MULTI-SCALE, MULTI-SEASON, MULTI-INDICATOR EVALUATION OF AGRICULTURAL DROUGHT TRENDS IN ETHIOPIA

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List of abbreviations

CRU	Climate Research Unit
DTVCMK	Detrended Variance Correction Mann–Kendall
EPA	Environmental Protection authority
GPCC	Global Precipitation and Climatology Center
GDP	Gross Domestic Product
ITCZ	Inter Tropical Convergence Zone
LULC	Land Use Land Cover
MKT	Mann–Kendall Test
NCDC	National Climate Data Center
NOAA	National Oceanic and Atmospheric Administration
PDSI	Palmer Severity Drought Index
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
WMO	World Meteorological Organization

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Abstract

Agriculture plays an important role in Ethiopian economy and country's GDP livelihood relay on it. Most of agriculture in Ethiopia is rainfed even small household farms without irrigation facilities. Ethiopia is drought-prone country therefore, droughts significantly affect crop production. Understanding droughts is therefore important for food security of Ethiopia. Intra-season and seasonal drought trends in Ethiopia were studied using a suite of drought indicators—standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), Palmer drought severity index (PDSI) and Z-index for Meher (long-rainy), Bega (dry), and Belg (short-rainy) seasons to identify drought-causing mechanisms. Trend analysis indicated shifts in late-season Meher precipitation into Bega in the southwest and southcentral parts of Ethiopia. Droughts during Bega (October – January) are largely temperature controlled. Short-term temperature-controlled hydrologic processes exacerbate rainfall deficits during Belg (February–May) and highlighted the importance of temperature and hydrology-induced soil dryness on production of short-season crops such as tef. Droughts during Meher (June – September) were largely driven by precipitation declines arising from the narrowing of the intertropical convergence zone (ITCZ). Increased dryness during Meher had severe consequences on the production of corn and sorghum. PDSI is an aggressive indicator of seasonal droughts suggesting the low natural resilience to combat the effects of slow-acting, moisture-depleting hydrologic processes. SPI shows significant drying trends (meteorological droughts) and it is most rampant during December, February and July within seasons of Bega, Belg and Meher respectively. SPEI indicates drying trend in December, March and September. Z-index shows moisture deficit (agricultural drought) in October, March and September during Bega, Belg and Meher season respectively. This affects both long cycled and short cycled crops. The lack of irrigation systems in the nation limits the ability to combat droughts and improve agricultural resilience. There is an urgent need to monitor soil moisture (a key agro-hydrologic variable) to better quantify the impacts of meteorological and agricultural droughts on agricultural systems in Ethiopia.

Keywords: SPI; SPEI; PDSI; Z-index; Ethiopia; Food security; Climate change; Droughts; Trend analysis; Autocorrelation

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1. Chapter-one: General Introduction

1.1 Introduction

The Horn of Africa is drought- prone area for extreme climatic events such as floods and droughts, with severe negative impacts especially socio-economic sectors. All Natural resources like water, wildlife, vegetation; in general flora and fauna that determine the livelihood of communities are impacted by these extreme events. Therefore, climate variability has far-reaching implications for the livelihoods of most of horn of Africa. According the IPCC Fourth Assessment Report any change in climate will have more undesirable socio-economic impacts in developing countries than in other parts of the world; this is because of the vulnerability of society and the environment. Environmental hazards namely droughts, desertification, locust swarm, floods and resources-based armed conflicts continued that causes loss of property, food insecurity, injury, environmental degradation, death, health hazards, poor economic performance, displacement of people, environmental refugees and other miseries. Climate change is projected to increase the risk of drought that cause more extensive damage to the Greater Horn of Africa’s population than any other in the 21st century and partly through changing the frequency of El Niño events.

In Ethiopia drought has a spatial and temporal distribution over the last sixty years and eastern, south eastern and rift valley regions in the country are highly affected by drought more frequently. The recurrence period of drought decreasing from time to time for example, Haile (2008) reported that earlier periods the recurrence frequency was one in ten-twelve years and nowadays drought in Ethiopia to occur with return period of 3–5 and 6–8 years in northern parts of the country and every 8–10 years for the entire country. The report of (USGS, 2017) shows that in recent times it was observed that drought frequency shortens and occurred in three successive years (USGS, 2017) .

In Ethiopia drought occurs at the different seasons that occur in different regions and it exists when seasonal rainfall drops below normal by in between 30% to 50% (Hughes, 2014). Droughts are in general defined by a lack in total rainfall amounts on average during one or more of the rainy seasons (Bega, Kiremt and Belg) even if impacts can occur with changes in the time or frequency of the rains in excess of a season. Due to the virtual importance of the rainy season to agriculture production, Ethiopia also faces frequent food insecurity (USAID, 2017). In Ethiopia the agriculture sector is highly sensitive to climate variability and change such as drought. Agriculture is the most important economic sector in Ethiopia and 80% of nation depends on rained agriculture. However, the existence of climate change influences agricultural sector. In dry land and semiarid parts of countries, it is common crop failure that leads agricultural drought. Dry land in Ethiopia covers about 46% of total arable land but, this area contributes less than 10% of total production crop production in the country that implies how rain fall risky in terms of distribution and amount, in this place evapo-transpiration is highly concerned as well (Georgis and Kidane, 2008).

Drought can be meteorological, agricultural, hydrological and socio-economic drought. Meteorological drought is usually an expression of rainfall departure from average rainfall over time. Agricultural drought is a deficit of soil moisture to support agricultural activities. Hydrological drought indicates to deficiencies in subsurface and surface water sources. It can be simply judged by observing stream flow, lake, reservoir, and groundwater levels. Unlike meteorological and agricultural drought, there is a time lag between lack of rain and less water in streams, lakes, rivers and reservoirs, so hydrological measurements are not the earliest indicators of drought. It is obvious that an extreme agricultural drought can lead countries like Ethiopia to a famine, which is a prolonged shortage of food in a given region causing that widespread disease and death from starvation. Another type of drought is Socio-economic drought that correlates the supply and demand of goods and services with the three mentioned types of drought for example; when the supply of some goods or services such as water and electricity are weather dependent then drought may cause shortages in supply of these economic goods.

1.2 Statement of the problem

Impacts of climate change and variability are manipulated significantly in the agriculture, water supply and hydropower sectors and adversely affect the socio-economy of Ethiopia. The country has been shrunken by persistent drought of varying extent leading to social and economic consequences. Rainfall anomalies in the form of extreme dry (1971–1973, 1984–1986, 1992 and 2002–2004) years in the country substantially affected the agricultural sector (Wgesho et al., 2013).

Agriculture is an important part of Ethiopian economy it covers 45% of GDP and 80% of livelihood. Most agriculture in Ethiopia is rainfed, small household farms without irrigation technologies. Agriculture in Ethiopia occurs in two seasons. Belg (February - May) it is minor growing season 10% of crops, Meher (June - September) which is major growing season, Bega (October - January) it is not a growing season but has implications on agriculture. Ethiopia is drought-prone country therefore, droughts significantly affect crop production. Several studies have undertaken emphasizing trends in in rainfall using SPI (Seleshi and Zanke, 2004) but SPI consider only deficit in rain fall. Most of these studies regional use short-span (30 - 40 years), focus on long-term (12 month) droughts, national-scale studies are limited and has long periods of missing records. Investigation of precipitation and related pattern, and possible trends as functions of spatial and temporal scale over the country is necessary and also helps in deriving mitigation measures and evaluating ecosystem resilience towards such variability. Analysis of droughts using multiple indicators at different time scale is necessary to build a better understanding of droughts (Karamouz et al., 2009; Ziese et al., 2014). Understanding droughts is therefore important for food security of Ethiopia.

Therefore, this study focuses on evaluation of agricultural and meteorological drought trends on the basis of Multi-season (Bega, Belg and Kiremt), Multi-scale (SPI2, SPI6, SPEI2 and SPEI6) and Multi-indicators (SPI, SPEI, PDSI and Z-Index) through entire country. A simultaneous evaluation of drought trends using multiple drought indicators is important for drought planning and management studies. While some indicators might detect droughts in one season another might exhibit greater sensitivity in a different season. If various drought indicators (which are computed using different parameters and conceptualizations) which exhibit similar trends, then there will be greater confidence in the detected trend as all available information is pointing to the change.   There is an insistent need to monitor and manage soil moisture which is an important variable to better quantify the impacts of meteorological droughts on agricultural systems throughout country. This enable the nation to cope out the drought related impacts.

1.3 Goal of this research

Evaluation of agricultural and meteorological droughts trends on the basis of Multi-season (Bega, Belg and Kiremt), Multi-scale (SPI2, SPI6, SPEI2 and SPEI6) and Multi-indicators (SPI, SPEI, PDSI and Z-Index) in Ethiopia.

1.3.1 General Objective

The primary goal of the study is to undertake a multi-indicator evaluation of agricultural and meteorological drought trends with an emphasis on agricultural production in the three different seasons (Bega, Belg and Meher) in Ethiopia. Despite the growing recognition of the need to use multiple drought indicators to fully assess droughts, a simultaneous comparison of drought trends from multiple indicators at multiple scales is an important knowledge gap in Ethiopia that this study seeks to address.

1.3.2 Research questions

Are there trends in agricultural drought indictors?

Are these trends different in different parts of the country?

Are agricultural drought trends different from meteorological drought trends?

Are agricultural trends different between different growing (rainfall) seasons in Ethiopia?

Do commonly used agricultural drought indicators depict similar trends?

What is the spatial variability of these intra-seasonal indicators across Ethiopia?

Do some indicators exhibit greater intra-seasonal variability than others? Why?

1.3.3 Specific objectives of the research

- ✓ To evaluate trends of various drought indictors across Ethiopia during Bega Season.
- ✓ To see the magnitude of the observed trend throughout country during Bega Season.
- ✓ To asses trends of various drought indictors across Ethiopia during Belg Season.
- ✓ To see the change in magnitude and compare the observed trend of Bega with Belg. Season.
- ✓ To estimate trends of various drought indictors across Ethiopia during Mehr Season.
- ✓ To quantify the observed trend throughout country during Meher Season and to identify which months within the season are seeing major shifts

1.4 Structure of the thesis

This thesis is written based on Jimma University guidelines, whereby a collection of relevant publications is presented as part of the body in the thesis. The thesis work is organized in six chapters. The **first chapter** is general introduction that includes back ground, statement of the problem, objectives, significance and research questions as well as the overall thesis outline. **Chapter Two** covers the review of the main related facts from references used in the study and review of earlier studies in the various basins. **Chapter Three** covers materials and methods of the study. Model input data, and methods of data analysis are presented. **In chapter four**; the detail evaluation of Long-Term Drought Trends in Ethiopia with Implications for Dryland Agriculture had presented. **In Chapter Five** dealt with Intra-seasonal Drying and Wetting Trends in Ethiopia and their Implications to Dryland Agriculture. **In Chapter six** the general discussions, strengths and limitation of the study, Conclusions and Recommendations of the thesis work are discussed in this Chapter**.** Finally, appendices in the form of figures and serving as a supporting document to this thesis are attached to make the work a complete one.

2. Chapter – Two: Literature review

2.1 Introduction

The world population is increasing it is projected to reach more than 7.5 billion, the farmers in the world will have to produce 40% more grain in 2025, but the difficult is to revive agricultural growth at the global level (Sivakumar et al., 2010). According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) world has been more drought-prone for past 25 years and climate projections scenario shows that an increasing frequency in the future. This carries significant implications particularly for the agriculture sector. Human activities and social, demographic and economic processes exert pressures on water resources and these pressures are in turn affected by factors such as public policies and climate change (WWDR3, 2009).

The Horn of Africa is drought- prone area for extreme climatic events such as floods and droughts, with severe negative impacts especially socio-economic sectors. All Natural resources like water, wildlife, vegetation; in general flora and fauna that determine the livelihood of communities are impacted by these extreme events. Therefore, climate variability has far-reaching implications for the livelihoods of most of horn of Africa. According the IPCC Fourth Assessment Report (IPCC, 2007a) any change in climate will have more undesirable socio-economic impacts in developing countries than in other parts of the world; this is because of the vulnerability of society and the environment. Environmental hazards namely droughts, desertification, locust swarm, floods and resources-based armed conflicts continued that causes loss of property, food insecurity, injury, environmental degradation, death, health hazards, poor economic performance, displacement of people, environmental refugees and other miseries. Climate change is projected to increase the risk of drought that cause more extensive damage to the Greater Horn of Africa's population than any other in the 21st century (IPCC , 2007b)and partly through changing the frequency of El Niño events. Drought impacts are often provoked by poor policies and conflicts over limited water, food, and grazing resources. As a result, societies that have little resilience and preparedness mainly affected by drought. Even though drought affects all sectors, its impact is usually more marked in the agricultural sector, with abandoned farm-land, dried crops and dried pastures being common signs of drought. Drought differs from other natural hazards because of its slow onset, with temporal and spatial dimensions difficult to determine accurately (David Haro-Monteagudo and Jerry Kno, 2017).

The agricultural drought most of time caused by the propagation of meteorological anomalies based on catchment characteristics such as geology, land cover and soil (Van Loon et al., 2016)

2.2 Agricultural Drought

Agricultural drought leads many complex webs that cover many economic sectors. Among this agriculture is the main economic sector that influenced by agricultural drought mainly, short term agricultural drought at growth stage of crop has sever impacts on agriculture (Mokhatari, 2005). Most limiting factor for crop production is moisture deficit. The agricultural drought most of time caused by the propagation of meteorological anomalies based on catchment characteristics such as geology, land cover and soil (Van Loon et al., 2016). It is clear that the deficiency of water from hydrological or meteorological sources lessens the irrigation water for production of crop and this water is supposed to be stored in soil as soil moisture that ultimately affected as well. Consequently this scarce soil moisture causes Agricultural drought occurrence due to serious crop stress and affects the productivity of the crop. Therefore, a period with declining soil moisture content and consequent crop failure said to be Agricultural drought (Mishra and Singh, 2010).

2.3 Agricultural drought in Ethiopia

Ethiopia is a country of great geographical and climate variety. There are many factors that influence the climate of Ethiopia and one of these factors is the Inter-Tropical Convergence Zone (ITCZ) that moves to the north and to the south between March and September, and October and January respectivly. It is low pressure zone formed by convergence of two winds (North east trade winds and the equatorial westerlies) and shifts North and South of equaitor following the position of Sun (McSweeney et al., 2003).

