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Agricultural Drought Analysis in Amhara and Tigray Regions of Ethiopia

by

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Science Pledge

By my signature below, I certify that my project report is entirely the result of my own work. I have cited all sources of information and data I have used in my project report and indicated their origin.

Addis Ababa, June 22, 2020



Place and Date

Signature

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Abstract:

Droughts are the most common natural disasters affecting the socioeconomic activities and livelihoods of people all over the globe. In 2015, Ethiopia was stricken by a big drought that was the most severe in 50 years. That drought killed 1.2 million animals, affected another 7 million livestock, and affected 10.2 million people, and caused many other socioeconomic impacts in the country. The purpose of this study was to analyze the spatiotemporal characteristics of the agricultural drought that affected the Amhara and Tigray regions of Ethiopia in 2015 using drought indices derived from MODIS and CHIRPS.

The MODIS/006/MOD13Q1 (MODIS/Terra Vegetation Indices 16-day L3 Global 250m Version 6) and MODIS/006/MOD11A2 (MODIS/Terra Land Surface Temperature & Emissivity 8-day L3 Global 1 km Version 6) data were downloaded from the NASA LPDAAC and used to compute the NDVI&VCI, and TCI indices; MCD12Q1 products (Modis/Terra and Aqua combined Land cover Types yearly Global 500m SIN GRID V006) from the same source was used to extract the agricultural land and mask the results; and CHIRPS data from Fast Early Warning System Networks portal (FEWSNet) was used for rainfall analyses. The MODIS and CHIRPS raster data were extracted, mosaiced, re-projected, clipped before they were used in the analysis, and the final NDVI, VCI, and TCI results were masked with the agricultural land. The crop covered areas and crop productions for the same year were also obtained from CSA and used to see performances of the SPI, NDVI, VCI, and TCI indices to detect the drought. At last, the results were integrated into the shapefile of the study area and mapped accordingly. The results showed that about 24.5 to 62% of the agricultural land in Amhara and Tigray regions were affected by a mild to extreme drought in 2015, the eastern part was more affected by the drought than the western part, and proportionally Tigray was more affected than the Amhara region. It was also found that NDVI ($R^2 = 0.53$) has strong positive correlations, TCI ($R^2 = 0.64$) very strong negative correlation, and VCI ($R^2 = 0.22$) moderate correlation with SPI. The remote sensing and GIS methodologies used in this work were also found applicable and useful for agricultural drought monitoring, and early warning systems in the study area.

Table of Contents

Science Pledge	1
Acknowledgments.....	2
Abstract.....	3
Table of contents.....	4
List of Tables	5
List of Figures and Maps.....	5
List of Abbreviations.....	6
Chapter-1. Introduction	8
1.1. Background	8
1.2. Statement of the problem.....	9
1.3. Objectives	10
1.4. Scope	11
1.5. Study area.....	11
1.6. Literature review.....	14
Chapter-2. Methodology	29
2.1. Data types, data sources, Software.....	29
2.2. Methods & processing,	32
Chapter-3. Processes and Results	40
3.1. Rainfall Analysis.....	41
3.2. Standard Precipitation Index (SPI) Analysis	44
3.3 Normalized Difference Vegetation Index (NDVI) analysis	46
3.4.Vegetation Condition Index (VCI) analysis	60
3.5 Temperature Condition Index (TCI) analysis	71
3.6 Crop covered areas and crop production analysis.....	81
3.7 Correlations of NDVI, VCI, TCI, and SPI.....	84
Chapter-4. Conclusions	86
References	90
Annexes	96

List of Tables

Table 1.1 Population of the study area in 2019 ('Thousands of People')	14
Table 1.2 Lists and descriptions of MODIS spectral bands	25
Table 2.1 Lists and descriptions of data types used in the study	31
Table 2.2 Drought classifications based on SPI	34
Table 2.3 Vegetation health and density classification based on NDVI	35
Table 2.4 Drought classifications based on VCI	36
Table 2.5 Drought classifications based on TCI	36
Table 2.6 Statistical strengths classifications based on the linear regression model (R ²)	38
Table 3.1 LULC types in Amhara and Tigray regions in 2016	41
Table 3.2 Rainfall condition in Amhara and Tigray regions from 2006 to 2015	42
Table 3.3 Vegetation health and density conditions of Amhara and Tigray regions from June to October of 2015 based on NDVI results	48
Table 3.4 Comparison of a pixel by pixel NDVI values between 2014 and 2015	57
Table 3.5 Agricultural land in Amhara and Tigray regions affected by drought from June to October of 2015 based on VCI results	61
Table 3.6 Comparison of a pixel by pixel VCI values between 2014 and 2015	64
Table 3.7 Agricultural land in Amhara and Tigray regions affected by drought from June to October of 2015 based on TCI results	75
Table 3.8 Crop covered area and crop production in Amhara and Tigray regions from 2014 to 2016	83
Table 3.9 Crop covered area and crop production reduction in Amhara and Tigray regions in 2015 by zone	84
Table 3.10 Correlation of the drought indices based on linear regression	85

List of Figures

Figure 2.1 Schematic diagram of study methodology	32
Figure 3.1 Trends of average rainfall in Amhara and Tigray regions in 10 years (2006 to 2015)	42
Figure 3.2 Drought trends in Amhara and Tigray regions from June to September in 10 years (2006 to 2015) based on SPI values	42
Figure 3.3 Trends of drought conditions in Amhara and Tigray regions from June to October of 2015 based on VCI values	47
Figure 3.4 Trends of drought conditions in Amhara and Tigray regions from June to October of 2015 based on VCI values	62

List of Maps

Map 1.1 Location of Amhara and Tigray regions in Ethiopia	12
Map 1.2 Elevation zones of Amhara and Tigray regions	13
Map 3.1 Land use land cover (LULC) of Amhara and Tigray regions	40
Map 3.2 Rainfall distributions in Amhara and Tigray regions from June to September of 2015	43

Map 3.3 Drought conditions in Amhara and Tigray regions in September 2015 based on SPI values	45
Map 3.4 Vegetation health and density conditions in Amhara and Tigray regions in June 2014 and 2015 based on NDVI values.....	49
Map 3.5 Vegetation health and density conditions in Amhara and Tigray regions in July 2014 and 2015 based on NDVI values.....	51
Map 3.6 Vegetation health and density conditions in Amhara and Tigray regions in August 2014 and 2015 based on NDVI values	53
Map 3.7 Vegetation health and density conditions in Amhara and Tigray regions September 2014 and 2015 based on NDVI values.....	55
Map 3.8 Vegetation health and density conditions in Amhara and Tigray regions in October 2016 of 2014 and 2015 based on NDVI values	56
Map 3.9 Drought condition in Amhara and Tigray regions in June 2014 and 2015 based on VCI values	63
Map 3.10 Drought conditions in Amhara and Tigray regions in July 2014 and 2015 based on VCI values	65
Map 3.11 Drought conditions in Amhara and Tigray regions in August 2014 and 2015 based on VCI values	67
Map 3.12 Drought condition in Amhara and Tigray regions in September 2014 and 2015 based on VCI values.....	69
Map 3.13 Drought condition in Amhara and Tigray regions in October 2014 and 2015 based on VCI values	70
Map 3.14 Drought condition in Amhara and Tigray regions in June 2014 and 2015 based on TCI value.....	73
Map 3.15 Drought condition in Amhara and Tigray regions in July 2014 and 2015 based on TCI values	74
Map 3.16 Drought condition in Amhara and Tigray regions in August 2014 and 2015 based on TCI values.....	77
Map 3.17 Drought condition in Amhara and Tigray regions in September 2014 and 2015 based on TCI values	79
Map 3.18 Drought condition in Amhara and Tigray regions in October 2014 and 2015 based on TCI values.....	80
Map 3.19 Crop covered area reduction in Amhara and Tigray regions in 2015 from 2014.....	82
Map 3.20 Crop production reduction in Amhara and Tigray regions in 2015 from 2014.....	83

List of Abbreviations

AMSU	Advanced Microwave Sounding Unit
A.m.s.l	Above mean sea level
AVHRR	Advanced very high-Resolution Radiometer
BMDI	Bhalme and Mooley drought Index
CHIRPS	Climate Hazard Group InfraRed Precipitations with Stations
CMI	Crop Moisture Index
CSA	Central Statistical Agency
CZCS	Coastal Zone Color Scanner
DrinC	Drought Indices Calculator
DRMC	Disaster Risk Management Commission
EOS	Earth Observation Systems

ESRI	Environmental Scientific Research Institute
FAO	Food and Agriculture Organization
FEWSNet	Fast Early Warning System Networks
GDP	Gross Domestic Product
GEOS	Geostationary Operational Environment Satellites
GIS	Geographic Information Science
HDF	Hierarchical data format
HIRS	High Resolution Infrared Radiation Sounder
ICRC	International Committee of the Red Cross
IGBP	International Geosphere Biosphere Program
IMF	International Monetary Fund
IR	Infrared
LP DAAC	Land Products Data Archival and Access Center
LULC	Land Use Land Cover
LST	Land Surface Temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
NAMSA	National Meteorological Stations Administration
NAPA	National Adaptation Program for Action
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
QGIS	Quantum GIS
RAI	Rainfall Anomaly Index
RCMRD	Regional Center for Mapping of Resources for Development
RSB	Reflectance Solar Band
SBRS	Santa Barbara Remote sensing
SMDI	Soil Moisture Drought Index
SMSI	Surface Water Supply Index
SPI	Standardized Precipitation Index
SSM/I	Special Sensor Microwave Imager
TCI	Temperature Condition Index
TEB	Thermal Emission Band
TIR	Thermal Infrared
TRRM	Tropical Rainfall Measuring Mission
UTM	Universal Transverse Mercator
USAID	United States Agency for International development
USD	United States Dollar
USGS	United States Geological Survey
VCI	Vegetation Condition Index

Chapter-1 : Introduction

1.1 Background

Precipitation is a major source of water to life on terrestrial earth in the majority of the world. Droughts are natural disasters that are caused mostly due to a natural reduction in the amount of precipitation received over an extended period (Wilhite, 1993; Wilhite et al., 2014). Droughts are classified into four categories as meteorological, hydrological, agricultural, and socioeconomic droughts (Wilhite, 2000; Kogan, 1997). Agricultural droughts are caused by the reduction of soil moisture due to reduced precipitation that leads to reduced crop production and plant growths (Heim Jr, 2002).

Droughts have been creating a multitude of impacts on the economy, social, and environmental segments worldwide (Benson and Clay, 1998; Wilhite et al., 2007). For example, drought causes 6 to 7 billion USD losses in the USA annually, and constitute 7% of the 1.4 trillion economic losses by natural disasters globally from 1990 to 2004 (Below et al., 2007); affected about 1.4 billion people globally between 1967–1991, killed more than 1.1 million, and affected above 230 million Africans (Kogan, 2001). Ethiopia has been frequently affected by many droughts in its history. These disasters caused famine, death of people and animals, displacements of people and separation of families, and political unrest, etc. (Degefu, 1987; Mera, 2018; Gray and Mueller, 2012; De Waal et al., 2006). In 2015, Ethiopia was stricken by a big drought, which was the most severe in 50 years. That drought-affected 10.2 million people, killed 1.2 million animals, affected 7 million livestock, and consumed 25% of the national GDP for its mitigation (Mera, 2018). The 2015 drought also caused 0.57% and 1.3 % reductions in the estimated crop covered area and volume of crop production from the earlier year at the country level. The 2015 drought also severely affected the Amhara and Tigray regions causing up to 7.1% reductions in the crop covered area and up to 31% in crop production in the regions from the same period of 2014 (CSA, 2016).

Drought monitoring and early warning systems provide useful information to decision-makers to reduce the adverse impacts of the natural disaster on people and the environment (Wilhite et al., 2000). The monitoring of droughts using space technology products like MODIS and CHIRPS has become a popular methodology in the science community. The advancements in remote sensing and GIS technologies also eased the analysis of satellite data for drought monitoring applications globally (AghaKouchak et al., 2015). The aim of this study was, therefore, to analyze the spatiotemporal characteristics of the agricultural drought that affected the Amhara and Tigray regions of Ethiopia in 2015 based on MODIS and CHIRPS data. It also included analysis of the drought conditions in 2014 to be used as a reference to better understand the degree of the drought in 2015.

This document was organized into four chapters. The topics of introduction, statement of the problem, overall and specific objectives, scope, and study area were covered in chapter 1; methodology and data processing in chapter 2; processes and results in chapter 3; and conclusion and recommendations in chapter 4.

1.2 Statement of the problem

Ethiopia has the highest population in Africa next to Nigeria, and it is also one of the poorest countries in the world although the economic reforms implemented in 1991 brought improvements in its economy (MoFED, 2011). Ethiopia has been affected by different droughts since 1984. Those droughts caused famine, death of people and animals, and various social and political destabilization in the country (Degefu, 1987; De Waal et al., 2006; Liou and Muluaem, 2019). The drought in 2015 was identified as the most severe in 50 years. And it affected 10.2 million people, killed 1.2 million animals and affected another 7 million livestock, caused 35% reductions in surface and groundwater, and consumed 25% share of the country GDP for its mitigation (Mera, 2018; Qu et al., 2019; Funk et al., 2016; Eshetie et al., 2016; Philip et al., 2018; Liou and Muluaem, 2019).

In Ethiopia, the agricultural sector employs above 80% of the labor force and contributes to 45% of its GDP, and hence it is usually called as the backbone of the Ethiopian economy. However, the Ethiopian agricultural activities are mainly rainfed and highly dependent on the long rainy seasons (June to September), which accounts for 70% of the total rainfall in the country (Bewket and Conway, 2007; Suryabhagavan, 2017). The rainfall in many places in Ethiopia is known by erratic, unreliable, and variable characteristics, and their frequency of occurrences are decreasing since the last few decades (Bewket, 2009). The droughts in Ethiopia were mainly caused by the prolonged absence of precipitation and extended dry seasons and sometimes strong rains during wet periods (Liou and Muluaem, 2019). Northern Ethiopia that includes Amhara and Tigray regions has been also associated with the drought history of the country. The erratic rainfall, high land degradation, high population density, and negligible irrigation agriculture are among the main reasons for the high frequency and intensity of droughts in those regions (Mengistu, 2011; Degefaw, 2007; Ayalew et al., 2012; Bewket, 2009). The geographic coverage and distribution of meteorological stations in Ethiopia are low and the data from those stations has also limited accessibility and low quality. This remained among the factors that are hampering the drought monitoring efforts in the country (Funk et al., 2016; Funk et al., 2015).

1.3 Overall and specific objectives

The overall objective of this study was to analyze the spatiotemporal characteristics of the agricultural drought that affected the study area in 2015. The study can be important for decision-makers to understand the usefulness of the methodology in drought monitoring and early warning systems to reduce the adverse effects of droughts on people and the environment.

The specific objectives were:

- To analyze the extent and intensity of the drought
- To analyze the performance of the vegetation indices in detecting the drought

- To analyze the degree of correlation of the drought indices with rainfall
- To show usefulness and applicability of the remote sensing and GIS methodologies for drought monitoring and early warning systems

1.4 Scope

The scope of the study was limited to the spatiotemporal analysis of the agricultural drought in the study area based on MODIS and CHIRPS precipitation data obtained from secondary sources. However, assessment of the drought impacts through the collection of primary data, and ground verification of data and results are beyond the scope.

1.5 Study area

1.5.1 Location and physiography

The study area is found in the Northern central part of Ethiopia and it covers the Amhara and Tigray regions. Its geographical location is between 35°15'28" E to 40°00'45" E longitude and 8°43'57" N to 14°51'28" N latitude and has a total area of 215 326 square kilometers (Sq. Km). The area borders Eritrea in the North, Sudan in the West, Afar region in the East, and Oromia and Benishangul-gumuz regions in the south (Map1.1). In the administrative set up of Ethiopia, regions are subdivided into zones, and hence the Amhara and Tigray regions have eleven and five zones respectively (CSA, 2015). In the physiography of Ethiopia, the areas within the elevation range of 2500m to 4500 m.a.s.l are classified as highlands, 1500m to 2500m in the central plateau, and less than 1500m in lowlands (Mera 2018). According to this, 32.2% of the Amhara and Tigray regions is highland, 52.1% plateau, and 15.7% lowland (Map 1.2).

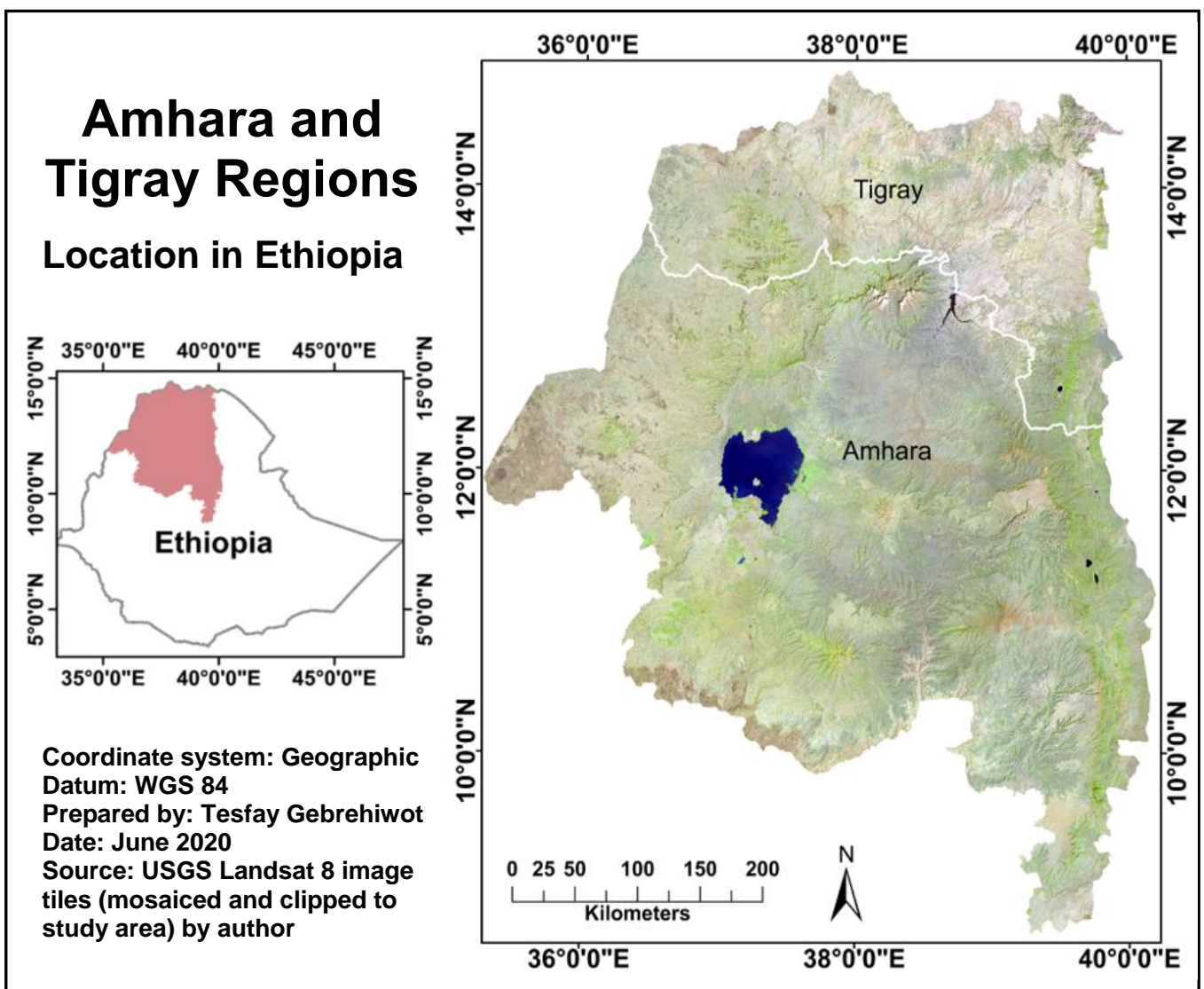
1.5.2 Climate

The climatic conditions in Ethiopia are mainly controlled by its topography (diversity of its terrain) and its location in the tropics. This makes the country have three seasons "Bega" (dry season), "Belg" (short rain season), and "Kiremt" (rainy seasons), unlike most tropics where two seasons (one wet and one dry season) are common. The duration of the Bega season is

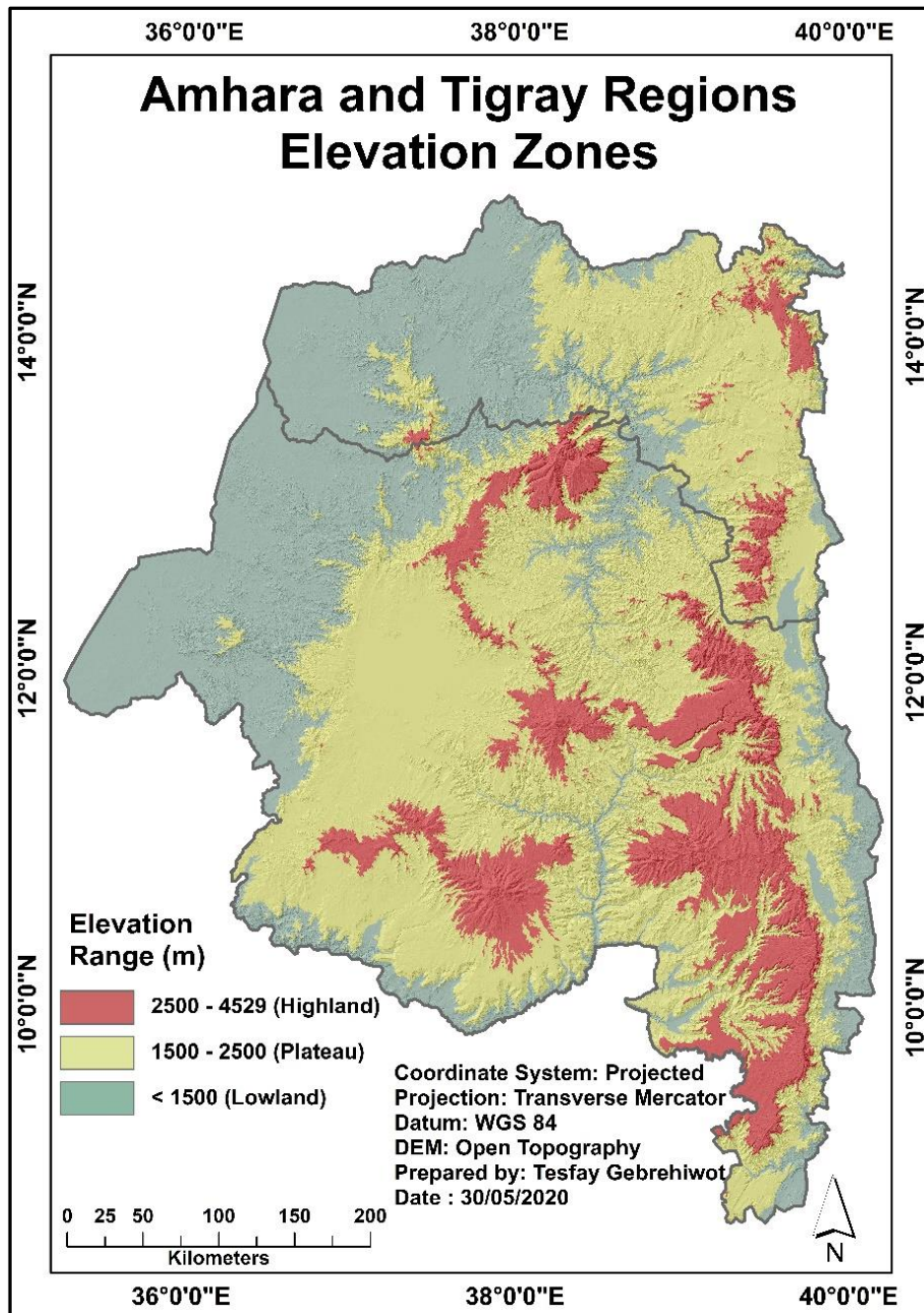
(October to January), Belg (February to May), and Kiremt (June to September). The rainy periods over the northern and central parts of Ethiopia including the current study area are acquired from June to September (Kiremt season) and this supports 70% to 85% crop productions nationally (Degefu, 1987).

The mean annual rainfall in Amhara and Tigray regions is between 500 and 1200 mm, and the average annual temperature ranges from 10 °C in the highlands to about 35 °C in the lowlands.

The El Nino and subsequent La Nina weather conditions are the main factors for the drought incidents affecting the two regions (Liou and Mulualem, 2019).



Map 1.1 Location of Amhara and Tigray regions in Ethiopia



Map 1.2 Elevation zones of Amhara and Tigray regions

1.5.3 Socioeconomy

Ethiopia has an estimated population of 98.5 million, which is the highest population in Africa next to Nigeria, from which 49.83 % are female and 50.17% are male. 78.86% of the total population lives in rural areas and 21.14% in urban areas. The population of the Amhara and Tigray regions is 27.3 million (accounting to 27.6% of the total population in the country) of which 21.8 million (80%) are living in Amhara and 5.4 million (20%) in Tigray regions. 79.3%

of the population (in Amhara 81.2% and Tigray 71.6%) is living in rural areas and 20.7% in urban areas. 50.1% of the population is female and 49.9% are male. The percentage of the female population in Amhara (49.9%) is slightly lower than Tigray (50.1%) (Table 1.1). The population density of the Amhara and Tigray regions is 133 people /sq. km and 96.6 people / sq. km respectively (CSA, 2013).

Agriculture is the most important sector in the Ethiopia economy employing more than 70% of the population. It is also referred to as the backbone of the country’s economy since it is a source for 85% of the national revenue and half of the GDP (Napa, 2007). The economy of Ethiopia has been growing on average of 9.9% between 2007/2008 and 2017/2018, and this makes it one of the fastest-growing states among 188 IMF member countries. As a result, the percent of people living below the poverty line has been declining from 44% (45% in rural and 35% in urban) in 2000 to 24% (25% in rural and 14% in Urban) in 2016 (CSA, 2016). The poverty ratio is 18.4% in the Amhara and 19.2% in Tigray regions, and the livelihood of the people in the two regions is mainly rain-fed cropping agriculture (CSA, 2015).

Table 1.1: Population of Amhara and Tigray regions in 2019 (‘Thousands of People’)

Region	Total	Male	Female	Urban			Rural		
				Total	Male	Female	Total	Male	Female
Amhara	21844	10943	10901	4090	2049	2041	17754	8894	8860
Tigray	5443	2686	2757	1547	763	784	3897	1923	1974

Source: (CSA, 2013)

1.6 Literature review

1.6.1 Introduction

In this section, the topics on concepts and definitions of drought, drought impacts, drought monitoring, and early warning systems, drought in Ethiopia, drought indices, applications of remote sensing and GIS in drought monitoring, and relevance of study topic are discussed based on a review of the literature.

1.6.2 Concepts and definitions of drought

Droughts are the most known natural disasters that occur in all climatic conditions in the world basically due to a natural reduction in the amount of precipitation received over an extended period (Wilhite, 1993). They can usually take three or more months to develop depending on the initiation of the precipitation deficiency but this time can vary considerably (Wilhite, 2000). Droughts differ from other natural hazards like floods, earthquakes, volcanoes, and tropical cyclones in several ways. The major ones are first, the effects of drought often accumulate slowly and they may continue for years after termination, and their onset and ends are difficult to determine (Kogan, 2001); second, drought has no precise and universally agreed definitions, and third, the impacts of drought cover large geographic areas hence are not visible (Wilhite, 1993; Wilhite et al., 2000; Below et al., 2007).

The definitions of drought are broadly categorized as conceptual or operational (Wilhite and Glantz, 1985). The conceptual definitions focus on generic descriptions of the phenomena and they are stated in relative terms (AghaKouchak, 2013). While the operational definitions mostly focused on defining droughts based on their special characteristics like onset, severity, continuation, and termination of the episodes. So, they can be used to analyze drought frequency, severity, and duration for a given historical period (Wilhite, 1993). Nonetheless, drought has no universal definition because of the complexities in the sectors that it affects, geographical occurrences, and temporal and spatial impacts (Wilhite, 1993). For more information on concepts and definitions of drought see the comprehensive reviews by (Wilhite and Glantz, 1985; Wilhite, 1993; Wilhite, 2000; Belal et al., 2014). Droughts are classified into four classes: meteorological, hydrological, agricultural, and socioeconomic droughts (Kogan, 1997; Wilhite, 2000; Jeyaseelan, 2003; Wilhite and Glantz, 1985); and all the drought types are associated with continued precipitation shortages (AghaKouchak et al., 2015).

A. Meteorological droughts

Meteorological droughts are caused by a lack or deficit of precipitation over a region for a period (Belal et al., 2014). These definitions are based on the degree of dryness of an area in

comparison to a normal average amount of rainfall, and the intensity and duration of the precipitation (Wilhite, 2000). Meteorological droughts are often accompanied by above-normal temperatures and precede and cause of other droughts (Dai, 2011).

B. Hydrological droughts

Hydrological droughts are associated with the effects of precipitation decreases in a region shown by the reductions of surface waters (streams, rivers, lakes, reservoirs, springs) and subsurface water (groundwater) used for a given water resources management systems (Belal et al., 2014; Wilhite, 1993). Hydrological droughts can continue for some period after the termination of meteorological droughts since recharge of reservoirs and groundwater is a long process. So they are often out of phase or lag with meteorological and also agricultural droughts (Wilhite, 2000).

C. Agricultural droughts

Agricultural droughts are usually related to a period of low soil moisture caused by absence or reduction of precipitation which leads to a decrease of crop production and plant growth (Heim Jr, 2002). The definitions of agricultural droughts are often linked to precipitation shortages, departures from normal, or other factors such as evapotranspiration that exceed the normal limits (Dai, 2011; Wilhite and Glantz, 1985). The water demand of plants is determined by the meteorological conditions, biological characteristics of the specific plant, the growth stage of the plant, and the physical and biological properties of the soil. So agricultural droughts may lag with meteorological droughts and their relationships are more complex (Wilhite, 2000).

D. Socioeconomic droughts

Socioeconomic droughts occur when people are affected by a physical shortage of water, and they are associated with demand and supply of economic goods associated with elements of meteorological, agricultural and hydrological droughts (Heim Jr, 2002). This definition supports the strong symbiosis that exists between drought and human activities (Wilhite, 2000).

