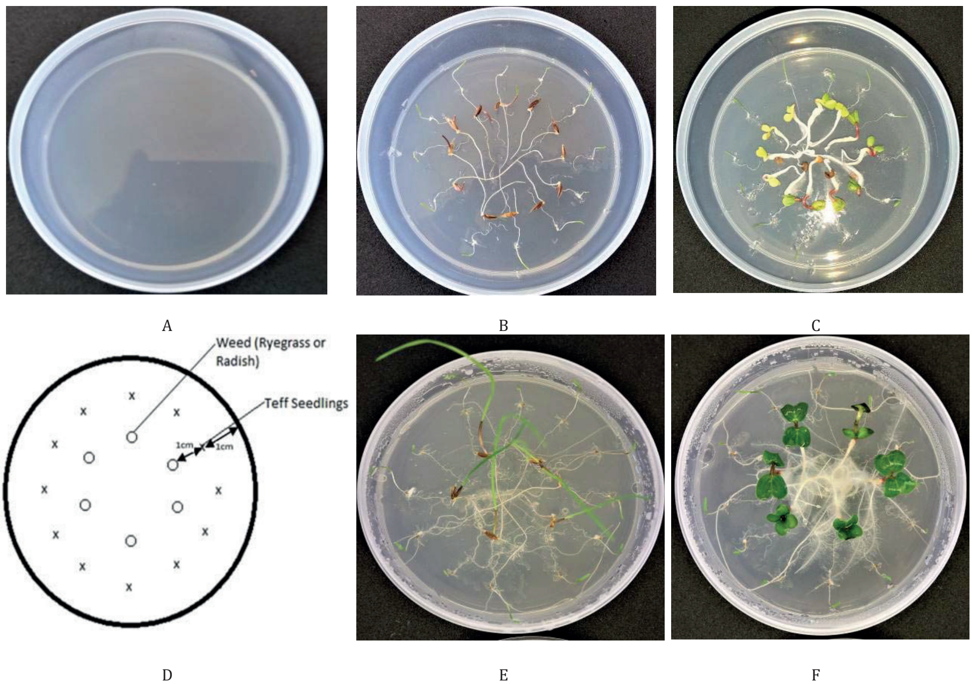

Figure 2. Seedling transplanting and growth of teff and model weeds in water agar
(A) Plastic tissue culture vials filled with 30 ml water agar; (B) Teff (DZ-01-1681) and ryegrass transplanted into water agar; (C) Teff (DZ-01-1681) and radish transplanted into water agar; (D) Transplanting design for teff and model weeds; (E) Teff (DZ-01-1681) and ryegrass after their stay at the growth chamber for 7 days; (F) Teff (DZ-01-1681) and radish after their stay at the growth chamber for 7 days

iii. Root analysis and weight measurements

After 7days, the agar vials along with the teff, ryegrass and radish seedlings were withdrawn out of the growth chamber. The roots of the model weeds were carefully withdrawn from the agar manually and scanned to measure their area, length, volume and diameter using an image analyzer (WINRHIZO ARABIDO 2013) (Figure 3). Vials with only the weed species were used as controls.

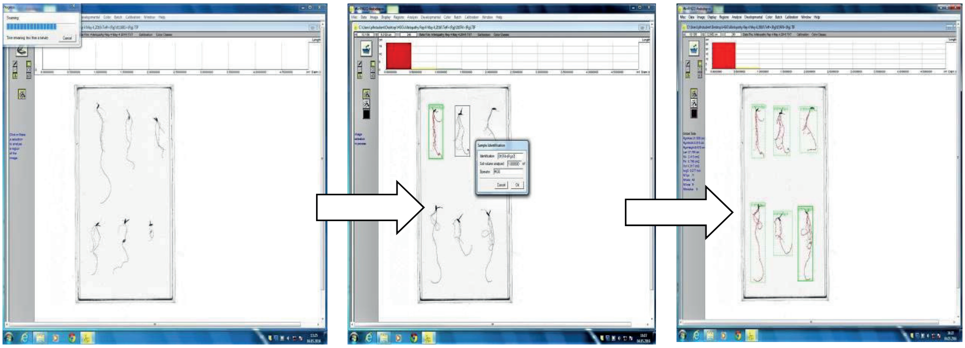

Figure 3. Model weed root scanning and analysis using WINRHIZO ARABIDO 2013

Roots of ryegrass and radish were dried at 60ºC for 48 hours and dry weight was measured after removal of the emerging shoots.

Part II: Traits of teff varieties explaining weed competitive ability

Haftamu et al. (2018) studied the weed competitive ability of teff varieties and potential traits, (e.g. canopy heights and tillering), that can explain their differences. The contribution of these traits on the competitive ability of teff varieties was not included in the study of Haftamu et al. (2018). In this study, we tested what traits, found by Haftamu et al. (2018) and extended by the allelopathic potential found in part I of this study, could explain the different weed competitive ability of teff varieties.

In this paper, we have only included some information about experimental design and treatments and data collection, more information and details about the research sites etc. can be found in Haftamu et al. (2018).

Field experimental design and treatments

We used a split plot design with two levels of weeding (with and without hand weeding) on the main plots and the ten teff varieties as sub plot treatments with three blocks. The plot sizes were 2 m by 3 m for sub plot and 2 m by 39 m for the main plot. There were 1 m space between the subplots, 1 m between main plots within block and 1.5 m between blocks to control border effect (mixing of the seeds from each teff varieties).

Crop data collection

The collected data can be classified within two classes i.e. (i) data related to crop traits, (ii) and (ii) weed data.

Data related to crop traits

The crop data includes days to emergence, heading/flowering and maturity, tiller number/plant, plant height, biomass yield, and grain yield. The phenology data were obtained by recording the dates when the teff plants covered 50% of the plot area emerged, flowered and matured. Tillering and plant height were measured by taking randomly 10 teff plants from each plot and averaged the values. Tillering was recorded by counting the number of tillers in a single teff plant. Plant height (i.e. height of the teff plant from node separating root and shoot until the tip of the panicle) were measured using *meter* and *centimetre* graduated flexible metal. Biomass yield is the sum of the straw or the vegetative part and the seed/grain or the reproductive part of the crop plant.