Different Analysis indicates that Ethiopia has faced continuous spells of drought for last sixty years and the periods of 1970 ,1973 ,1984 and 1987 were the years when much of the country was affected by agricultural drought but, 1984 was the worst period in terms drought for the country (Mesfin , 1984). Degene (1990) and Pankhurst (1986) identified three major Agricultural droughts with a wide range of impacts in Ethiopia; The Tigray famine of 1958 which killed more than 100,000 people, The Wollo Famine of 1973/74 and The Wag – Lasta famine of 1966. These droughts affected large number of people over the years in the country. The number varied significantly between 2 million and 14 million. Due to the failed belg rains and soon after delayed kiremt rains were severely affecting 9.7 million Ethiopians in a national emergency in 2015. In December 2016, the Government of Ethiopia along with the united nation released a joint Humanitarian Response Document, calling for emergency assistance for around 10.2 million people, in addition to the 7.9 million people already under support (World Bank, 2012). The number of people that needed food aid at 2015 drought varies by region; Somali, Tigray and Afar Regions were hardly affected and the percentage of population that affected were 21%, 24% and 21%, respectively. In the same year more food aid was required by Oromia followed by Amhara and Tigray Regional states. In terms of large geographic coverage, more areas were affected in Somali and Afar Regions (UNOCHA, 2016).

In Ethiopia highly drought vulnerable areas with frequent and severe drought impacts exist in arid, semi-arid areas and peripheral pastoralist areas, and these areas cover about 25–30% of the entire country. .According report of UN (2017), the number of people who needed lifesaving food aid in 2015/2016 agricultural drought has increased from 191 to 229 woredas which covers 30% of the country's population, while about 461 woredas that covers 60% of country were categorized as being in at least some kind of challenges. Generally it was fully recognized that agricultural drought affected areas were increasing both in terms of geographic coverage and the number of population affected. The areas that are highly eroded in the highland part of the country are recipient of the foods aid because these areas fail to produce ample food to meet the need of their household food requirements. One thing that the decision maker the country to know is drought is part of the normal climate that will come and go as it did in the past time and will continue to occur in the future time perhaps with greater frequency and severity due to a varying climate and increased vulnerabilities. To overcome this serious threat, the people and the government of Ethiopia should be willing to bring about a exemplar shift in the overall drought governance and response mechanism (Getachew, 2018).

2.4 Spatial and temporal variability of rainfall and temperature in Ethiopia

Ethiopia and the horn of Africa experience marked spatial and temporal variations of rainfall; the spatial variation is associated result of the strength and nature of prevailing weather systems. It is clear that Ethiopia's rainfall is characterized by seasonal variation. In term of rainfall distribution both in space and time five types of rainfall regions can be identified in Ethiopia and around the horn of Africa these are; Year-round rainfall region, summer rainfall region, Autumn and spring rainfall, Merged Spring Summer, Winter rainfall region and autumn rainfall region (Gashaw et al., 2011). Characterization of the intra and inter-annual spatiotemporal trend of meteorological variables like precipitation and temperature in the context of a changing climate is important to assess climate-induced changes and suggest feasible adaptation strategies and agricultural practices. In a highly agrarian community like Ethiopia, where the livelihood of the population and the gross domestic product of the country are almost dependent upon rain-fed agricultural production, analysis of temperature and precipitation patterns has vital importance to cope with impacts on crop yields, animal breeding and ecosystem management. Considering the history of recurrent agricultural drought and rainfall variability in Ethiopia, conducting long term trend and variability studies with robust methods to obtain important information on what has been changing in the past few decades has a vital contribution to nation (Daniel et al., 2014).

. In Ethiopia and elsewhere in the horn temperatures vary from season to season for example in most of Ethiopia high temperatures are recorded from march to June conversely low temperatures are recoded form November to February these variations are primarily due to; The tilting of the earth to the normal elliptic and the distance of the overhead sun its apparent north south movement across the equator as the earth revolves around the sun. Ethiopia‗s and the horn‗s weather systems result from the apparent movement of the overhead sun, prevailing winds and the associated inter tropical convergence zone. Inter-tropical convergence zone (ITCZ) it is a low pressure zone formed by the convergence of northeast trade winds and the equatorial westerlies it shifts north and south of the equator following the position of the overhead sun. In July its position is at the tropic of cancer during the time Ethiopia and the horn come under the influence of the equatorial westerlies and easterlies these winds bring moisture to the highland but decrease their magnitude and length of rainy periods northwards (Weldesnbet et al., 2011) (Weldesemait et al., 2011). In January its position shifts to the tropic of Capricorn leaving the region for the prevalence of the northeast trade winds that are non- moisture laden during this time only the Eritrean coastal land and the afar region receive rain in most of Ethiopia western Eretria and Somalia it becomes dry season. In March and September the position of the ITCZ is around the equator hence the equatorial easterlies provide rain to the highland of Somalia and to the central and southeastern lowlands and highlands of Ethiopia.

2.5 Seasons in Ethiopia

In terms of rainfall occurrence, in Ethiopia there are three seasons, namely Bega (dry season), Belg (short rainy season) and Meher (long rainy season).

2.6.1 Bega (dry season)

The dry season that occurs between October and February locally known as Bega (dry season). During Bega season the inter-tropical convergence zone shifts to farthest south at this season many parts of Ethiopia under the influence of North-East trade wins these winds are cold and dry. The winter rainfall region consists of the eastern escarpment of the western highland, the middle rift valley section, the afar subdivision and read sea coastal plains nation (Daniel et al., 2014).

2.6.2 Belg (short rainy season)

The Belg season ranges from February to May. During Belg season Inter-Tropical convergence zone shifts to North over the Sudan and it develops Strong low pressure zone here. South easterly winds blow across central and south eastern Ethiopia. Belg rainfall region covers the southeastern highland of Ethiopia and its associated lowlands up to the Somalia coasts. Rainfall in the short rainy season (belg) is caused by moist easterly and south-easterly winds from the Indian Ocean. The region's moisture bearing winds are pick up moisture form the Indian Ocean and they blow over the Belg rainfall region of Ethiopia. In the belg season of the year's 1971, 1973, 1975, 1977 and 1984 more than half of Ethiopian regions were affected by droughts. The regions highly affected by drought were Wello, Tigrai, and Gamo Gofa with high rate of probability of occurrence (EPA, 1998).

2.6.3 Meher (long rainy season)

During the main rainy season and it ranges (June–September), and result of convergence in low-pressure systems and the Inter- tropical Convergence Zone (Tabari et al, 2011). Meher rain accounts for about 80% of annual rainfall totals in Ethiopia, which has high contribution to agricultural productivity and major water reservoirs. Thus, the most severe droughts in Ethiopia are usually related to a failure of this rainfall to accommodate the agricultural and water resource needs.

Therefore, agricultural production in Ethiopia is predominantly rain-fed whereas inter and intra-annual rainfall variability is high and droughts are recurrent in many parts of the country, variation of rainfall in space and time affects the agricultural production system and needs a close study (Woldeamlak, B., 2014).

For agrarian community like Ethiopia, where the livelihood of the population and the gross domestic product of the country are almost entirely dependent upon rain fed agricultural production, evaluation of precipitation and temperature patterns has vital importance to cope with impacts on crop yields, power production, animal breeding, and ecosystem management (Woldeamlak, BandDaniel, M. , 2014).

Conducting long-term trend and variability studies with robust methods to obtain important information on what has been changing in the past few decades, considering the history of recurrent drought and rainfall variability in Ethiopia has a vital contribution particularly for agricultural sector. Therefore, accurate estimation of the Spatio-temporal distribution of rainfall; and observing its trends are essential input parameters for securing sustainable agricultural production (Dereje et al., 2012).

Different studies on trend analysis have been conducted in Ethiopia at different Spatio-temporal scales and came up with mixed results. For example (Gebremedhin et al. , 2016) in Northern Ethiopia revealed a mix of non-significant positive and negative trends. Daniel et al. (2014) disclosed a statistically significant increasing trend of temperature while the case for precipitation was mixed at the upper Blue Nile river basin of Ethiopia. Seifu and Abdulkarim (2006) had tried to cover relatively wider spatial coverage and revealed no significant trend of Belg rainfall totals while Meher rainfall exhibited a significant declining trend. Sauerborn and Osman (2002), on the other hand, had reported a clearly decreasing trend of annual and Meher rainfall which was started around the end of the 1910s and continued with a progressive downward trend. National Meteorological Service Agency in 2001 had reported an increasing trend in annual rainfall in central Ethiopia while a declining trend has been observed over the Northern half and Southwestern part of the country. The spatiotemporal variability of annual and seasonal rainfall over Ethiopia and reported declining trends of Meher and annual rainfall in northern, northwestern and western parts of the country, and an increasing trend in annual rainfall was observed in a few grid points in eastern parts of the Ethiopia (Negash et al., 2013).

Trends can be identified by using either parametric or non-parametric tests. The parametric test works based on an assumption that the sample data come from a population of that a normal distribution. However, parametric test are rarely used for environmental data without adjustments for outlier and missing data and additional uncertainties associated with using the model and difficulties in applying the methods make parametric tests less preferable in hydrological studies. The non-parametric tests have been favored in studies of hydrological time series analysis due to simplicity and suitability for data with outliers and missing. The most commonly used non-parametric tests in trend analysis is Mann–Kendall's trend test (Bekele et al., 2017). However, the use of linear regression or traditional Mann-Kendall tests may not be appropriate in some instances due to the presence of autocorrelation in these datasets.

For many reasons, reliable information regarding trends in seasonal and intra-seasonal rainfall in the Ethiopia is not yet available. There are few studies that are case study based climatic trend studies have included few parts the country (Alemayehu, A.; Bewket, W, 2017) and study that include entire country not documented yet. The existing research related to agricultural and meteorological trend has a number of limitations. For example, most of the previous studies used short time record length (Viste et al., 2013). Another limitation is related to data analysis techniques that many studies in Ethiopia used linear regression to assess trends but, trend analysis can be significantly affected by the use of linear regression (Gautam, M, 2016). In general, the existing studies in the country or elsewhere have limitations with respect to data record length, data quality, the approach of analysis, intensity, and the data analysis techniques.

According to World Meteorological Organization there is no single indicator that can be used to determine appropriate actions for all types of droughts given the number and variety of sectors affected (WMO, 2016). Ideally, selection of indicators involves prior study to determine which indicators are suited to the area and type of climate and drought. The major trend analysis studies in Ethiopia summarized in the following table.

Table 1: Major Hydro-climatic Trend Analysis Studies in Ethiopia

Study	Year	Indicator	Region	Period	Findings	Approach
Seleshi and Zanke (2004)	2004	Rainfall	11 Key Stations across Ethiopia	1965-2002	Annual and Kiremt rainfall declines in Eastern, Southern and Southwestern Ethiopia	Original Mann Kendall Test
Seleshi and Camberlin (2006)	2006	Rainfall extremes	11 Key Stations across Ethiopia	1965-2002	Extreme Seasonal Rainfall of Belg and Kiremt declined in Eastern, Southern and Southwestern Parts	Original Mann Kendall Test
Bewket and Conway (2007)	2007	Rainfall; Standardized Rainfall Anomaly	Amhara Region (12 stations)	Longest Period 1961-2003 but varies across stations	No Consistent pattern or trends in daily rainfall. Both increasing and decreasing trends were noted in the region	Correlograms; Regression and Sperman Rho (correlation coefficient)
Cheung et al., (2008)	2008	Rainfall	13 Watersheds and 124 stations	1960-2002	Kiremet rainfall declines at a few gaging stations in Baro-Akobo, Omo-Ghibe, Rift Valley, and Southern Blue Nile Watersheds. However no regional or watershed scale trends	Regression against time
Edossa et al., (2010)	2010	SPI	Awash River Basin	30 stations with a maximum period of record of 1963-2003	SPI2 correlates well with streamflow (hydrologic droughts); Middle and Lower Awash Basin is more prone to droughts with comparison on SPI 12	Theory of runs and GIS mapping
Rientjes et al., (2011)	2011	Rainfall, Landcover and Streamflow	9 Weather Stations Upper Gilgil Abbey - Blue Nile Basin	1973 - 2005	Statistically decreasing trend in rainfall for most months but increasing trends during most of Kiremt (June, July August)	Monthly Mann Kendall Test
Funk et al. (2012)	2012	Rainfall, Temperature	Ethiopia; Gaging stations	Mid 1970s - late 2000s	Belg and Kiremt rainfall has declined in parts of southern, south central, southwestern and southeastern Ethiopia. Temperature has increased over this time period	Kriging, Spatial Mapping and Trend analysis
Viste et al. (2013)	2013	SPI 3,4 6, 9, 12, 24 months	Ethiopia; GPCC gridded data (2.5° x 2.5°); ERA reanalysis products as well as 238 Gage Stations	1970 - 2011	Precipiation Decline in Southern Ethiopia for both Belg and Kiremt; No trends in Central and Northern Parts	Regression against time; Bootstrap confidence Intervals
Wondie and Terefe (2016)	2016	PDSI and PDSI-sc	Northen and Northwest parts of Ethiopia	1901-2014; CRU Data (0.5 x 0.5 grid)	Increase in temperature and characterization of drought frequencies	GIS Mapping and Visualization
Bekele et al., (2016)	2016	Rainfall	12 Stations in Awash River Basin	Variable. Maximum Period of Record 1980 - 2012	No significant change in Belg but a decline in Kiremt Rainfall	Mann-Kendall and Sen Slope
Abebe (2017)	2017	Rainfall, Temperature and Agricultural Production	18 stations across Ethiopia	Variable Maximum Period of Record 1952-2015	No discerning trends overall in precipiation; Annual temperature has risen over the period	Exploratory analysis using charts and tables
Suryabhagvan (2017)	2017	Rainfall and Temperature; SPI and STARDEX Indices	87 - 120 weather stations across Ethiopia	1982-2012	No significant change in annual or bimodal (Belg and Kiremt rainfall); Increase in temperatures; Increase in rainfall intensity in most stations	Regression against time and GIS mapping
Asfaw et al., (2018)	2018	Rainfall and Temperature; PDSI	North Central Ethiopia (Woleka Sub-basin)	1901-2014	Annual, Kiremt and Belg rainfall has declined. Annual and Kiremt rainfall declines are statistically significant	Mann-Kendall with Autocorrelation

Chapter Three: Methods and materials

3.1 Description of study area

Ethiopia is a country of great geographical variety with high and rugged mountains, flat-topped plateau, deep gorges, river valleys, and plains. This diversity in Topography makes the country unique in Africa. Ethiopia is the most elevated part of Northeast Africa. The altitude ranges from the highest peak at Ras Dashen (4,620 meters above sea level), in Gondar down to the Danakil depression (120 meters below sea level) with the Afar depression, one of the lowest dry land points on the earth next to the dead sea. Ethiopia is located between approximately 3^0-15^0N latitude and 33^0-48^0E longitude. The country covers a land area of about 1.2 million km^2, occupying a significant portion of the Horn of Africa. It shares boundaries to the east and southeast with Djibouti and Somalia, to the north with Eritrea, to the south with Kenya, and to the west with Sudan. Ethiopia is the most populous nation in Eastern Africa and the second-most populous in Africa next to Nigeria with an annual population growth of more than 2% (FDRE, 2012).