1.6.3 Impacts of drought

Drought has been affecting “more than half of the terrestrial earth each year” (Du et al., 2018) causing different economic, environmental and societal impacts (Benson and Clay, 1998; Sheffield et al., 2012; Wilhite et al., 2007; Hao and AghaKouchak, 2013). The impacts of droughts are often referred to as direct and indirect (Ding et al., 2011). The direct impacts refer to the reductions on crop productions, deaths, or other effects on animal and human life, and damages on the ecosystem while indirect impacts refer to consequences of those impacts (Jeyaseelan, 2003). The impacts of drought can be generalized principally into economic, environmental, and social sectors (Quiring, 2015).

A. Economic Impacts

The economic impacts of drought cover the direct losses in the agricultural and other sectors related to it. It also includes the losses in recreation, transportation, banking, and energy; increases in unemployment, food prices and overall disruption of food supply; the economic pressure on financial institutions due to foreclosure of farms; increased costs of new or supplemental water resource development; and the strains on local, state, and federal government due to losses of revenue (Benson and Clay, 1998; Wilhite, 1993).

For example, drought caused 6 to 8 billion USD economic losses annually in the USA only (Below et al., 2007); the 1988 drought in America (recorded as the highest loss of all-natural disasters occurred in the 20th century) caused 40 billion USD economic losses, and; the El Nino and subsequent La Nina caused droughts to cost billions of economic losses globally. The global drought perspective between 1990 to 2004 also indicated droughts constitute 7% of the 1.2 trillion economic loss caused by all-natural disasters globally (Kogan, 2001; Ding et al., 2011).

B. Social Impacts

The social impacts of drought include the issues of public safety, health, conflicts among water users, loss of life, increased social unrest, depopulation of rural areas, fairness issues in the

distribution of impacts and disaster relief programs, and reduced quality of life (Kogan, 2001; Wilhite, 1993). From 1967 to 1991, 2.8 billion people faced different problems from all-natural disasters and the suffering in 51% of them were caused by droughts. Droughts also killed about 12 million and affected 1.87 billion people between 1900 to 2004, which is the largest of all other natural disasters (Kogan, 2001). Those droughts also killed above 1.1 million people and affected above 243 million people in Africa.

C. Environmental Impacts

The environmental impacts of drought are related to the damages on plant and animal species, wildlife habitat, air, and water quality, forest and range fires; degradation of landscape quality; soil erosion; reduced water levels, increased livestock and wildlife mortality rates, and damage to of their habitats. The environmental impacts of drought are difficult to quantify due to less focus of public officials to the problem, but these are improving with time because of the growing public awareness and concern for environmental quality (Wilhite, 1993).

1.6.4 Drought monitoring and early warning systems

The world is suffering from the effects of droughts due to their complex, recurrent, frequent, and inevitable characteristics (Quiring, 2015; Jordaan et al., 2018). With the projections of future climate changes and their associated effects (increases in temperature and evapotranspiration), the frequency and severity of the drought are predicted to increase in future due to global warming (Wilhite et al., 2007; Dai, 2011; Jordaan et al., 2018; Sheffield et al., 2012). So, countries must establish national drought policies that include comprehensive drought monitoring systems. The drought monitoring systems help to get early information on the onset, severity, and spatial extent of the drought so that decision-makers can take timely and appropriate actions to save the lives of people and the economy (Wilhite et al., 2000; Hayes et al., 2011).

The drought monitoring and early warning systems used worldwide have gaps since the density of meteorological and hydrological stations is inadequate, the data sharing among

agencies and governments are weak, the data used from early warning systems are not user-friendly, the long-term drought forecasts lack reliability, the available drought monitoring tools are not sufficient, the drought monitoring products globally do not illustrate the current and emerging drought conditions in an easily and timely accessible way, etc. (Wilhite et al., 2000)

1.6.5 Droughts and drought management systems in Ethiopia

Ethiopia has been frequently reported as a drought-stricken country in the media and scientific literature. Though the major cause of the droughts in the country was precipitation deficits, the timing of the onset and cessation, as well as frequency and duration of the dry spell during the wet seasons, have also remarkable effects (Viste et al., 2013). The warm phase of ENSO had been the major cause of the rain shortages over the northern and central parts of Ethiopia during the wet seasons (Funk et al., 2016, Viste et al., 2013). The reviews of historical droughts in Ethiopia made by (Degefu, 1987, Viste et al., 2013) revealed that the years 1984, 2002, and 2009 were the driest periods. According to (Ayalew et al., 2012), Ethiopia had been stricken by many drought events between 1964 and 2016. Those droughts resulted in the death of 1.2 million people, death of 3.2 million livestock, and affected a total of more than 83 million people and above 2 million livestock. In their analysis of meteorological drought in Ethiopia from 1971 to 2011, (Viste et al., 2013) identified 2009 as the second driest season surpassed by the drought in 1984 while 2002 was also referred to as a dry period.

The drought in 2015 was also recorded as the most severe of all droughts observed in the country in 50 years. It affected 10.2 million people, killed over 1 million livestock, and put another 1.7 million livestock into danger. The drought had also caused low agricultural production; a decrease of electric power; shortages of domestic, industrial and irrigation water supplies; migration of productive manpower; and political instability (Mera, 2018). The drought also caused 0.57% and 1.5% reductions in cropped area and crop productions respectively from the year before (CSA, 2015).

Ethiopia introduced a national drought policy since 1976, and the “Disaster risk management commission (DRMC)” has been responsible for drought responses in the country. Since 2015,

the country has also established a disaster risk management council at a high level, and early warning committee at national, regional, and woreda level. The established systems worked in very coordinated ways and helped in reducing the impacts of the 2015 drought (Mera, 2018).

1.6.6 Drought Indices

Drought indices are the quantitative measures that characterize drought levels by assimilating data from one or several variables (indicators) such as precipitation, evapotranspiration, and other hydrological variables (Morid et al., 2006) into a single numerical value that is more readily usable than raw indicator data (Zargar et al., 2011). Worldwide, there are over 100 indices developed for drought monitoring using data including ground observations, modeling, reanalysis, and remote sensing measurements (Qu et al., 2019). But, due to the complexity of drought definitions, no index is the best while some are still well suited for certain uses (Niemeyer, 2008). So, the application of more indices gives better results than a single index (AghaKouchak et al., 2015).

Some of the common drought indices used globally are Standardized Precipitation Index (SPI) by McKee, et al., 1993; the normalized difference vegetation index (NDVI) by Tucker 1979; NDVI based vegetation condition index (VCI) by Kogan 1995; temperature condition index (TCI) by Kogan 1995 (Keyantash and Dracup, 2002, Ghulam et al., 2007, Niemeyer, 2008). These indices were applied and used in this study.

A. Normalized Difference Vegetation Index (NDVI)

NDVI is the simplest, effective and most commonly used vegetation index (Shi et al., 2008, Dutta, 2018, Gao, 1996) for assessing and monitoring ecological variables such as vegetation cover, surface biomass, and Leaf Area Index (Ghorbani et al., 2012), vegetation monitoring, crop yield assessment and drought detection (Peters et al., 2002), agricultural drought monitoring and early warning at a regional scale worldwide (Chakraborty and Sehgal, 2010), and for operational drought assessment (Dutta, 2018, Gamanayake et al., 2016). NDVI is directly related to photosynthetic capacity and energy absorption of plant canopies (Shi et al.,

2008), and it retains the ability to minimize topographic effects while producing a linear measurement scale (Silleos et al., 2006, ShadA et al., 2017). Such observations have improved the understanding of people on characteristics and variability of vegetation covers at a pixel, local, regional, and global scales (Shi et al., 2008).

NDVI is based on the ratio of maximum absorption of radiation in the red band (R) spectral band versus a maximum reflection of radiation in the near-infrared (NIR) spectral bands. It is mathematically expressed as:

$$\text{NDVI} = (\text{NIR}-\text{R}) / (\text{NIR} + \text{R}), \text{ (Volcani et al., 2005) Equation (1)}$$

The NDVI values range from -1 to 1 with the negative values refer to water bodies, 0 represent no vegetation (barren lands) and clouds, and positive values to vegetation (Silleos et al., 2006, Dutta, 2018, Gamanayake et al., 2016). The higher values of NDVI show good greenness and photosynthetic capacity, and lower values indicate reductions on the chlorophyll and wilting of the vegetation for the same period of observation (ShadA et al., 2017). The major limitation of NDVI are it can only monitor a very thin layer of the canopy and cannot provide information on woody biomass(Shi et al., 2008), has lagged response to rainfall deficits (Chakraborty and Sehgal, 2010), affected by soil characteristics and reflectance from lower plant communities in the semi-arid area (Wilhite, 2005).

B. Vegetation Condition Index (VCI)

VCI is a vegetation index that scales NDVI values between its maximum and minimum values to separate the short term weather signals from the long-term ecological signals for drought monitoring (AghaKouchak et al., 2015). It has an excellent ability to detect drought and to measure the time of its onset, intensity, duration, impacts on vegetation, and has been used successfully to monitor drought conditions and crop yields in various parts of the world (Peters et al., 2002). VCI also provides drought information for well defined, prolonged, widespread, and intense droughts as well as very localized, short term, and non-well defined droughts (Kogan, 1995). The performance of VCI in capturing rainfall dynamics is better than NDVI especially in the areas of geographic inhomogeneity (ShadA et al., 2017). VCI is calculated as

$$VCI = (NDVI_i - NDVI_{min}) / (NDVI_{max} - NDVI_{min}) * 100 \dots\dots\dots \text{Equation (2)}$$

NDVI_i refers to NDVI value of data *i*, and NDVI max and NDVI min refer to the maximum and minimum NDVI values of all the images used in the dataset (Gamanayake et al., 2016, Degefu, 1987, AghaKouchak et al., 2015)

C. Temperature Condition Index (TCI)

TCI is used to determine temperature-related vegetation stresses based on thermal infrared (TIR) observations (AghaKouchak et al., 2015). Mathematically it is expressed as

$$TCI = (BT_{max} - BT_i) / (BT_{max} - BT_{min}) \dots\dots\dots \text{Equation (3)}$$

where, BT_i refers to the seasonal average for weekly brightness; BT_{min} and BT_{max} refer to a multiyear absolute minimum and maximum brightness (ShadA et al., 2017, AghaKouchak et al., 2015). TCI provides additional information about vegetation stress if it is due to dryness or excessive wetness (Du et al., 2018). TCI coupled with VCI provides a powerful tool for monitoring vegetation stress and drought conditions, and the two indices have been used to study drought conditions in different regions of the world (AghaKouchak et al., 2015).

1.6.7 Applications of remote sensing and GIS in drought monitoring

Drought monitoring has been done historically based on data of drought-related variables (precipitation, near-surface air temperature, wind speed, atmospheric water vapor, relative humidity, etc.) captured using ground based-point observations or interpolated grids. However, the ground observations mostly have uneven and limited distribution to capture the spatiotemporal variability of drought variables, and the data from the various stations have variability in recording times and data quality. This has remained a major challenge in drought monitoring globally (AghaKouchak et al., 2015). The Earth Observation satellites (EOS) provide comprehensive, synoptic, and multi-temporal coverage of large areas in real-time and at frequent intervals using their spectral bands. So, they become valuable for continuous monitoring of atmospheric as well as surface parameters related to droughts. Besides, the advancements in the remote sensing technology and the Geographic Information Systems

(GIS) help in real-time monitoring, early warning and quick damage assessment of both drought and flood disasters (Jeyaseelan, 2003, Cox et al., 2014), and proactive decision making and disaster preparedness (AghaKouchak et al., 2015).

The heritage remote sensing sensors like Advanced Very High Resolution Radiometer (AVHRR), Landsat Thematic Mapper (TM), Coastal Zone Color Scanner (CZCS), and High Resolution Infrared Radiation Sounder (HIRS) (Justice et al., 2010, D'Souza et al., 2013); and new remote sensing instruments like Moderate resolution Imaging Spectroradiometer (MODIS) (Sun et al., 2007) have been used for drought monitoring worldwide. Satellite observations from geostationary satellites (Meteosat-8 & Geostationary Operational Environment Satellites (GEOS)), microwave sensors (Special Sensor Microwave Imager (SSM/I), Tropical Rainfall Measuring Mission (TRMM), and Advanced Microwave Sounding Unit (AMSU)), and combination of space and ground observation like Climate Hazard Group InfraRed Precipitation with Station (CHIRPS) have been also used to make rainfall estimates for drought monitoring. The MODIS observations and CHIRPS data were applied and used in this study.

A. Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS instruments are on-board of the Terra and Aqua space crafts, which are flagship satellites of the National Aeronautics and Space Administration (NASA) (Barnes et al., 2003). The MODIS instrument was launched in Terra spacecraft on December 18, 1999, as a successor of AVHRR (Wan et al., 2004), and in Aqua spacecraft on May 4, 2002 (Xiong et al., 2009, Xiong et al., 2005). MODIS has a swath of 10km (nadir) along cross-track by 2330 km cross-track, and it completes global coverage in less than 2 days (Xiong et al., 2005). It has been also described as a keystone instrument for Terra and Aqua satellites because of its capabilities to address a range of interdisciplinary science objectives with frequent multispectral global observations (Xiong et al., 2009).

MODIS data are made in a broad spectral range from visible to long-wave infrared with a wide-field view of 55 from instrument nadir (Xiong et al., 2005). It has 36 spectral bands of which 20 are in reflective solar Bands (RSB) and 16 in Thermal emissive bands (TEB) (Xiong et al.,

2005, Xiong et al., 2009, Xiong et al., 2007, Sun et al., 2007). The RSB includes the bands 1 to 19 & 26 having wavelengths that range from 0.41um to 2.2 um, and it collects daytime reflected solar radiance at three nadir spatial resolutions. Two bands (Band 1 and band 2) have 0.25km spatial resolution; five bands (band 3 to band 7) 0.5 km; and 13 bands (band 8 to 19 and band 26) 1km. The TEB has 16 bands (band 20 to 25, and bands 27 to 36), and it collects both day time and night time thermal emissive bands at 1km spatial resolution (Xiong et al., 2009, Xiong et al., 2005), (Table 1.2). The MODIS data are prefixed with MOD for terra and MYD for Aqua and MCD for combined data.

B. Climate Hazard Group InfraRed Precipitation with Stations (CHIRPS)

The CHIRPS is a new environmental record for monitoring of events that gives gridded precipitation time series from 1981 to near present (Funk et al., 2014). CHIRPS was created from five data sources namely: monthly precipitation climatology CHPClim, quasi-global geostationary thermal infrared (IR) satellite observations from two NOAA sources, the Tropical Rainfall Measurement Mission (TRMM) 3B42 produced from NASA and atmospheric model rainfall fields from the NOAA climate forecast system version 2(CFS V2), and in situ precipitation observation obtained from a variety of sources including national and regional meteorological sources. At present, there are about 52743 anchor locations used in the production of CHIRPS, and the data from the different sources was compiled as 5 days rainfall accumulations (Funk et al., 2014). CHIRPS has a quasi-global (50 S – 50N) & (180 E to 180 W), high resolution (5km); daily, pentadal and monthly precipitation dataset (Funk et al., 2014, Funk et al., 2015). The CHIRIPS data is suitable for hydrological modeling and drought early warning system because it has a reasonably long period of record, low latency, high resolution, daily disaggregation, and near real-time availability. It is also suitable for drought monitoring in regions like Ethiopia that have complex topography, changing observation networks, and deep convective precipitation surfaces (Funk et al., 2015; Dai, 2011).

Table 1.2: Lists and descriptions of MODIS spectral bands

Spectral band type	Band no	Center wavelength in um	Bandwidth in um	Primary use
RBS	1	0.645	0.05	Land/cloud/aerosols boundaries
	2	0.858	0.035	
	3	0.469	0.02	
	4	0.555	0.2	Land/cloud/aerosols properties
	5	1.24	0.02	
	6	1.64	0.024	
	7	2.13	0.05	
	8	0.412	0.015	
	9	0.443	0.01	Ocean color, phytoplankton & biogeochemistry
	10	0.488	0.01	
	11	0.531	0.01	
	12	0.551	0.01	
	13	0.667	0.01	
	14	0.678	0.01	
	15	0.748	0.01	
	16	0.869	0.015	
	17	0.905	0.03	Atmospheric water vapor
	18	0.936	0.01	
	19	0.940	0.05	
	26	1.375	0.03	Cirrus clouds water vapor
TBS	20	3.75	0.18	Surface/cloud temperature
	21	3.96	0.06	
	22	3.96	0.06	
	23	4.05	0.06	Surface/cloud temperature
	24	4.47	0.07	Atmospheric temperature
	25	4.52	0.07	
	27	6.72	0.36	Water Vapor
	28	7.33	0.3	
	29	8.55	0.3	Cloud properties
	30	9.73	0.3	Ozone
	31	11.03	0.5	Surface/cloud temperature
	32	12.02	0.5	
	33	13.34	0.3	Cloud top altitude
	34	13.64	0.3	
	35	13.94	0.3	
	36	14.24	0.3	
	20	3.75	0.18	
21	3.96	0.06		

Source: (Xiong et al., 2009)

1.6.8 Relevance of study topic

The drought analysis using remote sensing and GIS techniques based on drought indices from space technologies have been applied in various researches (Chakraborty and Sehgal, 2010,

Dutta, 2018, Gamanayake et al., 2016, Klisch and Atzberger, 2016, ShadA et al., 2017, Wan et al., 2004, Vicente-Serrano et al., 2012, Wardlow et al., 2007, Du et al., 2018). The authors of (Funk et al., 2016, Funk et al., 2015, Funk et al., 2014, Philip et al., 2018, Bayissa et al., 2015, Bewket and Conway, 2007, Bewket, 2009, Gidey et al., 2018a, Gidey et al., 2018b, Meze-Hausken, 2004, Eshetie et al., 2016, Qu et al., 2019, Tonini et al., 2012, Liou and Mulualem, 2019, Viste et al., 2013) applied remote sensing drought indices in different drought analysis studies in Ethiopia, and (Mera, 2018, Gebrehiwot et al., 2011, Liou and Mulualem, 2019, Degefu, 1987) studied impacts of drought in Ethiopia. The review of some of the studies is as follows:

- (Dutta, 2018) researched drought monitoring in dry zones of Myanmar using MODIS derived NDVI and CHIRPS derived precipitation data. The study tried to derive correlations between the NDVI and CHIRPS derived precipitation to establish empirical relationships between the two variables. It found that NDVI and precipitation have very strong relationships, and the droughts in the study area were caused by insufficient precipitations. The research also concluded that NDVI and CHIRPS derived precipitation could provide near real-time information about vegetation stress in the region.
- (Qu et al., 2019) conducted research on monitoring of extreme agricultural drought over the horn of Africa using Remote sensing measurements. The paper aimed to investigate the extreme drought events in the region using MODIS derived vegetation indices (NDVI, VCI, TCI, and VHI) and precipitation data from TRMM. The study concluded that from 2001 to 2017, the precipitation, VHI, and TCI values in the region were decreasing significantly indicating deterioration of croplands due to severe drought in the region.
- (Sruthi and Aslam, 2015) researched on Agricultural drought analysis using NDVI and LST data in Raichur District., India. The study aimed to analyze the vegetation stress in the area using two indices NDVI and LST. The research concluded NDVI and LST provide useful information for agricultural monitoring and early warning for farmers when used in combination.

- (Gidey et al., 2018b) researched modeling of the statistical relationship between meteorological and agricultural drought in Raya and its environ in Northern Ethiopia using drought Indices. The study aimed to model the relationships between NDVI, TCI, VCI, VHI, and 3 months SPI. The study found that NDVI and LST have strong and significant negative relationships, strong and significant positive relationships between VCI and TCI, and the positive relationship between SPI and VHI. The study also concluded that SPI and VHI are suitable for the incidence of meteorological and agricultural droughts.
- (Gidey et al., 2018a) researched analyses of the long-term agricultural onset, cessation, duration, frequency, severity, and spatial extent using VHI in Raya and its environs in Northern Ethiopia. The study used MODIS 11 A Terra Land surface temperature and eMODIS NDVI at 250m. It concluded Remote sensing and GIS-based agricultural droughts can be better monitored using indices composed of VHI, NDVI, LST, and VCI drought indices.
- (Eshetie et al., 2016) researched the evaluation of vegetation indices for monitoring of agricultural drought in East Amhara, Ethiopia. The research modeled the relationship between the 3 months SPI and the respective season's vegetation indices using ordinary least square to vegetation conditions respond to rainfall variability. The result showed that the Drought Severity Index (DSI) showed the highest relationship ($R^2=0.85$) and VCI lowest relationship ($R^2=0.53$). The study also examined the relationship of NDVI, VCI, and DSI and crop yield to determine the performance of the vegetation indices in drought detection and monitoring. The research concluded that DSI is best to define agricultural drought phenomena ($R^2=0.76$) followed by VCI and NDVI was put at the last.
- (Bewket, 2009) conducted a study on rainfall variability and crop production in Ethiopia taking the Amhara region as a case study. The author used long-term rainfall data from meteorological stations in the region to analyze rainfall variability based on precipitation concentration index, and agricultural statistics in the crop harvesting period from CSA. The correlation and regression analysis method were used to examine the relationship between rainfall and crop productions. The study concluded that the rainfall amount is higher, and its

variability is lower in the western parts of the Amhara region than in the eastern, and inter-annual and seasonal variability of rainfall is a major cause of fluctuations in the production of cereals in the region.

This study topic focuses on the analysis of the agricultural drought that affected the Amhara and Tigray regions in 2015. So, the reviews in this section showed the study topic is relevant as it tries to address a known problem associated with the study area based on methodologies that were applied and tested in various scientific studies.

Chapter-2: Methodology

The current study was conducted based on remote sensing drought indices derived from MODIS and rainfall estimates from CHIRIPS. First, the trend of rainfall in the study area was analyzed for ten years (2006 to 2015) based on the CHIRPS data. This was used to identify the years with high and low rainfalls in the decade. Next, the SPI for the 10 years was analyzed using the decadal rainfall data to see the trends and distributions of meteorological droughts in the study area during the ten years. After that, the analysis of agricultural drought in 2015 and 2014 continued using the drought indices (NDVI, VCI, TCI) derived from MODIS data. The analysis was done for every 16-day observations from June to October, and nine results were obtained from the different observations in each year in total. The drought analysis results for September and October were used to make overall evaluations of the drought in the years while the results between June to August were used to understand the drought developments and see their associations with the rainfall trends in the same period. Since the purpose of this study was to analyze the agricultural drought in 2015, the drought analysis results for 2014 were used only for comparison to better understand the scale and intensity of the 2015 drought. Because 2014 was considered as a better year than 2015 in terms of drought in Ethiopia (CSA, 2016). This chapter contains the topics of data and softwares, methods, data processing and analysis techniques, and study limitations.

2.1 Data, data sources, and Softwares

MODIS, CHIRIPS, Ethiopia Sentine2 land use land cover, study area extent, and crop covered area and crop productions in the study area data types were used in this study. The monthly averaged MODIS/006/MOD13Q1 (MODIS /Terra Vegetation Indices 16-day L3 Global 250m Version 6), and MODIS/006/MOD11A2 (MODIS/Terra Land Surface Temperature & Emissivity 8-day L3 Global 1 km Version 6) were respectively used for computing NDVI&VCI, and TCI indices (Table 2.1). These data were downloaded from NASA LPDAAC collections in the USGS data portal. The MODIS13Q1 and MOD9A1 data were downloaded for June, July,

August, September, and October at every 16-day interval, and a total of 9 files were downloaded for a single year. Each file contains two grids at a 10X10 degree geographic extent. That means a total of 180 MOD13Q1, and 180 MOD11A1 were downloaded for 2006 to 2015 and used in the study. The MODIS International Geosphere-Biosphere Program (IGBP) land use type classification of MCD12Q1 products (Modis/Terra and Aqua combined Land cover Types yearly Global 500m SIN GRID V006), which are good for cropland monitoring over Africa (Qu et al., 2019) were used to extract land cover types of the study area. The croplands, grasslands, Cropland / Natural Vegetation-Mosaics were used for masking of the results. However, since the IGBP dataset could not pick some land use and land cover types, the Ethiopia Sentinel2 LULC of 2016 with 20 meters resolution was used to prepare the LULC map. But, it is in a prototype and hence was not used to extract the agricultural land. The CHIRPS data for June to September of 2006 and 2015 was also downloaded from the Fast Early Warning System Networks portal (FEWSNet). The data of 2006 and 2015 were used for rainfall analyses in the crop growing seasons and to assess the capability of the indices in detecting droughts. The MODIS datasets were in HDF format and CHIRPS in tiff(Table 2.1). The shapefile of the study area was obtained from CSA and used to extract all the above data types for the study area from downloaded global raster file, associate, and map the results by administrative divisions. The data of crop covered land and crop productions for the years of 2014, 2015, and 2016 got from central statistical agency agricultural bulletins were used to compare results from the drought analyses.

The ArcGIS 10.4 software was extensively used in the processing and analysis of the MODIS and CHIRPS data, extraction of quantitative information of the drought indices from the raster data, and integration and mapping of the results. Microsoft Excel was also used for tabular presentations of results and correlations of the different indices as well as graphical analysis of the data. Microsoft Word was used to compile the different results and produce the final report. Other supplementary softwares like DrinC, QGIS, Google Earth, and Snip were also used in the study.

Table 2.1 Lists and descriptions of data types used in the study

Data name	Description	The Observation period for 10 years (2006 to 2015)								
		10-Jun	26-Jun	12-Jul	28-Jul	13-Aug	29-Aug	14-Sep	30-Sep	16-Oct
MODIS13Q1	MODIS Terra, Version 6, 16-day and 250 m spatial resolution (Didan, (2015)) used to derive NDVI and VCI	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MODIS11A2	MODIS Terra, Level 3, 8-day and 1km spatial resolution provides a day and night time land Surface temperature as well as emissivity TCI(Wan, (2015))	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MCD12Q1	MODIS Terra/Aqua, 500m spatial resolution provides global land cover type assessments and quality control information (Land Cover) (Friedl, 2019)	2015								
Ethiopia Sentinel2	A prototype of Ethiopia Sentinel2 Land use Land cover dataset with 20m spatial resolution in tiff format provided by Regional Center for Mapping of Resources for Development (RCMRD)	2016								
CHIRPS	Tiff format, 5km resolution, Monthly (Single) and global extent in Clarke, 1866, Albers projection	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Study Area	Shapefile in UTM Zone 37 N projection	2007								

Source: NASA LPDAAC (<https://earthexplorer.usgs.gov/>), FEWSNET (<https://earlywarning.usgs.gov/fews/datadownloads/Global/CHIRPS%202.0>), RCMRD (<http://opendata.rcmrd.org/datasets/ethiopia-sentinel2-lulc2016>), CSA, 2007

2.2 Methods

Different data processing methods were applied to the raw MODIS and CHIRPS datasets before they were used in the drought analyses (fig 2.1). After that the various drought indices were computed, results were linked to the study area and mapped accordingly.

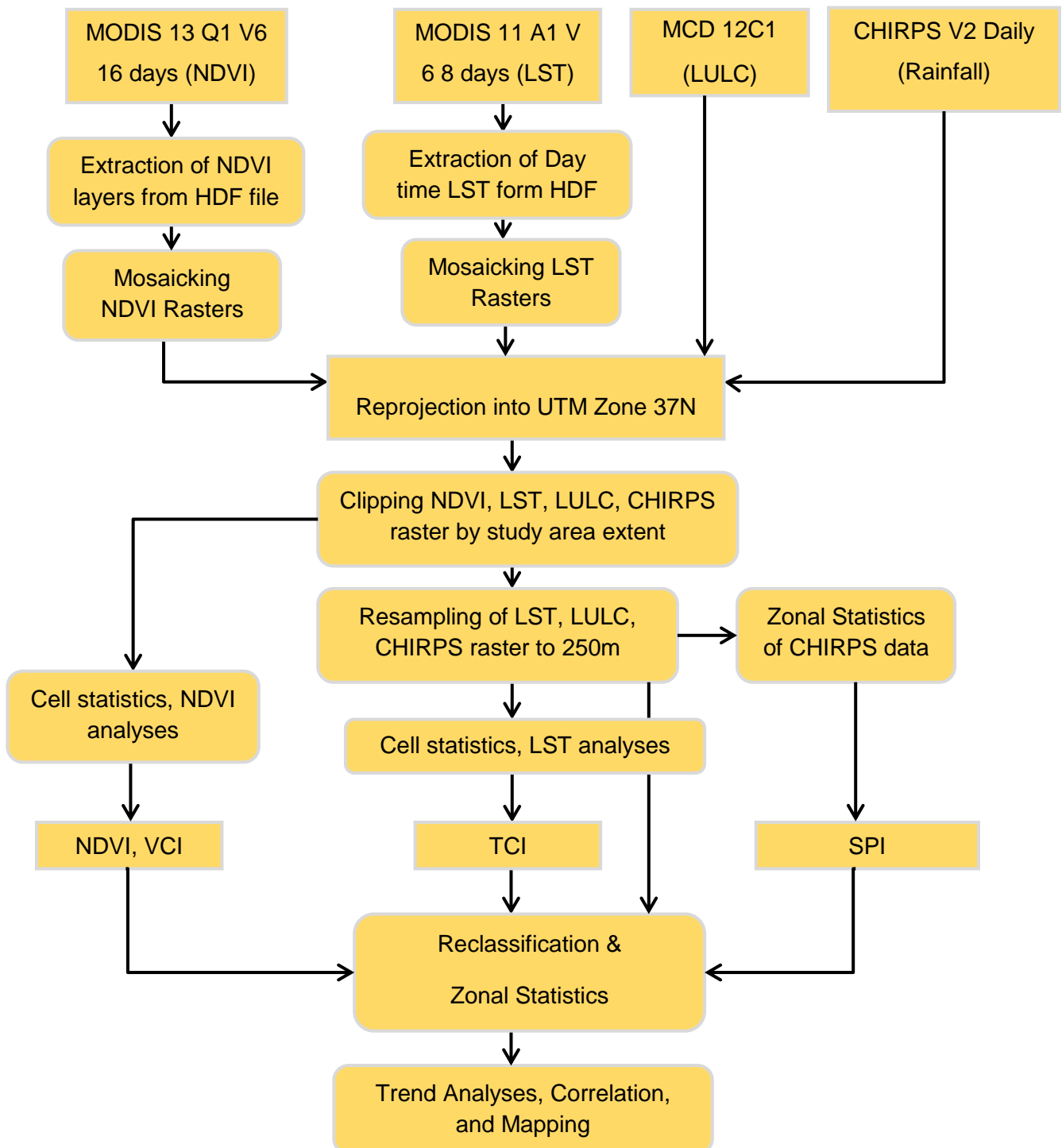


Fig 2.1 Schematic diagram of the study methodology

2.3.1 Data processing

The extraction, mosaicking, re-projection, clipping, masking, resampling, and unit conversions were some of the techniques applied in the processing of the raster data. Since the MODIS 13Q1 raster layers in HDF format downloaded from USGS geoportal holds many datasets, the NDVI as well as the NIR and Red band layers were extracted from the raster datasets covering the study area first. Since the filtering of raster layers from HDF files in ArcGIS 10.4 is not automatic, this was done using the Extract Subdataset tool (Data management > Raster > Raster Processing > Extract Subdataset). The same technique was also applied to extract land surface temperature (day time) layers from the land surface temperature rasters in HDF format, and the land cover types also. In most of the data, the study area was covered by at least two grid files of 10x10 degrees geographic extent. So, the two extracted raster files were merged into one file using the Mosaic to New Raster tool (Data management toolbox > Raster > Raster dataset > Mosaic to New raster). In that process, the pixel types and number of bands for the output rasters were matched with that of the input rasters. Next, each of the mosaiced rasters originally in sinusoidal projection was re-projected into the Universal Mercator Transverse projection (UTM) Zone 37N, which is applied in dominant parts of Ethiopia including the study area. That was done using the project raster tool in the ArcGIS environment (Data management toolbox > Projections and transformations > Raster > Project raster). The projected MODIS raster data for the study area was clipped from each of the global raster files using the Clip tool (Data management toolbox > Raster > Raster Processing > Clip). In the clipping process, the MODIS layers were used as input raster and the shapefile of the study area as a mask from the raster analysis environment settings. Next, all the above-processed MODIS rasters were resampled into the spatial resolution of the MODIS13Q1 (250m) using the resample tool in ArcGIS applying the nearest resampling technique (Data management toolbox > Raster > Raster Processing > Resample). The final NDVI layer was multiplied by the scale factor (0.0001) (Didan, (2015)), Land surface temperature by (0.02) (Wan, (2015)) to get the

appropriate results. After that, the unit of temperature values of the Land Surface Temperature (LST) raster dataset in Kelvin was converted into Degree Celsius (0C) using a raster calculator based on the formula $LST = (w \times 0.02) - 273.15$, where w is a specific data. Finally, the raster datasets of the three drought indices that passed all the above processing were used in the computation of the drought indices.