Effects of different teff varieties on weeds

Density, biomass and cover

Weed shoot density and aboveground weed biomass were assessed three times before harvest in one randomly placed quadrate (25 cm * 25 cm) per plot. Weed density or infestation was estimated by counting the weed plants within the quadrate by weeding time (first, second and third weeding). The space occupied by the crop and the most abundant weed species on all small plots was expressed as percentage ground coverage. The area covered by crop, weed species and bare soil was summed up to 100%. The biomass samples were dried at 65^0C for 48 hrs to determine the dry weight.

Data Analysis

Backward multiple regression and correlation analysis of the data from both bioassay and field experiments was conducted using SAS 9.4. Effects of the different teff varieties on root growth of ryegrass and radish during bioassay experiment were correlated with each other to identify the variable that can explain well to the allelopathic effect of the varieties. PAA, potential allelopathic activity, was calculated based on the formula stated in (Bertholdsson 2005) as PAA = (1- A1/A2)*100 with A1 = weed root area in presence of teff varieties and A2 = weed root area without teff varieties. Based on PAA, specific potential allelopathic activity (SPAA) was calculated as SPAA = PAA/weed root dry weight (this is the root dry weight of the model weed mixed with the specific teff variety based on which SPAA is calculated). PAA values can be positive or negative. Its values are positive when the weed root area is lower in the presence of teff varieties than in their absence and negative when the weed root area is higher in the presence of teff varieties. Positive PAA values indicate that teff has allelopathic effect on the model weeds and vise versa.

Result

All the teff varieties tested showed differences in their potential allelopathic effect on weeds. Days to emergence, heading, maturity, plant height, biomass yield and potential allelopathic activity were the traits of teff varieties significantly contributed on the variation in weed dry weight, cover and density.

Allelopathic effect on ryegrass

Highest root length and root area and among the highest root dry weight, were observed in the teff variety DZ-Cr-387 ('*Quncho*') when mixed with ryegrass with average values of 19.4 cm, 0.53 cm^2 and 13.6 mg respectively. A much lower root length, root area and root dry weight of ryegrass were observed when mixed with the teff variety DZ-01-2675 with average values of 17.3 cm, 0.5 cm^2 and 12.7 mg and local landrace 16.7 cm, 0.47 cm^2 and 12.5 mg, followed by DZ-Cr-358 and *Boset* (Figure 4). Teff varieties resulting in lower root diameter, root dry weight, root area and root length of ryegrass have higher PAA and SPAA. The highest average potential allelopathic activity was recorded from local land race with an average values of PAA 11.77 % and SPAA 1.21 %/mg and *DZ-01-2675 with PAA 10.89 % and SPAA 1.14 %/mg.* The least was from *DZ-Cr-387 with an average values of PAA 0.19 % and SPAA 0.11 %/mg*.

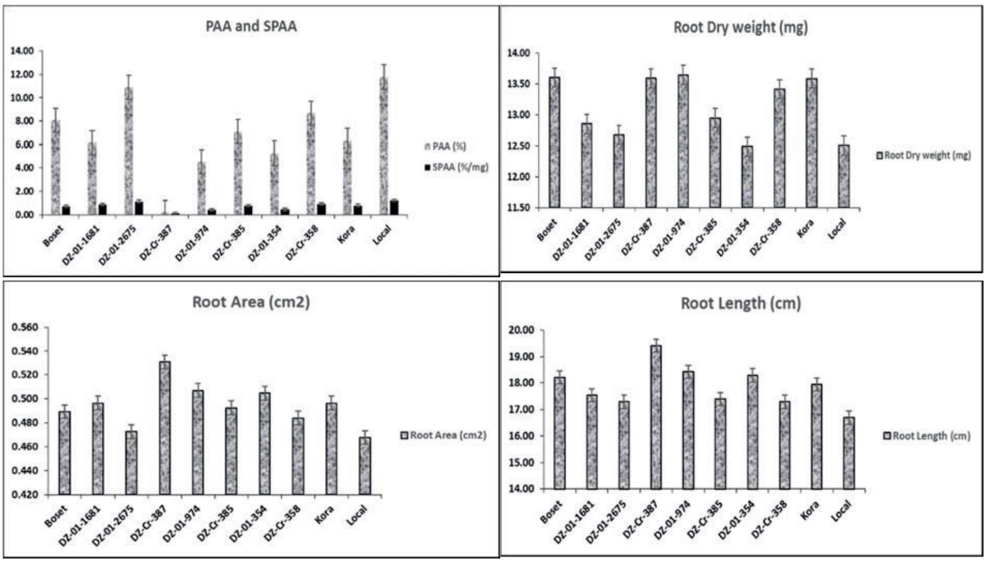

Figure 4. Potential allelopathic activity of different teff varieties and their effect on root growth of ryegrass. Root area, root length and root dry weight of ryegrass without teff varieties (control) were 0.61 cm^2, 20.6 cm and 15.2 mg respectively

There was significant and strong negative correlation between PAA and SPAA of teff varieties and root length, root area, root dry weight and root volume of ryegrass (Table 2). There was also correlation among most of the response of ryegrass (Table 1 in Appendix A). Significant strong positive correlation was observed among root length, root area and root volume but root diameter and root dry weight did not show correlation between each other and with the other responses. Backward multiple regression analysis indicated that root length, root area and root dry weight of ryegrass significantly contributed to 99.94 % of the variability of PAA of teff varieties (Table 3). The analysis also showed that only root area and root diameter of ryegrass contributed to 97.02 % of the variability of SPAA of teff varieties (Table 3). However, root volume, though it had strong negative correlation with PAA and SPAA, did not show significant contribution on their variability (Table 2 and 3).