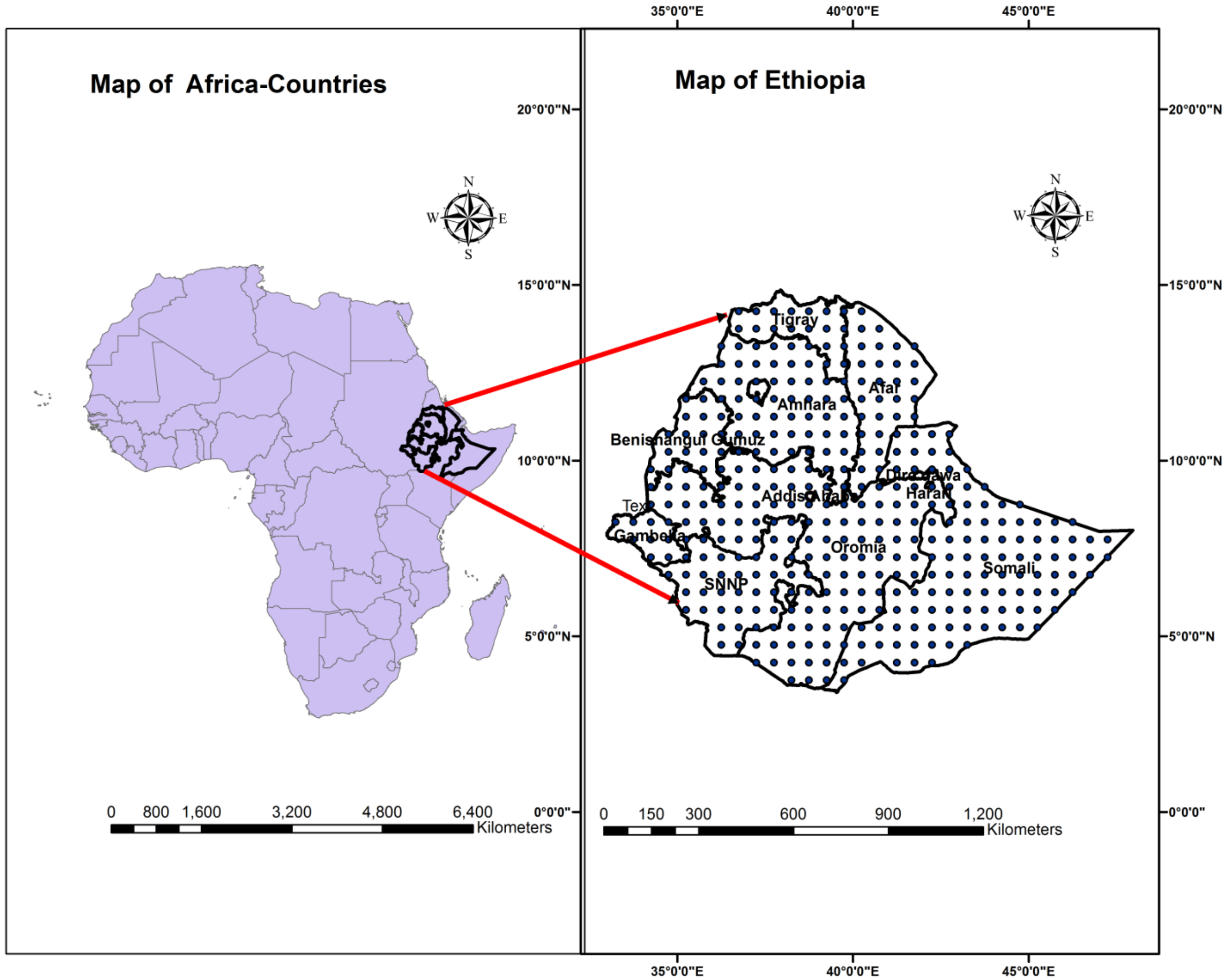


Figure 3.1 Map of study area

3.2 Water resources potential of the Ethiopia

Ethiopia has abundant water resources and hydropower potential, which is the second next to the Democratic Republic of Congo, yet only few percentage of this potential, has been used from 12 major river basins as shown in Figure 4.2. The country‘s annual renewable fresh water resources amount is about 124 BCM/yr from the twelve river basins. Nevertheless, only 3% remains in the country. The rest 97% is flew as runoff to the lowlands of adjoining countries. The country withdraws less than 5% of its fresh water resources for consumptive uses (MoWE, 2007). It is estimated that up to 3.5 Million hectares and 155,102Gwh/yr of power respectively can be developed using the available potential and clean water supply to its entire people. However, only less than 300,000 hectares has been developed for the irrigation and 3 to 5 % has been developed for hydropower (MoWE, 2007).

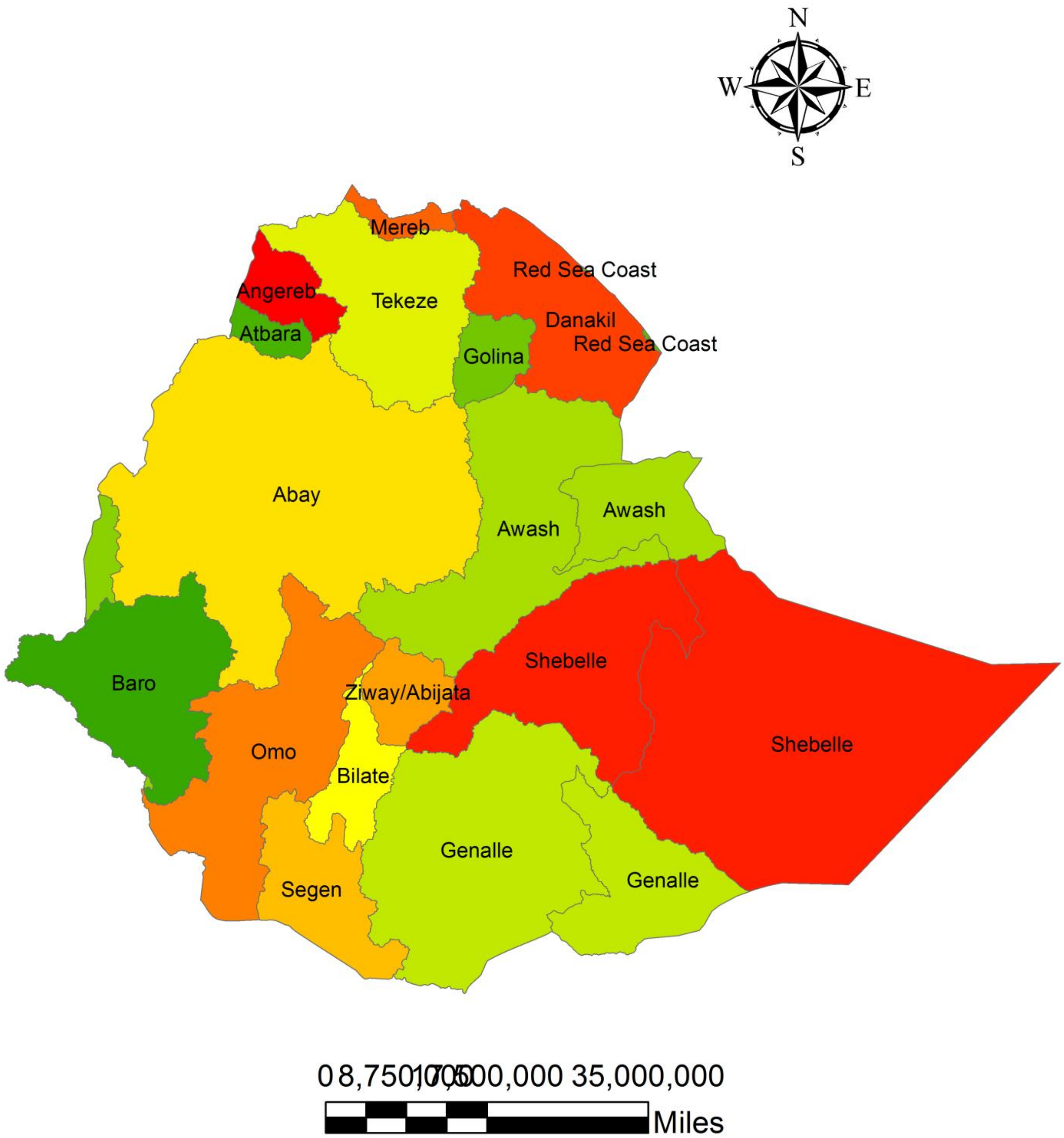


Figure 3. 2River Basins in Ethiopia

3.3 Climate of the study area

The climate of Ethiopia varies from a hot arid climate in the southern part of the country to a tropical humid one in the highlands that include the north and north-western part of the country. Mean annual rainfall distribution has ranges from 2400 mm over the South-western parts of country and 300 mm over South-eastern and North-eastern lowlands. The mean annual temperature ranges from 15^o C to 25 ^{o}C over the highlands and the lowlands respectively (Kassa Fekadu, 2015).

3.4 Data sources

Climatic data obtained from Global Precipitation and Climatology Center (GPCC), and Climate Research Unit (CRU).

The GPCC provides gridded gauge-analysis products derived from quality controlled station data from over 80,000 stations worldwide. Precipitation data from GPCC Dataset has 0.5^o x 0.5^o resolution and has long record available from 1891 – 2016 known to work well in Ethiopia (Afsaw et al., 2018).

Temperature is obtained from CRU which covers data ranges from 1850-present and has 5° x 5° grid resolution. The aim of the Climatic Research Unit (CRU) is to improve scientific understanding of the climate system and its interactions with society. The common period 1901 – 2016 was used in this study.

The Statistical software package R version 3.5.2 was used for data extraction and data analyses. R is a programming language and free software environment for statistical computing and graphics supported by the R Foundation for Statistical Computing. Although R has a command line interface, there are several graphical user interfaces, such as R Studio, an integrated development environment.

The R language is widely used by statisticians and data miners for developing statistical software and data analysis. Data mining surveys and studies of scholarly literature databases show substantial increases in uses and popularity.

3.5 Drought Indicators

Different literature reported that there are over 150 drought indicators and careful selection of drought indicators is, therefore, an important decision in any trend analysis studies. The choice of the drought indicator used in this study was based on suitability of the indicators for use in agriculture dominant regions such as Ethiopia.

Four drought indicators, namely, the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), the self-calibrating Palmer drought severity index (PDSI), and the Palmer Z-index (Z-index), were selected for this study and each indicators described as follows.

3.6 Standardized Precipitation Index (SPI)

Over the years, many drought indicators were developed and used by climatologists and meteorologists around the world that ranges from simple indices such as percentage of normal precipitation to more complicated indices. Scientists in the United States realized that drought indicators needed to be simple, easy to calculate and statistically relevant and meaningful. Furthermore, the understanding of deficit in precipitation has different impacts on reservoir storage, groundwater, soil moisture and streamflow. American scientists McKee, Doesken and Kleist developed the Standardized Precipitation Index (SPI) in 1993.

The SPI is a powerful, flexible index that is simple to calculate and precipitation is the only required input parameter, and it is just as effective in analyzing wet periods/cycles as it is in analyzing dry periods/cycles (Guttman, 1994). The SPI was designed to quantify the precipitation deficit for multiple timescales (SPI-2, SPI3, SPI-4, SPI-6 and extra... These timescales reflect the impact of drought on the availability of the different accumulation period.

Precipitation is normalized using a probability distribution function and a normalized distribution allows for estimation of both dry and wet periods. Accumulated values can be used to analyse drought severity (magnitude).

3.7 Standardized Precipitation Evapotranspiration Index (SPEI)

SPEI developed by Vicente-Serrano at the Instituto Pirenaico de Ecologia in Zaragoza, Spain. SPEI uses the basis of SPI but includes a temperature component, allowing accounting for the effect of temperature on drought development through atmospheric water balance calculation. SPEI has intensity for both positive and negative values are calculated, detecting wet and dry events. The inclusion of temperature along with precipitation data allows SPEI to account for the impact of temperature on a drought condition. The output is applicable for all climate regimes because they it is standardized. With the use of temperature data, SPEI is an ideal index when looking at the impact of climate change in model output under various future climate scenarios.

3.8 Palmer Drought Severity Index (PDSI)

PDSI was developed in the 1960s as one of the first attempts to identify droughts using more than just precipitation data. Palmer was tasked with developing a method to incorporate temperature and precipitation data with water balance information to identify droughts in crop-producing regions of the United States of America. PDSI calculated using monthly temperature and precipitation data along with information on the water-holding capacity of soils. Palmer Drought Severity Index accounts moisture received (precipitation) as well as moisture stored in the soil, accounting for the potential loss of moisture due to temperature effects.

Having established the value of K (weighting factor) to determine monthly PDSI we can use the following equation.

$PDSI_i = PDSI_{i-1} + \frac{1}{3}Z_i - 0.103PDSI_{i-1}$---4.1

Where, Z represents moisture anomaly.

For actual calculation of a monthly measure of moisture abnormality P

D = P-p Where, D is moisture departure from the normal and D is weighted by another parameter K.

Z = DK-- 4.2

The value of Z is regarded as the moisture anomaly index, Each Z expresses on monthly basis and from a moisture standpoint, the departure of the weather of a particular month from the average moisture climate of that month.

3.9 Palmer Z Index

The Palmer Z Index is good to responds to short-term conditions better than PDSI and is normally calculated for much shorter timescales to identify rapidly developing drought conditions. As part of the original work done by Palmer in the early 1960s, the Palmer Z Index is usually calculated on a monthly basis along with PDSI output as the moisture deficit. Most of times Z- Index referred to as the ‘Moisture Anomaly Index’ and the derived values provide a comparable measure of the relative anomalies of a region for both dryness and wetness and it can be shown as equation described in equation 4.2.

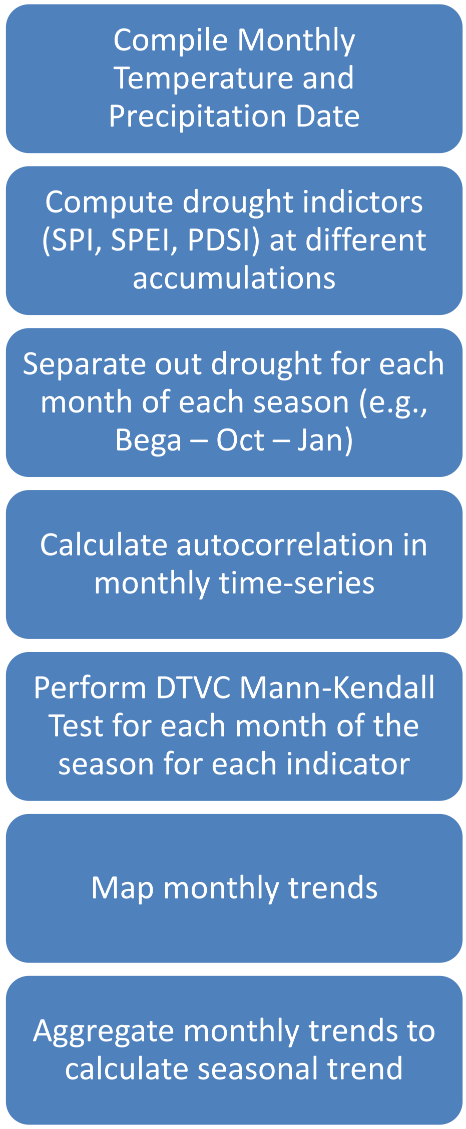


Figure 3.1 Conceptual frame work of study.