2.3.2 Data Analysis

A. Standard precipitation index (SPI) calculation

The monthly rainfall data was extracted from the CHIRPS raster using the Zonal Statistics tool (Spatial Analyst > Zonal > Zonal Statistics as Table). The results of rainfall values were used to compute the SPI values in each of the months using DrinC software. The SPI results were classified based on Table 2.2 and mapped to understand the distribution and pattern of the drought in the study area in 2015 (Map 3.3, Fig. 3.2). The author understood that the ranges in the SPI classification should be continuous for such a data type instead of missing some digits in the ranges between the first and last rows. Moreover, the listing of the data in the table should begin with the higher SPI values and end up with lower values. However, the classification ranges and tabular representations used in the reference were applied in this study.

Table 2.2 Drought classifications based on SPI

SPI Value	Category
- 2 <	Extreme drought
-1.5 - -2	Severe drought
-1 to -1.49	Moderate drought
0 to -0.99	Mild drought
>0	No drought

Source: Bhuiyan *et al.*, 2006 as cited in (ShadA *et al.*, 2017)

B. Normalized Difference Vegetation Index (NDVI) calculation

The NDVI values for June to October of 2014 and 2015 were derived from each of the 9 MOD13Q1 raster files using a raster calculator tool (Spatial Analyst > Map Algebra > Raster Calculator) based on the formula in equation 1.1. The results were compared with the NDVI dataset in the HDF package already computed and the results were found almost the same.

The derived NDVI values were then masked by the LULC raster layer to exclude the values of the non-vegetated areas from the results. At last, the NDVI raster layers were classified based on the scores in Table 2.3. The maps of the nine NDVI results for 2015 were compared with the results of the same period in 2014 for every 16 days to understand the temporal and spatial variations of the droughts in 2015.

Table 2.3 Vegetation health and density classifications based on NDVI

NDVI Value	Vegetation health and density descriptions
0.72 to 1	Very good
0.42 to 0.72	Good
0.22 to 0.42	Moderate
0.12 to 0.22	Poor
-0.1 to 0.12	Very poor

Source: (Gidey et al., 2018b)

C. Vegetation Condition Index (VCI) calculation

The VCI values for June to October of 2014 and 2015 were derived from the 9 NDVI of the same period, and the NDVI max and NDVI mins. The NDVI min and NDVI max were computed from the NDVI raster datasets of (2006 to 2015) using the cell statistics tool (spatial Analysts > Local > Cell statistics. In the process, the NDVI raster datasets of the 10 years were taken as input rasters, and MIN and MAX were chosen from the overlay statistics dropdown box to calculate the NDVI min and NDVI max values respectively. Then the VCI was calculated using a raster calculator tool based on the formula in equation 2. The final VCI raster was masked by the LULC layer to exclude values of the non-vegetated areas from the results and classified based on the scores in Table 2.4. The author understood that the ranges in the VCI classification should be continuous for such a data type instead of missing some digits in the ranges between the first and last rows. Moreover, the listing of the data in the table should begin with the higher VCI values and end up with lower values. However, the classification ranges and tabular representations used in the reference were applied in this work. The maps of the nine VCI results for 2015 were compared with the results of the same period in 2014 for every 16 days to understand the temporal and spatial

variations of the droughts in 2015. The difference of the NDVIs during the 9 observation periods of 2015 and 2014 was also derived using a raster calculator and used to analyse the increase and decrease of NDVI values between the two years (Table 3.2 and 3.3).

Table 2.4 Drought classification based on VCI

VCI value (%)	Drought description
<10	Extreme drought
10 – 19.9	Severe drought
20 – 29.9	Moderate drought
30 – 39.9	Mild drought
>= 40	No Drought

Source: Bhuiyan *et al.*, 2006 as cited in (ShadA *et al.*, 2017)

The difference of the VCIs during the 9 observation periods of 2015 and 2014 was also derived using raster calculator and used to see the increase and decrease of VCI values between the two years (Table 3.4 and 3.5)

D. Temperature Condition Index (TCI) calculation

The TCI values for June to October of 2014 and 2015 were calculated based on the land surface temperature (LST) values derived from each of the 9 MOD11A2 raster files using a raster calculator tool (Spatial Analyst > Map Algebra> Raster calculator) based on the mathematical expression in equation 1.3. The BTi for the ten years was calculated, and then BTimin and BTImax values were derived from the ten BTi values using a cell statistics tool (Spatial Analyst > Local> Cell statistics). Then the TCI values were masked by the LULC raster layer to exclude values of the non-vegetated areas from the results. Finally, the TCI raster layers were classified based on the scores in Table 2.5 and mapped (Table 3.6). The author has the same reflection as to the other indices on the classification of the TCI ranges between the first and last rows and also on the listing of the TCI values in the table.

Table 2.5 Drought classification based on TCI

TCI value (%)	Drought description
<10	Extreme drought
10 – 19.9	Severe drought
20 – 29.9	Moderate drought
30 – 39.9	Mild drought
>= 40	No Drought

Source: Bhuiyan *et al.*, 2006 as cited in (ShadA *et al.*, 2017)

E. Spatial analysis and mapping of results

The results from the above scores were linked to the administrative regions of the study area to further analyze the results. These associations were used to make a quantitative analysis of the drought magnitude and variability to better assess the performances of the indices. The results from the drought indices were extracted by using zonal statistics as table tool (Spatial Analyst > Zonal > Zonal Statistics as a table). In the zonal statistics computation process, the shapefile of the study area by region was used as a feature zone data, the region name was chosen for the Zone field, and the final NDVI, VCI and TCI rasters analyzed above were consecutively used as the input raster values. The derived tables were then changed into excel using the table to excel tool (Conversion toolbox > Excel > Table to excel). The raster data of the final indices were also reclassified using a reclassify tool (Spatial Analysts > Reclass> Reclassify tool), then converted to a polygon using a raster to polygon tool (Conversion Toolbox > From Raster > Raster to Polygon). Then the area of the classified values in each index was calculated using the calculate Geometry from the feature tables of each polygon layer (km²). Finally, the areas covered by each of the drought classes were summarized by drought severity classes (for VCI and TCI) and vegetation health and density classes (for NDVI) exported as tables. At last, the dbf files of those indices were converted into excel using the Table to Excel tool in ArcGIS (Conversion > Table to Excel). The extent of the results was compared with the crop covered area and crop production in the study area in 2015 (CSA 2014, 2015) mapped by administrative zones, and that was used to test performances of the different indices in detecting droughts.

F. Correlations of NDVI, VCI, and TCI with SPI

The NDVI and VCI have positive, and TCI negative correlations with precipitation. Hence, the degree of correlation between the drought indices and SPI was analyzed based on this assumption. The classified values of each of the drought indices and the classified SPI data for the same period were compared using the trend analyses function in excel and the correlation function with the best fit to the scatter plot was chosen. Then the statistical

significance (R2) value was added into the graph. Finally, the correlation of the indices was analyzed based on the R2 values (Table 2.6).

Table 2.6 Statistical strengths classification based on the linear regression model (R2)

Correlation value	Level of statistical strength
0.64 to 1	Very strong
0.36 to 0.63	Strong
0.16 to 0.35	Moderate
0.04 to 0.15	Weak
0 to 0.036	Very weak

Source: (Evan 1996 as cited in (Gidey et al., 2018b)

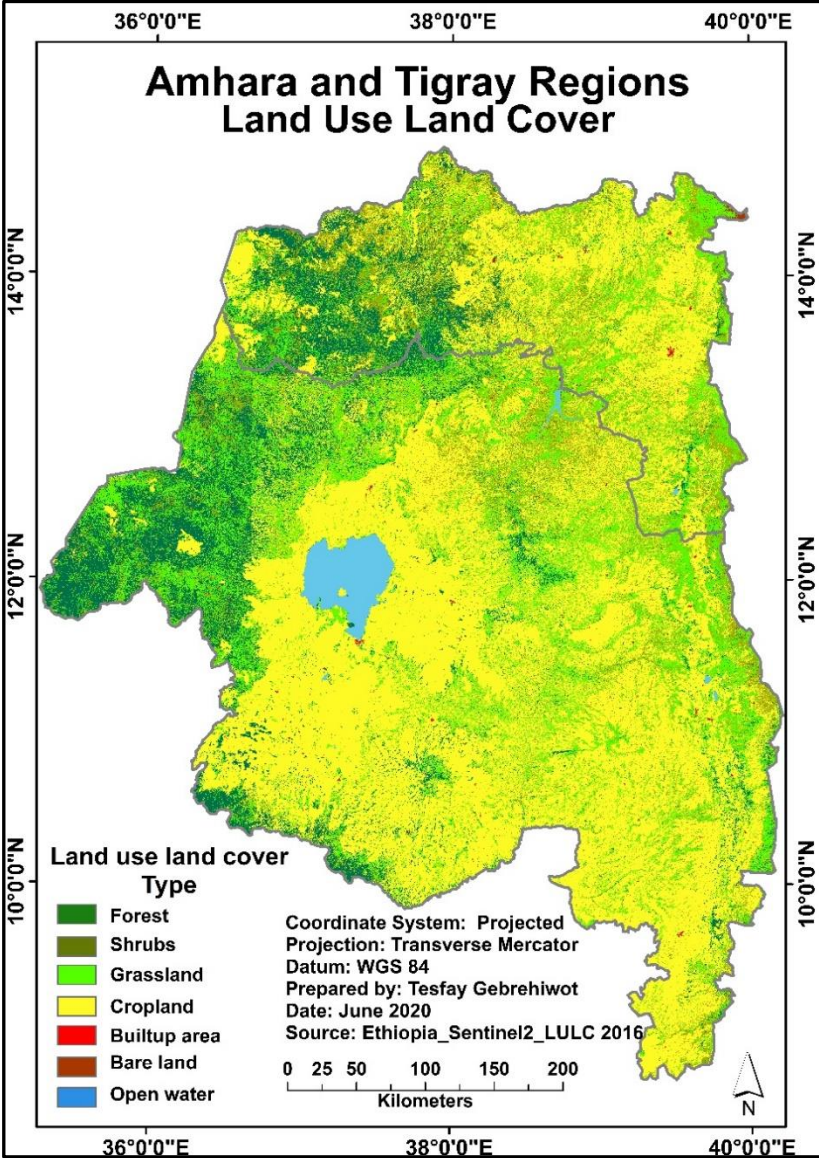
2.3 Study Limitations

This study was conducted entirely based on analysis of satellite data from MODIS and CHIRPS data from FEWSNet as to obtain data from primary sources such as meteorological stations was difficult due to the reasons mentioned in the previous sections. In addition to this, primary data like crop productions in the year collected from the field were not used to verify the results. However, the rainfall distribution in the study area in 2015 obtained from the analysis of the CHIRPS data; and analyses of the reductions in crop covered area and crop productions in 2015 from 2014 from CSA data were used to fill the gaps. These results were used as references to check the results from the NDVI, VCI, and TCI analyses and see the performances of the indices to detect the drought condition in the study area. The study also used the agricultural land extracted from MODIS based on type 1 classification in IGBP and the recommendations in (Qu et al., 2019). However, the author realized that the LULC from MODIS dataset based on the IGBP type 1 classification could not properly pick some classes like the forest, built up, and barren areas that have significant coverage in the study area at such a scale. This was verified through analyses of the prototype Ethiopia sentienle2 LULC for 2016 dataset that was available in RCMRD at a spatial resolution of 20m in tiff format. The classifications of the LULC classes using this dataset were found more realistic. It was also observed that the area of agricultural land extracted by taking the crop, grass, and crop Natural vegetation mosaic classes from MODIS was

much bigger than the crop and grassland classes extracted from the Ethiopia Sentinel2 LULC. But, the drought analysis in this study was done based on the agricultural land extracted from MODIS while the LULC from RCMRD was used to prepare the LULC maps only (Map 3.1) since it is in a prototype. So, the extent of agricultural land used to show the distribution of the NDVI, VCI, and TCI values in this study can be exaggerated compared to the actual situation on the ground. Therefore, the author recommends considering these limitations in using this product for any purpose.

Chapter-3: Processes and Results

The agricultural drought analysis results under this section were discussed based on interpretation of the rainfall, SPI, NDVI, VCI, TCI, and crop covered area and crop production results, as well as the correlations among the drought indices. The NDVI, VCI, and TCI results were analyzed based on the 16 days MODIS observations from June to October. The agricultural land extracted from MODIS using the IGBP type 1 classifications was used to mask the drought indices. But, the prototype dataset Ethiopia Sentinel2 LULC in 2016 was used to present the LULC situation of the study area (Map 3.1, Table 3.1).



Map 3.1 Land use land cover (LULC) of Amhara and Tigray regions

Table 3.1 LULC types in Amhara and Tigray regions in 2016

Land use and Cover Type	Area in Sq.Km (000')	% of the total area
Cropland	118	55.6%
Grassland	42	19.8%
Forest	27	12.7%
Shrubs	21	10%
Openwater	3.5	1.6%
Builtup Area	0.4	0.2%
Bare land	0.3	0.14%

Source: Own computation based on Ethiopia_Sentinel2_LULC 2016 from ESA

3.1 Rainfall Analysis

The 2006 to 2015 decadal rainfall shows a general decreasing trend in the four months (June to September) with the lowest values recorded in 2015. In the ten years, the highest rainfall of June was recorded in 2007 followed by 2012, and the lowest was in 2015. The amount of rainfall in June 2015 showed an 8.5% reduction from the same period of 2014. Similarly, the rainfall in July was highest in 2007 followed by 2012 and the lowest was in 2015. The rainfall in July 2015 had shown a 30.3% reduction from 2014 which is big compared to the earlier month (June). The rainfall in August was highest in 2006 followed by 2010 and the lowest in 2015 and 2014. In September, the highest rainfall was recorded in 2007 followed by 2008. The rainfall in August and September of 2015 was almost like 2014 (Table 3.2 and Fig. 3.1). In 2006, 2008, 2010, and 2011 the rainfall in the regions showed an increasing trend from June to August and decreases in September. But in the other years, it was increasing from June to July and then decreasing in August and September. This depicts that the decadal rainfall in the regions had been showing variations in pattern and amount during the crop growing seasons. The decreasing trend of the decadal rainfall was in agreement with (Qu et al., 2019) who concluded that rainfall in East Africa was decreasing between 2001 to 2017. In 2015, the study area received a minimum rainfall of 2 mm and a maximum of 512 mm. The rainfall ranges received in the crop growing seasons in 2015 were 2 mm to 290 mm in June, 9mm to 450 mm in July, 31 mm to 512 mm in August, and 3 mm to 488 mm in September.

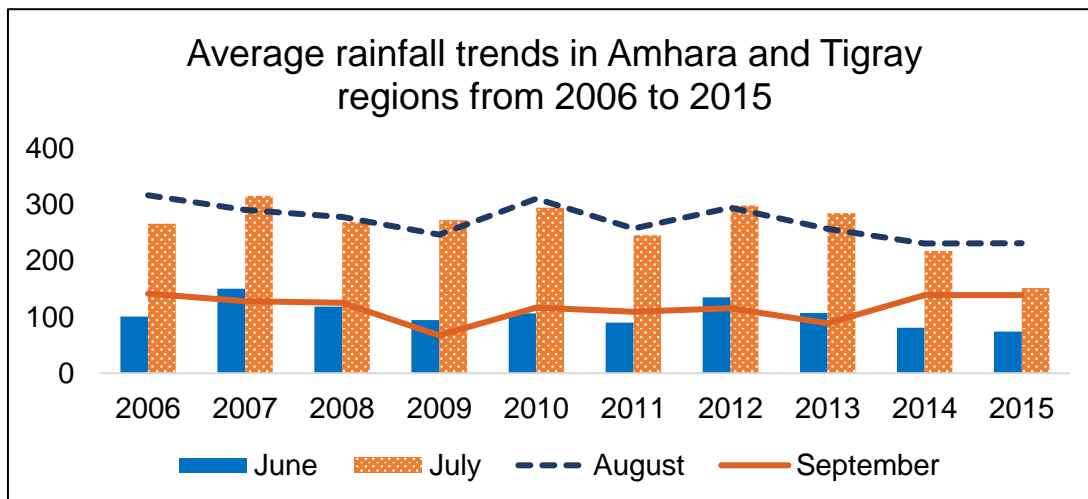


Fig.3.1 Trends of average rainfall in Amhara and Tigray regions in 10 years (2006 to 2015)

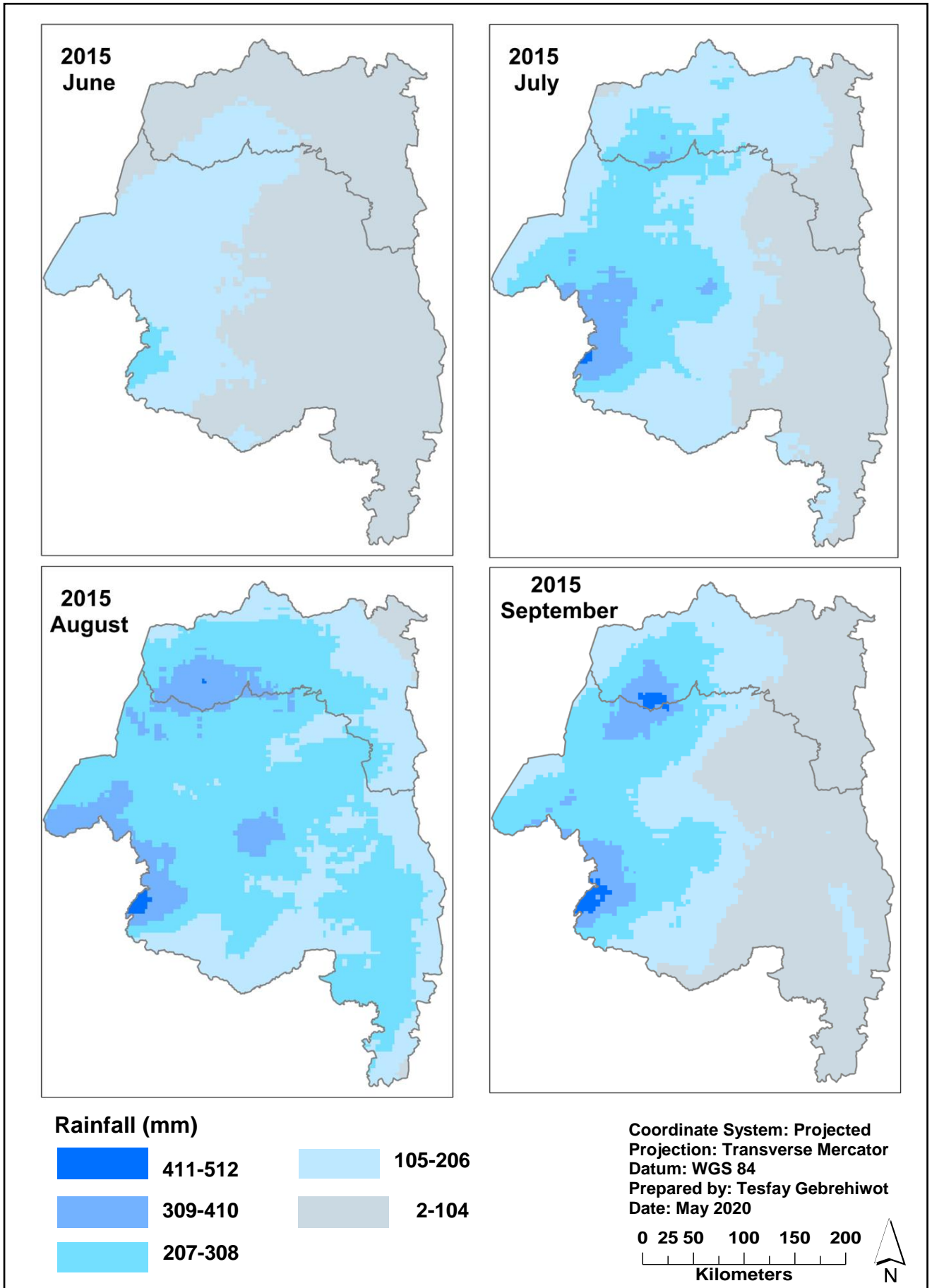
Table 3.2 Rainfall condition in Amhara and Tigray regions from 2006 to 2015

Month	Average Rainfall (mm)									
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
June	101	150	119	95	107	90	136	107	81	74
July	266	316	270	273	295	246	298	285	218	152
August	317	291	278	247	311	258	295	257	231	232
September	142	129	126	67	117	109	116	89	139	139

Source: Own computation based on CHIRPS data from FEWSNet

The rainfall distribution in 2015 shows, the western and southwestern part covering larger parts of Amhara, and few areas in the Tigray region had received high rain in June compared to other parts of the regions. The northern and northwestern extremes as well as the central and eastern parts of the regions got low rainfall in comparison to the other parts. In July, the amount of rainfall in the areas that had good rain in June showed increases, and the coverage of the small rainfall expanded into some parts on the eastern side that includes the central parts of the Tigray and Amhara regions. In August, the coverage and amount of distribution of the rainfall have improved and expanded to the majority of the study area except in the northeast extremes in Tigray where the amount remained low. In September, the rainfall distribution again receded into the western and southwestern, as well as north and northwestern parts of the regions (Map 3.2).

Amhara and Tigray Regions: Distribution of Rainfall in 2015



Map 3.2 Rainfall distribution in Amhara and Tigray regions from June to September of 2015 Page | 43

Overall, the results showed that the rainfall had a general decreasing trend from the western to the eastern parts of the Amhara and Tigray regions except for very few areas in southeastern and southern parts of Amhara that got relatively higher rainfall (Map 3.2). The results in this study were also found in agreement with the conclusion of (Bewket, 2009, Bewket and Conway, 2007).

3.2 Standard Precipitation Index (SPI) Analysis

The SPI analysis showed that the highest drought of the decade (2006 to 2015) in the Amhara and Tigray regions was observed in 2015. The regions were affected by severe drought in June and September, and extreme drought in July, August, and October of 2015 (fig 3.2). From the decadal data analysis, it was observed that there were also droughts in Amhara and Tigray regions in 2009, 2011, 2013 (mild), and 2014. This may indicate that the effects of the drought in 2015 could be a cumulative of the droughts in 2014 and 2013 also. The drought distribution in September 2015 also showed extreme and severe droughts limited in the southeastern Extreme of Amhara region. It also showed that the eastern side of the study area was under drought in comparison to the western part. The SPI analysis also indicated that about 40.5% of the study area was hit by mild to extreme drought in 2015 (Map. 3.3).

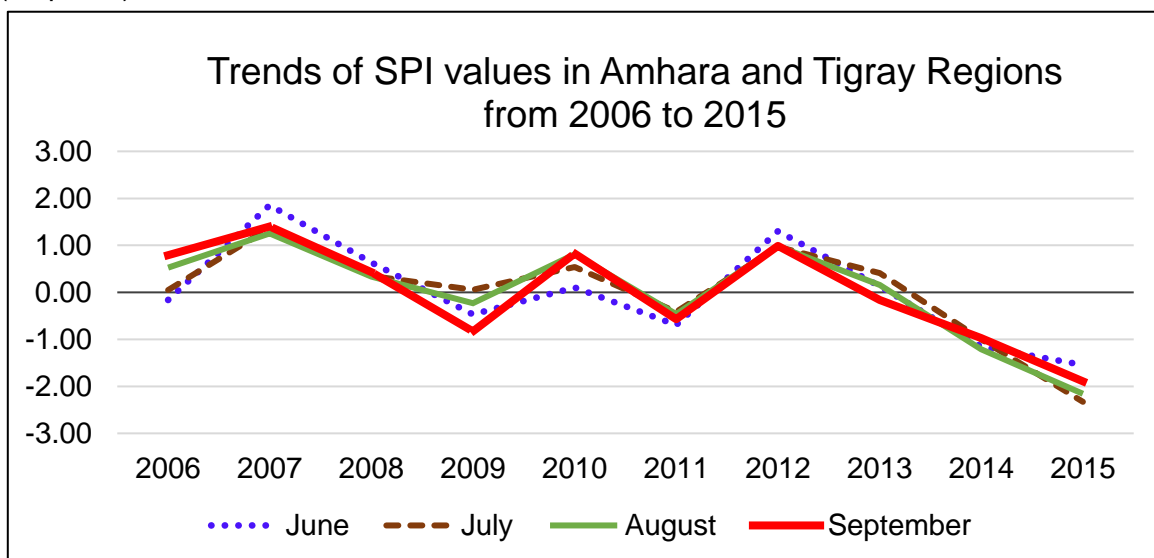
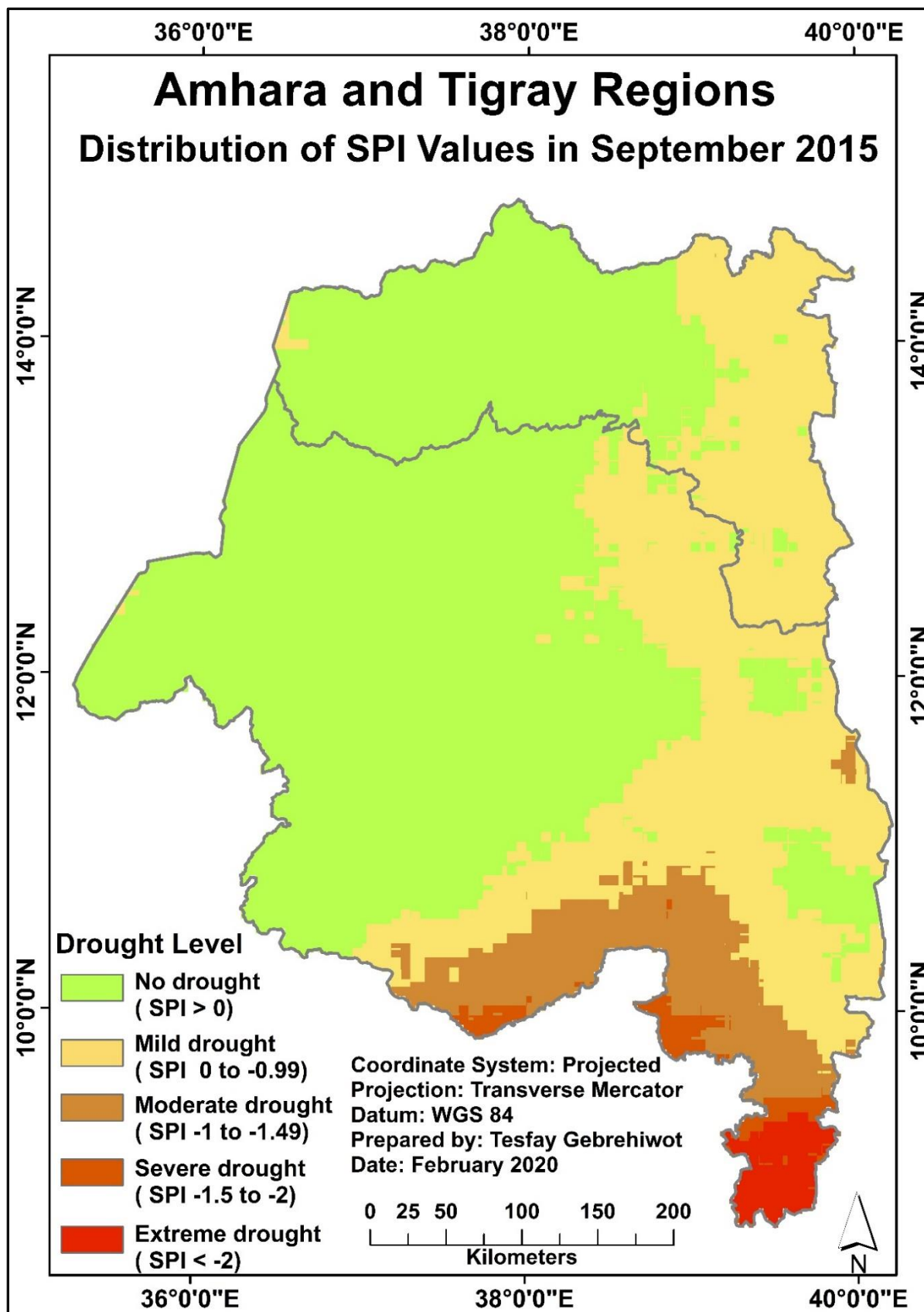


Fig.3.2 Drought trends in Amhara and Tigray regions from June to September in 10 years (2006 to 2015) based on SPI values



Map 3.3 Drought conditions in Amhara and Tigray regions in September 2015 based on SPI values

3.3 Normalized Difference Vegetation Index (NDVI) Analysis

The agricultural drought in the Amhara and Tigray regions was analyzed by looking at the vegetation health and density conditions in the agricultural land in the regions through observation of the spatiotemporal distributions of the NDVI values. The NDVI values for the agricultural land in the study regions were analyzed based on the observations in nine periods from June 10 to October 16 of 2015 every 16 days. The results from the analysis of the June to August data were used to understand the trends of vegetation health and density and their relationships with other parameters mainly rainfall. But, the results for September and October were used for evaluation of the vegetation situation and the agricultural drought in the year. The drought situation in 2014 was also analyzed in a similar way for every 16 days observation from June 10 to October 16. The NDVI values for 2014 were used as a reference to evaluate the degree and extent of the agricultural drought in 2015. Because 2014 was considered better than 2015 in terms of the drought in Ethiopia in the statistical bulletins of CSA (CSA, 2016).