Table 2. Pearson correlation of PAA and SPAA of teff varieties with the responses of ryegrass and radish to allelopathic effect of the crop

Variables	**PAA_{rye}**	**$SPAA_{rye}$**	**PAA_{rad}**	**$SPAA_{rad}$**
Root Length (cm)	-0.9109***	-0.9536***	-0.8443***	-0.8036**
Root Area (cm2)	-0.9988***	-0.9589***	-0.9941***	-0.8993***
Root Dry weight (mg)	-0.4978ns	-0.4956ns	0.0029ns	-0.21ns
Root Volume (cm3)	-0.7627*	-0.7177*	-0.7526*	-0.6387*
Root Diameter (mm)	0.2853ns	0.5228ns	0.4133ns	0.3372ns
n	10	10	10	10

significant at P < 0.05, **significant at P < 0.01, ***significant at P < 0.001, ns not significant **NB: each values of the correlation coefficient was squared to get the coefficient of determination (r^2) of each variables.*

Table 3. Backward multiple regression of PAA and SPAA of teff varieties as dependent variables and the responses of ryegrass and radish to allelopathic effect of the crop as independent variables

Multiple Regression models **Whole model**	**PAA_{rye}**	**$SPAA_{rye}$**	**PAA_{rad}**	**$SPAA_{rad}$**
R2 (%)	99.94	97.02	98.83	98.22
P-value	<.0001	<.0001	<.0001	<.0001
P-values of independent variables				
Root Length (cm)	0.0065(0.49)	-	-	0.0003(-1)
Root Area (cm2)	<.0001(-199.4)	<.0001(-16.58)	<.0001(-87.6)	0.0084(10.1)
Root Dry weight (mg)	0.0227(-0.25)	-	-	-
Root Volume (cm3)	-	-	-	-
Root Diameter (mm)	-	0.0107(11.3)	-	0.0003(-63.7)
n	10	10	10	10

(1) The values in the brackets are the estimates of the regression coefficients for the independent variables significantly contributing on the variance of PAA and SPAA. (2) The backward multiple regression began from all the five independent variables and ended with those with the estimates of the regression coefficients. (3) The R^2 with its corresponding P-value was from the final model of the backward regression.

Allelopathic effect on radish

The highest radish root length, 28.5 cm, was recorded from DZ-Cr-387 followed by DZ-01-1681 with 25.3 cm and DZ-01-354 with 25.2 cm (Figure 5). Similarly the highest value of root area was found in DZ-Cr-387 (1.1 cm^2) followed by DZ-01-1681 (1.05 cm^2) and DZ-01-974 (1.02 cm^2) (Figure 5). The highest radish root dry weight was recorded for DZ-01-1681 (12 mg) followed by DZ-Cr-358 (11.1 mg) and Local landrace (10.7 mg). Relatively lower root length (24.2 cm), root area (0.98 cm^2) and root dry weight (9.7 mg) were recorded from *DZ-01-2675* (Figure 5).

The different teff varieties showed highly variable PAA and SPAA on radish (Figure 5). When comparing the PAA of the teff varieties, *Boset* had recorded the highest PAA with 16.3 % followed by *DZ-01-2675* with 12.6 % and *Kora* with 12 %. The least PAA values was from *DZ-Cr-387* with a value of 1.8 %. The teff varieties had also variability in SPAA where the highest value, 1.53 %/mg, was observed from *Boset* followed by *Kora* and *DZ-Cr-385* both having an average value of 1.56 %/mg. The least SPAA value was from the variety *DZ-Cr-387* (0.24 %/mg). The variety *DZ-Cr-387 ('Quncho')* has shown consistent low allelopathic effect on both ryegrass and radish. This variety had lower allelopathic effect than the other teff varieties.

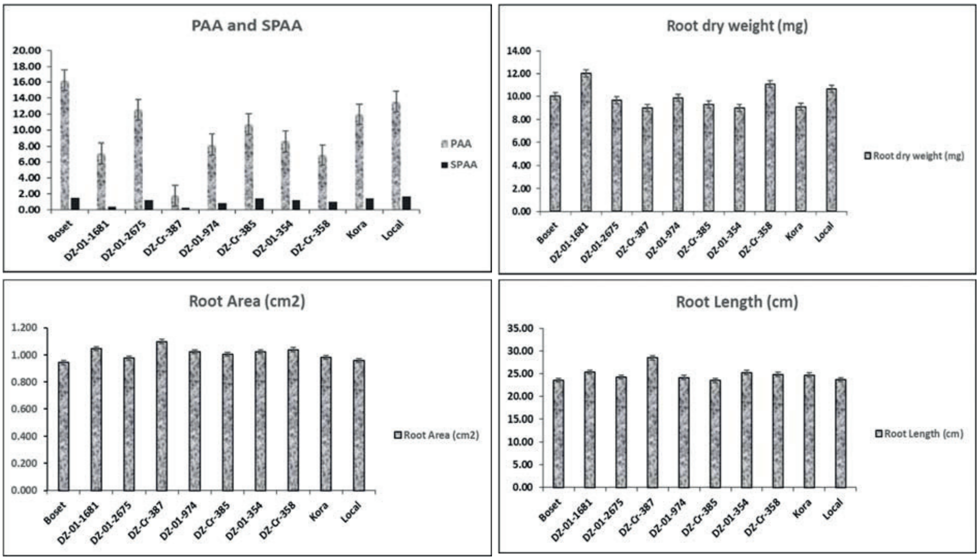

Figure 5. Potential allelopathic activity of different teff varieties and their effect on root growth of radish. Root area, root length and root dry weight of ryegrass without teff varieties (control) were 1.4 cm^2, 31.4 cm and 14.3 mg respectively

The PAA and SPAA of teff varieties estimated using radish as model representing dicot weeds during bioassay experiment has a significant strong negative correlation with root length, root area and root volume of the weed (Table 2). There was also correlation among most of the response of radish (Table 2 in Appendix A). Significant strong positive correlation was observed between root length and root area but it had significant strong negative correlation with root diameter. There was also significant strong positive correlation between root area and root volume. However, root dry weight did not show significant correlation with the other responses. Backward multiple regression analysis showed that root area significantly explained 98.8 % of the variability of PAA and root length, root area and root diameter significantly explained 98.2 % of the variability of SPAA of teff varieties on radish (Table 3).