Chapter – Four: Long-Term Drought Trends in Ethiopia with Implications for Dryland Agriculture

4.1 Abstract

Intra-season and seasonal drought trends in Ethiopia were studied using a suite of drought indicators - standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), Palmer drought severity index (PDSI) and Z-index for Meher (long-rainy), Bega (dry), and Belg (short-rainy) seasons-to identify drought-causing mechanisms. Trend analysis indicated shifts in late-season Meher precipitation into Bega in the southwest and southcentral portions of Ethiopia. Droughts during Bega (October–January) were largely temperature controlled. Short-term temperature-controlled hydrologic processes exacerbated rainfall deficits during Belg (February–May) and highlight the importance of temperature- and hydrology-induced soil dryness on production of short-season crops such as tef. Droughts during Meher (June–September) were largely driven by precipitation declines arising from the narrowing of the intertropical convergence zone (ITCZ). Increased dryness during Meher had severe consequences on the production of corn and sorghum. PDSI was an aggressive indicator of seasonal droughts suggesting the low natural resilience to combat the effects of slow-acting, moisture-depleting hydrologic processes. The lack of irrigation systems in the nation limits the ability to combat droughts and improve agricultural resilience. There is an urgent need to monitor soil moisture (a key agro-hydrologic variable) to better quantify the impacts of meteorological droughts on agricultural systems in Ethiopia.

Keywords: SPI; SPEI; PDSI; Palmer z-index; Ethiopia; food security; climate change; droughts; trend analysis; autocorrelation

3.2 Introduction

Ethiopia is predominantly rural with a large population depending on agriculture and pastoral activities, but there has been limited development of surface water and groundwater resources for irrigation (Ewonetu, G., 2012). Dryland farming is widely practiced in Ethiopia and accounts for over two-thirds of all agricultural land (MoA, 2011) . Unfortunately, droughts have frequently plagued Ethiopia and are a major climatic hazard that impacts the long-term sustainability of this rapidly growing African nation (Meze-Hausken, 2004; Mersha, A.A, 2018).

The government of Ethiopia has adopted a national policy to deal with droughts (FDRE, 2015) and requires local stakeholder-driven drought contingency planning to foster sustainable water resources management (Megersa et al., 2014). Droughts are primarily caused by atmospheric moisture deficits (meteorological droughts). They propagate through hydrologic systems and cause reductions in water supplies (hydrologic droughts). Meteorological droughts also have the potential to disrupt agricultural production by diminishing soil moisture availability (agricultural droughts). Thus, droughts can have grave implications on the socio-economic well-being (socio-economic droughts) of rural areas (Linke et al., 2015).

Droughts are multidimensional in nature, manifest at different temporal scales, and cannot be fully characterized using a single indicator (Wilhite et al, 1985). Agriculture and hydrologic droughts are affected not only by rainfall but also other processes such as plant water uptake (evapotranspiration). Rainfall deficits tend to create warmer temperatures due to lowered humidity. Droughts also affect many other hydrologic processes such as exfiltration and baseflow to streams. Analysis of droughts using multiple indicators calculated at different time spans is, therefore, necessary to build a better understanding of droughts (Karamouz et al.,2009; Ziese et al., 2014).

As Ethiopia relies heavily on rainfed agriculture, there has been a significant emphasis on evaluating trends in rainfall, rainfall anomalies, or precipitation-derived rainfall drought indicators such as the standardized precipitation index, SPI (Seleshi and Zanke, 2004). Most of these studies, however, tend to be regional and utilize short-span (approximately 30 - 40 years) datasets with a focus on long-term (12 months) droughts. Even national-scale studies are limited in the number of stations that are used because there are long periods of missing records. Trend studies are often noted to be contradictory or inconclusive and are known to depend upon regional divisions and the quality of the data that are used to estimate trends (Cheung etal.,2018;

Easterling et al., 2000). A few recent studies have utilized the Palmer drought severity index, PDSI (Wondie and Terefe,2016; Asfaw et al.,2018), which attempts to define droughts using the principles of water budget. However, these studies are limited to a few watersheds in the country and do not always compare the performance of PDSI with other drought indicators.

Meteorological droughts focus on the atmospheric moisture deficits, and delineating their trends is undoubtedly important in Ethiopia given its high reliance on rainfed agricultural practices. However, the onset of an agricultural drought is typically marked by deficiencies in soil moisture (Keyantash et al., 2002), which is a complex function of precipitation as well as soil and land use characteristics of the watershed. The onset and cessation of agricultural droughts need not coincide with the beginning and end of meteorological droughts. Antecedent soil moisture can help buffer the soil initially to withstand meteorological droughts. In a similar vein, soil dryness may continue to occur even after the cessation of meteorological droughts because of deep percolation and evapotranspiration. Therefore, trends in meteorological droughts may not translate to trends in agricultural droughts or vice-versa. In countries, such as Ethiopia, with multiple growing seasons, differences between meteorological, agricultural, and hydrologic droughts can vary across the seasons because of the variations in underlying drought generation processes.

There are three main seasons in Ethiopia. The main rainy season (June–September), also known as Kiremt, exists over all of Ethiopia except perhaps in southern and southeastern parts. The agricultural season corresponding with this rainfall is referred to as Meher. Both Meher and Kiremt are used interchangeably in local parlance, and this practice will be adopted here as well. The country is generally dry during the months of October–January, except for the central part, which receives some rainfall. This relatively dry period is locally referred to as Bega. The Belg is the shorter rainy season that extends from February–May but is the primary source of water in the southern and southeastern part of the nation (Seleshi and Zanke, 2004).

Agriculture in Ethiopia is adapted around the rainy seasons. The major crops in Ethiopia include a variety of grains (cereals), oilseeds, and coffee (Ofcansky, 1991) . Single-season crops (wheat, tef, sorghum, and barley) are harvested during both Belg and Meher. Long-cycle crops (e.g., maize, millet, and sorghum) are grown over both the seasons (Belg and Meher) and account for nearly 50% of the total crop production (Verdin et al., 2005). The period between April–September/October represents the growing phase of the long-season crops. Given the seasonal nature of agriculture practices in Ethiopia, drought studies need to focus on short (1–3 months) to medium (3–6 months) time scales to properly capture the moisture dynamics during the growing seasons.

A simultaneous assessment of drought trends using multiple drought indicators is useful for drought planning and management studies. While some indicators may detect droughts in one season (say dry), another might exhibit greater sensitivity in a different (say wet) season. If various drought indicators (which are computed using different parameters and conceptualizations) all exhibit similar trends, then there will be greater confidence in the detected trend as all available information is pointing to the change. In such an instance, the use of a simpler drought index (e.g., one based on precipitation alone) would be validated and deemed reasonable for trend detection. If different drought indices exhibit diverging trends, then additional insights with regards to the underlying mechanisms driving droughts can be ascertained (Uddameri et al., 2019). Identification of such underlying factors is helpful to guide future data collection activities and identify mechanistic shifts in drought-producing processes (Hernandez et al., 2014).

The primary goal of the present study is to undertake a multi-indicator evaluation of drought trends with an emphasis on agricultural production across the three different seasons (Bega, Belg, and Meher) in Ethiopia. Despite the growing recognition of the need to use multiple drought indicators to fully assess droughts, a simultaneous comparison of drought trends from multiple indicators at multiple scales is an important knowledge gap in Ethiopia that this study seeks to address.

3.3 Selection of Drought Indicators

There are over 150 drought indicators reported in the literature (Wilhite et al.,1985) . Careful selection of drought indicators is, therefore, an important decision in any trend analysis studies. The choice of the drought indicator used in the study was based on several factors including (1) the availability of reliable data to compute these indicators, (2) those based on sound technical principles, (3) those based on standardized approaches that allow comparisons in space and time, (4) widespread acceptance of the indicators, and (5) suitability of the indicators for use in agriculture dominant regions such as Ethiopia.

Four drought indicators, namely, the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), the self-calibrating Palmer drought severity index (PDSI), and the Palmer Z-index (Z-index), were selected for this study. Furthermore, SPI and SPEI were computed at short (1–3 months) and long (4–6 months) timescales to account for intraseasonal and full-season droughts. In a similar vein, PDSI is known to better capture long-term droughts (Vicente etal.,2009; Liu et al.,2018) and used for full-season assessment, while the Z-index is designed to model the short-term moisture dynamics better (Karl et al.,1998; Dai,2018) and used for intraseasonal drought comparisons.

As Ethiopia is largely agrarian, a drought indicator that is directly based on soil moisture would be ideal. The lack of soil moisture measurements in the country is, however, a key limitation. While global gridded soil moisture estimates have become available, the underlying algorithms have not been ground-truthed for Ethiopian conditions because of the lack of soil moisture data and, as such, may not be reliable. Therefore, while recognizing the limitation, surrogate meteorological drought indicators that exhibit strong correlations to soil moisture and that can be computed using reliable data had to be resorted to in this study. Table 1 summarizes the key references and salient characteristics of drought indicators selected in this study.

Table 1. Salient characteristics of drought indicators selected for this study (numbers in parentheses refer to key references pertaining to the indicators).

Indicator	Primary Variables	Conceptualization	Remarks
Standardized Precipitation Index (SPI) (McKee et al., 2010; Guttman,1999)	Accumulated Rainfall	Rainfall during an accumulation period compared to historical average for that period	Widely used meteorological drought indicator but based on rainfall alone, which is both a strength and a shortcoming.
Standardized Evapotranspiration Index (SPEI) (Vicente et al.,, 2009)	Accumulated precipitation and Accumulated Evapotranspiration (ET)	Net atmospheric moisture supply accounting for ET losses	Potential ET is used for simplicity as it can be calculated using average monthly temperature and latitude information. A meteorological indicator that is known to correlate well with agriculture droughts due to incorporation of surficial drying (Mishra and Singh, 2010; Zambreski,2018). Improves SPI still retaining simplicity. Does not account for soil moisture dynamics
Palmer Drought Severity Index (PDSI) (Dai,2008; Palmer,1965)	Precipitation, Temperature, Soil parameters	Two-layer bucket model to simulate watershed. Indicator based on water budget calculations.	Another widely used meteorological drought indicator. Known to correlate well with hydrological (Zhai, 2010) and agricultural droughts (Palmer,1965; Gunda,2016) . The conceptualization is complex and comprehensive (strength) but requires more data and self-calibration (weakness).
Palmer Z-Index (Palmer,1965; Karl,1986)	Precipitation, Temperature, Soil parameters	Computed by removing the long-term effects from PDSI.	An indicator of short-term variations in water budget largely attributable to soil moisture dynamics. A good indicator for intraseason agricultural droughts (Palmer,1965). The conceptualization is complex and comprehensive (strength) but requires more data and self-calibration (weakness).

3. 4 Datasets and Methods

Following Asfaw et al. (2018), Full Data Monthly Product Version 2018 from the Global Precipitation and Climatology Center (GPCC), available on 0.5° × 0.5° grid (Schneider,2017), was used along with temperature data from the Climate Research Unit (CRU TS 4.21) as described in Harris et al. (2014) . GPCC Full Data Monthly Product is the most comprehensive gridded rainfall dataset available today and is based on measurements from over 80,000 stations worldwide. When this study was conducted, the dataset covered a period ranging from January 1891 to December 2016 (Ziese et al.,2014; Becker,2013). While GPCC data are available at different spatial resolutions, the data with 0.5° × 0.5° spatial resolution were used to be consistent with the resolution of the available temperature data. The rainfall data at the adopted resolution is known to provide reasonable estimates in Ethiopia (Asfaw et al. , 2018) .

The CRU Climate Dataset is produced by the Climate Research Unit at the University of East Anglia and is also gridded at a resolution of 0.5° × 0.5° over the land mass, and during the time of this study, data were available at a monthly time-step from 1901–2017. The CRU dataset is again based on long-term observations from several thousand stations worldwide that are compiled under the auspices of the World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA through its National Climate Data Center, NCDC). This dataset has also been used in several hundred climate change assessment studies and known to provide reasonable estimates for temperature (Becker et al.,2013).

The adopted spatial resolution of 0.5° corresponds to roughly 50 km in Ethiopia and resulted in 377 locations across the country where trend analysis was carried out (see Figure 4.4 A). The 15 major water basins in Ethiopia are shown in Figure 1B and represent the federal-level water planning boundaries of the nation. Figure 4.4 C shows the land use land cover (LULC) classification, which highlights the rural nature of the country with high reliance on climate-dependent agricultural and pastoral activities. As depicted in Figure 4.4 D, Ethiopia exhibits a great variation in relief ranging from areas below mean sea level to mountain ranges that are over 4000 m high. Rainfall correlates strongly with elevation, with higher elevations getting more rainfall than lowlands as a result of air traveling from the Indian Ocean and the north (Viste and Korecha,2013).