A. NDVI analyses in June 2015

The NDVI values on June 10 showed that the vegetation health and density in the largest part of the agricultural land (69.2%) in the Amhara and Tigray regions was under moderate to very poor conditions. These situations were mainly observed in the northern, central, and southern Amhara, as well as northern, northeastern, and western parts of the Tigray regions. The moderate vegetation health and density were covering southwestern and western parts of Tigray, and western, central, eastern, and southeastern parts of the Amhara regions. The good vegetation condition was dominantly observed in the Amhara region covering some areas in northwestern, western, southwestern, central, and pocket areas in eastern, and southeastern parts. This was also shown in few areas in the western and southwestern, as well as pocket areas in southern parts, of the Tigray region. The very good vegetation condition covered very few areas in southern extremities, northwestern and some pocket areas in the western and southwestern parts of the Amhara region. This was

also seen in very limited areas in southwestern of the Tigray region. The NDVI values on June 10 of 2015 had similarities to that in 2014 except the moderate and good vegetation conditions had better coverage in the later. On June 26, the NDVI values in the regions showed improvements and the agricultural land covered with moderate to very poor vegetation conditions decreased to 58.6%. The moderate vegetation condition was observed in the majority of the Tigray region including central and northwestern as well as eastern and southern parts. It was also improved in very big parts of the Amhara region in central, northeastern, eastern, and southeastern as well as southern parts. The coverage of good vegetation conditions also showed improvements in the western, northwestern parts of the Amhara and southern parts of the Tigray regions. At this period, the very good vegetation cover was also expanded into few parts in Northern parts as well as southern parts of the Amhara region. The comparison of the NDVI values and their distributions on June 26 of 2015 with the same period in 2014 also showed that the agricultural land under moderate to very poor vegetation conditions had covered lesser areas in 2015 than the later (Map 3.4, and Table 3.3). This showed that the greenness of the Amhara and Tigray regions in June 2015 was better than in 2014.

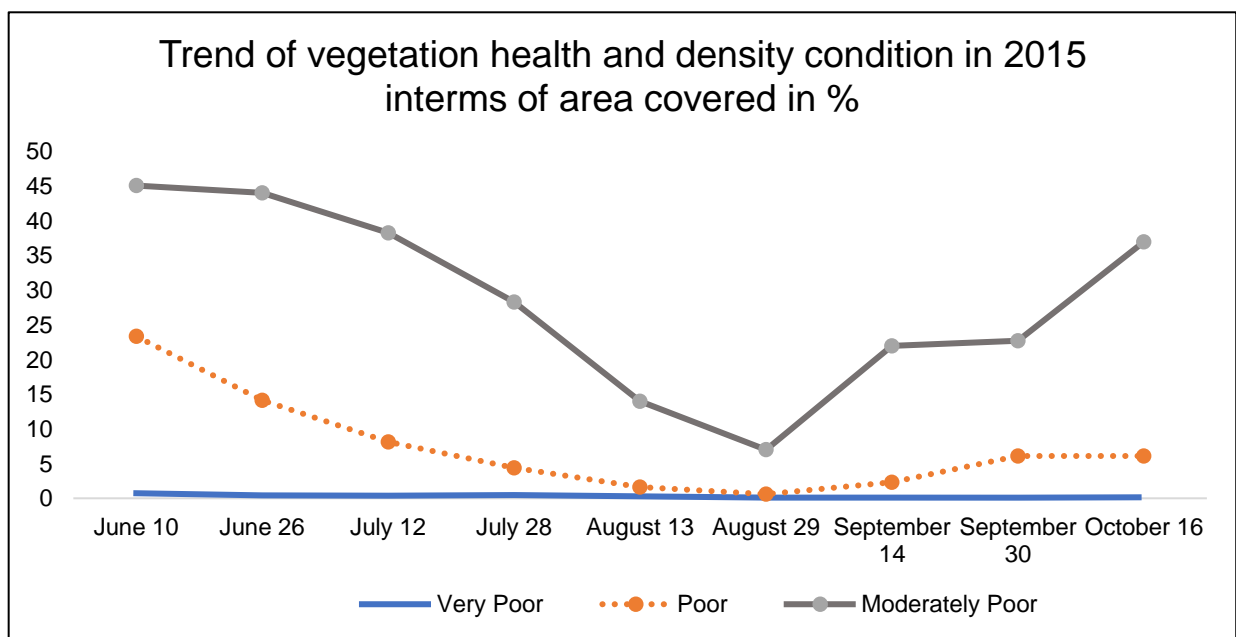


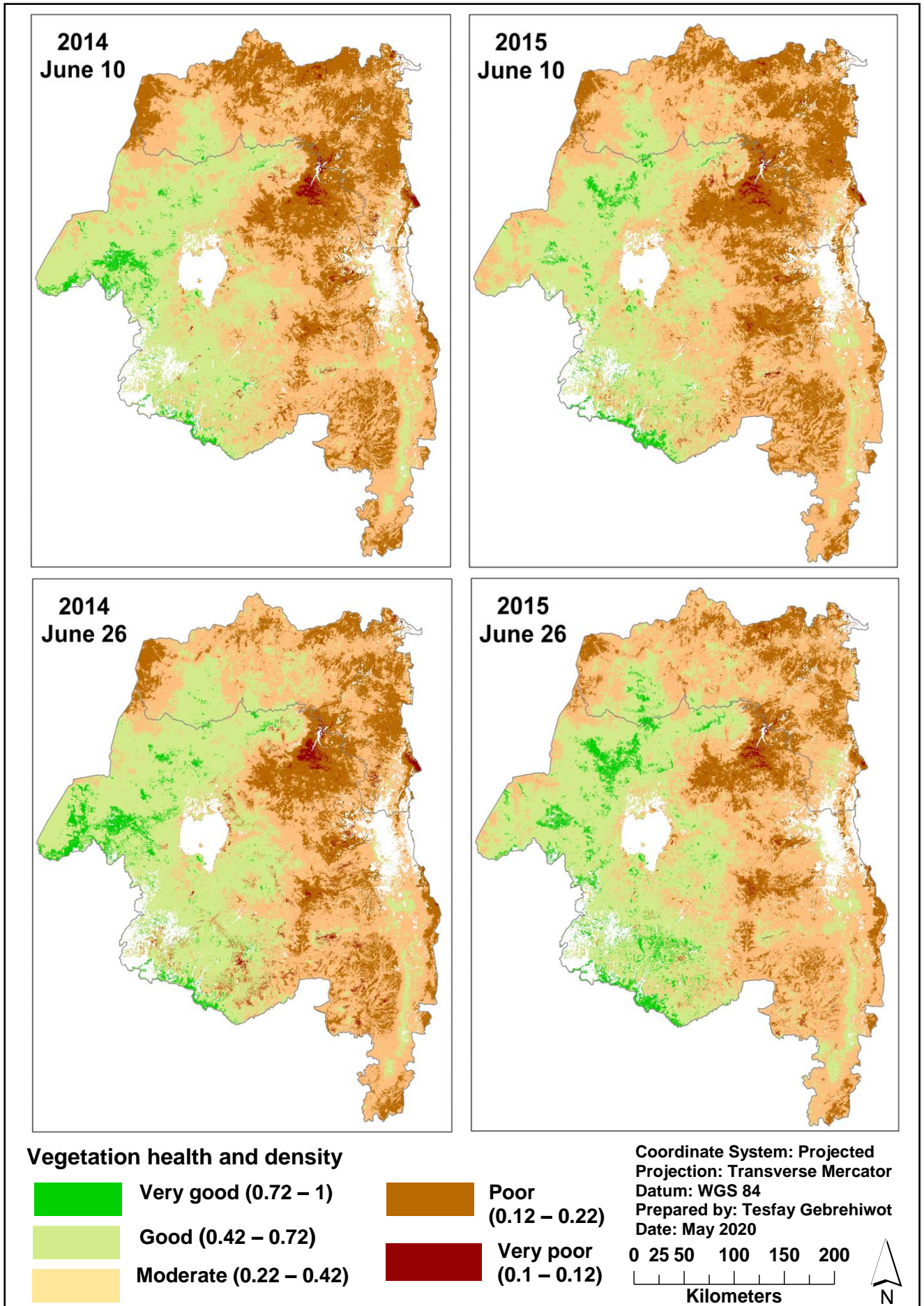
Fig.3.3 Vegetation health and density situation in Amhara and Tigray regions from June 10 to October 16 of 2015 based on NDVI values

Table 3.3 Vegetation health and density condition of the agricultural land in Amhara and Tigray regions from June to October of 2015 based on NDVI values

Time	Vegetation health and density									
	Very Poor		Poor		Moderately poor		Good		Very Good	
	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%
June 10	1397	0.7	44738	23.4	86396	45.1	55820	29.1	3274	1.7
June 26	828	0.4	27062	14.1	84396	44.1	71939	37.6	7374	3.8
July 12	751	0.4	15620	8.2	73320	38.3	87374	45.6	14555	7.6
July 28	928	0.5	8442	4.4	54248	28.3	104519	54.6	23432	12.2
August 13	540	0.3	2219	1.2	26789	14	121835	63.6	40140	21
August 29	233	0.1	1096	0.6	13362	7	118934	62.1	57959	30.3
September 14	194	0.1	4390	2.3	42237	22	115814	60.4	28989	15.1
September 30	181	0.1	4447	2.3	43498	23	115672	60.4	27814	14.5
October 16	312	0.2	11730	6.1	70572	37	96156	50.2	12844	6.7

Source: Own computation of NDVI based on MODIS13Q1A

Amhara and Tigray Regions: Distribution of NDVI Values in June

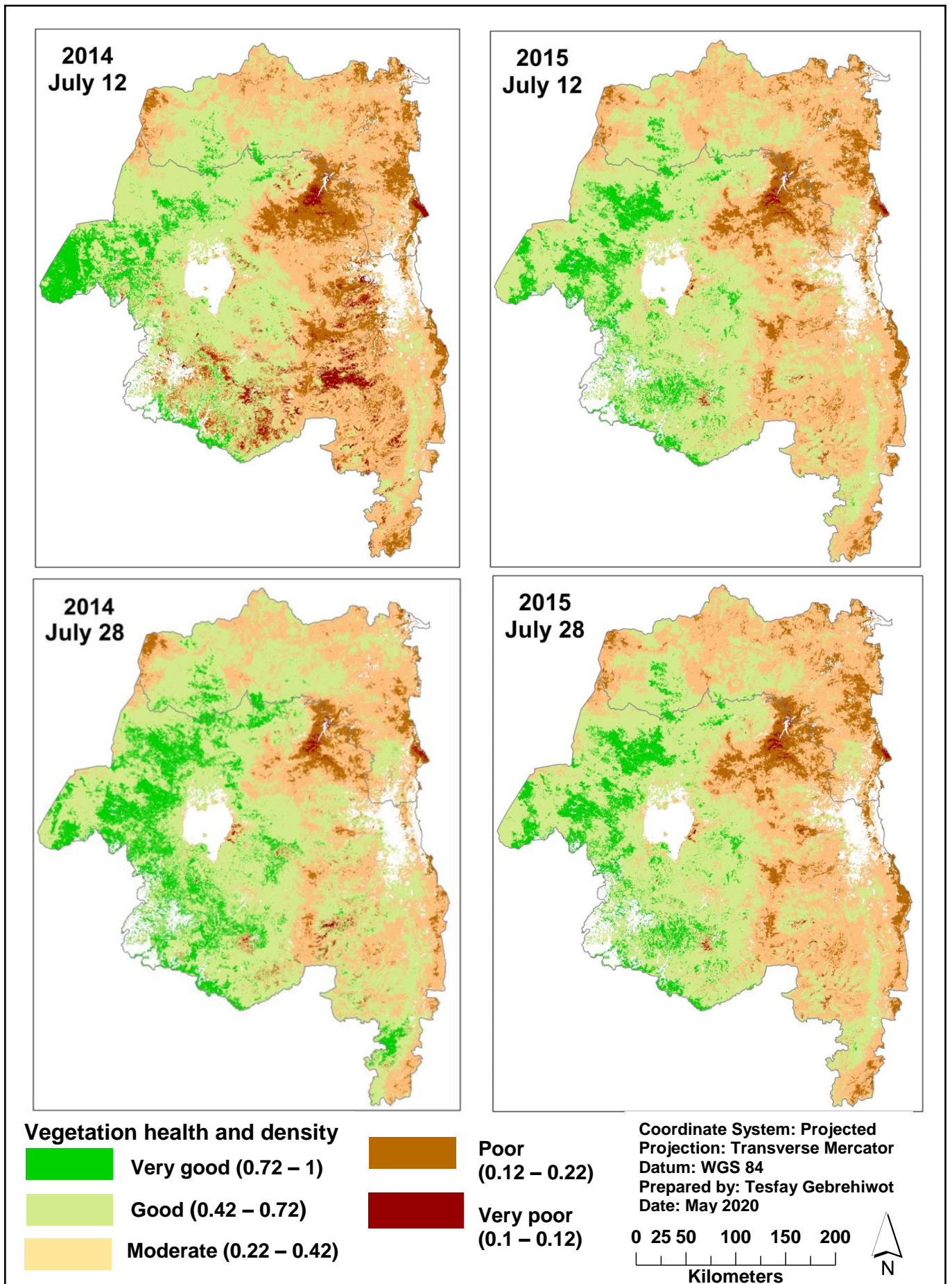


Map 3.4 Vegetation health and density conditions in Amhara and Tigray regions Page | 49
 in June 2014 and 2015 based on NDVI

B. NDVI analyses in July 2015

The NDVI values on July 12 indicated that the agricultural land covered with moderate to very poor vegetation conditions decreased to 46.8%. In the Amhara region, these conditions were observed in the Northern, Eastern, and southeastern extremes, as well as pocket areas in central and southern parts. In the Tigray region, the Eastern, southeastern, northeastern, and northwestern extremes as well as some pocket areas in central and northern parts were under such conditions. The coverage of very good vegetation increased from previous observation, but it was limited majorly to western, northwestern, and southwestern parts of the Amhara region. In Tigray, this condition was limited in the southwestern parts. The good vegetation condition also covered more areas in Northwestern, Western, and Southwestern as well as few wares in the central, eastern, and southeastern parts of the Amhara region. In Tigray, it showed better coverage in a few areas in the extreme northwestern and southern parts. The comparison of NDVI values in 2015 and 2014 also indicated that more places were under poor and very poor vegetation conditions in 2014 than 2015 except for some places in the Amhara region that was under very good vegetation cover in 2014. On July 28, the very poor to moderate vegetation conditions decreased to 32.3%. Those decreases were observed in the northern, eastern extremes and pocket areas in central parts of Amhara; and in the extreme west, extreme northeastern, eastern, and pocket areas in the other parts of Tigray regions. The very good vegetation covered large parts of the Amhara region in the Western, Northern, Southwestern, and small areas in the southeastern parts. In Tigray, this was mainly limited to the southwestern parts. The good vegetation condition also showed significant expansion in the majority of the Amhara region except for some areas in the northern, central, southern, and southeastern parts. This vegetation condition had also covered significant areas in western, central, and southern parts of the Tigray region (Map 3.5). The comparison of the NDVI in 2015 and 2014 also indicated that many parts of the regions were under moderate, good and very good vegetation conditions in 2015 than in 2014 (Table 3.3).

Amhara and Tigray Regions: Distribution of NDVI Values in July

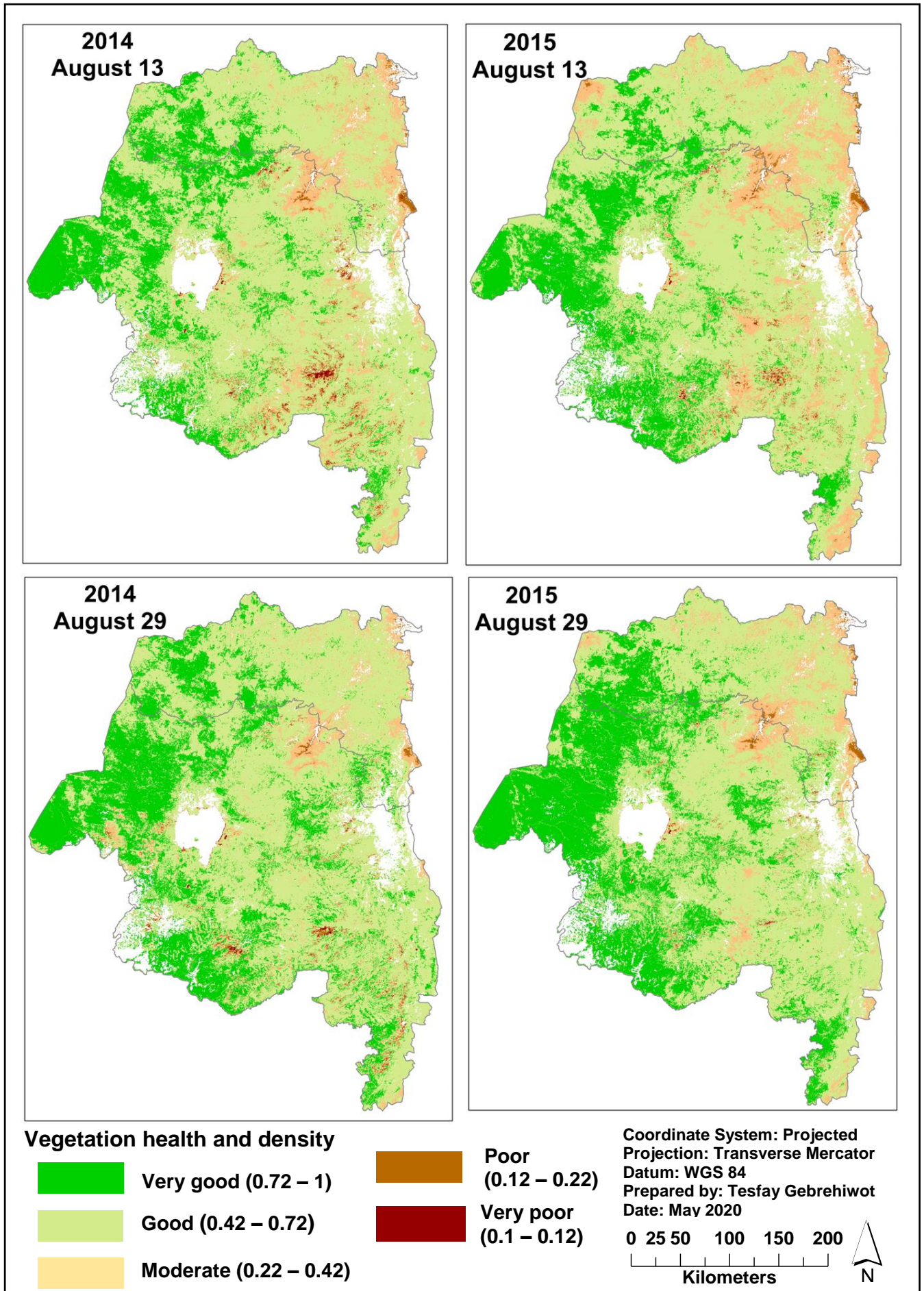


Map 3.5 Vegetation health and density conditions in Amhara and Tigray regions in July 2014 and 2015 based on NDVI values

C. NDVI analyses in August 2015

The NDVI values on August 13 revealed that the vegetation health and density of the agricultural land in the majority of the Amhara and Tigray regions were under good and very good conditions. The moderate to very poor conditions were observed only in 15.44% of the agricultural land in the regions. The very good vegetation condition was dominantly observed in Amhara mainly in the western, southwestern, northern, and few parts of southern; and also showed improvement in coverage from July. This condition had also shown increases in the Tigray region mainly in southwestern, western, and northwestern parts, and very few areas in central and southern parts. The good vegetation condition was observed in the majority of the study area. The moderate vegetation condition was low compared to July and that was observed in few areas of the Amhara region in the northern, eastern extremes, and pocket areas in central as well as southern parts. In the Tigray region, the moderate condition was observed relatively larger areas in the western extreme, central, eastern, and northeastern, and southeastern parts. The poor and very poor vegetation conditions were limited to very few areas in the northern, and south-central parts of Amhara; and the western, eastern, and southeastern parts of Tigray. The good and very good vegetation conditions also covered large areas of the Amhara and Tigray regions in 2014 compared to 2015 unlike the situations in June and July (Map 3.6). On August 29, the very good and good vegetation conditions showed increases in western and northwestern parts as well as the southern parts of the stud regions. This also covered significant areas in central, southern, and eastern parts of the Amhara and Tigray regions. In this period, the agricultural land under moderate to very poor vegetation conditions decreased to 7.7% (Map 3.6). The comparison of the vegetation health and density situation in 2014 and 2015 also showed that the agricultural land under very good and good conditions in 2014 was bigger than in 2015. Though the results showed a better situation of the agricultural land in 2014 than in 2015, poor and very poor conditions were significantly observed in 2014 (Table 3.3).

Amhara and Tigray Regions: Distribution of NDVI Values in August

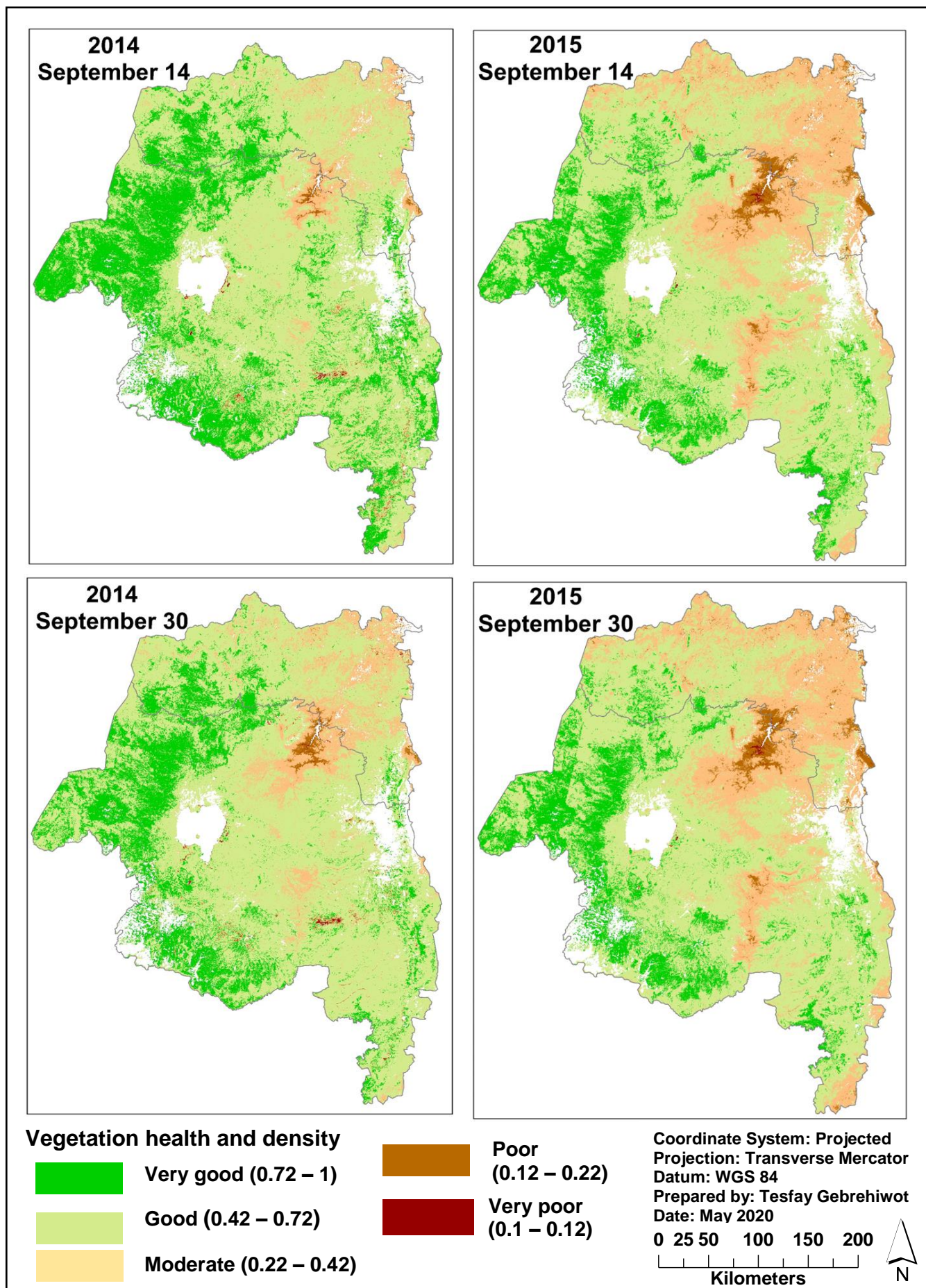


Map 3.6 Vegetation health and density conditions in Amhara and Tigray regions in August 2014 and 2015 based on NDVI values

D. NDVI analyses in September and October 2015

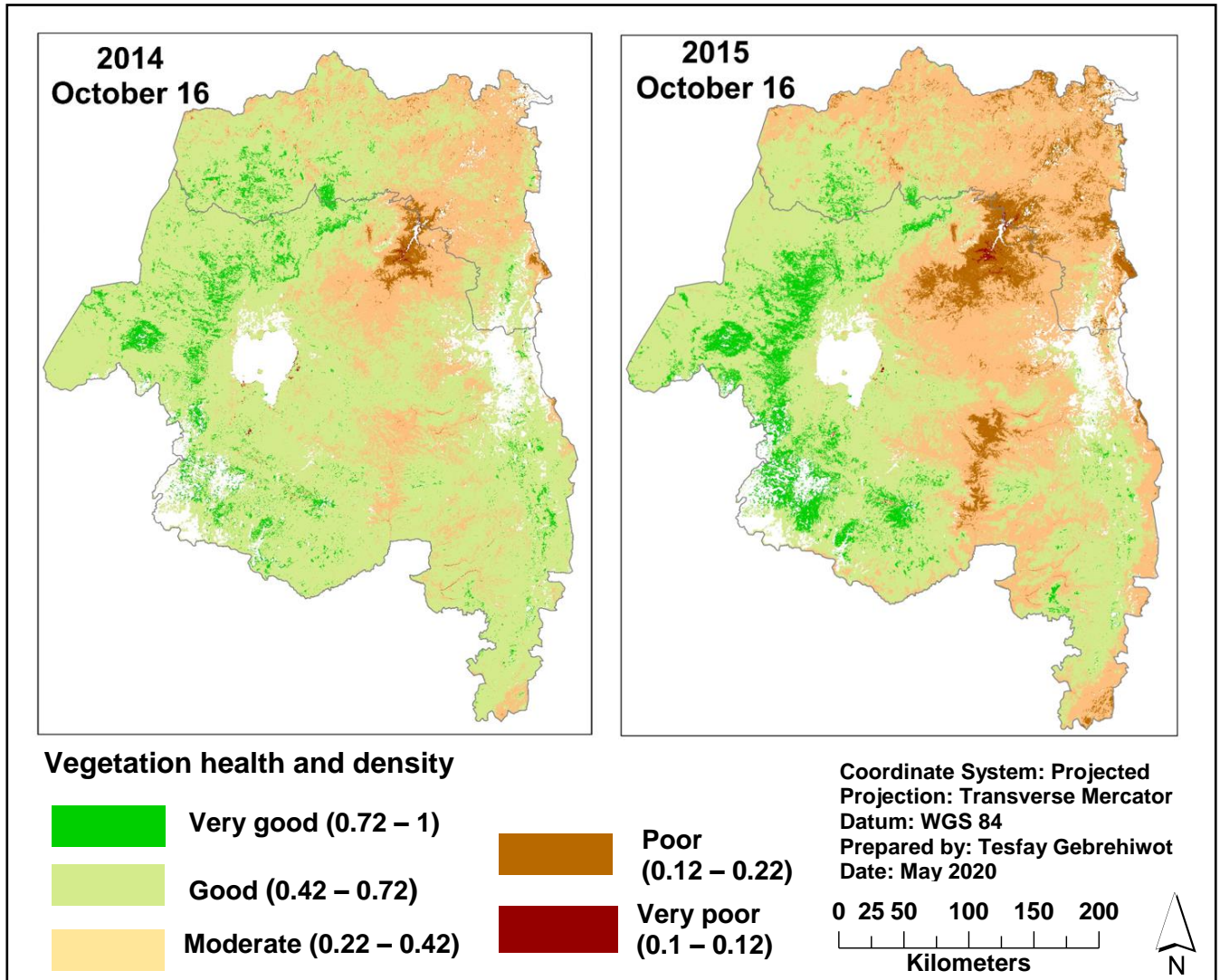
The NDVI value on September 14 showed that the agricultural land in Amhara and Tigray regions covered with moderate, poor, and very poor vegetation conditions increased to 24.4% and on the contrary area under very good and good vegetation conditions decreased from August. These conditions were mostly seen in the majority of the Amhara region except in the northern, some areas in central-south, and very few areas in eastern extremities and northeastern parts. In Tigray, the very good to good vegetation conditions at this period were observed in the western, central, and very few places in the southern parts. The decreases of good vegetation conditions were also more observed in the Tigray region than in the Amhara region. Significant parts in northern and few pocket areas in central Amhara, as well as southeastern and northeastern parts of Tigray, had poor and very poor vegetation conditions. The area of agricultural land covered with very good and good vegetation conditions on September 14 was also lesser in 2015 than in 2014. The characteristics of the change on vegetation conditions of the agricultural land in the regions on September 30 were more or less like that of September 14 except the areas covered with moderate to very poor conditions (25.1%) were slightly higher in the latter than the former (Map 3.7, and Table 3.3). The NDVI values on October 16 also indicated that the agricultural land covered with good and very good vegetation reduced significantly and it was observed in the northwestern, western, southern, and southeastern parts of the study regions. On October 16, the Tigray region except in the southwestern and few areas in central and southern parts were under moderate, poor, and very poor vegetation conditions. In the Amhara region, many areas in the northern, central, south, and eastern extreme parts were also under the same condition. The NDVI values for 2014 also showed that the very good and good vegetation conditions in October reduced from September and August of the same year. But, the agricultural land under very good and good vegetation cover was bigger in 2014 than the same period of 2015 (Map 3.8, and Table 3.3). This intern showed that the agricultural drought in the regions was worse in 2015 than in 2014.