Relationships between traits of teff varieties and weeds

Most of these weed assessments, i.e. weed biomass, cover and density, had a significant positive strong correlation with the crop phenology especially with days to emergence, and heading (Table 4). This means that those teff varieties which were late to emerge, and flower faced strong weed competition during vegetative growth period. Such a correlation was clearly observed in both locations and years. The trait, days to emergence, showed very strong correlation with weed biomass, density and cover in 2015 in *Axum* (Table 4) but it did not have such correlation in *Mekelle* in any of the years except for weed cover in 2015. Heading showed temporal and spatial inconsistencies in its correlation with weed biomass, cover and density.

For most of the sites and years, plant height, tiller number per plant, crop biomass yield and potential allelopathic activity had negative correlation with weed biomass, cover and density but the significance of their correlations were not spatiotemporally consistent (Table 4). Plant height and total tiller number per plant showed significant strong negative correlation with weed density in 2016 in *Axum*. Teff tillering potential had significant negative correlation with weed cover in *Mekelle* in 2016. Crop biomass yield had significant negative correlation with all the weed biomass, cover and density. Though not significant in most of the locations and years, potential allelopathic activity of the teff varieties showed negative correlation with all these weed responses. Such a negative correlation of weed biomass, cover and density with potential allelopathic activity of teff varieties estimated using radish as a model weed (PAA_{Dicot}) was very consistent spatially and temporally. Most of the agronomic traits of teff showed significant correlation among each other (Table 3 in Appendix A). Days to emergence had significant strong negative correlation with biomass yield of teff. Days to heading had significant strong positive correlation with days to maturity and plant height and that of days to maturity with plant height and tiller number per plant. Both PAA and SPAA of teff showed no significant correlation with either of the agronomic traits of the crop.

Backward multiple regression analysis indicated that the traits of the different teff varieties i.e. days to emergence, heading (flowering), maturity, plant height, number of tillers per plant, crop biomass yield and potential allelopathic activity significantly contributed for 70.3 % - 99.7 % of the variation in weed biomass, cover and density (Tables 5 and 6). Most of the traits had more of a combined effect than separately. The contribution of crop emergence on the variance of the weed biomass, cover and density was significant spatiotemporally. The same trend was observed in crop biomass yield. Among the traits, emergence and crop biomass yield significantly contributed on the variance in weed biomass, weed cover and weed density in 2015 in *Axum* (Tables 5 and 6). Heading, maturity and number of tiller per plant significantly contributed on the overall variability of the weed biomass, cover and density in 2016 in all the experimental locations. The variance of such responses due the difference in plant height of teff varieties was not consistent except it was significant on weed biomass in 2016 in *Mekelle* and on weed cover in both *Axum* and *Mekelle* in 2016. Potential allelopathic activity of teff varieties had significant contribution on the variance of weed biomass, cover and density (Tables 5 and 6). PAA of the teff varieties contributed on average from 21.5 % to 28.2 % of the variance in weed biomass, cover and density.

Table 4. Coefficient of correlation between weed biomass, density, cover and the different teff varieties traits

Crop Traits	Weed biomass				Weed density				Weed cover			
	Axum		Mekelle		Axum		Mekelle		Axum		Mekelle	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Days to Emergence	0.959***	-0.2065ns	0.3689ns	-0.359ns	0.793**	-0.2797ns	0.3964ns	0.3198ns	0.8146***	0.7438**	0.7719**	0.4026ns
Days to Heading	0.2416ns	0.3453ns	0.3468ns	-0.0485ns	0.3302ns	0.5559*	0.6263*	0.1626ns	-0.0193ns	0.2005ns	0.6968*	-0.2673ns
Days to Maturity	0.4421ns	0.1602ns	0.1601ns	-0.1499ns	0.3798ns	-0.3127ns	0.1395ns	0.1959ns	0.4056ns	0.404ns	0.2148ns	-0.2251ns
Plant height	0.2716ns	0.1603ns	0.0471ns	-0.155ns	0.4075ns	-0.5705*	-0.1936ns	0.0465ns	-0.0045ns	-0.157ns	-0.0735ns	-0.3527ns
Total Tiller no. Per plant	0.2716ns	0.181ns	-0.2087ns	-0.3489ns	-0.1073ns	-0.524*	0.2831ns	-0.538*	-0.0447ns	0.0028ns	0.0263ns	-0.5266*
Crop Biomass Yield	-0.8784***	0.421ns	0.0258ns	-0.5686*	-0.7859**	0.1844ns	0.2452ns	-0.4408ns	-0.8632***	-0.8417***	-0.1496ns	-0.5355*
PAA $_{Monocot}$	0.1196ns	0.0196ns	-0.5306*	-0.0223ns	-0.0298ns	0.0053ns	-0.0533ns	-0.0502ns	0.0418ns	0.3731ns	0.0751ns	0.464ns
PAA $_{Dicot}$	-0.2807ns	-0.2001ns	0.155ns	0.3154ns	-0.322	0.1101ns	-0.0845ns	-0.504*	-0.2412ns	-0.0657ns	-0.1511ns	0.0797ns
n	10	10	10	10	10	10	10	10	10	10	10	10

significant at $P < 0.05$, **significant at $P < 0.01$, ***significant at $P < 0.001$, ns not significant;* PAA $_{Monocot}$ *= Potential Allelopathic Activity of teff varieties estimated using Ryegrass as a reference weed;* PAA $_{Dicot}$*= Potential Allelopathic Activity of teff varieties estimated using radish (Cherry Belle) as a reference weed **NB: each values of the correlation coefficient was squared to get the coefficient of determination (r^2) of each variables.*