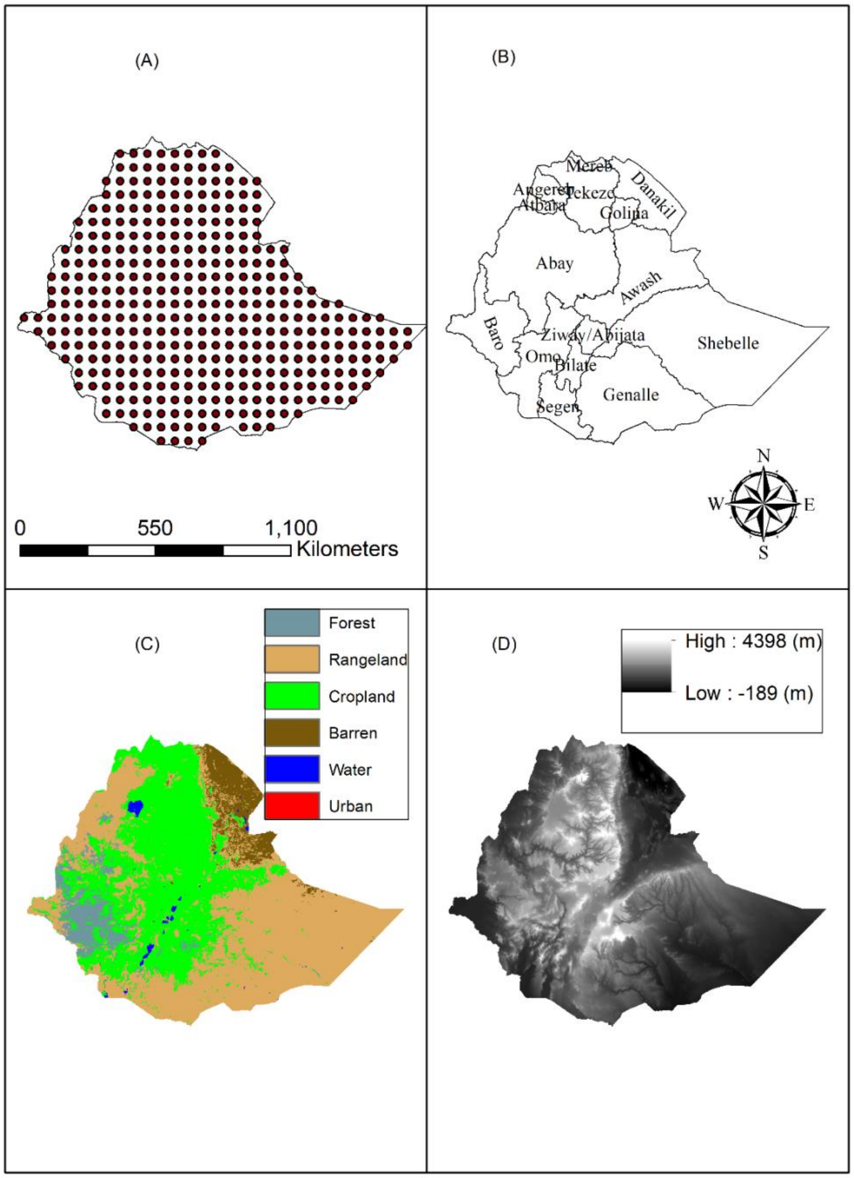


Figure 4.4 Study grid and geographical characteristics of Ethiopia

The SPI and SPEI calculations were carried out using procedures presented in Stagge et al. (2015) to correct for zero rainfall values that are likely during dry months. As the interest is on agricultural systems, SPI and SPEI were computed at 2, 3, 4, and 6 months of accumulation to evaluate both intraseasonal and full-season trends. The analysis indicated that the results of intermediate accumulation periods (3 and 4 months) yielded results that were similar to the bracketing accumulation periods of 2 and 6 months. As such, the results are only presented here for 2 months (intraseason) and 6 months (full-season) of accumulation in the interest of brevity.

The drought indicators were all computed on a monthly basis and then aggregated to obtain values for seasonal climate states. For a hydrologic year, the seasons were defined as Bega (October–January), Belg (February–May), and Meher (June–September). Trend analysis was carried out over hydrologic years 1902–2016 (October 1901–September 2016), and to the best of the authors' knowledge, this represents the longest assessment period in Ethiopia that has been documented in the literature. Century-scale trend assessment studies, such as the one conducted here, better capture a higher degree of climate variability than what is observed at shorter timespans, which in turn helps minimize artifacts associated with any short-term or cyclical effects present in the climate signals.

The Mann–Kendall (MK) test is a robust nonparametric test that has been widely used for trend assessment but is also sensitive to autocorrelation effects in time-series data used for trend detection (Hamed and Ramachandra,1998; Yue et al.,2004). Exploratory data analysis indicated the presence of autocorrelation even when drought indicators were aggregated over the season to create an annual time-series. Furthermore, autocorrelation structures that were observed varied across indicators and in space (see Figure 4.5 for an illustrative example). In all cases, at least the lag-1 autocorrelation was significant. Autocorrelation effects from higher-order lags were also significant and had to be corrected for at several locations. Many approaches have been suggested in the literature to properly assess trends in autocorrelated time-series (Hamed and Rao (1998) , Yue et al. (2002), Rao et al. (2003), Yue and Wang (2004) and need to be used, as the presence of autocorrelation induces spurious trends in the data and invalidates trend analysis studies. Autocorrelation effects have not been accounted for in many previous studies in Ethiopia (Seleshi and Zanke,2004; Abebe,2017), which could be another factor for inconsistencies and divergence in results that have been noted in them.

The detrended variance correction Mann–Kendall (DTVCMK) approach of Yue and Wang (2004) was adopted here because it has lower false detections than rank-based variance corrections methods (Yue et al.,2002; Yue and Wang,2004). In addition, the DTVCMK approach is also known for its ability to deal with higher-order dependencies (Khaliq et al., 2009) and exhibits statistical power that is comparable to more computationally intensive block bootstrap methods (Önöz and Bayazit, 2012) . The detrended variance correction approach entails the following computations.

To begin the procedure, an observation (X_i) is split into a trend component (T_i) and residual component £:

$$X_i = T_i + \varepsilon_i. \quad (1)$$

The Theil–Sen slope trend (Theil, 1950; Sen, 1968) offers a robust non-parametric approach to estimate the trend component of the observation. In this approach, the slopes of the lines drawn between an observation (X_i) and each successive observation (X_l) are computed to form a series of slopes. The median value of the slope series is taken as the representative trend value (see Equation (2)):

$$T_i = median\left(\frac{X_i - X_l}{i-l}\right) \forall\, i < l. \quad (2)$$

The trend component is subtracted from the observed value to obtain the residual component. The lagged correlation coefficients of the residual components ($r_{£k}$) are computed and used to obtain the detrended variance correction factor (*CF*) as:

$$CF = \left[\frac{N^*}{N}\right] = 1 + 2\sum_{k=1}^{n-1}(1 - \frac{K}{N})r_{£k} \quad (3)$$

The correction factor (*CF*) is used to correct the raw Mann–Kendall variance (Var(S)) that is obtained using Equation (4) to calculate the detrended variance *Var(S)** (Equation 5). As autocorrelation causes information to be shared between adjacent datapoints, the correction factor is a measure of the fraction of estimated independent (uncorrelated) measurements within the dataset. In Equation (3), *N* is the sample size, and *N** is the effective sample size after correcting for the presence of autocorrelation.

$$Var(S) = \frac{N(N-1)(2N+5) - \sum_{m=1}^{s} ti(m-1)(2m+5)m}{18} \quad (4)$$

Again, *N* is the sample size, and *ti* refers to ties in the data which are indexed using *m* in Equation (4).

$$var(S)^* = CF * var(S), \quad (5)$$

Where *S* is the Mann–Kendall slope obtained using Equation (6).

$$S = \sum_{i-1}^{N-1} \sum_{j=i+1}^{N} sgn(X_j - X_i) \ \forall \, i \ \leq j \tag{6}$$

The detrended variance, $Var(S)^*$, is then used to obtain the detrended variance correction Mann–Kendall statistic (*DTVCMK*) as follows:

$$DTVCMK = \begin{cases} \frac{S-1}{\sqrt{var(S)^*}} \ S > 0 \\ \ 0 \ \rightarrow S = 0 \\ \frac{S+1}{var(S)^*} \rightarrow S < 0 \end{cases} . \tag{7}$$

The *DTVCMK* statistic is used to test the null hypothesis of no-trend against the alternative of an upward (or downward) test by comparing the theoretical distribution of the statistic.

Custom scripts were developed in R software (Core,2018) that made use of available libraries and packages for pre-processing data (Pierce ,2017), calculating drought indicators (Gudmundsson and Stagge, 2016; Zhong et al., 2018), and performing variance-corrected Mann–Kendall tests (Patakamuri and O'Brien, 2019) as appropriate.

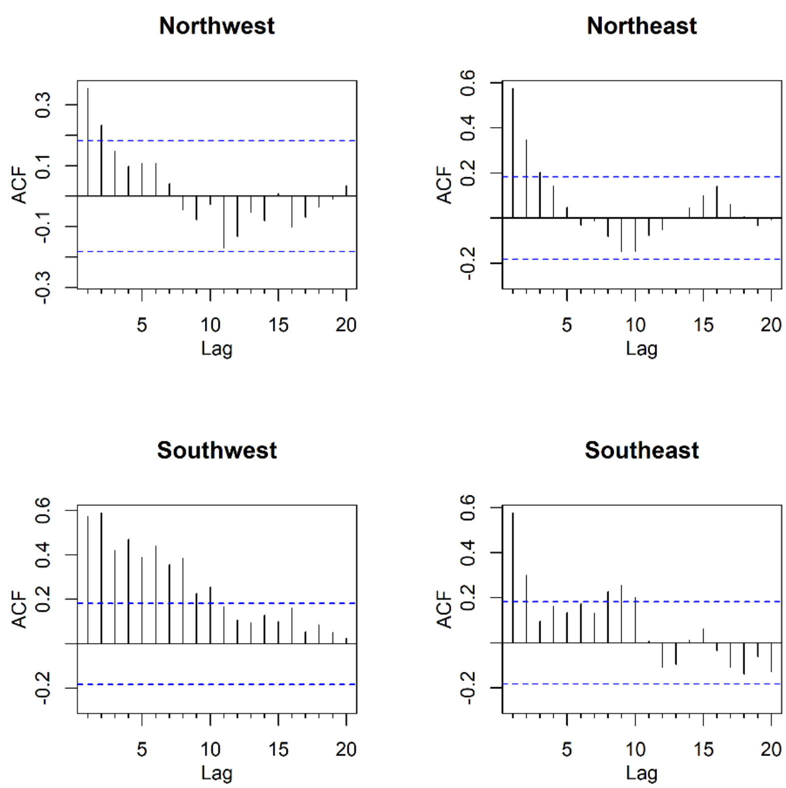


Figure 4.5 Illustrative autocorrelation functions at different location s in Ethiopia for PDSI (Note lags are in month)

Indicators used in this study specify droughts with negative values (below a threshold) and wet periods using positive values (above a threshold). As trend analysis was carried out using the seasonally aggregated sum of the drought indicator, a negative trend implied the drought indicator became more negative (or less positive) over time (i.e., increase in drought severity or a drying trend), while a positive trend implied a shift towards more positive (or less negative) values over time (decrease in drought severity or a wetting trend).

4.5 Results and Discussion

4.5.1 Trends across Ethiopia during Bega Season

The Bega season (October–January) had the lowest rainfall amounts compared to other seasons within the year (~2% of the annual rainfall of the country). Nonetheless, rainfall during Bega is important for several reasons. Bega rains can be significant in the central portions of the country. Bega rains provide much needed antecedent soil moisture that facilitates the tilling and planting of Belg crops. Bega rains are also important to maintain grasses in rangelands that pastoralists depend upon throughout the year. Therefore, droughts during Bega can have devastating impacts on both agricultural and pastoral activities of the nation.

Figure 4.5.1 depicts the century-scale drought trends during the Bega season across Ethiopia. The left panel depicts short-term (intraseason) drought trends captured using SPI-2, SPEI-2, and Z-index, while the right panel depicts full season effects captured using SPI-6, SPEI-6, and PDSI. Declines in rainfall (increased meteorological droughts) can be seen in southeastern and northwestern portions of the country. Decreased meteorological drought intensities or increased rainfall can be at some locations in the east. The null hypothesis of no drought trend could not be rejected over much of the southwestern and northeastern as well as western portions of the nation. Bega rains are critical in the central portions of Ethiopia, and the short-term meteorological droughts have either not changed or decreased in the west-central portions, while statistically significant (P-value 0.01 at 0.05 significance level) increasing trends can be seen in the east-central sections of the country.

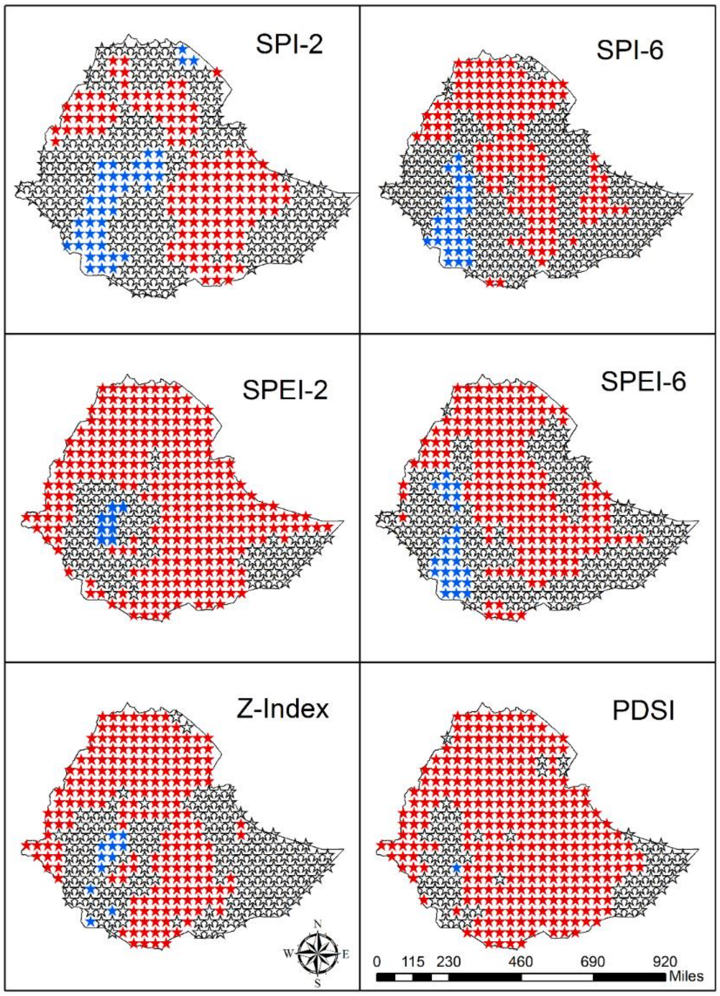
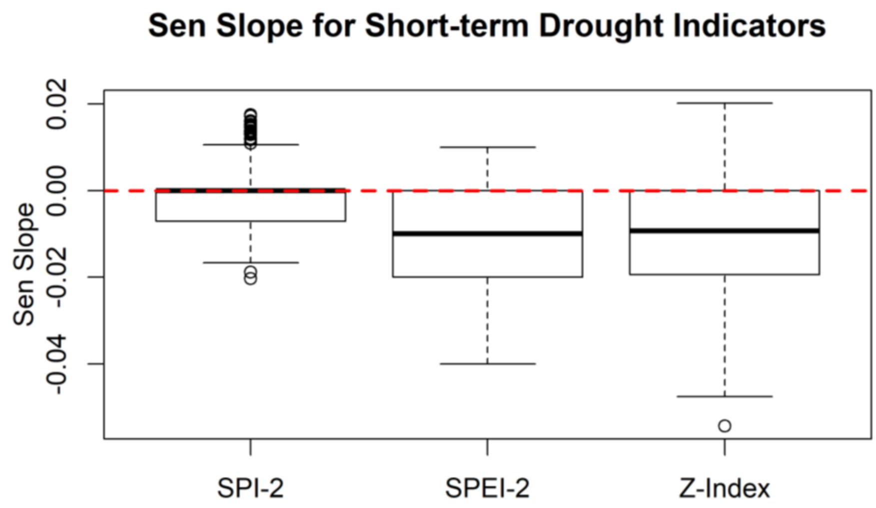


Figure 4.5.1 Trends in Bega drought indicators (red: drying trend, blue, wetting trend, and black: no statistical trend)

Many locations that have a wetting SPI-2 trend either have no trend or exhibit drying trends for SPI-6, which accumulates more of Meher and Belg rainfall. This result appears to indicate that some of the noted increased wetness could be attributable to shifts in rainfall patterns. In a similar vein, there are a greater number of wetting trends noted with SPEI-6 than SPEI-2. This result points out to likely drying in the winter months (October–January), which is dampened over longer accumulation periods. The PDSI is the most aggressive indicator in terms of predicting long-term agriculture-related droughts. The Z-index does not point to significant wetting trends, nor is it able to discern negative trends in the southeastern portions of the country. SPEI-2 appears to exhibit slightly better statistical power in discerning short-term agricultural droughts in this region for the Bega season, indicating the importance of temperature on moisture deficit conditions in this mostly dry season.