Amhara and Tigray Regions: Distribution of NDVI Values in September



Map 3.7 Vegetation health and density conditions in Amhara and Tigray regions September 2014 and 2015 based on NDVI values

Amhara and Tigray Regions: Distribution of NDVI Values in October



Map 3.8 Vegetation health and density conditions in Amhara and Tigray regions in October 2016 of 2014 and 2015 based on NDVI values

The difference between the NDVI values in each of the periods in 2015 and 2014 was also analyzed. The NDVI values were lower in 2015 than in 2014 in 54% of the agricultural land in the Amhara and Tigray regions on June 10, in 58% on Jun 26, in 61% on July 12, in 80% on July 28, in 56% on August 13, in 54% on August 29, in 81% on September 14, in 73% on September 30, and in 74% on October 16 (Table 3.4). The results also revealed that the NDVI condition of the study area in June and July of 2015 was better than the same period of 2014. But, the reverse was true in August, September, and October. Regarding geographic distribution, the vegetation health and density in the eastern parts of the study area was more deteriorated than the western revealing the drought situations in the regions.

The NDVI results from September 14 to October 16 indicated that the vegetation health and density in 24.5% to 43.1% of the regions were under moderately to very poor conditions (Table 3.3, Fig 3.3). The spatial distribution also showed the northern, central-north, and central parts of Amhara, and some places in the southeastern, eastern-central, northern, and northeastern parts of Tigray were more affected by the drought than the other parts of the regions. From the general pattern, it can also be depicted that the vegetation condition in the eastern parts of the regions was much affected by the drought than the western parts. Moreover, all parts of the Tigray region except few places in the southwestern and some pocket areas in the southern part were highly affected by the drought. The Amhara region was also severely affected but proportionally large parts in this region were in better condition compared to the Tigray region (Map 3.7 and map 3.8). The pixel by pixel comparison of the NDVI results in 2015 and 2014 also indicated that the NDVI values in 2015 were lower than 2014 in 72% to 81% of the regions (Table 3.4). But, many places in the western, southwestern, northwestern, and few areas in southeastern parts of the Amhara region had also higher NDVI values in 2015 than in 2014.

Table 3.4 Comparison of a pixel by pixel NDVI values between 2014 and 2015

Time	NDVI values in 2015 compared to 2014			
	Lower		Higher	
	Area (sq. Km)	%	Area (sq Km)	%
June 10	103784	54	87808	46
June 26	111295	58	80240	42
July 12	117153	61	74352	39
July 28	152605	80	38865	20
August 13	107771	56	82857	44
August 29	103863	54	86591	46
September 14	155046	81	35874	19
September 30	139543	73	51165	27
October 16	142012	74	49005	26

Source: Own computation of NDVI based on MODIS13Q1A

The overall NDVI analysis results showed similarity with the rainfall distributions for the same period. The places covered with lower NDVI classes were represented with lower rainfall amounts while the areas with very good and good NDVI aligned with the highest amount of rainfall in the study area. The low NDVI results in June can be attributed to the dry season before it, and a smaller amount of rainfall not sufficient for the growth of crops. But, it could be also because June is a season to sow crops in the regions. The low NDVI in July can also be attributed to the low rainfall. However, the same NDVI pattern and distribution were also observed during the same season in 2014 where the area received more rainfall (above 30%) than in 2015. So, the other reason for the lower NDVI values in July could be also because the grown crops did not grow to cover the land so more of the reflectance recorded by the satellite was from the bare soil of the farmlands. This shows more correlation with the idea that NDVI values during cropping growing seasons could be attributed to bar soils in farmlands. The improvement in NDVI values in August can be attributed to the better rainfall distribution during the month and due to the good growing stage of the crops to cover the bare soil, which is the most commonly observed phenomenon in the agriculture of the study area. However, the NDVI condition in August 2015 was lesser than in 2014. On the other side, the amount of rainfall in the study area in August in 2015 and 2014 was very similar (Table 3.2). This could lead us to conclude that the better NDVI distributions in 2014 could also be attributed to the better rainfall amount received during July that might sufficiently water the root zone and helped the soil to get more moisture after that time. In September, most of the crops in the study area are under flowering and maturation stages. The traditional farmers in most of the study area believe that the crops will be in very good condition and productivity when the crops receive significant rains in September. So, the NDVI results in this month could better tell the conditions of the crops in the regions. From the results, it was also showed that large parts of Tigray and significant parts in the Amhara region had lesser NDVI conditions in 2015 in comparison to the earlier year. The low NDVI conditions in this month could be partly attributed to maturation and

wilting of fast-growing crops or poor crop conditions. Since the rainfall amount in the study area during September 2014 and 2015 was also similar, the better NDVI conditions in 2014 could be due to the high rainfall in July that might create sufficient soil moisture followed by the smaller rainfall in August and September. The results in October are also good indicators of bad crop conditions observed in about 56% of the study area in 2015. These results might indicate that the rainfalls in July are very important for the growth of crops in the majority of the study area when followed by small rainy events in August and September. On the other side, the very good and good vegetation greenness in August is also indicative of the time lag of NDVI with rainfall. These results strengthen the idea that NDVI has lagged in response to rainfall deficit (Chakraborty and Sehgal, 2010). The NDVI had also shown a strong relationship with rainfall, and the drought in the area was mostly derived from a deficit of precipitation. This is also in harmony with (Dutta, 2018). The NDVI results also showed that the majority of the western, northwestern, southwestern, and few areas in the southeastern parts of the study area had good vegetation conditions throughout the study period. The greenness in these areas may be attributed to the cold weather conditions due to their high elevations, or clayey soils that retain moisture to keep the meadows and grasslands stay green throughout a year. On the contrary, the northern, eastern, central, and southern parts of the study area had moderate to very poor vegetation conditions. Especially the few areas in northern Amhara, Southeastern, and northeastern parts of Tigray were in very poor to poor vegetation conditions throughout the crop growing periods in 2015 and 2014. So, these communities in these places need special attention from the government bodies to protect them from the impacts of the successive droughts affecting the areas. From the overall NDVI results, it can be said that the vegetation health and density decrease as one moves from west to east, and south to north in the study area, and hence is the drought.

3.4 Vegetation Condition Index (VCI) Analysis

The agricultural drought in the Amhara and Tigray regions was also analyzed based on the results of VCI analyses conducted on the agricultural land between the period of June 10 to October 16 of 2015. The VCI results obtained from the analysis of the data from June to August were used to understand the trends of drought conditions and their relationships with rainfall. But, the results for September and October were used for evaluation of the situation of the agricultural drought in the year. The drought situation in 2014 was also analyzed in a similar way for every 16 days observation from June 10 to October 16. The VCI values for 2014 were used as a reference to evaluate the degree and extent of the agricultural drought in 2015. Because 2014 was considered better than 2015 in terms of the drought in Ethiopia in the statistical bulletins of CSA (CSA, 2016).

A. VCI analyses in June 2015

The VCI values on June 10 showed that 34.1% of the agricultural land in the Amhara and Tigray regions was affected by mild to extreme drought. That drought condition was observed in the Amhara and Tigray regions mainly in the western, northeastern, southeastern, and central parts. In Tigray, the drought-affected the agricultural land in many places in the western, northwestern, and eastern parts, as well as some pocket areas in central parts. In Amhara, it affected some areas mainly in the northern, central-eastern, and south as well as western parts. The VCI results for the same period of 2014 showed the northern, northwestern, southeastern, and some pocket areas in the central parts of the study area were affected by mild to extreme droughts. The drought was also observed more in Tigray than in the Amhara region. But, the drought has shown similar patterns and distributions in 2014 and 2015 (Map 3.9). On June 26, the agricultural land affected by the mild to extreme drought conditions increased to 42.7% and that was also observed in both the regions (Table 3.5). The drought-affected many areas in northwestern, central, northeastern, and southern parts of Tigray; and the north, central north, central, and south-central, as well as eastern and southeastern, parts of the Amhara region.

Table 3.5 Agricultural land in Amhara and Tigray regions affected by drought from June to October of 2015 based on VCI results

Time	Drought Level									
	Extreme drought		Severe drought		Moderate drought		Mild drought		No drought	
	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%
June 10	16722	8.7	13457	7.0	16973	8.9	18109	9.5	126318	65.9
June 26	17716	9.2	21814	11.4	22322	11.7	20012	10.4	109690	57.3
July 12	34949	18.2	15060	7.9	14930	7.8	14084	7.4	112551	58.8
July 28	47369	24.7	9903	5.2	10794	5.6	11259	5.9	112211	58.6
August 13	45654	23.8	10218	5.3	11429	6.0	11754	6.1	112421	58.7
August 29	39565	20.7	9612	5.0	11200	5.8	12203	6.4	118919	62.1
September 14	29279	15.3	17445	9.1	23121	12.1	25661	13.4	95782	50.1
September 30	59233	30.9	12867	6.7	13797	7.2	13705	7.2	91920	48.0
October 16	49715.	26.1	19088	10.0	18443	9.7	17147	9.0	86133	45.2

Source: Own computation of VCI based on MODIS13Q1A

The drought conditions on June 26 in 2015 also showed similar patterns and distribution to the same period in 2014. But, the drought in the western Tigray; northwestern, western, and eastern extremes of the Amhara region was higher in 2014 than in 2015 (Map 3.9).

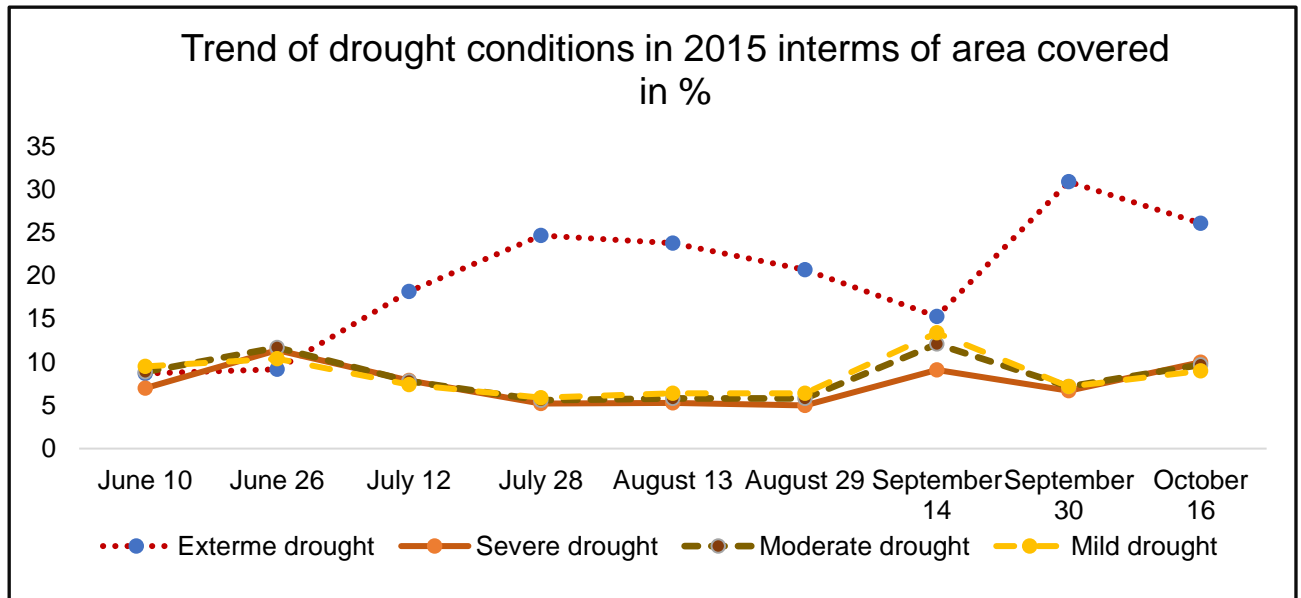
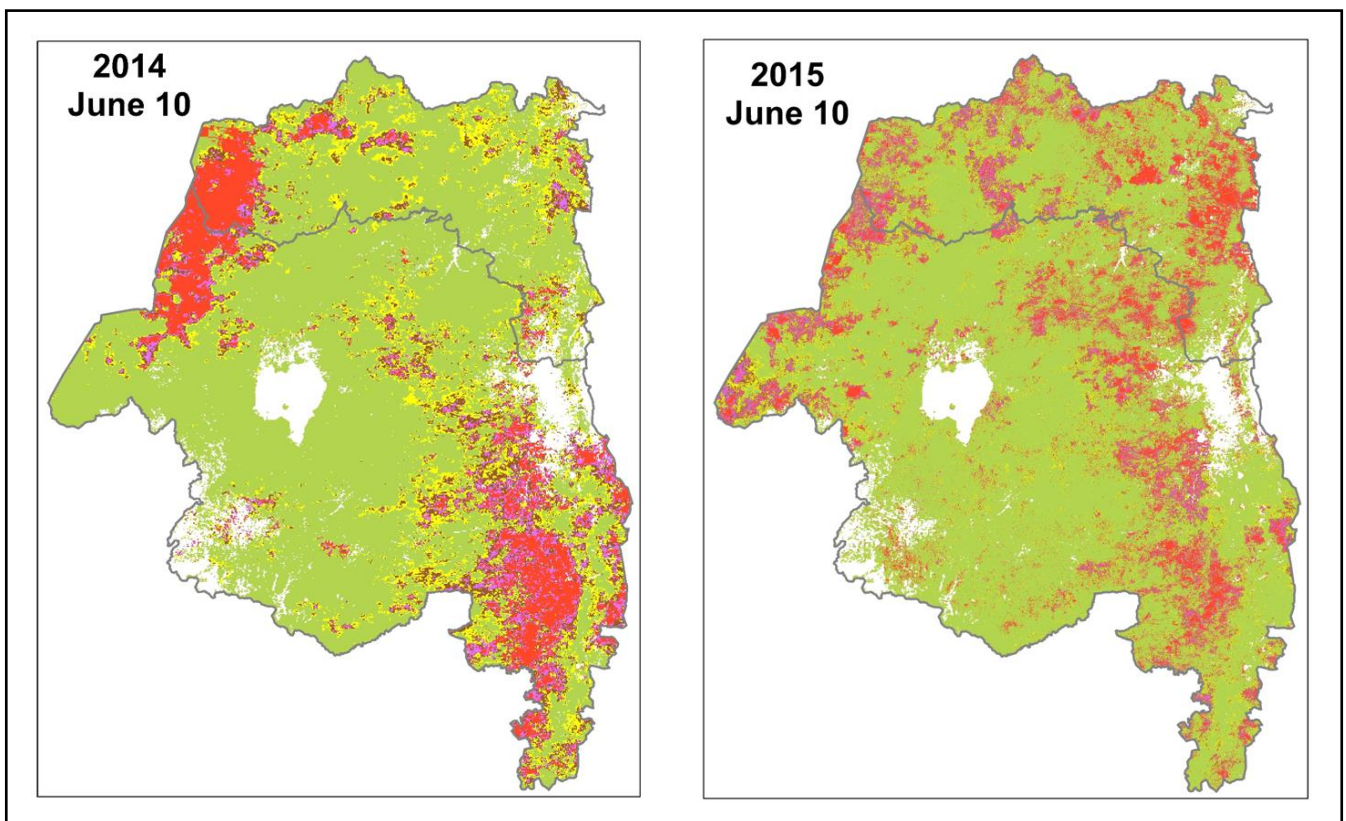
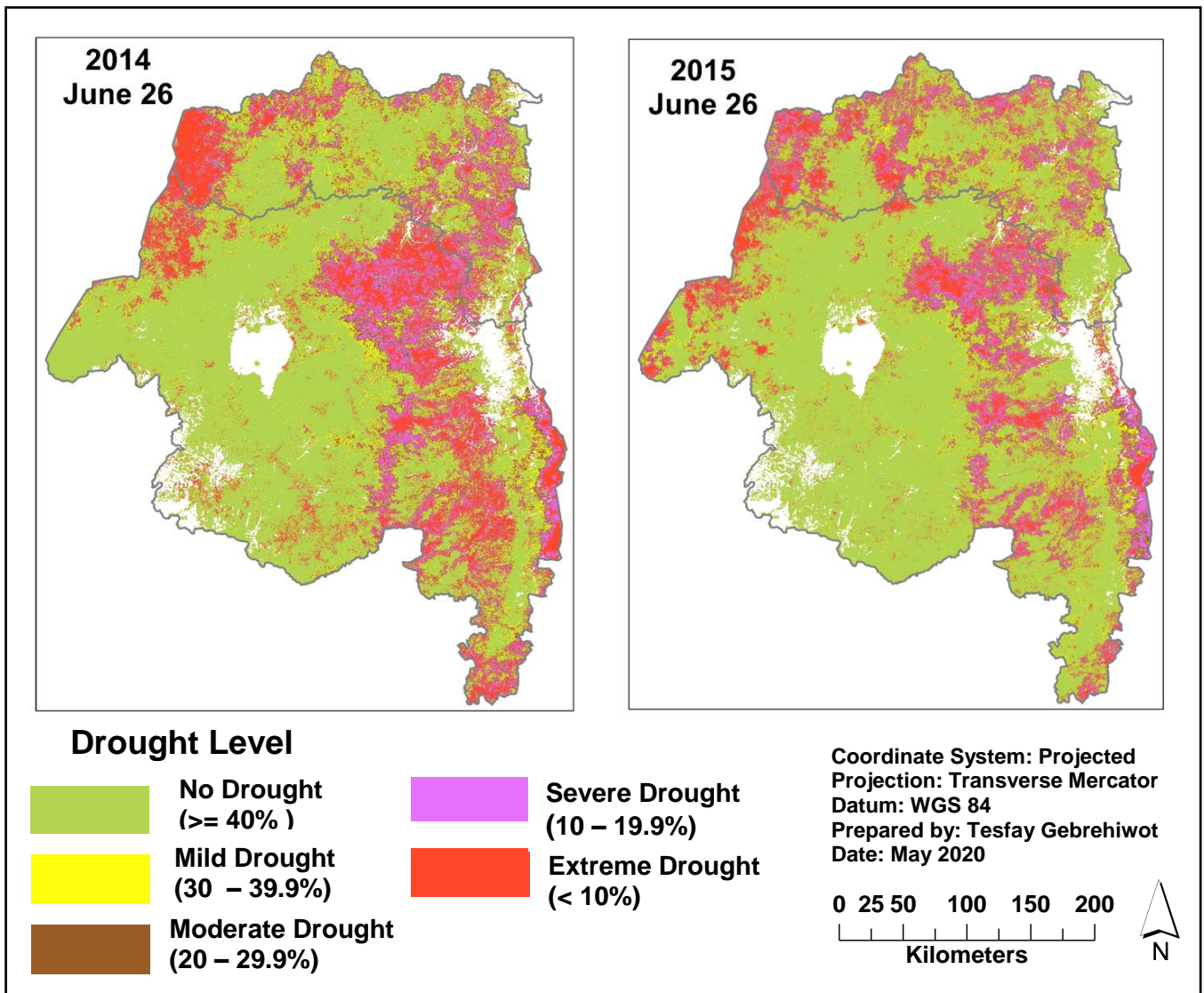


Fig.3.4 Trends of drought conditions in Amhara and Tigray regions from June to October of 2015 based on VCI values

Amhara and Tigray Regions: Distribution of VCI Values in June





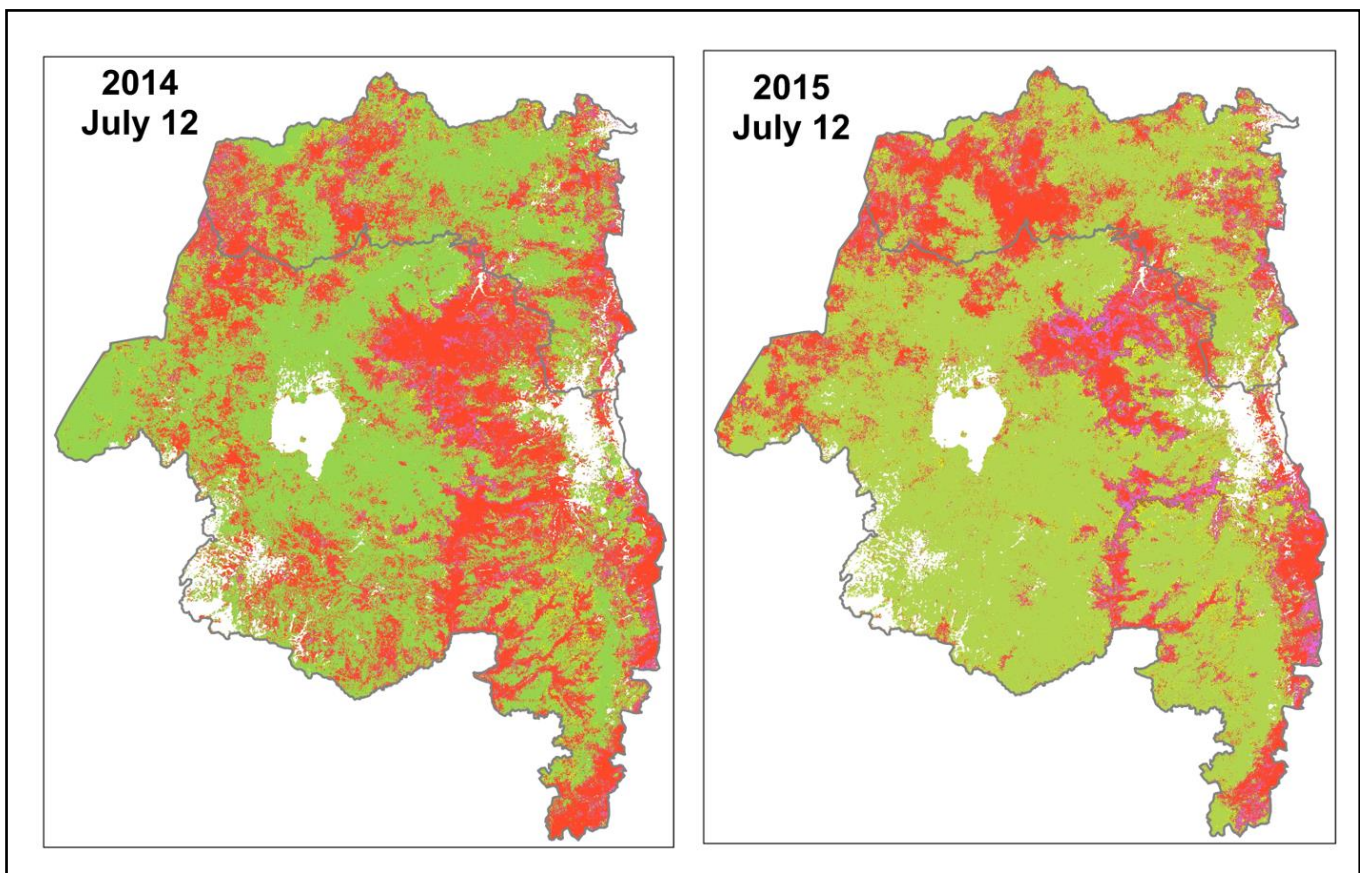
Map 3.9 Drought condition in Amhara and Tigray regions in June 2014 and 2015 based on VCI values

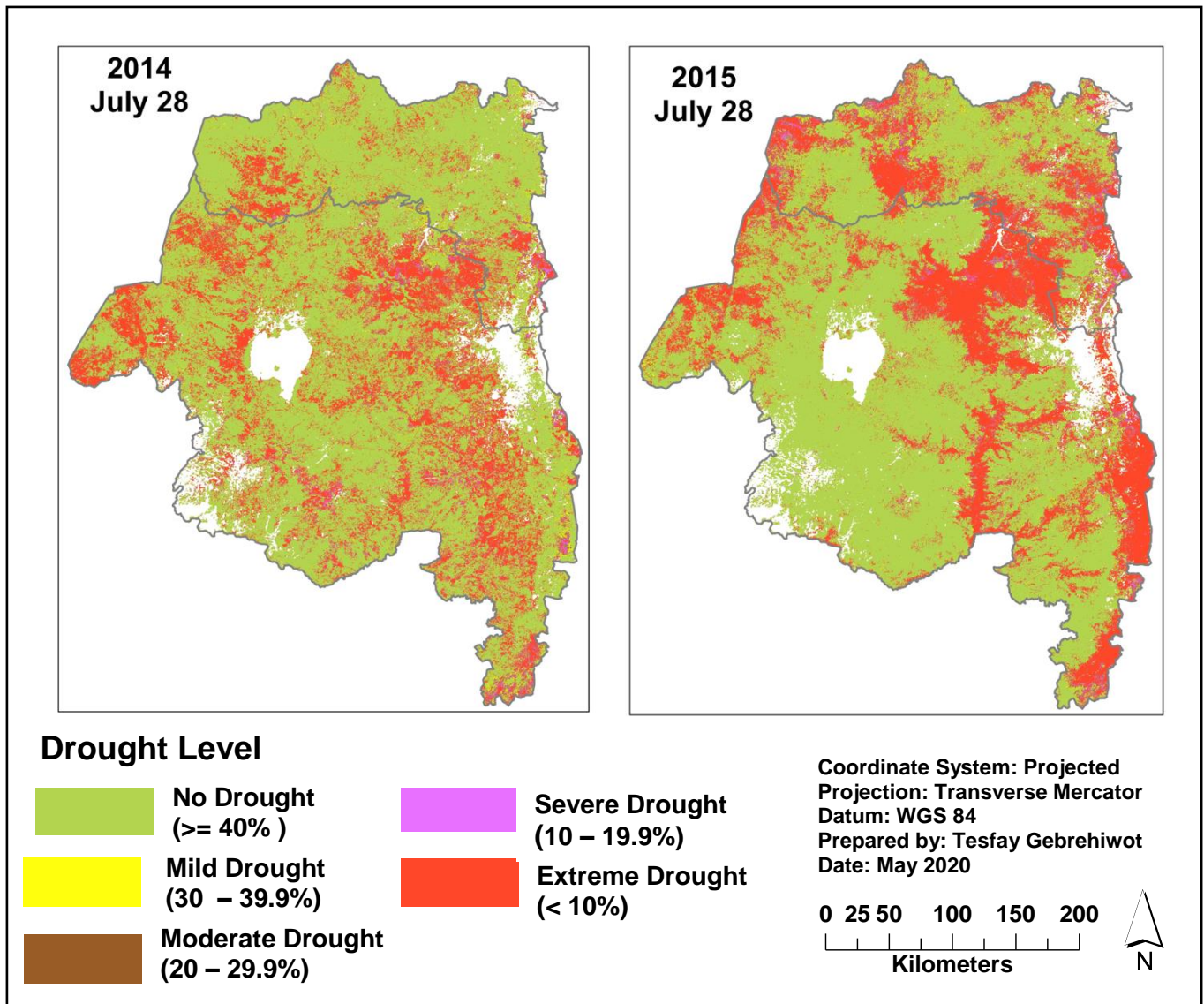
B. VCI analyses in July 2015

The VCI values on July 12 indicated that the agricultural land affected by mild to extreme drought increased to 51.3%. It also showed that the area of agricultural land under extreme and severe droughts also increased from June. The drought conditions on July 12 expanded to many places in the western and northwestern parts of Tigray; northern, and eastern extremes, as well as some parts of western, parts of Amhara regions from the situation in June. The comparison of the drought situation in 2015 with the same period of 2014 also showed the distribution of the drought was higher in 2015 than in 2014 but the reverse was true for the drought intensity. On July 28, the agricultural land affected by drought decreased

to 41.4%, and the improvements were mostly observed in the northwestern parts. But, the drought intensity increased from the previous observation, and 24.7% of the agricultural land in both regions was affected by extreme drought. The drought had affected bigger agricultural land in 2015 than in the same period of 2014. In 2014, the drought situation on July 28 was improved in many parts of the study area except some places in the southwestern and southeastern of Tigray, and northern, northwestern, western, and eastern parts as well as some pocket areas of the Amhara region. The intensity of the drought in 2015 was higher mainly in the western, southwestern, and eastern Tigray, and the eastern, central south, northern and extreme western parts of the Amhara region. The overall trends and distributions of the VCI values showed the drought condition in 2015 affected greater and has higher intensity compared to the droughts in the same period of 2014. But, in terms of distribution, the drought in 2014 is observed in many places in the study area (Map 3.10).