Table 5. Backward multiple regression analysis of the teff traits with weed biomass and cover as dependent variables and emergence, heading, maturity, plant height, crop biomass yield PAA of teff on ryegrass and PAA of teff on radish as independent variables

Multiple regression models	Weed biomass				Weed cover			
Whole model	Axum		Mekelle		Axum		Mekelle	
	2015	2016	2015	2016	2015	2016	2015	2016
R2 (%)	98.65	77.05	70.29	98.24	99.69	95.82	89.52	83.59
P-value	<.0001	0.1799	0.0691	0.0463	0.0108	0.0012	0.0024	0.0091
P-values of independent variables								
Emergence	<.0001(179.2)	0.0524(3.4)	0.0925 (55)	-	0.018(-3.3)	0.0005(0.4)	0.0004(4.3)	-
Heading	0.0068(29)	-	-	0.0039(11)	-	-	-	-
Maturity	0.0061(-13)	-	-	-	0.0096(0.5)	0.0047(-0.6)	-	0.017(-0.3)
Plant height	-	0.0741(-1.2)	-	0.0033(-6.3)	0.0072(-0.65)	-	0.0107(-0.4)	-
Tiller no./ plant	-	0.062(9)	-	0.0186(-33.8)	0.0973(-2.1)	-	-	0.0034(4.3)
Crop Biomass	-	0.0309(0.01)	-	0.0225(0.02)	0.0057(-0.004)	-	-	0.0114(0.002)
PAA *Monocot*	0.051(15.4)	-	0.0445(38.2)	0.0691(-2.8)	0.0319(1.4)	0.0016(0.6)	0.0831(0.6)	-
PAA *Dicot*	-	0.0591(2.5)	-	0.0047(7.4)	0.0493(-0.66)	0.01(-0.3)	-	-
n	10	10	10	10	10	10	10	10

(1) PAA $_{Monocot}$ = Potential Allelopathic Activity of teff varieties estimated using ryegrass as a reference weed; PAA $_{Dicot}$= Potential Allelopathic Activity of teff varieties estimated using radish (Cherry Belle) as a reference weed; (2) R^2 with its corresponding P-values is from the final model of the backward regression (3) The values in the brackets are the estimates of the regression coefficients for the independent variables significantly contributing on the variance of weed dry weight and weed cover. (4) The backward multiple regression began from all the eight independent variables and ended with those without the estimates of the regression coefficients .

Table 6. Backward multiple regression analysis of the teff traits with weed density as dependent variables and emergence, heading, maturity, plant height, crop biomass yield PAA of teff on ryegrass and PAA of teff on radish as independent variables

Multiple regression models Whole model	Weed density			
	Axum		Mekelle	
	2015	2016	2015	2016
R2 (%)	62.88	92.62	39.22	99.02
P-value	0.0062	0.0221	0.0527	0.0042
P-values of independent variables				
Emergence	0.0062(50.4)	-	-	-
Heading	-	0.0043(-20.7)	0.0527(10.2)	0.0042(18)
Maturity	-	0.0081(24.1)	-	0.0038(-21.8)
Plant height	-	-	-	-
Tiller no./ plant	-	0.0463(-19)	-	0.0061(-49.7)
Crop Biomass	-	0.0448(0.01)	-	0.0037(-0.06)
PAA *Monocot*	-	-	-	0.0134(5.9)
PAA *Dicot*	-	0.0075(-9.6)	-	0.0013(-11)
n	10	10	10	10

(1) PAA $_{Monocot}$ = Potential Allelopathic Activity of teff varieties estimated using ryegrass as a reference weed; PAA $_{Dicot}$= Potential Allelopathic Activity of teff varieties estimated using radish (Cherry Belle) as a reference weed; (2) R^2 with its corresponding P-values is from the final model of the backward regression (3) The values in the brackets are the estimates of the regression coefficients for the independent variables significantly contributing on the variance of weed density. (4) The backward multiple regression began from all the eight independent variables and ended with those without the estimates of the regression coefficients .

Discussion

Many studies have shown that competitive cultivars within cereal species can be an important tool within integrated weed management (Bertholdsson 2004; Andrew et al. 2015). As already claimed, however, there is little knowledge on differences in competitiveness between varieties of teff and what traits of the different varieties that may explain the differences in weed competitiveness. Beyond Haftamu et al. (2018), we have not found any studies showing the influence of different varieties of teff on weed growth. In the study of Haftamu et al. (2018), the weed biomass (DW) differed from 150.11 g to 356.37 g per m^2, in unweeded plots, between the most and less (plus 137%) competitive teff varieties.

Studies, e.g. Bertholdsson (2004), have shown that allelopathic activity can differ between cultivars within a cereal species and that this trait can also contribute to reduce weed interference. Genotypic effect of a single crop species and environment affect release of allelochemicals and their effects over time (Weston & Duke 2003). Inhibition of root growth of weeds and other plant species is among the indicators of allelopathic effects of crop plants (Inderjit et al. 1994; Inderjit & Duke 2003; Walker et al. 2003). Leaf extracts from different eucalyptus species and *Parthenium hysterophorus* had an effect on germination and early growth of teff (Lisanework & Michelsen 1993; Tefera 2002). Our experiment, where we used a method that did not allow competition between teff and model weeds, showed that the different teff varieties caused different overall root growth of ryegrass and radish. Our first hypothesis, "There are differences in allelopathic activity between teff varieties" was therefore supported. This is consistent with the idea that genotypic variation can impact allelopathic effect of crop species (Weston & Duke 2003). Among the tested teff varieties, the local land race and the variety *DZ-01-2675* were successful in reducing the root length, area and dry weight of both model weeds i.e. ryegrass and radish. According to Wu et al. (2000) and Bertholdsson (2005), the potential allelopathic activity (PAA) and specific potential allelopathic activity (SPAA) can be used as parameters to express allelopathic effect of crops on weeds. From all the varieties, local land race and *DZ-01-2675* had relatively higher allelopathic effect on ryegrass as they had the highest PAA and SPAA values. On the other hand, the variety *Boset* had the highest allelopathic effect on radish followed by DZ-*01-2675* and *'Kora'*. These are among the high yielding teff varieties in Ethiopia (Ketema 1997; EMAaRD 2014), indicating no trade-off between yield potential and weed suppression ability for these cultivars. The dominantly produced and high yielding variety widely grown in Ethiopia, *DZ-Cr-387 ('Quncho') (Kebebew et al. 2011)* had, however, the least allelopathic effect on both ryegrass and radish. In addition to root length, root area and root dry weight, root volume and root diameter of both weeds significantly contributed on the variance of the allelopathic effect of the different teff varieties.