The magnitude of the observed trend is important to evaluate the rate of progression of observed wetting and drying phenomena. Figure 4.5.2 depicts the Sen's slope values for different drought indictors for Bega season. The Sen slope was set to zero when the null hypothesis of no trend could not be rejected. Figure 4.5.2 shows that the median magnitude of the Sen's slope was ~0.005 drought units (DU)/year for SPI-2 and ~0.01 (DU/year) for SPEI-2 and Z-Index. At least 75% of the locations exhibited a drying rainfall trend, and this number increased considerably for SPEI-2. While Z-index is not as aggressive as SPEI-2 in identifying drying trends, the rate of drying for Z-index exhibited a much larger variability and was sometimes more intense than SPEI-2. The results suggest that rainfall-reduced dryness is increasing at a rate of 5% per decade, while the drought intensification rate is about 10% per decade when both rainfall and evapotranspiration effects are considered. This result implies that temperature increases roughly doubles the intensity of rainfall declines for short-term (intraseasonal) droughts during Bega.



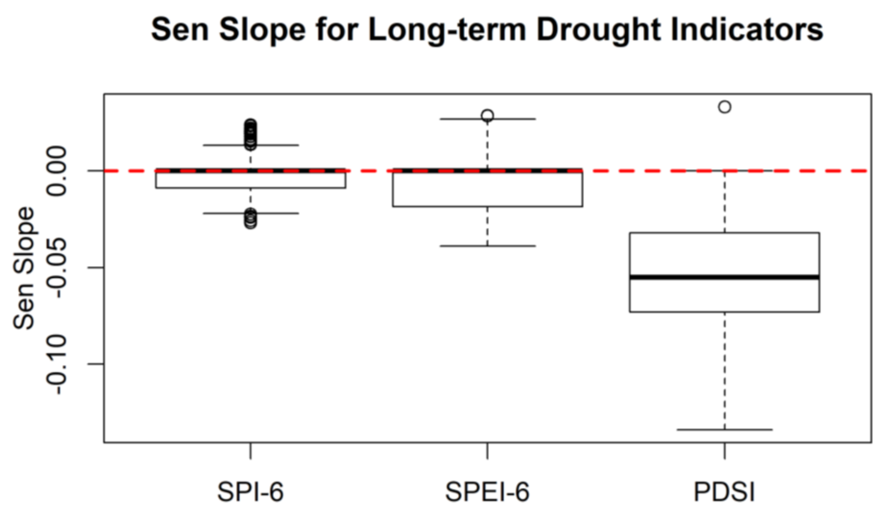


Figure **4.5.2** Variability of Sen's Slope for various indicators for the Bega season

The long-term wetting and drying trends produced a vastly different picture than short-term drying effects. The median rainfall-related drying intensity was much smaller, ~0.001 DU/year, for SPI-6 and only slightly higher for SPEI-2. PDSI on the other hand exhibited a strong drying intensity of ~0.05 DU/year (5% increase in dryness per year). This result indicates that while surficial dryness arising due to increased atmospheric temperature may not be significant for longer accumulation periods (SPEI-6), it does have a considerable effect on the hydrologic soil water balance as conceptualized and computed using PDSI. The long-term PDSI-based drying trends occur at an alarming rate. As PDSI is a long-term indicator, the results indicate that moisture-holding compartments (e.g., soil moisture) have very little resilience to combat the impacts of reduced rainfall and increased temperature. Accurate soil moisture measurements are critical to rigorously validate the trend projections of PDSI, and the absence of soil moisture networks is a major limiting factor to assess drought impacts on agriculture systems in Ethiopia (Teweldebirhan et al.,2019) .

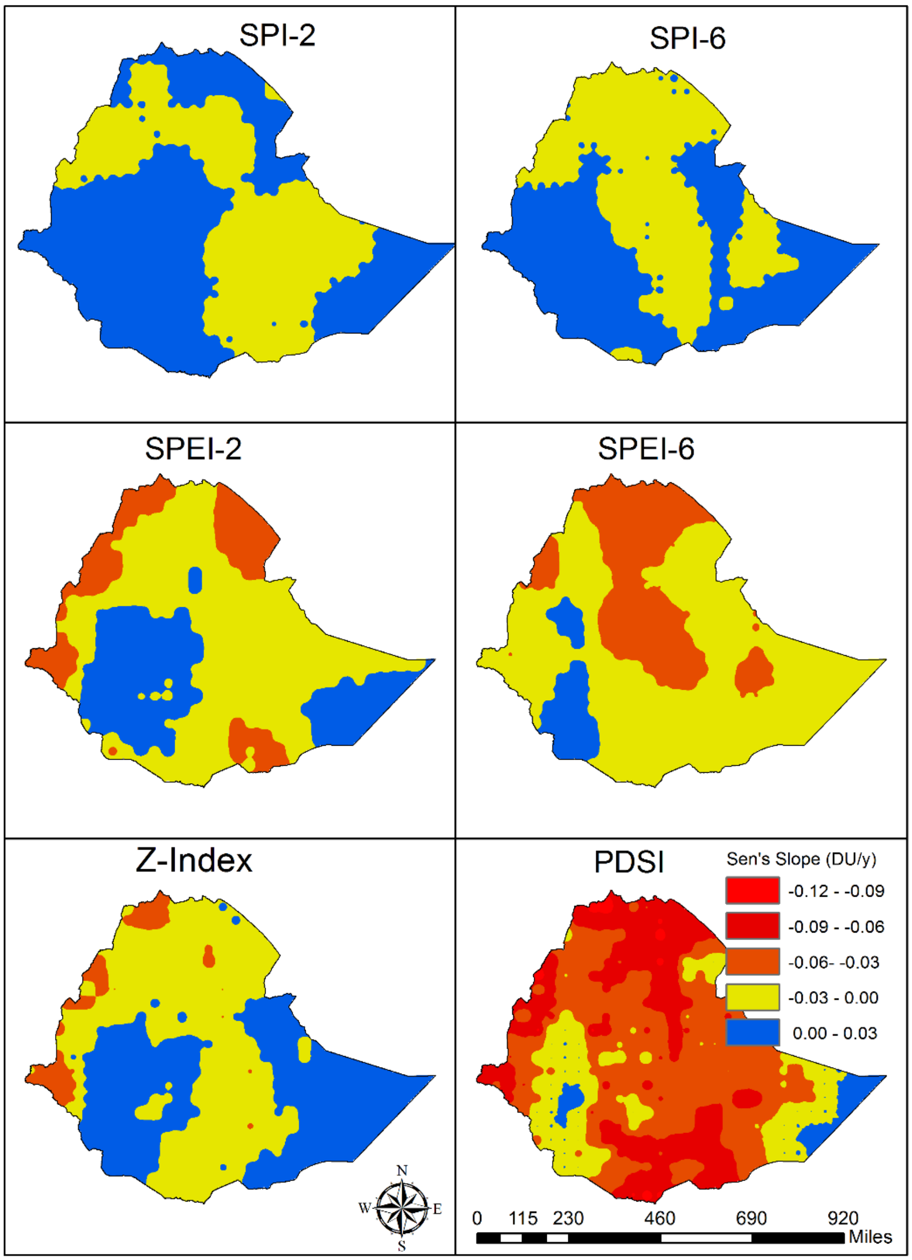


Figure 4.5.3 Variability of Sen's Slope accross Ethiopia for various drought indicators for the Bega season

As to be expected, the magnitudes of wetting and drying trends also exhibited considerable spatial variability (see Figure 4.5.3). The north and north-central portions of the country experienced the highest rate of drying intensity compared to eastern and western portions of the country. Short-term Bega rainfall deficits (as denoted by SPI-2) appeared to transition from a wetting to a drying trend moving west to east across the Rift Valley. It can also be seen that the trend variability was not uniform across the indicators, with PDSI and Z-index showing much different trends than SPI- and SPEI-based indicators. This result highlights the fact that a single indicator does not provide a complete picture of the droughts during Bega.

3.5.2 Trends across Ethiopia during Belg Season

Figure 6 indicates that drying trends were most prevalent during the Belg season, especially in comparison to the Bega season (Figure 4.5.4). Belg rainfall results from easterly and southeasterly winds, which bring considerable rainfall to eastern and southeastern parts of the country. Again, for short-term droughts, SPEI-2 provided the most aggressive trend detection (mostly drying trends) compared to SPI-2 and Z-index. For seasonal droughts, PDSI predicted drying trends over a much larger spatial extent than other long-term drought trend indicators (SPI-6 and SPEI-6), highlighting the important role of long-term hydrological processes in defining agricultural drought trends.

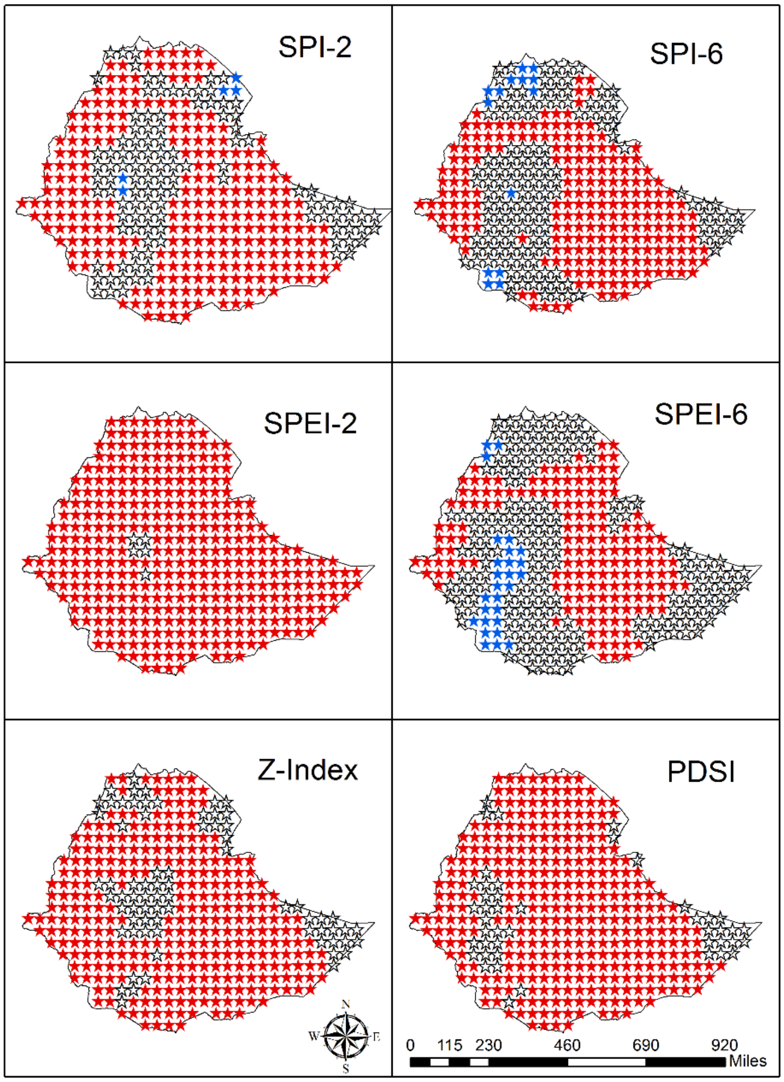


Figure 4.5.4 Trends of Various drought indicators across Ethiopia for Belg season

A comparison of SPI-2 and SPEI-2 indicates that many areas where SPI-2 (rainfall) had discerned no trend appear to show declining trends under SPEI-2, indicating that increased temperature is likely an important mechanism for controlling intraseasonal droughts. However, as declining SPI-2 (rainfall) trends can be seen across Ethiopia, rainfall declines during this season also exert a considerable amount of influence on short-term droughts. The SPEI-6 showed lesser drying trends and even some wetting trends compared to SPI-6. The small section in the northern portion where SPI-6 showed a wetting trend is masked by temperature effects of SPEI (resulting in no SPEI-6 trends in that area). However, some areas where rainfall has not changed (no trends in SPI) were marked as positive (wetting) trends by SPEI-6, especially in the south and south-central portions of Ethiopia. This result points to increased humidity and cloud cover that do not necessarily translate to rainfall. The moisture in the atmosphere is unable to condense into rainfall, but its presence reduces the evapotranspiration, which results in a wetting trend in SPEI but not in SPI.

As was the case with Bega (Figure 4.5.1), the Z-index and PDSI exhibited drought patterns that were considerably different from SPI and SPEI during Belg (Figure 4.5.4). While Z-index may be somewhat buffered by soil moisture storage in some pockets of the country (where no trends are detected), the PDSI trends indicated that this storage is short-lived and not sustained over the entire growing season due to the effects of hydrological processes that remove water from the soil column, once again pointing to the limited resilience of the soil moisture storage pool in the country.

From an agricultural perspective, the Belg season is important for growing tef (*Eragrostis tef*), which is a staple food in the Ethiopian diet. Empirical evidence of farmers unable to harvest their crops during this season has been discussed by Rossel and Holmer (2007) and supports the drying trends noted here. As tef grown during Belg is mostly consumed internally, droughts during Belg have profound implications for the food security and livelihoods of Ethiopia. Furthermore, if the production of tef is shifted to the longer Meher season, the growth of high-valued (export-oriented) crops comes under threat, affecting the economic viability of the nation, which depends extensively on agricultural production.

Rainfall during the Belg season is also important for long-cycle crops (e.g., corn, sorghum), which are planted in the Belg season but harvested in Meher. Droughts during Belg, particularly in the latter parts of Belg season, affect the planting of these long-season crops. Shifts in planting often have cascading effects on overall plant growth and crop yields. Shifting of planting dates can result in critical growth stages (e.g., grain-filling) to occur during drier parts of Meher when there is insufficient moisture in the soil to meet plant water demands. Strong correlations between Belg droughts and yields of long-cycle crops have been noted even when the Meher season was noted to be normal (Bewket, 2009) .