Amhara and Tigray Regions: Distribution of VCI Values in July





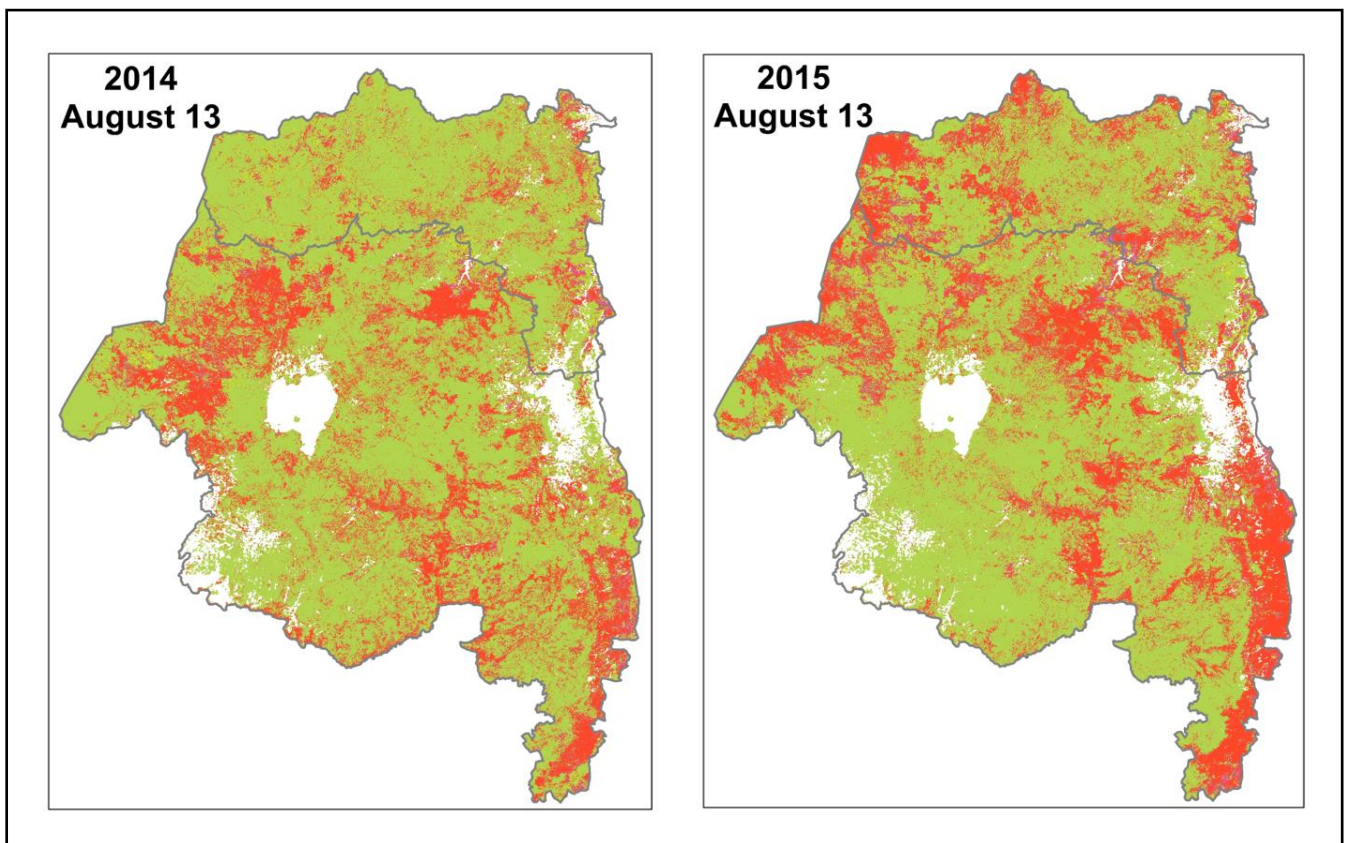
Map 3.10 Drought conditions in Amhara and Tigray regions in July 2014 and 2015 based on VCI values

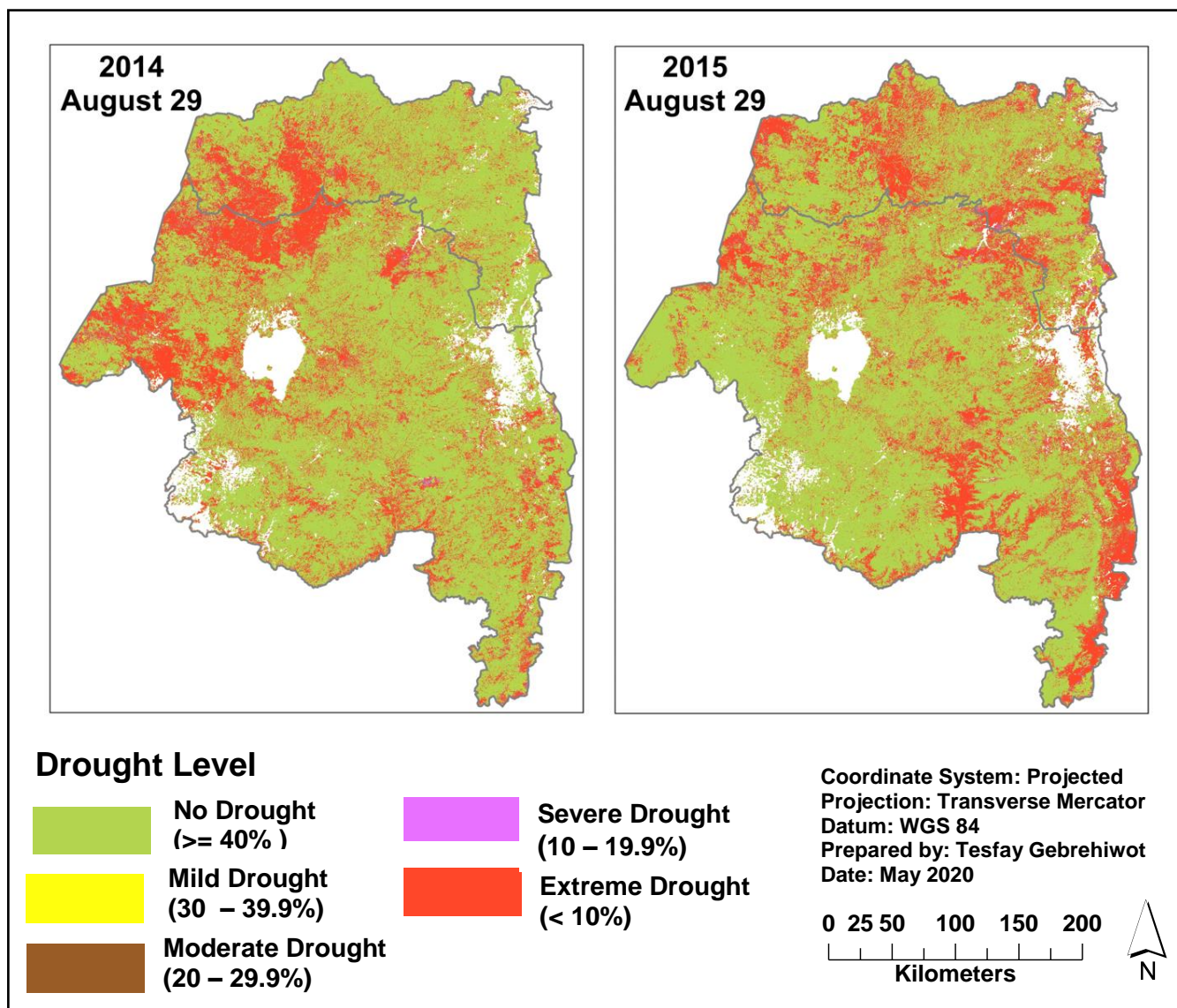
C. VCI analyses in August 2015

The VCI values on August 13 also showed the intensity and distribution of the agricultural drought decreased from July. The reduction in drought was observed in many places in Western, Central, and Eastern Tigray; and the Northern, Central, and Southern parts of the Amhara region. However, about 41.3% of the agricultural land in the regions was under mild to extreme drought, which was almost similar to the situations on July 28. On August 13, the severe and extreme drought conditions were mostly observed in many places in the northern, eastern, southeastern, and some parts of western Amhara; and the western, northwestern, eastern, and northeastern parts of Tigray. The comparison of drought

situations in 2015 and 2014 also showed the agricultural areas affected by the drought were bigger in 2015 than in 2014. But, the distribution was not the same all over the study regions. The intensity and distribution of the drought in 2014 were also in some parts of the northwestern, southwestern, as well as few pocket areas of northern and eastern, Amhara; and the southwestern, and western parts of Tigray regions and some parts of western parts of the Tigray regions. The situation on August 29 indicated the agricultural land affected by the drought reduced to 37.9% from the previous observation. In this period, many places of western and northwestern, central, and southeastern parts of the study regions were out of drought but still, a very large area was under extreme drought (Map 3.11, and Table 3.5). The pixel by pixel comparison of the VCI results in 2014 and 2015 also revealed that 51.8% of the agricultural land in the regions had higher VCI values in 2014 than in 2015, in 42.2% the VCI values in 2014 was lower than in 2015, and for rest of the areas the VCI values were the same in both years (Table 3.6).

Amhara and Tigray Regions: Distribution of VCI Values in August





Map 3.11 Drought conditions in Amhara and Tigray regions in August 2014 and 2015 based on VCI values

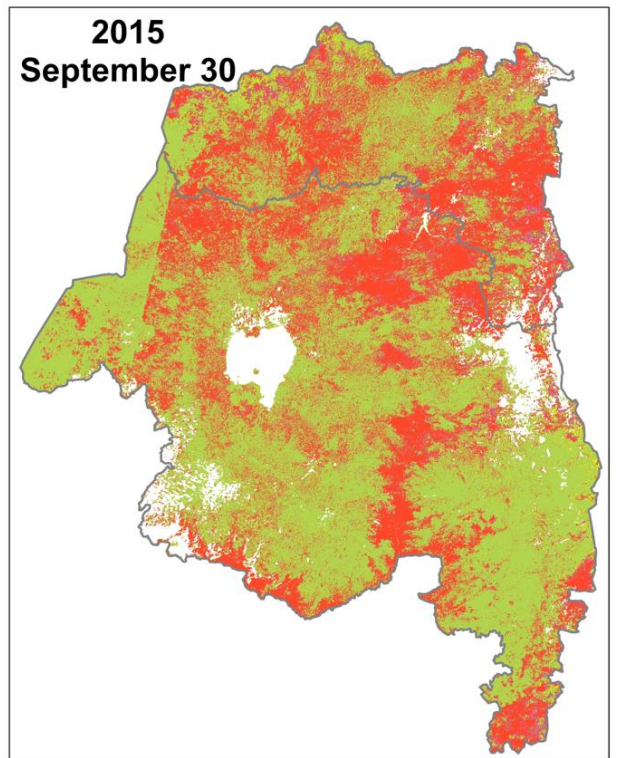
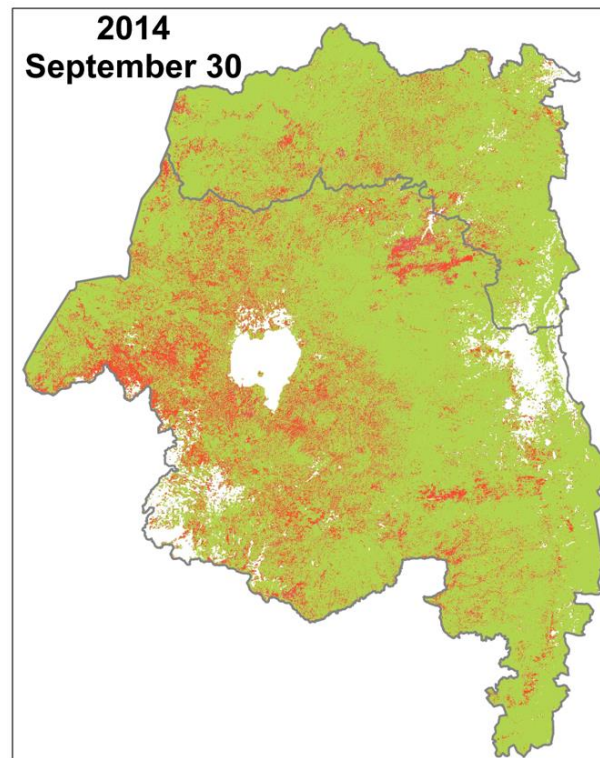
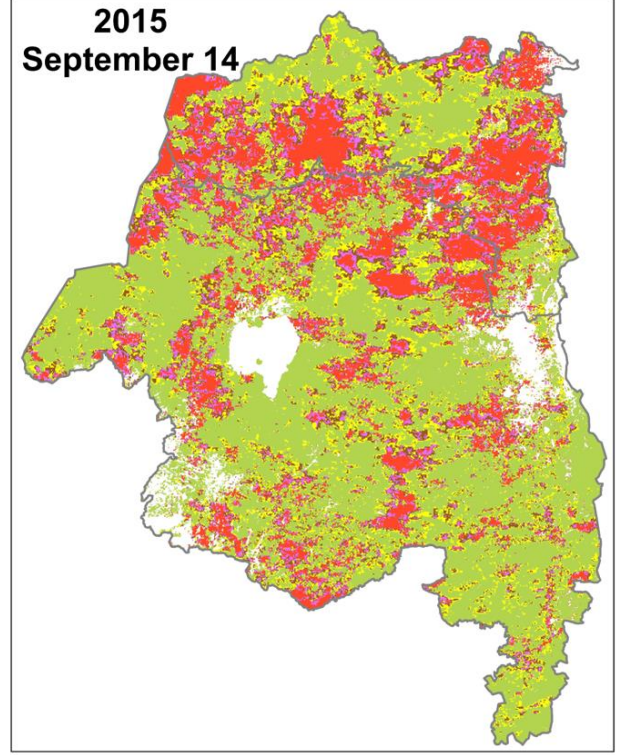
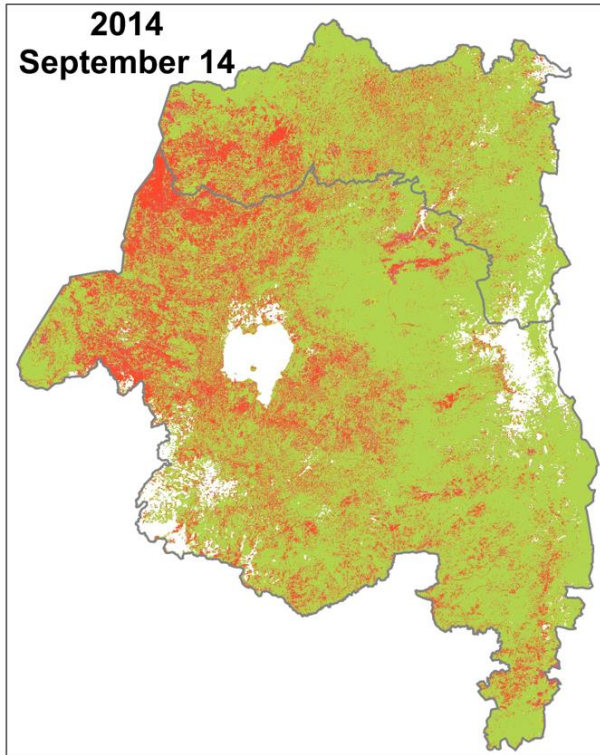
D. VCI analyses in September and October 2015

On September 14, about 50% of the agricultural land in the study regions was under drought and the intensity increased especially in the northeastern, northwestern, central-north, central, and southwestern parts of the study area. In this period, the largest part of the Tigray region was badly affected by the mild to extreme drought except for very few places in the northwestern, and southern parts. In the Amhara region, the situation was better in the majority of the places, but the northern, northwestern, as well as some pocket areas in southwestern, central-southern, and southeastern parts, were significantly affected by the mild to extreme drought conditions. The drought condition in the same period 2014

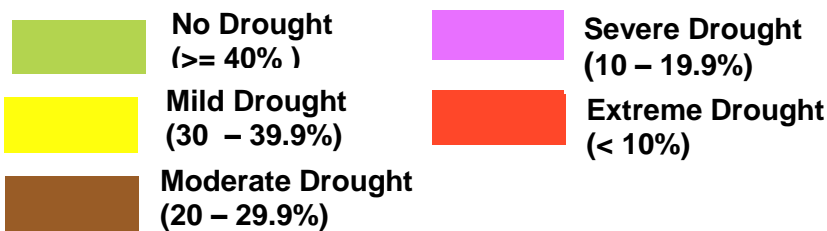
was better than 2015, but fragmented places in the northwestern, western, and southwestern, as well as central parts of the study area, were under mild to moderate droughts too. On September 30, large parts of the study area (62%) were also under extreme to mild drought conditions. This affected particularly the Tigray region; and also southern, southeastern, and northwestern parts of the Amhara region (Map 3.12 and Table 3.5). The situation on October 16 also indicated that 59% of the study area that included the central, and eastern, as well as northeastern parts was under mild to extreme drought conditions. This covered pocket areas in northwestern Tigray; western, northwestern, and southern and eastern extremities of the Amhara regions (Map 3.13, and Table 3.5 & 3.6).

The drought condition in 2015 was compared to the same period of 2014 by looking at the difference between the VCI results between the two years. The results showed the drought in 2015 was generally higher than in 2014. On August 13, about 52% of the study area that covered almost all parts Tigray except for some parts in northeastern, southern, and western and central parts; and the western, northern, eastern, and some areas in the central parts of Amhara region, was under higher drought in 2015 than in 2014. The situation on August 30 was also similar except for the slight decreases observed in the western parts of the study area from the earlier year. On September 14, 67.2 % of the study area was under higher drought in 2015 than in 2014. This was observed mainly in the northern, central, and eastern as well as southern parts of the study area. But, geographically the drought condition had also shown decreases from earlier years in many places in the western, northwestern, and southwestern as well as southeastern parts of Amhara; and few places of Tigray regions. On September 30, the drought in 70.9% of the study area was higher in 2015 than in 2014, and this increased to 72.4% on October 16. The highest drought increase was observed in northern, central, eastern, southern parts of the study area, and some pocket areas in western parts. The drought in 2015 was higher than in 2014 in almost all parts of the Tigray region, but in the Amhara region, there were exceptions in the northwestern, and southwestern parts (Table 3.6).

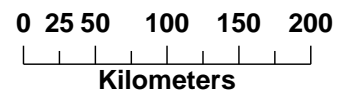
Amhara and Tigray Regions: Distribution of VCI Values in September



Drought Level

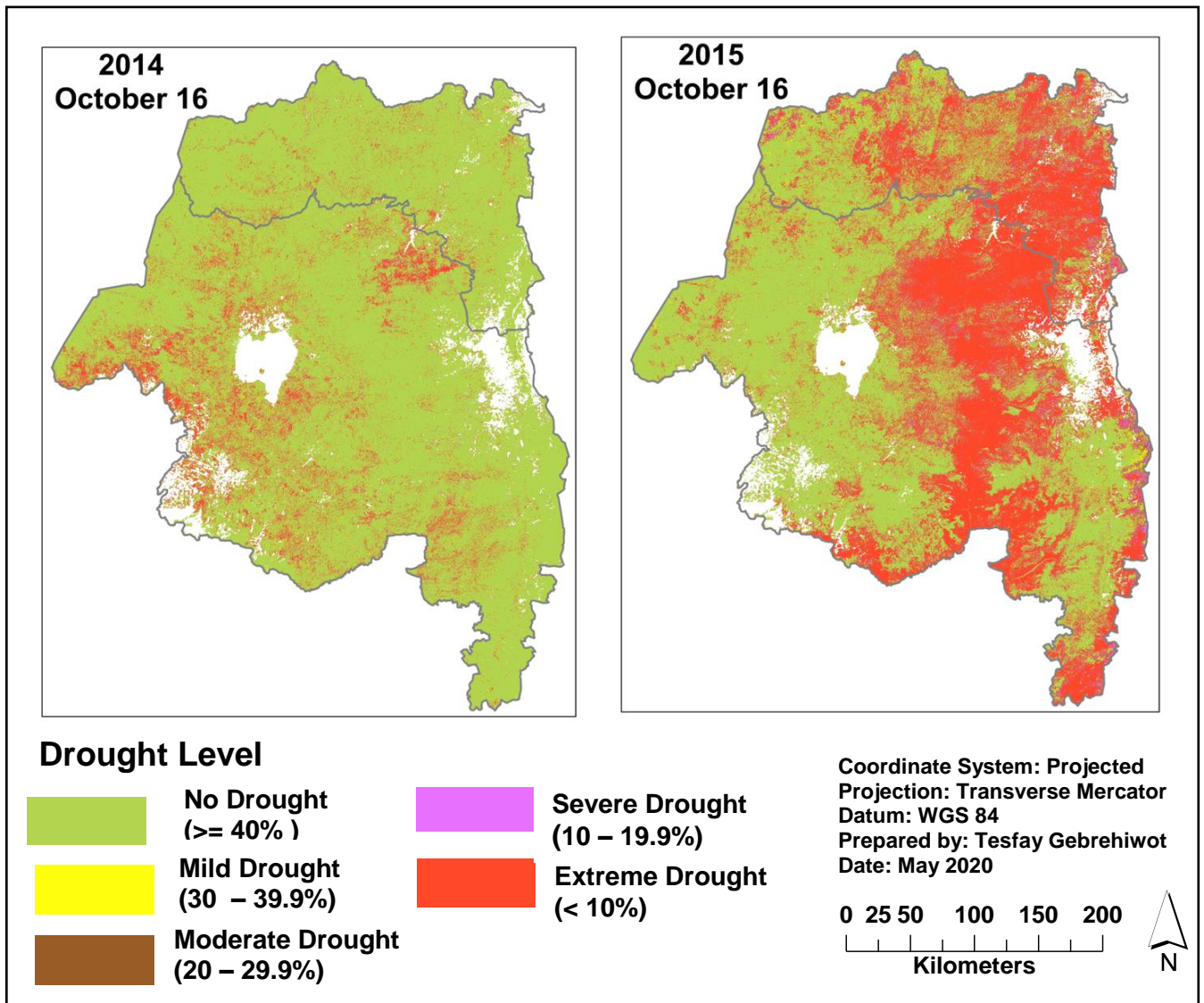


Coordinate System: Projected
 Projection: Transverse Mercator
 Datum: WGS 84
 Prepared by: Tesfay Gebrehiwot
 Date: May 2020



Map 3.12 Drought condition in Amhara and Tigray regions in September 2014 and 2015 based on VCI values

Amhara and Tigray Regions: Distribution of VCI Values in October



Map 3.13 Drought condition in Amhara and Tigray regions in October 2014 and 2015 based on VCI values

Table 3.6 Comparison of a pixel by pixel VCI values between 2014 and 2015

Time	VCI values in 2015 compared to 2014			
	Lower		Higher	
	Area (sq. Km)	%	Area (sq. Km)	%
August 13	106035	51.8	86935	42.4
August 29	106396	51.9	88467	43.2
September 14	137323	67.2	64277	31.4
September 30	145177	70.9	49451	24.1
October 16	148390	72.4	50055	24.4

Source: Own computation of VCI based on MODIS13Q1A

The overall VCI analysis showed the presence of drought in many parts of the study area during the observation periods. The VCI results in September and October, which showed the situation of the crops during flowering and before harvest period, revealed 50 to 62% of the agricultural land in the study area was under drought of different degrees. The 15.3% to 30.9% of the agriculture in the study area was under extreme drought, 6.7 to 10% under severe drought, 7.2% to 12.1% under moderate drought, and 7.2 to 13% under mild drought condition (Table 3.5, Fig 3.4). The results also showed the condition of the drought was severe in the northern, eastern, and southern parts than the western and southwestern parts of the study area. The findings also showed that a very large part of the Tigray region was highly affected by the drought except for the western, and very few areas in the northwestern and central parts. In Amhara, the northern, eastern, and some parts of central-north of the region were badly affected by drought. The overall pattern of the drought also indicated the eastern parts of the study area were much affected by the drought than the western parts (Map 3.12 and 3.13). The comparison of the drought conditions between the same period of 2015 and 2014 also indicated that the drought in 67.2% to 72.4% of the Amhara and Tigray regions was higher in 2015 than in 2014 (Table 3.6). But, the drought in the other parts, especially in the southern, western, and few areas in the southeastern parts of Amhara, was lesser in 2015 than in 2014.

3.5 Temperature Condition Index (TCI) Analysis

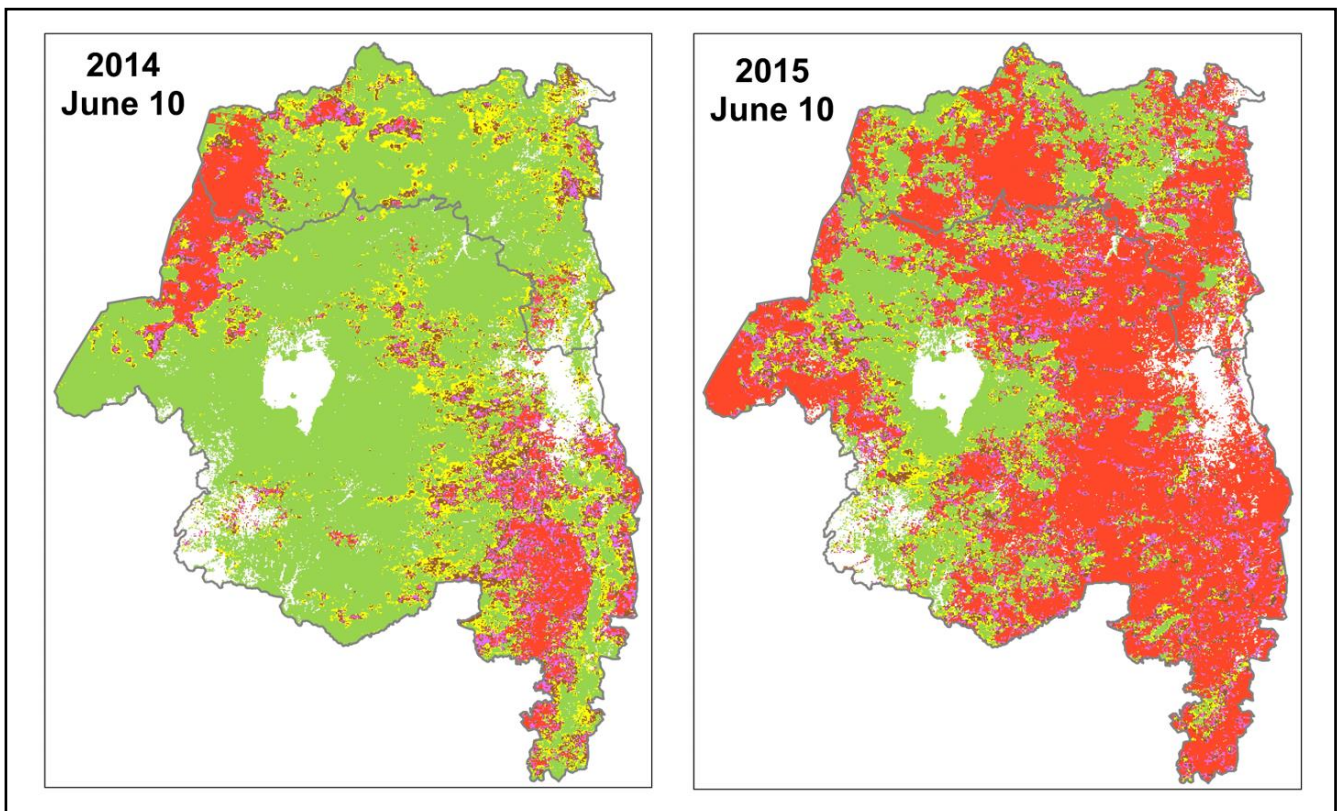
The spatiotemporal distribution of the drought condition of the study area was also analyzed based on the TCI values obtained from the analysis of land surface temperature data in the observation periods from June to October of 2015. Similar to the VCI and NDVI analysis, the results of June to August were used to understand the trends and compare the results with rainfall, crop covered area, and crop productions, and those of September and October were used to evaluate the agricultural drought of the year in the study areas. Besides, since 2014 was considered a better year in terms of drought than 2015 (CSA, 2015), the TCI

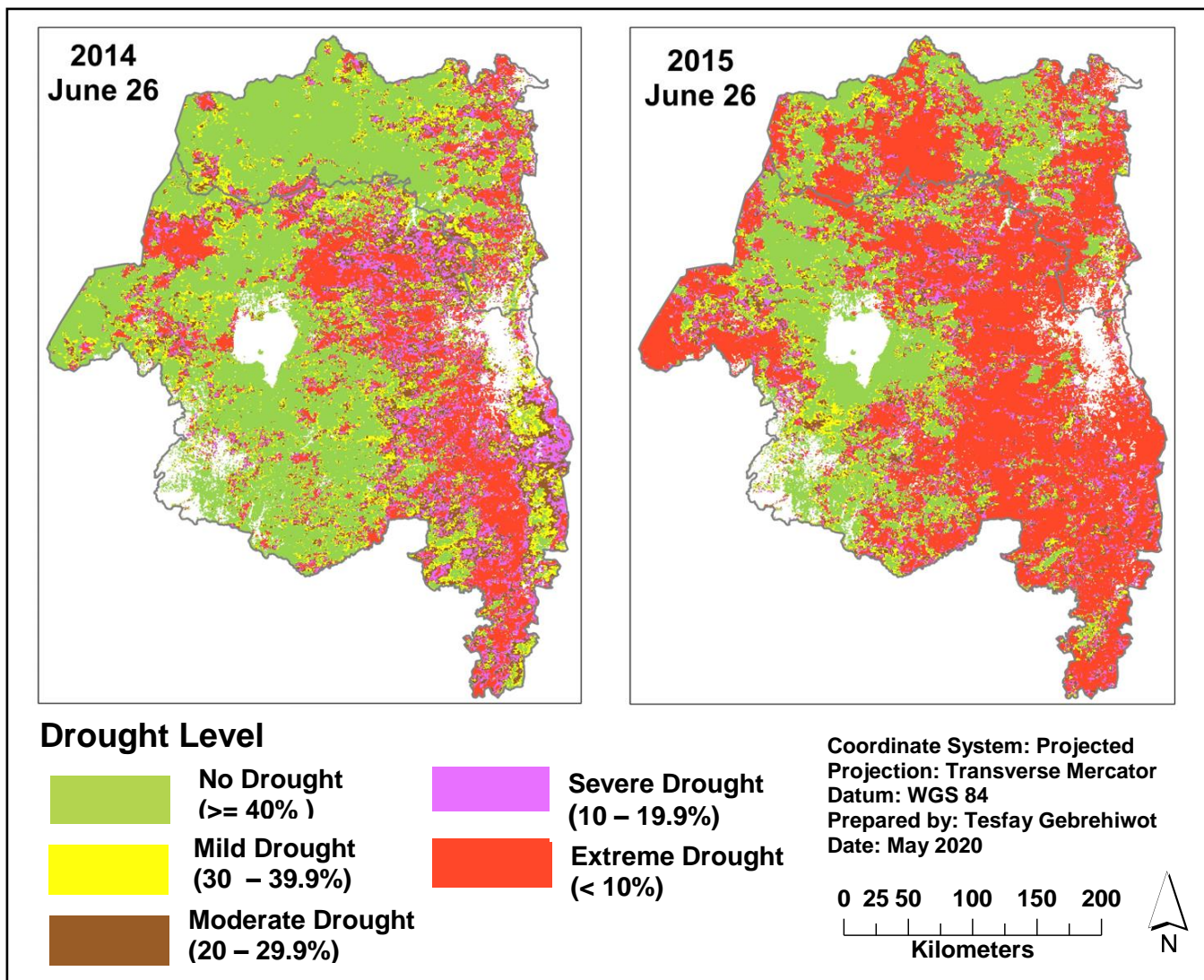
values for the same period of 2014 were also analyzed and used as a reference to make a better evaluation of the situation in 2015.