From the field experiments conducted in *Axum* and *Mekelle* in 2015 and 2016, the most important agronomic traits identified were days to emergence, heading, maturity, plant height, tiller no./plant and crop biomass yield. As already described, the allelopathic potential of the teff varieties obtained from our laboratory experiments was among the important traits of the crop. Most of these traits showed a strong and significant correlation with the weed biomass, cover and density. This is consistent with many other studies showed that crops with an 'early vigor' including early emergence, early flowering and maturity, often cause significant growth reductions of weed (Christensen 1995; Bertholdsson 2005). Furthermore, many other studies showed that taller plants (Christensen 1995; Lemerle et al. 1996) with highest tillering potential (Korres & Froud-Williams 2002), crop biomass yield and higher allelopathic effect (Bertholdsson 2005; Belz 2007; Andrew et al. 2015; Bajwa et al. 2017) have higher competitive ability and cause reasonable reduction on weed biomass, cover and density. Days to crop emergence is probably the main factor for crop weed competitive ability and release of root exudates i.e. allelochemicals (Bertholdsson 2005). Days to emergence was an important trait for explaining differences in weed intereference between cultivars in our study. Therefore, our second hypothesis "Emergence and allelopathic activity are the two most important traits for teff weed competitive ability" was partly supported. However, not only the early vigor but also the later stage of the teff varieties had affected the biomass, cover and density of weeds during teff production. Teff varieties with the earliest to emerge have the potential to compete with the weeds for water and nutrients. Most of the early emerging varieties have early maturing habits and mostly adapted to low to mid altitudinal environments of Ethiopia characterized by high weed intensity (Ketema 1997; Teklu & Tefera 2005; Esayas et al. 2013; EMAaRD 2014; Assefa et al. 2015). As already stated above, PAA of the teff varieties contributed on average from 21.5 % to 28.2 % of the variance in weed biomass, cover and density. That means this trait is important and it is interesting to recognize that this average is comparable to values found in spring barley, PAA in the model varied from 12-26 % of the variance in weed biomass (Bertholdsson 2005). He, however, found that PAA was less important trait in wheat compared to barley. Another interesting finding in our study, that the local landrace have a high allelopathic potential, is also found in barley in Sweden by Bertholdsson (2004). In this study, he summarized that "*the allelopathic activity of barley probably originated from different landraces, and in most cases from a specific landrace from the Swedish island of Gotland. We suspect that more than 100 years of selection and breeding have resulted in a dilution of the genes from landraces and consequently a declining allelopathic activity*".

In this study, teff phenology significantly explained the variance in weed biomass, cover and density confirming their contribution on reduction of the overall performance of weeds under field condition during production. The other agronomic traits i.e. plant height, tiller no./plant, crop biomass and allelopathic effect of teff contributed on the weed competitive ability of the crop as observed during the study period and explained significantly to more than 90 % of the variance in the weed responses. Temporal and spatial variability of the allelopathic effect of teff varieties had been observed which may show the impacts of environmental factors on potential allelopathic activity of crops as explained by Weston and Duke (2003). Generally the strong correlation between the weed responses and the agronomic traits of the different teff varieties indicated that these are the important traits explaining the potential weed competitive ability of teff during production and explaining more than 98 % of the variance in weed performance under field conditions.

Conclusion

All the teff varieties had allelopathic potential and had inhibited early root growth and development of both monocot and dicot weeds.

Allelopathic effect of teff had conspicuous role in affecting weeds during their late stages and were able to impact their biomass, cover and density.

In addition to allelopathic effect, emergence and crop biomass yield are the most important agronomic traits contributing on the weed competitive ability of teff though the contribution of plant height and tillering potential was also vital.

References

Andrew, I. K. S., Storkey, J. & Sparkes, D. L. (2015). A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research*, 55 (3): 239-248.

Assefa, A., Liben, M., Tadesse, T. & Yeshalem, B. (2008). The effect of tillage frequency and weed control on yield of tef (Eragrostis tef) in Yielmana-Densa Area, northwestern Ethiopia. *East African Journal of Science*, 2 (1): 35-40.

Assefa, K., Tadele, Z., Chanyalew, S., Ethiopian Institute of Agric. Research, D. Z. C. & Pflanzenwissenschaften, U. B. I. f. (2013). *Achievements and Prospects of Tef Improvement: Proceedings of the Second International Workshop, November 7-9, 2011, Debre Zeit, Ethiopia*: Universität Bern.

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.

Bajwa, A. A., Walsh, M. & Chauhan, B. S. (2017). Weed management using crop competition in Australia. *Crop Protection*, 95: 8-13.

Balesh, T., Aune, J. B., Johnsen, F. H. & Vanlauwe, B. (2008). The prospects of reduced tillage in tef (Eragrostis tef Zucca) in Gare Arera, West Shawa Zone of Oromiya, Ethiopia. *Soil and Tillage Research*, 99 (1): 58-65.