The Sen’s slope values were much higher in magnitude when compared to Bega season. The median drop rate was ~0.01 DU/year for SPI-2, ~0.03 DU/year for SPEI-2, and ~0.02 DU/year for Z-index. The intraseasonal drought indicators changed (declined) on average by 10%–30% over a decade. Again, the changes in SPEI-2 were 3 times that of SPI, which suggests that temperature-induced soil drying has a far greater influence than rainfall reductions. The comparison of Z-index and SPEI-2 points to some short-term buffering which is again not sustained over the long-term as evidenced by the declines in PDSI.

The changes in SPI-6 (~0.01 DU/year), SPEI-6 (~0.00 DU/year), and PDSI ~0.06 (DU/year) were noted. The median changes in short-term and long-term SPI were roughly the same, but with an improvement in SPEI over the long-term possibly from the decrease in evapotranspiration in the northern parts of the nation. PDSI changes were most drastic when compared across indicators, indicating the key role of slower hydrologic processes (baseflows, exfiltration, deep percolation) on soil moisture dynamics. The declines in rainfall during Belg, especially in relation to Bega, stood out, and the declines in rainfall played a much greater role in defining agricultural droughts in this season.

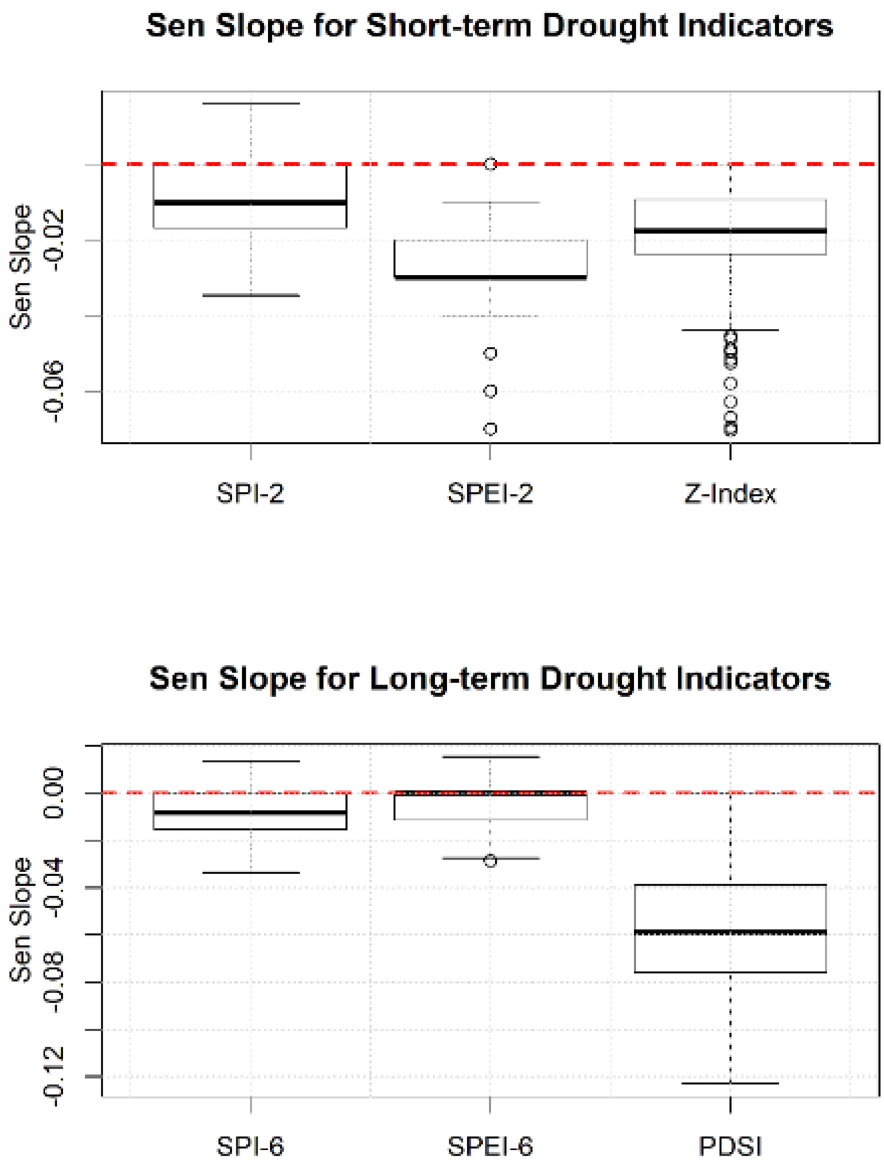


Figure 4.5.5 Variability in Sen's Slope for various drought indicators across Ethiopia during the Belg season

The variability of Sen's slope for various drought indicators during the Belg season is shown in Figure 4.5.6. Areas along the eastern border (Sudan and South Sudan) generally saw increased dryness in both short-term and long-term trends. This drying along the Sudan border will likely exacerbate the already existing scarcity of water resources and associated conflicts, especially the sharing of Trans boundary Rivers such as the Blue Nile between Ethiopia and her neighbors. Increased dryness can be seen across the east central portions, again, across all indicators, albeit with different intensities. This area includes cities such as Dira Dawa and Dolo Odo, which are critical for the development of eastern Ethiopia. All in all, both meteorological and agricultural droughts have increased over the last century. This declining trend in conjunction with a rapidly increasing population and limited irrigation systems has profound implications on the future food security of the nation and highlights the need for improved irrigation systems to build resilience into Ethiopian agricultural systems.

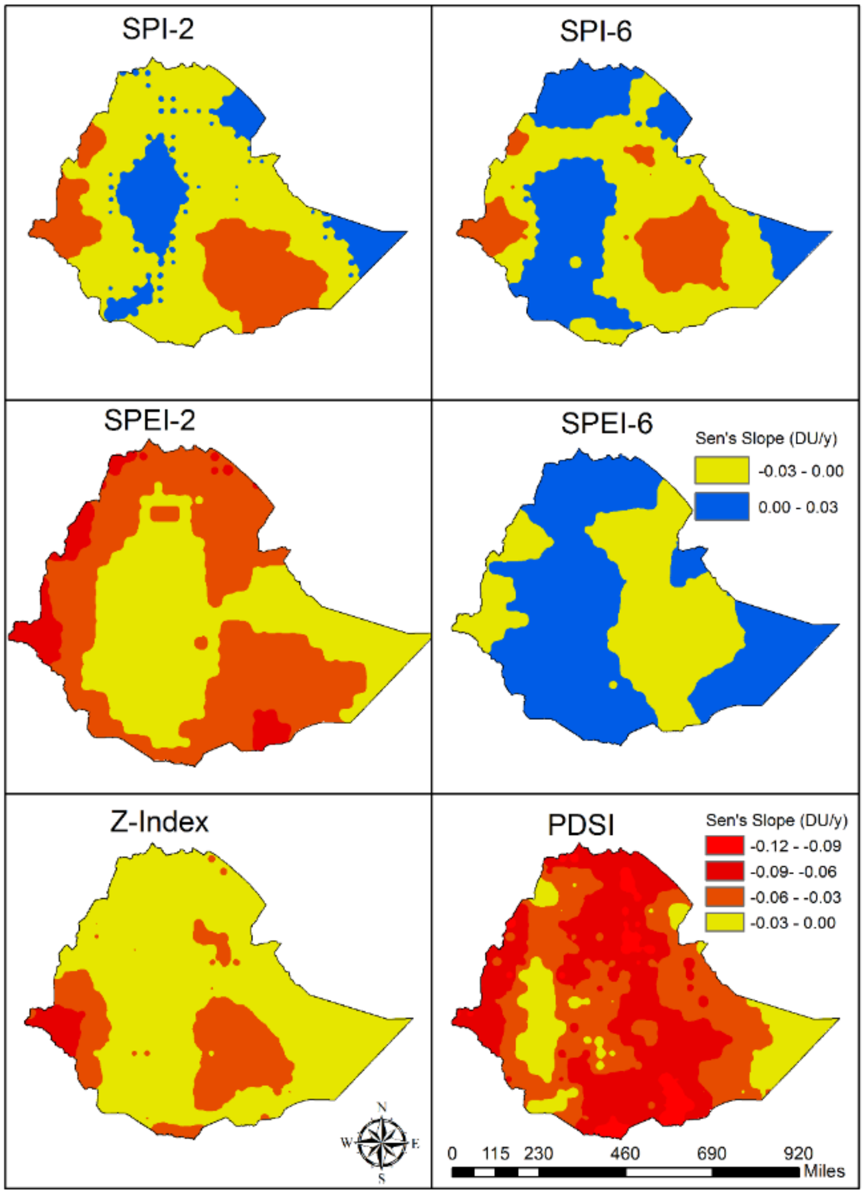


Figure 4.5.6 Variation in Sen's Slope across Ethiopia for various drought indicators for the Belg season

4.5.3. Trends across Ethiopia during Meher Season

Rainfall during Meher season is caused by the convergence of low-pressure systems and the intertropical convergence zone (ITCZ). This is the main rainy season across most of Ethiopia where the majority of crops are grown. Figure 4.5.7 shows the trends of various drought indictors across Ethiopia during the Meher season. Again, significant drying trends, both from rainfall declines as well as seasonal warming, could be seen over large parts of the country. A few locations did exhibit increasing rainfall trends (see SPI maps), which was dwarfed by changes in seasonal temperature (see SPEI maps). Warming effects could be noticed both in short-term and long-term drought indicators. Again, SPEI-2 was the most aggressive of all short-term drought indicators, while PDSI exhibited the greatest sensitivity to predicting long-term droughts. As rainfall during this season is mainly derived from ITCZ, the narrowing of ITCZ noted over the last century (Taffesse et al.,2012) explains some of the noted increased dryness. Seleshi and Zanke (2004) also indicate that warm El Niño–southern oscillation (ENSO) episodes correlate well with declines in June–September rainfall over the Ethiopian Highlands.

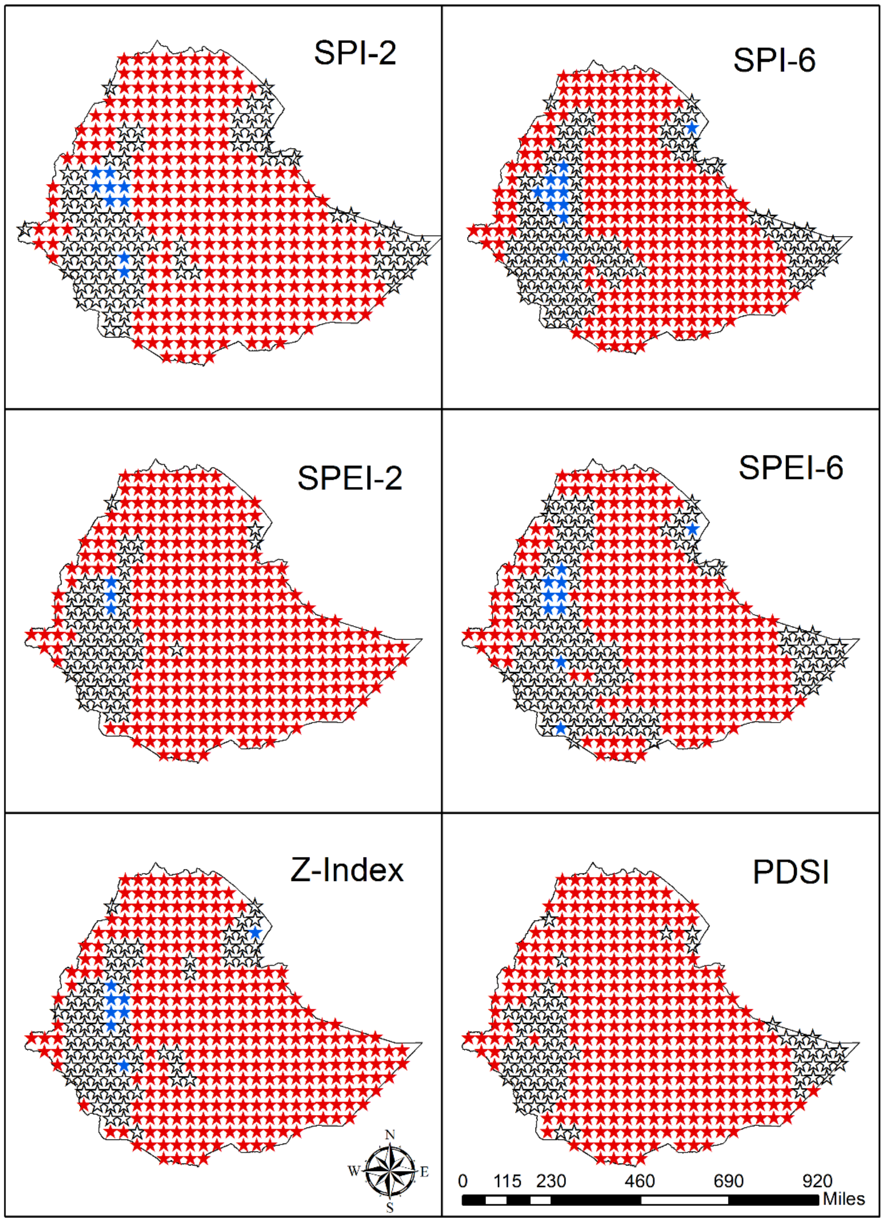


Figure 4.5.7 Trends across Ethiopia during the Meher season for various drought indicators

The magnitude of median Sen's slope was ~0.018 DU/year for SPI-2 and around 0.02 DU/year for SPEI-2 and Z-index, indicating that temperature changes exacerbated the dryness induced by rainfall declines for most parts of Ethiopia, but the difference was not as pronounced during the Meher season (Figure 4.5.8). For long-term droughts, SPI-6 and SPEI-6 had a median Sen's slope of ~0.01 DU/year, while PDSI had a value of about 0.06 DU/year (see Figure 4.5.8), indicating a 1%–6% increase in dryness on average across the country comparable to noted changes in Belg. The short-term dryness observed during the Meher Season is dampened by rainfall from other seasons, which factor in long-term meteorological and agricultural drought calculations. Comparison of short-term drought indicators of Meher (Figure 4.5.9) against those during Bega (Figure 4.5.1) appeared to indicate that some areas that exhibited declining trends during Meher exhibited increased SPI-2 during Bega, likely pointing towards shifts in late-season rainfall of Meher into Bega. As Meher is the major rainy season, which accounts for more than 50% of the annual rainfall of the country, even small changes in trends can imply significant changes in terms of rainfall declines. Funk et al. (2012) reported 50–150 mm declines in Kremit (Meher) rainfall over the last 50 year period, which is consistent with the estimates of this study and represents a significant proportion of water needs for many crops that are grown during the Meher season.