A. TCI analyses in June 2015

The TCI analysis results revealed that on June 10, 75.3 % of the study area was in mild to extreme drought conditions. The distribution covered all the study area except northern, northwestern, central-west, and southwestern parts. In general, the drought-affected the eastern side of the study area than the western parts. The TIC results in 2014 showed big differences with that of 2015 in that the drought-affected a very small area in the former compared to them. The drought condition on June 26 was more or less the same but it showed slight improvements in small areas. But, the drought in the same period of 2014 expanded into the eastern and southeastern parts affecting large areas. The results also showed that the areal coverage and intensity of the drought were higher in 2015 than in 2014 (Map 3.14).

Amhara and Tigray Regions: Distribution of TCI Values in June



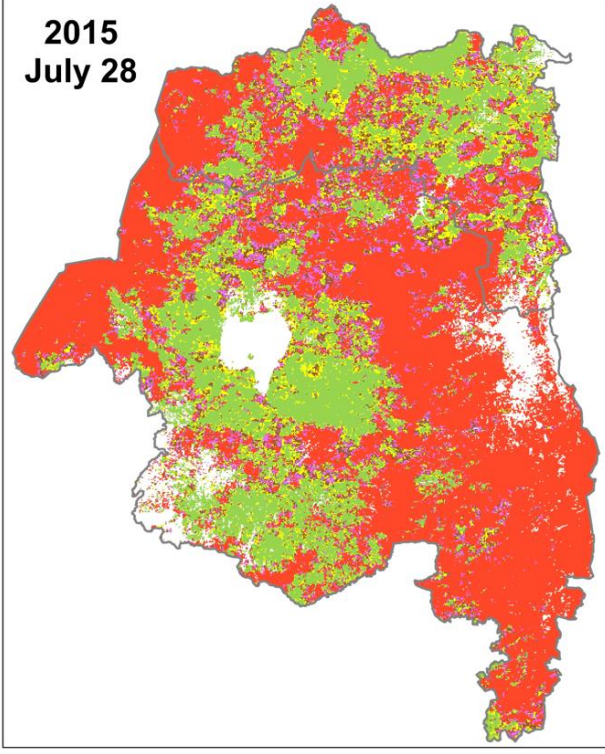
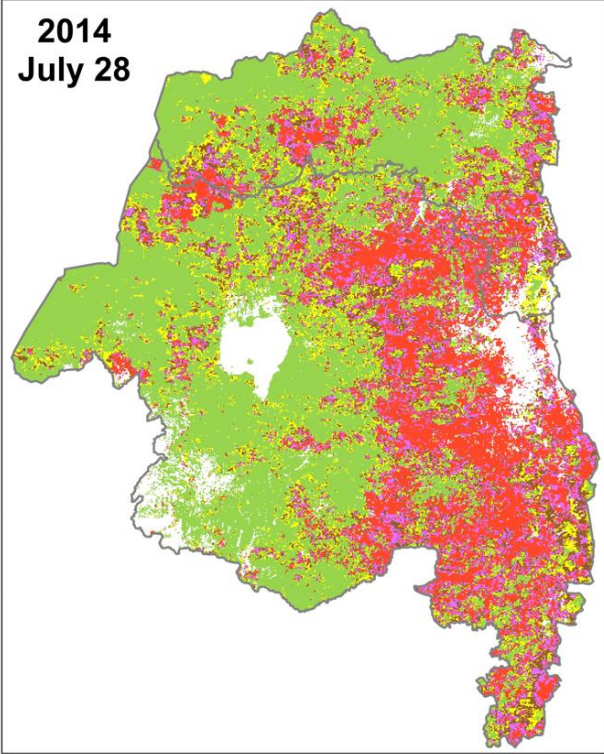
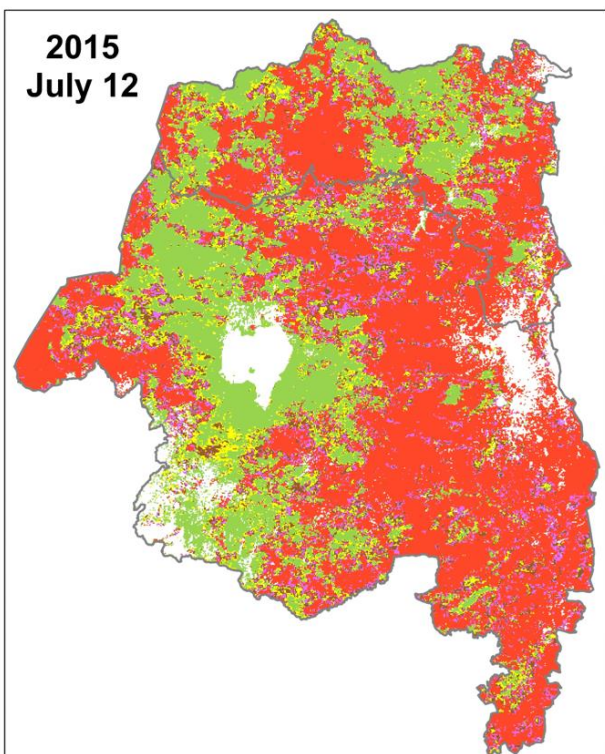
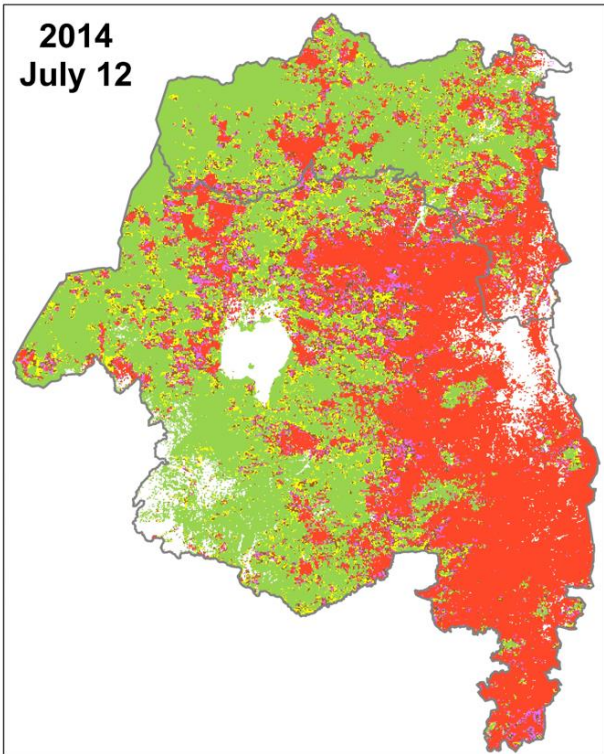


Map 3.14 Drought condition in Amhara and Tigray regions in June 2014 and 2015 based on TCI values

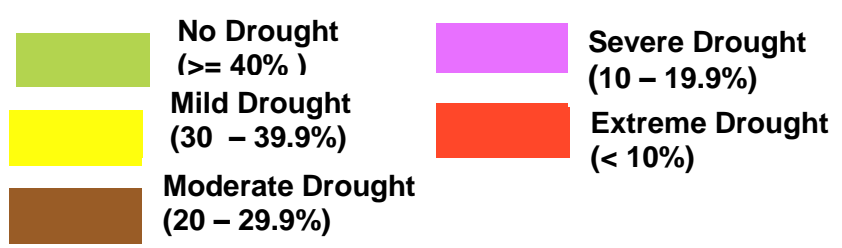
B. TCI analyses in July 2015

The drought on July 12 had also similar distributions with the earlier period except for the drought in 2014 that it covered more areas and it was more intense than in June. However, the drought in 2015 was in general higher than in 2014. On July 28, the area under drought decreased to 73.9%, and many places in the northeastern, as well as the northern part, showed improvements from the earlier observations. But, the condition in the western parts of the study area was much-deteriorated from the earlier observation period. The intensity of the drought in this period also increased and 65% of the study area was under severe to extreme drought conditions compared to 50% in the earlier period. On the contrary, the drought condition in 2014 showed greater improvement from the earlier period than in 2015 (Map 3.15).

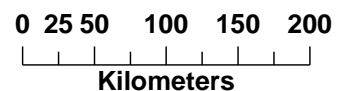
Amhara and Tigray Regions: Distribution of TCI Values in July



Drought Level



Coordinate System: Projected
 Projection: Transverse Mercator
 Datum: WGS 84
 Prepared by: Tesfay Gebrehiwot
 Date: May 2020



Map 3.15 Drought condition in Amhara and Tigray regions in July 2014 and 2015 based on TCI values Page | 74

Table 3.7 Agricultural land in Amhara and Tigray regions affected by the drought from June to October of 2015 based on TCI results

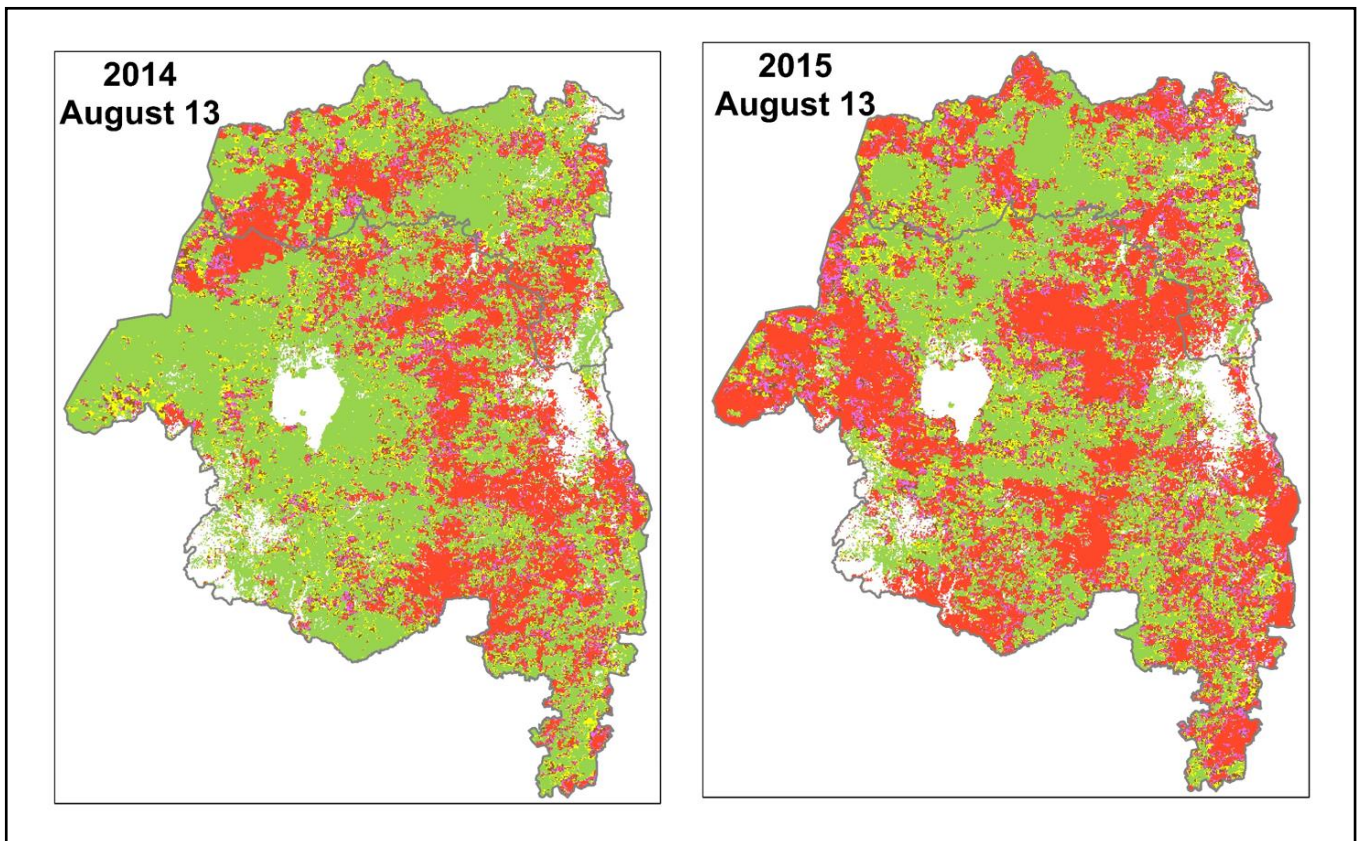
Time	Drought Classes									
	Extreme drought		Severe drought		Moderate drought		Mild drought		No drought	
	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%	Area (sq. Km)	%
June 10	92321	48.3	18300	9.6	18923	9.9	16660	8.7	44924	23.5
June 26	92321	48.3	18300	9.6	18923	9.9	16660	8.7	44924	23.5
July 12	92321	48.3	18300	9.6	18923	9.9	16660	8.7	44924	23.5
July 28	94537	49.5	16457	8.6	17511	9.2	16425	8.6	45945	24.07
August 13	65288	35	18318	9.8	20091	10.8	19493	10.4	63376	33.97
August 29	87142	45.9	21156	11.1	20084	10.6	17244	9.1	44139	23.26
September 14	29279	15.3	17445	9.1	23121	12.1	25661	13.4	95782	50.07
September 30	106185	55.5	19671	10.3	18649	9.7	15468	8.1	31402	16.41
October 16	60260	31.5	15110	7.9	16941	8.8	17225	9.0	81953	42.8

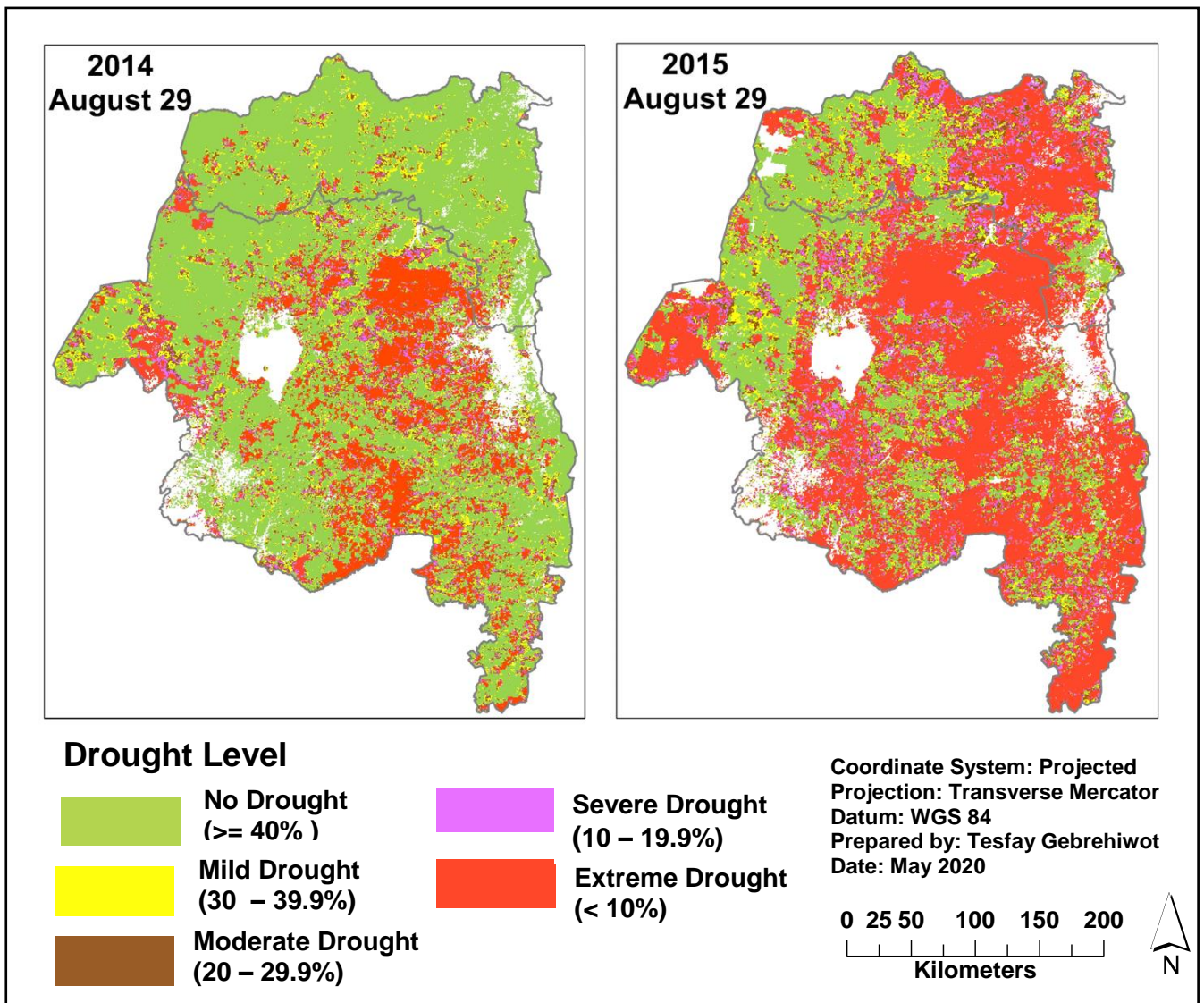
Source: Own computation based on the LST from MOD11A2 data

C. TCI analyses in August 2015

On August 13, 66% of the area in Amhara and Tigray regions was under severe to extreme drought. The degree and distribution of the drought in 2015 were also higher than in 2014, and it was mainly observed in the eastern than the western parts of the study area. In the Tigray region, the northern-central, and eastern parts were more affected than the western and southern parts. In the Amhara region, the drought also affected greater parts except for the northwestern and central-west, as well as southwestern, parts. In general, the condition of the drought was better in Amhara region except for the northern parts. But, the condition in the Tigray region was very deteriorated except for few areas in the northern and central parts. The drought conditions in the same period of 2014 were also better in intensity and distribution than the earlier observation, and it was even lesser than in the same period of 2015 (Map 3.16).

Amhara and Tigray Regions: Distribution of TCI Values in August





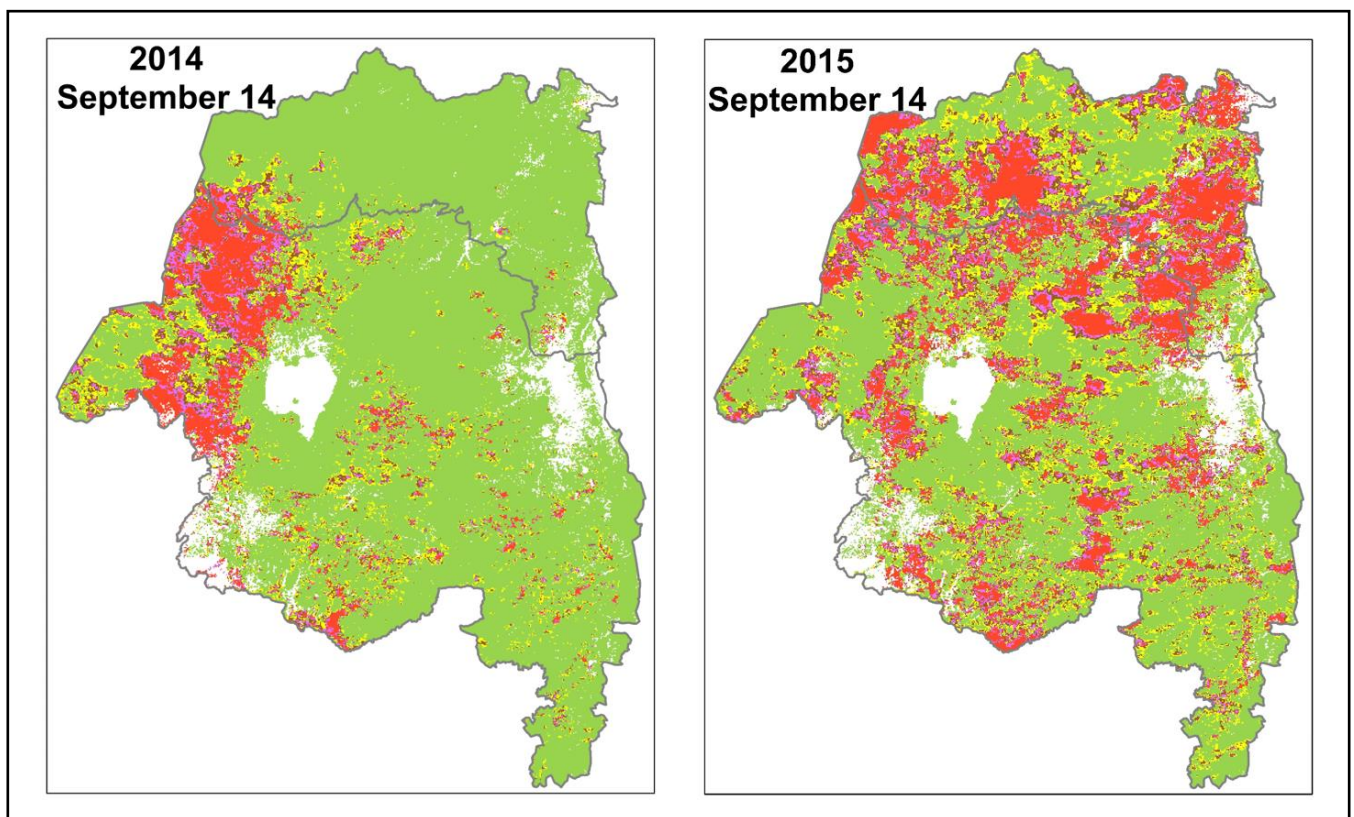
Map 3.16 Drought condition in Amhara and Tigray regions in August 2014 and 2015 based on TCI values

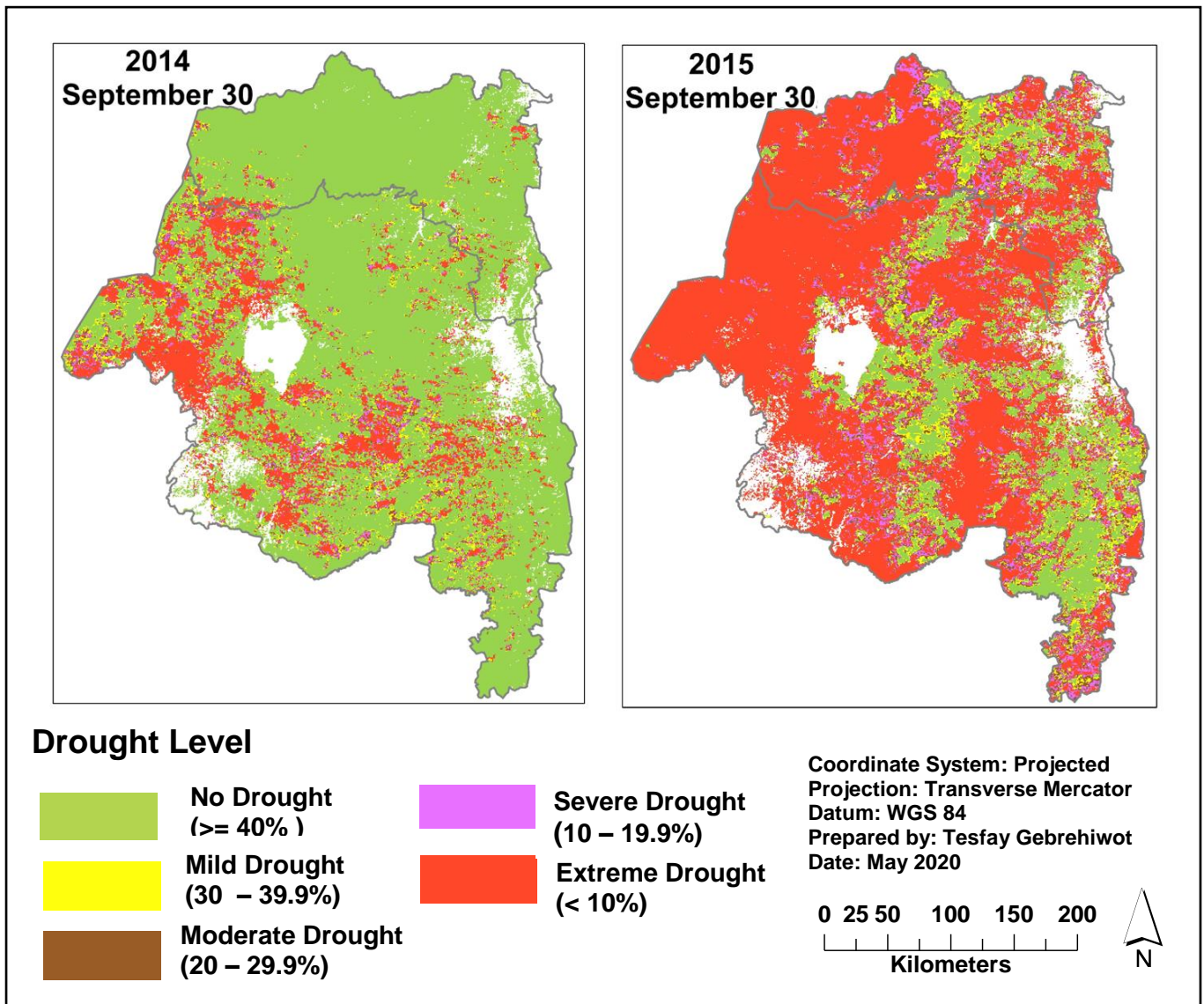
D. TCI analyses in September and October 2015

The agricultural land in the Amhara and Tigray regions affected by drought decreased to 50% on September 14. The decrease in drought was observed in the north-central parts of the study area covering large parts of the Tigray region except the northern and central parts. It was also seen in the northern, central, southern, western, eastern, and southeastern parts of the Amhara region. The comparison of the drought situation in 2015 and 2014 also showed that the agricultural drought in the later had a wider area of coverage and more intense in the latter than the former. The drought in 2014 at that period of observation was also limited to specific places in the western parts of the study area. The

TCI values on September 30 indicated drought occurrence in about 83% of the study area and the distribution were generally to the western and southwestern parts of the study area. The analysis for this period gave strange values in both the magnitude and distribution of the drought that is neither consistent with the trends in 2015 nor with 2014 so was not considered in the overall analysis. The condition on October 16 of 2015 was different from the end of September in both the intensity and distribution of drought conditions. On October 16, the severe to extreme drought was observed in 57.2% of the study area and the distribution of such drought conditions was higher in the northern, central, eastern, as well as extreme southeastern parts, of the study area (Map 3.18). The majority of the Tigray region except for the western part and few areas in the northern and central parts were highly affected by the drought. In the Amhara region, the northern, south-central, eastern, and southeastern, as well as some areas in the extreme south and western part of the region, were also more affected by the drought than the other parts (Map 3.17, map 3.18 and Table 3.7).

Amhara and Tigray Regions: Distribution of TCI Values in September



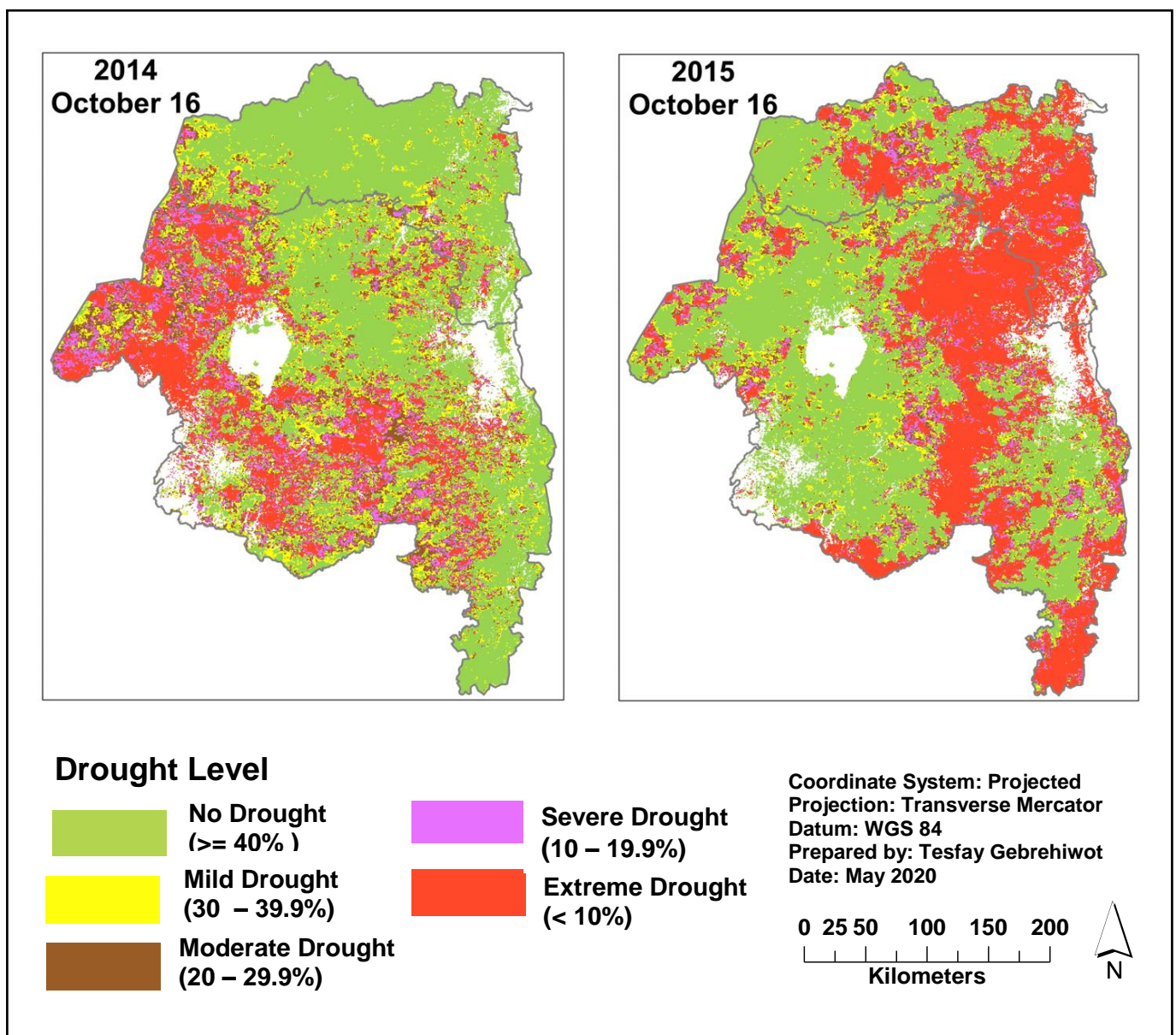


Map 3.17 Drought condition in Amhara and Tigray regions in September 2014 and 2015 based on TCI values

The overall TCI analysis showed that a large part of the agricultural land in the Amhara and Tigray regions were affected by mild to extreme droughts. The TCI results in September and October with the exclusion of September 30 showed that 50 to 53% of the agricultural land in the regions were under drought. The 15.3% to 31.5% was under extreme drought, 7.9 to 10.3% under severe drought, 7.2% to 12.1% under moderate, and 8.1 to 13.4% under mild drought conditions (Table 3.7). The distribution of the drought also showed the drought was intense in the northern, eastern, and southeastern parts than in the western and southwestern parts of the study area. The findings also showed that a very large part of the

Tigray region with the exception of the western, and some parts of northwestern parts was highly affected by the drought. In Amhara, drought was severe in the northern, eastern, and some parts of central-north parts of the region. The overall pattern of the drought also indicated the eastern parts of the study area were more affected by the drought than the western parts (Maps 3.17 and 3.18). In general, the results of the TCI analysis were found more consistent with the results of the VCI analyses.