Baye, K. (2014). *Teff: nutrient composition and health benefits*: International Food Policy Research Institute (IFPRI).

Belz, R. G. (2007). Allelopathy in crop/weed interactions—an update. *Pest management science*, 63 (4): 308-326.

Bertholdsson, N. O. (2004). Variation in allelopathic activity over 100 years of barley selection and breeding. *Weed Research*, 44: 78-86.

Bertholdsson, N. O. (2005). Early vigour and allelopathy – two useful traits for enhanced barley and wheat competitiveness against weeds. *Weed Research*, 45: 94-102.

Campbell, L. G., Snow, A. A., Sweeney, P. M. & Ketner, J. M. (2009). Rapid evolution in crop-weed hybrids under artificial selection for divergent life histories. *Evolutionary Applications*, 2 (2): 172-186.

Chou, C.-H. (1999). Roles of Allelopathy in Plant Biodiversity and Sustainable Agriculture. *Critical Reviews in Plant Sciences*, 18 (5): 609-636.

Christensen, S. (1995). Weed suppression ability of spring barley varieties. *Weed Research*, 35 (4): 241-247.

CSA. (2016). *Agricutlrual Sample Survey 2015/2016 (2008E.C): Report on Area, Production and Farm Management Practice on Belg Season Crops for Private Peasant Holdings*, vol. V (5). Addis Ababa, Ethiopia: CENTRAL STATISTICAL AGENCY. 131 pp.

Daniel, T., Teferi, A. & Tesfaye, W. (2016). Evaluation of Improved Varieties of Teff in West Belessa, Northern Ethiopia. *Review of Plant Sciences*, 3 (1): 1-6.

Dennis, C. O., Jose, V. F. & Nikol, H. (2016). Weed Control and Radish (Raphanus sativus) Response to S-metolachlor on Organic Soils. *HortScience*, 51 (1): 79-83.

EMAaRD. (2014). *Crop Variety Issue No.12: Summary of Released/Registered Varieties of Crops*, vol. 12. Addis Ababa: Ethiopian Ministry of Agriculture and Rural Development.

Esayas, T., Abraham, G. H. & Mashila, D. (2013). Weed Interference in Cotton (Gossypium hirsutum L.) in the Middle Awash, Ethiopia. *Ethio. J. Appl. Sci. Technol.*, 4: 41-49.

Grace, J. & Tilman, D. (1990). Perspectives on plant competition: some introductory remarks. In *Perspectives on Plant Competition*, pp. 3-7: Elsevier.

Haftamu, G., Aune, J. B., Netland, J., Torp, T., Eklo, O. M. & Brandsaeter, L. O. (2018). Weed competitive ability of tef varieties. *Crop Protection*, Submitted: 1-23.

IFPRI. (2006). *Atlas of the Ethiopian Rural Economy*. Addis Ababa, Ethiopia: International Food Policy Research Institute and Central Statistical Agency. 1-108 pp.

Inderjit, Dakshini, K. M. M. & Einhellig, F. A. (1994). *Allelopathy*. ACS Symposium Series, vol. 582: American Chemical Society. 396 pp.

Inderjit & Duke, S. O. (2003). Ecophysiological aspects of allelopathy. *Planta*, 217 (4): 529-539.

Kebebew, A., Sherif, A., Getachew, B., Gizaw, M., Hailu, T. & Mark, E. S. (2011). Quncho: the first popular tef variety in Ethiopia. *International Journal of Agricultural Sustainability*, 9 (1): 25-34.

Ketema, S. (1997). *Tef (Eragrostis tef (Zucc.) Trotter): Promoting the conservation and use of underutilized and neglected crops*, vol. 12. Rome, Italy: Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute.

Korres, N. E. & Froud-Williams, R. J. (2002). Effects of winter wheat cultivars and seed rate on the biological characteristics of naturally occurring weed flora. *Weed Research*, 42 (6): 417-428.

Lemerle, D., Verbeek, B., Cousens, R. D. & Coombes, N. E. (1996). The potential for selecting wheat varieties strongly competitive against weeds. *Weed Research*, 36 (6): 505-513.

Lisanework, N. & Michelsen, A. (1993). Allelopathy in agroforestry systems: the effects of leaf extracts ofCupressus lusitanica and threeEucalyptus spp. on four Ethiopian crops. *Agroforestry Systems*, 21 (1): 63-74.

Neli, R.-A., María, J. A. & Verónica, B. R. (2017). Effect of glyphosate application on soil quality and health under natural and zero tillage field conditions. *Soil Environ.*, 36 (2): 141-154.

Powles, S. B. (2008a). Evolution in action: glyphosate-resistant weeds threaten world crops. *Outlooks on Pest Management*, 19 (6): 256-259.

Powles, S. B. (2008b). Evolved glyphosate-resistant weeds around the world: lessons to be learnt. *Pest Management Science*, 64 (4): 360-365.

Qasem, J. R. & Foy, C. L. (2001). Weed Allelopathy, Its Ecological Impacts and Future Prospects. *Journal of Crop Production*, 4 (2): 43-119.

Singh, H. P., Batish, D. R. & Kohli, R. K. (2003). Allelopathic Interactions and Allelochemicals: New Possibilities for Sustainable Weed Management. *Critical Reviews in Plant Sciences*, 22 (3-4): 239-311.

Tefera, T. (2002). Allelopathic effects of Parthenium hysterophorus extracts on seed germination and seedling growth of Eragrostis tef. *Journal of Agronomy and Crop Science*, 188 (5): 306-310.

Teklu, Y. & Tefera, H. (2005). Genetic improvement in grain yield potential and associated agronomic traits of tef (Eragrostis tef). *Euphytica*, 141 (3): 247-254.

van der Meulen, A. & Chauhan, B. S. (2017). A review of weed management in wheat using crop competition. *Crop Protection*, 95: 38-44.