Amhara and Tigray Regions: Distribution of TCI Values in October

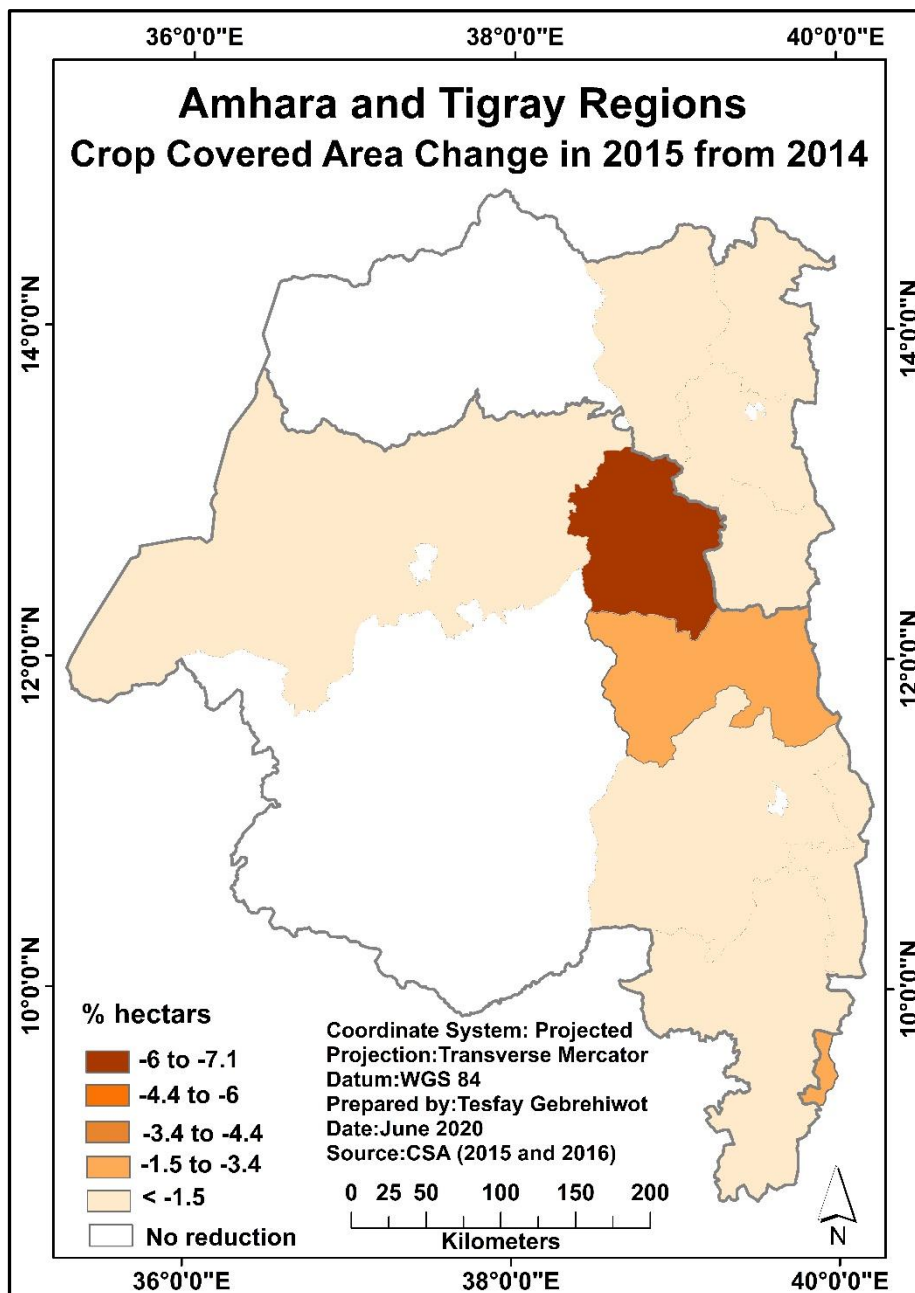


Map 3.18 Drought condition in Amhara and Tigray regions in October 2014 and 2015 based on TCI values

3.6 Crop covered areas and crop production analysis

The agricultural bulletins of CSA published in 2016 showed that crop covered area and crop productions in Ethiopia showed reductions in 2015 compared to 2014 due to the drought conditions in the country. Based on this information, a review was made on the same reports for 2014 and 2016 to further analyze the drought situation in 2015. The results showed that the crop covered areas and crop production in the Tigray region respectively showed 0.9% and 10.28% reductions on average in 2015 from 2014. The same analysis also indicated a 0.2% and 0.4% reduction in crop covered area and crop production in the Amhara region. The results of the analysis showed the reductions in both crop covered area and crop productions in the Amhara region were lower than the Tigray region (Table 3.8). The data of CSA was also analyzed by zone level since that was the lower administration level that the CSA data was got. The analysis of crop covered areas showed there was a reduction of about 0.1% to 5.5% in the Tigray region, and 0.1% to 7.1% reduction in Amhara region. The highest reduction in crop covered area was observed in the northern parts of the Amhara region that covered the Waghimra zone followed by the North Wollo Zones. In the remaining parts of the Amhara region and Tigray regions, there were no reductions in the cropped area and even in some places, there were increases in 2015 from 2014. The distribution of the results also showed that the reduction in crop covered area was mainly in the eastern part than the western parts of the study area in general (Map 3.19). The crop production reduction was also analyzed similarly based on the CSA data. The results showed that the crop productions in 2015 in the Tigray region decreased by about 7.1% to 25% from 2014 and the highest reductions occurred in the central zone of the region. In the Amhara region, the crop productions in 2015 also showed 25% to 31.1% reductions from 2014 that occurred in the northern and extreme southern parts of the regions. But, the largest part of the Amhara region especially the western side has no reductions in crop production, and in some zones, there were increases in 2015 from 2014. The crop production analyses in the Argoba and Oromia zones of the Amhara region showed strange

results that do not match with the results of the drought indices, the rainfall distributions, and crop covered areas (Table 3.9, Annex 1, and Map 3.20). The increase in crop productions in 2015 in those areas could be due to errors on the CSA data since such types of data mismatches were also observed on other data types like population projection. The 2016 CSA data also indicated lower crop covered area and crop productions in 2015. So, the overall analysis proved the Amhara and Tigray regions were in drought in 2015 compared to 2014 and 2016 (Annexes 2 and 3).

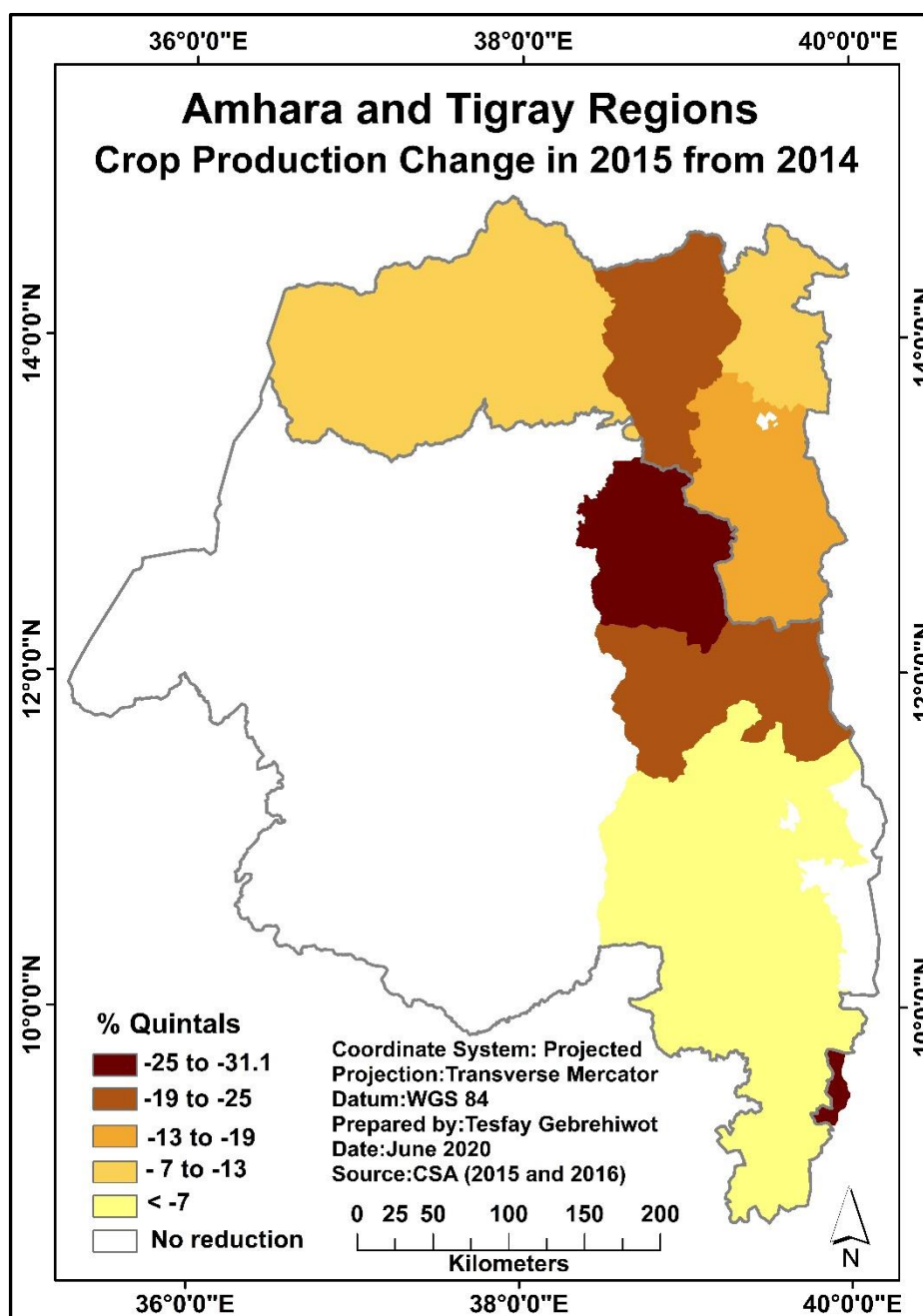


Map 3.19 Crop covered area reduction in Amhara and Tigray regions in 2015 from 2014

Table 3.8 Crop covered area and crop production in Amhara and Tigray regions from 2014 to 2016

Region	Cropped agricultural area (ha)			Crop Production (Quintal)		
	2014	2015	2016	2014	2015	2016
Amhara	4442036	4424475	4443390	87637545	87464268	95282956
Tigray	933108	924525	936908	17458541	15663285	18448000

Source: (CSA, 2015, CSA, 2016, CSA, 2017)



Map 3.20 Crop production reduction in Amhara and Tigray regions in 2015 from 2014

Table 3.9 Crop covered area and crop production reductions in Amhara and Tigray regions in 2015 by Zone

Sn	Region	Zone	Reduction in crop covered area ha (%)	Reduction in crop production qtl (%)
1	Amhara	North Gonder	0.1	0
		South Gonder	0.0	0
		North Wollo	1.7	22.3
		South Wollo	0.1	4.6
		North Shewa	0.1	1.1
		Easte Gojam	0	0
		West Gojam	0	0
		Waghimra	7.1	29.4
		Awi	0	3.3
		Oromia	1.5	4.6
		Argoba	2.4	31.3
2	Tigray	Northwest	0.0	8.0
		Central	0.1	22.8
		Eastern	0.1	7.4
		Southern	0.1	14.2
		Western	0.0	8.3

Source:(CSA, 2015, CSA, 2016, CSA, 2017)

3.7 Correlations of results

The SPI, NDVI, VCI, and TCI analysis all clearly showed the study area was under drought in 2015. They also showed the eastern parts of the study area were more affected by the drought than the western part. The above results except for TCI were also found matching with the rainfall amount and distribution in the study area in the crop growing periods, which also depicted a higher amount and distribution of rainfall in the western than the eastern parts of the study area. The harmony of the SPI, NDVI, and VCI results with the rainfall analysis results could show that the drought that affected the study area in 2015 was basically due to the reduction of rainfall, which is in harmony with the results of the study of (Dutta, 2018). However, the TCI results were not following the same trend with the rainfall in the majority of the observation periods indicating the negative correlation between the two variables. This may indicate the drought in the area was also affected by the rise in temperature, which is in agreement with (Liou and Muluaem, 2019). On the other side, the

NDVI, VCI, and TCI analysis results showed greater coincidence with the analyses of crop covered and crop production data from CSA, which also showed big reductions in both parameters in the western than the eastern parts of the study area. The temporal analyses in the drought indices also showed similarities in the areal coverage of the drought. The SPI and NDVI result estimated 40.5%, and 34.5 % to 43.1% of the study area respectively was under drought. The VCI and TCI results also indicated 50% to 62% and 50 to 53% of the study area respectively was affected by mild to extreme droughts. This showed the estimates between SPI and NDVI were very close and the same were between VCI and TCI. From the results, it was also seen that the proportion of drought-affected areas in Tigray was higher than in the Amhara region. This was also consistent with the analysis results of the rainfall distribution, and statistical information about crop covered area and crop production reductions in the study area in 2015. The correlation of the drought indices using statistical methods also showed that SPI has strong and moderate positive correlations with NDVI and VCI respectively, and a very strong negative correlation with TCI. The drought indices had also shown strong correlations among themselves (Table 3.10), and the results were partly in agreement with findings in (Gidey et al., 2018a, Eshetie et al., 2016, Gidey et al., 2018b, Sruthi and Aslam, 2015). The overall results of this study showed the drought indices and applied methodology worked very well to detect the agricultural drought that affected the Amhara and Tigray regions in 2015.

Table 3.10 Correlation of the drought indices based on linear regression

Index	Correlation results (R2)			
	SPI	NDVI	VCI	TCI
SPI	1	0.53	0.21	0.64
NDVI	0.53	1	0.44	0.56
VCI	0.21	0.564	1	0.52
TCI	0.64	0.56	0.52	1

Source: Own computation based on regression correlations of values of the indices

Chapter- 4: Conclusions

Droughts are natural disasters that are caused mostly due to a natural reduction in the amount of precipitation received over an extended period. And they are classified as meteorological, hydrological, agricultural, and socioeconomic droughts. Agricultural droughts are caused by the reduction of soil moisture due to reduced precipitation that leads to reduced crop production and plant growths. Droughts have been creating a multitude of impacts on the economy, social, and environmental segments worldwide in history. For example, droughts caused 6 to 7 billion USD losses in the USA annually, and they constitute 7% of the 1.4 trillion economic losses caused by natural disasters from 1990 to 2004 globally. Droughts also affected 1.4 billion people globally; killed more than 1.1 million and affected above 230 million Africans between 1967–1991. Ethiopia has been also frequently affected by droughts in its history. The disasters caused famine, death of people and animals, displacements of people and separation of families, and political unrest, etc. In 2015, Ethiopia was stricken by a drought recorded as the most severe in 50 years. That drought-affected 10.2 million people, killed 1.2 million animals, affected 7 million livestock, and consumed 25% of the national GDP for its mitigation. The 2015 drought also caused 0.57% and 1.3 % reductions in the estimated crop covered area and volume of crop production from the earlier year at the country level. The 2015 drought also severely affected the Amhara and Tigray regions causing up to 7.1% reductions in the crop covered area and up to 31% in crop production in the regions from the same period of 2014.

Drought monitoring has been done historically based on data of drought-related variables (precipitation, near-surface air temperature, wind speed, atmospheric water vapor, relative humidity, etc.) captured using ground based-point observations or interpolated grids. However, the ground observations mostly have uneven and limited distribution to capture the spatiotemporal variability of drought variables, and the data from the various stations have variability in recording times and data quality. The Earth Observation satellites (EOS) provide comprehensive, synoptic, and multi-temporal coverage of large areas in real-time

and at frequent intervals using their spectral bands. The advancements in remote sensing and the Geographic Information Systems (GIS) technologies also become very helpful in real-time monitoring, early warning and quick damage assessment, and proactive decision making and drought disaster preparedness. The new remote sensing instruments like Moderate resolution Imaging Spectroradiometer (MODIS) have been used for drought monitoring worldwide. Satellite observations from a combination of space and ground observations like Climate Hazard Group Infra Red Precipitation with Station (CHIRPS) have been also used to make rainfall estimates. The vegetation drought indices such as Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Temperature Condition Index (TCI) derived from MODIS data have been widely used for agricultural drought monitoring. Standard Precipitation Index (SPI) is commonly used for meteorological drought monitoring. The aim of this study was therefore to analyze the spatiotemporal characteristics of the drought that affected the Amhara and Tigray regions in 2015 using the abovementioned four drought indices derived from MODIS satellite data and CHIRPS data.

In the study, the MODIS/006/MOD13Q1 (MODIS /Terra Vegetation Indices 16-day L3 Global 250m Version 6), and MODIS/006/MOD11A2 (MODIS/Terra Land Surface Temperature & Emissivity 8-day L3 Global 1 km Version 6) downloaded from the NASA LPDAAC collections in the USGS data portal were used to analyze the NDVI, VCI, and TCI indices. The CHIRPS data downloaded from the Fast Early Warning System Networks (FEWSNet) portal was used for the rainfall and SPI analysis. The MCD12Q1 products (Modis/Terra and Aqua Combined Land Cover Types Yearly Global 500m SIN GRID V006) from NASA LPDAAC collections was used to extract the agricultural land (crops, grassland, Crop and natural vegetation mosaic) based on MODIS International Geosphere-Biosphere Program (IGBP) land use type 1 classification. The agricultural land was then used to mask the NDVI, VCI, and TCI results. The processing and analysis of the MODIS and CHIRPS data were done based on remote sensing principles and GIS techniques using ArcGIS 10.4

software. In addition to this, crop covered areas and crop production data in the Amhara and Tigray regions for 2014, 2015 and 2016, which was obtained from the agricultural surveys reports of the Central Statistical Agency of Ethiopia (CSA) was also analyzed to understand the effects of drought on the agriculture in the two regions. The results from all of the above processes were integrated into the shapefile of the study regions and mapped using ArcGIS 10.4 software.

The overall results showed that the Amhara and Tigray regions were affected by mild to extreme agricultural drought in 2015.

- The rainfall analysis results showed the Amhara and Tigray regions received the lowest rainfall amounts (June to September) of the decade (2006 to 2015) in 2015. The monthly rainfall amount of the regions in 2015 was higher in August than the rest of the months. The rainfall results also showed that the western part of the study area had better rainfall distribution from June to September than the eastern part. The SPI results also indicated that the Amhara and Tigray regions were affected by a meteorological drought in 2015 that was the highest in the decade (2006 to 2015). The decadal trend of SPI values also revealed the two regions were affected by mild to extreme drought in 2014 and mild drought in 2013 as well. The SPI results in September 2015 showed 40.3% of the Amhara and Tigray regions were under meteorological drought. The SPI values distribution for the same period also shown moderate to extreme drought in the southern and few areas in eastern parts of the Amhara region. The same results also showed the drought distribution was more pronounced in the eastern part than the western part of the study area. The NDVI, VCI, and TCI values also reveal the occurrence of agricultural drought in the two regions in 2015 and also 2014. The NDVI results in September and October 2015 showed the vegetation health and density in 24.5% to 43.1% of the agricultural land in Amhara and Tigray regions were in moderate to very poor conditions. The VCI results for the same period also showed 50 to 62% of the agricultural land in the two

regions was affected by mild to extreme drought. The TCI results in the above period also indicated 50 to 53% of the agricultural land in the regions was in mild to extreme drought conditions. The analysis of crop covered and crop productions in 2015 also indicated the reductions in both of the parameters were observed in the eastern than in the western part of the two regions.

- The values and distributions of SPI, NDVI, VCI, and TCI indices consistently showed that the eastern part of the Amhara and Tigray regions were more affected by the drought than the western parts. These results were in high agreement with the rainfall values and distributions in the regions in the same period of 2015. Likewise, the results of the drought indices were also in agreement with the crop covered and crop production analyses results that were used for evaluations of the results. Therefore, it can be concluded that the four indices have identified the drought in the two regions. However, the results from the VCI and TCI analyses results showed extreme droughts in the larger areas of the two regions than the NDVI. On the other side, the VCI values in all the nine observation periods were more consistent and showing better agreements with the results of rainfall, crop covered, and crop production results. Therefore, the study also concludes VCI followed by TCI and NDVI showed higher performance in picking the agricultural drought that affected the study regions in 2015. From the results of the drought indices, it can also be concluded that the agricultural drought in the study regions is caused by the shortage of rainfall.
- The statistical correlations of the vegetation indices with SPI also showed that NDVI ($R^2 = 0.53$) has strong positive correlations, TCI ($R^2 = 0.64$) very strong negative correlation, and VCI ($R^2 = 0.22$) moderate correlation with SPI.
- The overall agreement of the results of the vegetation drought indices with the other parameters also leads to the conclusion that the remote sensing and GIS techniques used in this study are applicable for agricultural drought monitoring, and early

warning systems in the Amhara and Tigray regions. The use of MODIS and CHIRPS data for agricultural drought analysis in the regions also gives very good results. But, the land use land cover MODIS data based on the IGBP type 1 classifications did not pick the basic land use classes such as forests, built up and shrubs, etc. while the area of crop and grasslands are exaggerated. This in turn exaggerated the area of agricultural land used in the drought analysis in this study and hence are the results. So the author does not recommend this dataset and the classification type for land use and land cover mapping in the Amhara and Tigray regions.

In this study, it was also seen that the Amhara and Tigray regions were also affected by mild to moderate droughts in 2014 and 2013 as well. From the NDVI, VCI, and TCI values distributions it was observed that the northeastern and southeastern parts of the Tigray region and the northern and southeastern parts of the Amhara regions were most affected by extreme and severe droughts in 2014. Therefore, it can be understood that the severity of the impacts of the drought in 2015 can be an accumulation of the effects of the drought conditions in the years before it. In our view, we recommend drought monitoring studies for a decade or two to be conducted at zone or woreda scales especially in the areas that sustained frequent droughts. Such studies can be important for the authorities to better understand the problem and devise pertinent strategies to alleviate the impacts of the drought in the areas. From the rainfall analysis of 2014 and 2015, it was also understood that the Amhara and Tigray regions received higher rainfall in June and July of 2014 than in 2015. But, the regions have received almost the same amount of average rainfall in August and September in both years. So, we recommend further studies to understand whether the better drought condition in 2014 from 2015 was due to the better rainfall amount got in June and July, or good rainfall distributions in August and September, or other. The results can be useful to develop area-specific knowledge about the relationships of the monthly rainfalls with the agricultural productions to establish applicable drought management systems in the regions.

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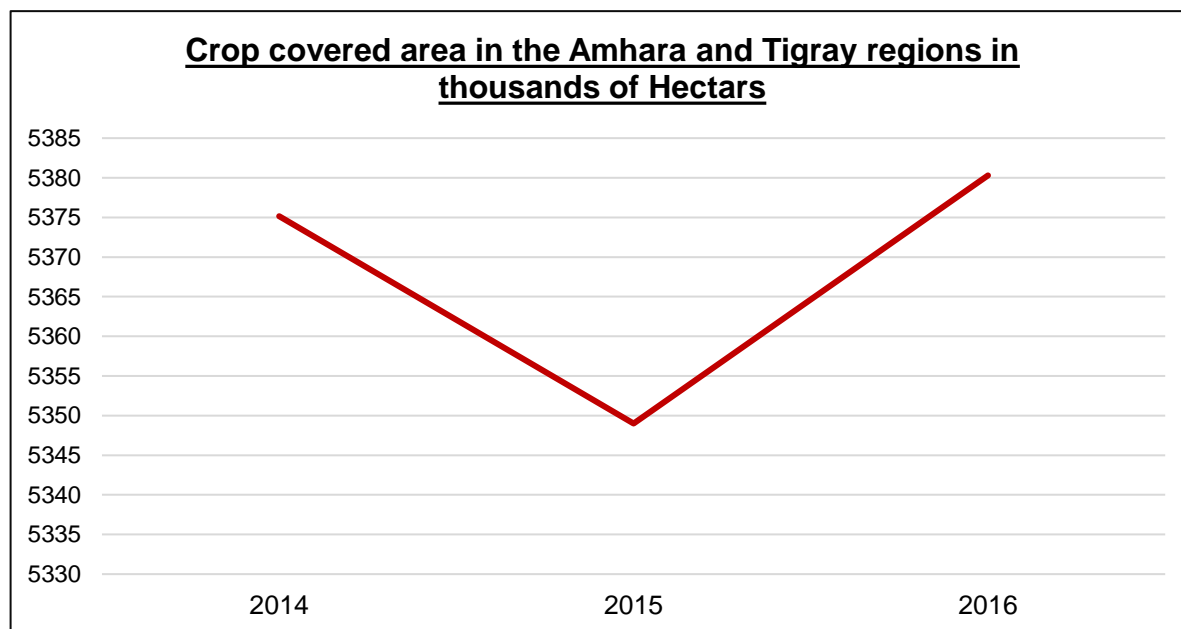
Annexes

3.1 Average SPI of the study area in the crop growing seasons (June to October) between 2006 to 2015

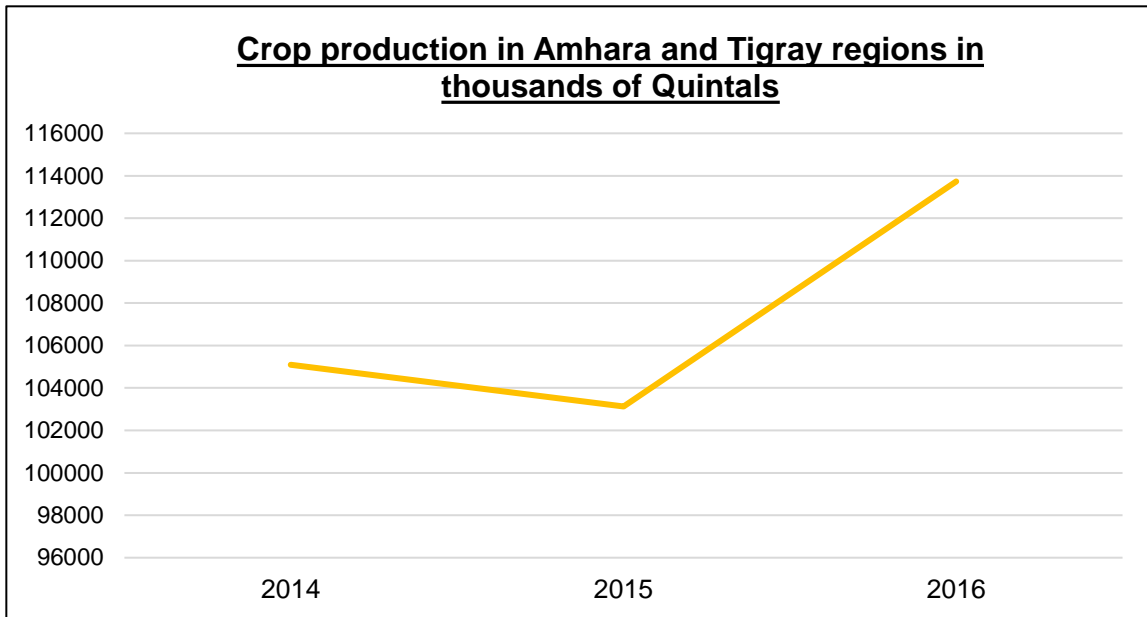
Year	June	July	August	September	October
2006	-0.16	0.05	0.52	0.79	1.04
2007	1.85	1.37	1.25	1.40	1.20
2008	0.63	0.35	0.34	0.43	0.17
2009	-0.47	0.05	-0.23	-0.83	-1.38
2010	0.11	0.54	0.81	0.83	1.00
2011	-0.69	-0.41	-0.46	-0.57	-0.89
2012	1.30	0.97	0.98	0.99	0.78
2013	0.13	0.41	0.16	-0.16	-0.56
2014	-1.16	-1.00	-1.21	-0.98	-1.35
2015	-1.54	-2.33	-2.16	-1.89	-2.14

Source: Own computation based on rainfall data from CHIRPS

3.2 Trends of crop productions in Tigray and Amhara regions in 2014, 2015 and 2016



3.3 Trends of Agricultural area covered with crops in Tigray and Amhara regions in 2014, 2015 and 2016



3.4 Agricultural area covered with crops and crop productions in Tigray and Amhara regions in 2014 and 2015 by zone

Sn	Region	Zone	Crop covered area (ha)			Crop Production in Quintals (qt)		
			2014	2015	Change in 2015 (%)	2014	2015	Change in 2015 (%)
1	Amhara	North Gonder	874,334	874,106	-0.1	16,205,068	16,513,489	0
		South Gonder	529,143	529,480	0.0	9,424,409	9,587,356	0
		North Wollo	272,510	268,067	-1.7	4,240,824	3,336,285	-22.3
		South Wollo	445,789	445,254	-0.1	7,936,782	7,571,866	-4.6
		North Shewa	561,073	556,416	-0.1	11,514,177	11,376,271	-1.1
		Easte Gojam	664,386	664,840	0.0	13,740,698	14,296,712	4.0
		West Gojam	619,475	619,951	0.0	15,318,506	15,843,117	3.0
		Waghimra	120,638	112,092	-7.1	1,479,211	1,045,039	-29.4
		Awi	291,193	291,731	0.0	6,468,750	6,679,639	3.3
		Oromia	57,189	56,384	-1.5	1,182,387	1,127,484	4.6
		Argoba	6,305	6,154	-2.4	126,733	87,009	-31.3
2	Tigray	Northwest	224,261	224,549	0.0	5,171,978	4,760,564	-8.0
		Central	217,601	215,043	-0.1	3,596,728	3,135,579	-22.8
		Eastern	87,747	86,491	-0.1	1,399,321	1,295,979	-7.4
		Southern	211,147	206,864	-0.1	3,628,428	3,113,535	-14.2
		Western	192,351	191,579	0.0	3,662,085	3,357,628	-8.3

Source: Own computation based on CSA (2015, 2016)