Walker, T. S., Bais, H. P., Grotewold, E. & Vivanco, J. M. (2003). Root Exudation and Rhizosphere Biology. *Plant Physiology*, 132 (1): 44.

Weih, M., Didon, U. M. E., Rönnberg-Wästljung, A. C. & Björkman, C. (2008). Integrated agricultural research and crop breeding: Allelopathic weed control in cereals and long-term productivity in perennial biomass crops. *Agricultural Systems*, 97 (3): 99-107.

Weston, L. A. & Duke, S. O. (2003). Weed and Crop Allelopathy. *Critical Reviews in Plant Sciences*, 22 (3-4): 367-389.

Willis, R. J. (2007). *The History of Allelopathy*. P.O.Box 17,3300 AA Dordrecht, The Netherlands: Springer. 315 pp.

Wu, H., Pratley, J., Lemerle, D. & Haig, T. (2000). Evaluation of seedling allelopathy in 453 wheat (Triticum aestivum) accessions against annual ryegrass (Lolium rigidum) by the equal-compartment-agar method. *Australian Journal of Agricultural Research*, 51: 937-944.

Appendix A

Table 1. Pearson correlation of the responses of ryegrass to allelopathic effects of teff

	Root length (cm)	Root area (cm²)	Root diameter (mm)	Root volume (cm³)	Root (dry weight (mg)
Root length (cm)	1	0.9239	-0.5848	0.6483	0.57582
		0.0001	0.0758	0.0426	0.0815
Root area (cm²)	0.92394	1	-0.3229	0.7592	0.48459
	0.0001		0.3627	0.0109	0.1558
Root diameter (mm)	-0.58483	-0.323	1	-0.2644	-0.16693
	0.0758	0.3627		0.4603	0.6448
Root volume (cm³)	0.64831	0.7592	-0.2644	1	0.44691
	0.0426	0.0109	0.4603		0.1954
Root (dry weight (mg)	0.57582	0.4846	-0.1669	0.4469	1
	0.0815	0.1558	0.6448	0.1954	

Table 2. Pearson correlation of the responses of radish to allelopathic effects of teff

	Root length (cm)	Root area (cm²)	Root diameter (mm)	Root volume (cm³)	Root (dry weight (mg)
Root length (cm)	1	0.8388	-0.8121	0.3109	-0.1913
		0.0024	0.0043	0.3819	0.5966
Root area (cm²)	0.83882	1	-0.3893	0.7674	0.01436
	0.0024		0.2662	0.0096	0.9686
Root diameter (mm)	-0.81207	-0.389	1	0.2546	0.43235
	0.0043	0.2662		0.4777	0.2121
Root volume (cm³)	0.31092	0.7674	0.2546	1	0.19908
	0.3819	0.0096	0.4777		0.5814
Root (dry weight (mg)	-0.19126	0.0144	0.4324	0.1991	1
	0.5966	0.9686	0.2121	0.5814	

Table 3. Pearson correlation of the agronomic traits of teff

	Emergence	Heading	Maturity	Plant height	Tiller no. Per plant	Biomass yield (kg/ha)	PAA_{rye}	$SPAA_{rye}$	PAA_{rad}	$SPAA_{rad}$
Emergence	1	0.56923	0.58938	0.24164	0.56447	-0.79402	-0.03352	-0.124	-0.3327	-0.00824
		0.0859	0.073	0.5012	0.0891	0.0061	0.9268	0.7329	0.3475	0.982
Heading	0.56923	1	0.93377	0.83025	0.59615	0.00091	-0.26368	-0.23276	-0.5653	-0.149
	0.0859		<.0001	0.0029	0.0689	0.998	0.4617	0.5175	0.0886	0.6812
Maturity	0.58938	0.93377	1	0.73715	0.65183	-0.0289	-0.08545	0.00143	-0.4591	-0.07745
	0.073	<.0001		0.015	0.0411	0.9368	0.8144	0.9969	0.182	0.8316
Plant height	0.24164	0.83025	0.73715	1	0.43478	0.20518	-0.00891	-0.04849	-0.2027	0.14782
	0.5012	0.0029	0.015		0.2092	0.5696	0.9805	0.8942	0.5743	0.6836
Tiller no. Per plant	0.56447	0.59615	0.65183	0.43478	1	-0.32473	-0.02873	0.05773	-0.5719	-0.41598
	0.0891	0.0689	0.0411	0.2092		0.3599	0.9372	0.8741	0.0841	0.2318
Biomass yield (kg/ha)	-0.79402	0.00091	-0.0289	0.20518	-0.32473	1	-0.16876	-0.01427	0.03512	-0.07146
	0.0061	0.998	0.9368	0.5696	0.3599		0.6412	0.9688	0.9233	0.8445
PAA_{rye}	-0.03352	-0.26368	-0.08545	-0.00891	-0.02873	-0.16876	1	0.94648	0.75023	0.70771
	0.9268	0.4617	0.8144	0.9805	0.9372	0.6412		<.0001	0.0124	0.022
$SPAA_{rye}$	-0.124	-0.23276	0.00143	-0.04849	0.05773	-0.01427	0.94648	1	0.61775	0.5442
	0.7329	0.5175	0.9969	0.8942	0.8741	0.9688	<.0001		0.057	0.1039
PAA_{rad}	-0.33272	-0.5653	-0.45908	-0.20272	-0.5719	0.03512	0.75023	0.61775	1	0.8805
	0.3475	0.0886	0.182	0.5743	0.0841	0.9233	0.0124	0.057		0.0008
$SPAA_{rad}$	-0.00824	-0.149	-0.07745	0.14782	-0.41598	-0.07146	0.70771	0.5442	0.8805	1
	0.982	0.6812	0.8316	0.6836	0.2318	0.8445	0.022	0.1039	0.0008	

ISBN: 978-82-575-1552-2
ISSN: 1894-6402

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no

101550 / ANDVORDGRAFISK.NO