Short-season, cereal crops such as barley, teff, and wheat are extensively grown during the Meher season, especially by small landowners. The cereal production during Meher accounts for over 90% of the total cereal production of the nation (Byrne, 2018). These crops typically reach grain-filling stages during the October–December timeframe. Availability of soil moisture is critical during this period to maximize crop yields. The noted shifts in late-season rainfall from Meher to Belg or even within Meher, therefore, can have devastating impacts on short-season rainfed grain production in Ethiopia. Crop failures due to lack of moisture during grain-filling stages have been documented through field observations during drought years (Dorosh et al.,2013). Corn (*Zea mays*) production is particularly sensitive to droughts because of its relatively high water requirements and sensitivity to moisture deficits over much of its growing cycle (USDA-FAS,2008)

Sorghum (*Sorghum bicolor*) is often viewed as a drought-tolerant, long-season crop that can be produced even in areas with marginal soil quality in Ethiopia. Sorghum production is, therefore, important to sustain food security of the nation (ICRISAT, 1998). Sorghum is the second most important cereal crop after tef (Thornton, 2009). Empirical evidence, however, suggests that rainfed farming of sorghum is vulnerable to droughts. In Ethiopia, sorghum is mostly grown as a long-season crop and is planted late in Belg and harvested near the end of Meher; therefore, its yield can be affected by droughts in both these seasons. As with other cereals, droughts during the grain-filling stage have been shown to critically affect sorghum production (Thornton, 2009). Recent research has indicated that droughts during the early part of Meher (June/July), when sorghum plants are in rapid growth stages, can also have a serious impact on crop sustainability and yields that cannot be compensated by rainfall at other times (Amelework et al.,2016).

Farmers in Ethiopia generally recognize the robustness of sorghum to withstand dry conditions, especially in comparison to other cereal crops. They also know that the crop yields are sensitive to water deficits during critical growth stages and, therefore, tend to use indigenous drought-tolerant landraces that tend to mature early but generate lower yields (Thornton, 2009) Nearly all of the cultivable land has been exploited and put into production in Ethiopia (Eggen et al., 2019). Therefore, increased food production is only possible by increasing crop yields. Adaption of low-yielding, drought-tolerant varieties of sorghum may build some resilience for subsistence farmers in Ethiopia, but this is not a step in the right direction to tackle the food security of the nation. There is a critical need to breed cereal varieties that are both high yielding and drought tolerant. Understanding seasonal and intraseasonal trends in droughts is important for this effort (Amelework et al.,2016).

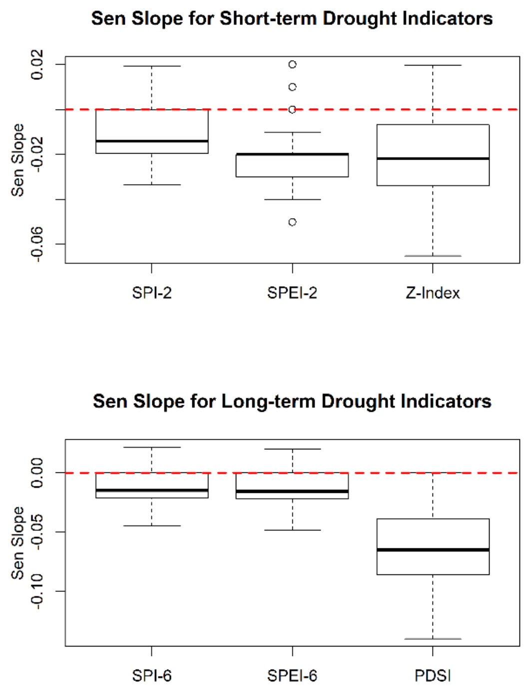


Figure 4.5.8 Variability of Sen's Slope across short- term and long- term drought indicators during Meher

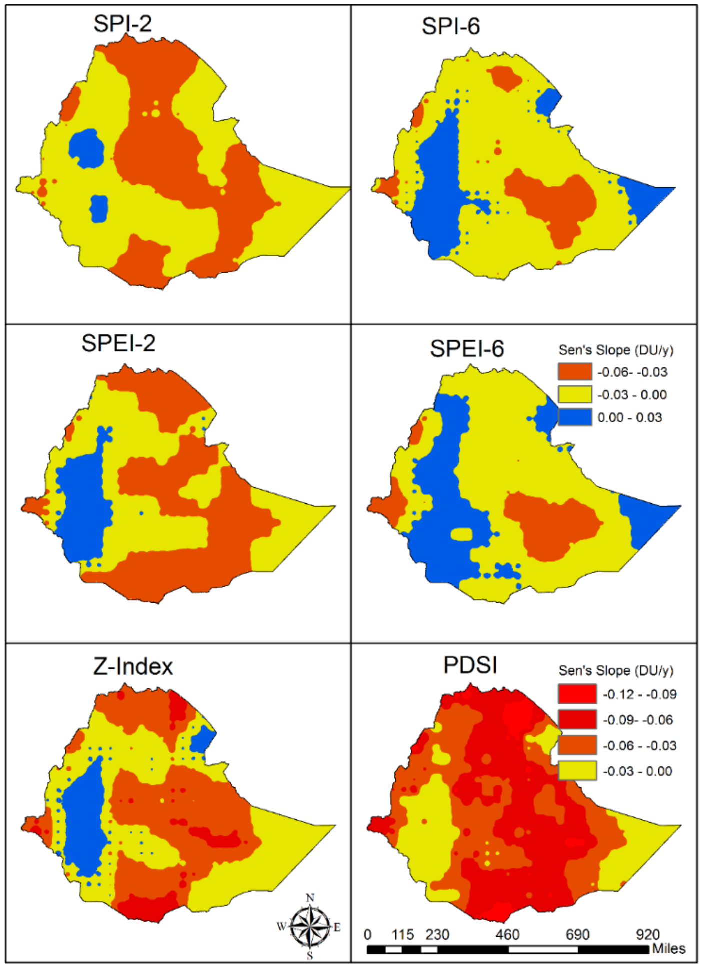


Figure 4.5.9 Variability of Sen'Slope across Ethiopia for various drought indicators for Meher

The spatial variability in drought indicators for the Meher season (mapped in Figure 4.5.9) again points to the east-central band that runs across the nation. Changes in drought indicators are prominent along the Ethiopia–Eretria border but relatively subdued along the eastern borders with Sudan and South Sudan. Nonetheless, the contributions of the Blue Nile to overall flow of the Nile is over 80% during the Meher season, and even small declines in rainfall trends in the catchment area can have profound implications on these transboundary river systems.

The drying trends noted resulting from rainfall declines and temperature increases in the central parts of the country (37.5° E–42.5° E) place greater risk on agricultural production of the nation, as a large proportion of agricultural lands and rangelands lie in this portion of the country (see Figure 4. 1c). High-valued crops such as corn are grown during this season, and increasing drying trends in major agricultural production regions significantly increases the risk to food and economic security of the nation.

3.5.4. Conclusion

As a rainfall-dependent country, droughts can cause major economic, environmental, and sociopolitical disruptions in Ethiopia. Agriculture is the primary economic driver in Ethiopia, and understanding how meteorological droughts propagate through agro-hydrological systems is of paramount importance. Given most agriculture systems are rainfed, there has been many studies that have evaluated regional trends in the standardized precipitation index (SPI). However, in addition to rainfall, soil dryness (the master variable for defining agricultural droughts) can be caused by increased temperatures as well as other persistent hydrologic processes. Drought indicators that account for both rainfall and temperature effects are, therefore, better suited for quantifying agricultural droughts than those based on rainfall alone. In this study, the standardized precipitation evapotranspiration index (SPEI), the Palmer drought severity index (PDSI), and the associated Z-index are used to characterize short-term (two-month accumulation) and long-term (six-month accumulation) droughts during the three major seasons (Bega, Belg, and Meher) in Ethiopia.

The results consistently indicate that SPEI-2 (two-month accumulation) was the most aggressive drought indicator for characterizing short-term droughts, indicating surficial drying due to increased temperatures are important in characterizing intraseason droughts over much of the country. Intraseasonal droughts over much of the country exhibited declining trends when evaluated on a century-scale (1902–2016). Winter temperatures had a major influence on Bega droughts. Temperature increases further exacerbated soil dryness caused by rainfall declines during Belg, during which many crops are grown for internal food consumption. Declining trends were also noted during Meher but were largely attributable to changes in rainfall more so than changes in temperature. Even small changes in the magnitude of rainfall had a greater impact, as this is the major rainy season over much of Ethiopia.

Long-term (six months) drought indicators typically had a slightly subdued response than short-term intraseason droughts, but similar trends noted over the short-term also manifested in the long-term for the most part. The subdued long-term signals arise because rainfall in other seasons that accumulates in the longer-term droughts help buffer intraseasonal changes. PDSI was noted to be the most assertive drought indicator for long-term droughts, indicating that noted precipitation and temperature declines create delayed but more prominent changes in hydrologic and soil moisture dynamics that other indicators (SPI and SPEI) do not capture fully because of their conceptualization limitations.

Increased dryness trends during Belg were noted along the eastern borders of Ethiopia with Sudan and South Sudan. These changes create additional water scarcity and make transboundary water sharing more contentious. A band approximately between (37.5° E–42.5° E) is a climate hot-spot where a significant percent of the Ethiopia population resides and practices agricultural and pastoral activities. The increased dryness coupled with exponential population growth places an enormous stress on the agricultural systems of the country, which are generally not buffered by blue water (irrigation) supplements.

The results of the study indicate that climate has changed considerably over the last century in Ethiopia, which in turn has affected the drought characteristics. This study focused on assessing long-term trends and changes in drought intensities. In addition to changes in intensities, the patterns of wet–dry spells and transitions between these climate states is also important to fully understand drought characteristics (Chowdhury et al., 2019). The reader is referred to a complementary study presented in that addresses this aspect. The available datasets limit the evaluation of drought characteristics on a monthly timescale. The meteorological network of the country must be expanded to provide better nationwide coverage and operated to collect data at higher frequencies (i.e., daily timescale) with little to no downtime to avoid large data gaps as they currently exist to further improve drought assessments and better characterize the impacts of trends and wet–dry spells.

Agricultural systems are affected by short-term soil drying during increased temperatures. Hydrologic changes caused by precipitation declines and temperature increases act slowly but affect soil moisture availability over the growing season. The comparison of multiple drought indicators suggests that precipitation-based SPI, while useful, does not provide a more complete picture of long-term drought trends noted in Ethiopia. Soil moisture is also affected by surficial drying and other hydrological processes (e.g., deep percolation) that remove water from the soil. Therefore, it is recommended that multiple drought indicators be used during water policy planning and management endeavors. The creation of a national-scale soil moisture sensing program and improving agriculture resilience through irrigation should be top priorities for sustaining the agricultural-dependent economy of Ethiopia.

5. Chapter – Four: Intra-seasonal Drying and Wetting Trends in Ethiopia and their Implications to Dryland Agriculture

5.1 Abstract

Understanding intra-seasonal effects of agricultural and meteorological drought trend at country scales is very important in planning to increase agricultural productivity. This is especially essential for country such as Ethiopia where there is very high dependence on rain-fed agriculture. Ethiopian agriculture is not only affected by meteorological droughts but also soil moisture deficits that cause agricultural droughts. The aim of the study is to evaluate intra-seasonal (short term) agricultural and meteorological drought trends in Ethiopia. Assessment of meteorological and agricultural drought trends was carried out to characterize century-scale (1902 – 2016) changes in droughts. For assessing intra-season drought trends SPI and SPEI calculated for each month and for each season, and the PDSI and its Z-index were also used for each month. Seasonal Mann-Kendall test was used for trend analysis during Bega (dry), Belg (short-rainy) and Meher (long-rainy) seasons. SPI shows significant drying trends (meteorological droughts) and it is most rampant during December, February and July within season of Bega, Belg and Meher respectively. SPEI indicates drying trend in December, March and September. Z-index shows moisture deficit (agricultural drought) in October, March and September during Bega, Belg and Meher season respectively. This affects both long cycled and short cycled crops.

Keywords: Autocorrelation, Droughts, Ethiopia, PDSI, Palmer Z-index, SPEI, SPI, Trend Analysis

5.2. Introduction

Ethiopia is the second most populous country in Africa and one whose economy is growing. Ethiopia's bio-diversified physical landscape is characterized by undulating topography with lowlands and highlands, which directly influence settlement patterns and occupation option (World Bank, 2017). Drought is unarguably one of the most complex and challenging natural disasters from management perspective and it has been a part of the climate and it has affected several countries in the world including Ethiopia (Gutierrez et al., 2014). Drought is a common part of the climate, and it can happen in any climate regime throughout the world from deserts to rainforests. Drought is one of part of more costly natural hazards on a year-to-year basis; its impact is significant and wide spread, affecting many economic sectors and people at any time. In Ethiopia drought occurs at the different seasons and arises when seasonal rainfall drops below historical average (Hughes, 2014). Due to the importance of the rainy season to agriculture production, Ethiopia also faces frequent food insecurity due to droughts (USAID, 2017).

Agriculture is the most important economic sector in Ethiopia and 80% of nation depends on rainfed agriculture (Hailu et al., 2018). However, the existence of climate change influences agricultural sector. Agricultural drought leads to crop failure which is common in dry land and semi-arid parts of Ethiopia. Dryland in Ethiopia covers about 46% of total arable land but, this area contributes less than 10% of total production crop production in the country that implies how rainfall risky in terms of distribution and amount, in this place evapotranspiration is highly concerned as well (Georgis et al., 2008). In addition to precipitation declines, temperature increases have also been noted in Ethiopia this precipitation deficits and increased temperature affect soil moisture (Ayalew et al., 2012).

Agriculture is the main economic sector which is influenced by intra-seasonal effects of agricultural drought mainly; short term agricultural drought at growth stage of crop has severe impacts on agriculture (Mokhatari, 2005). As part of rainfed country, understanding intra-seasonal effects of agricultural drought and Meteorological Drought is important for proper drought possibility planning in agricultural areas of Ethiopia. In Ethiopia, although many farmers grow crops during the Meher season, the shorter rain season (Belg) often provide the soil moisture for farmers preparing lands for planting activities, and also improve pastures for livestock (Afsaw et al., 2018).

Leszek .L and Bogdan M. (2014) reported that while meteorological droughts propagate through soil to create agricultural droughts, the two droughts need not exhibit similar trends. World Meteorological Organization (WMO) in 2009 recommended that SPI as the main meteorological droughts index that country should use to monitor and follow drought conditions. By identifying Standardized Precipitation Index (SPI) as an index for extensive use, WMO provided direction for countries trying to establish a level of drought early warning (WMO, 2016). Standardized Precipitation Index (SPI) can be calculated for each calendar of month at different time scale from 1-48-month time scales using long-term series of precipitation measurements at different meteorological stations all over the country (Bonaccorso et al., 2007).

Several studies have been undertaken in recent years to evaluate drought trends and drought characteristics in various parts of Ethiopia (Mohammed, Y,2018, Bekele et al,2017, Edosa et al. ,2010) and most of these studies are case study and often employs with shorter record data sets. However, (Vista et al,2013, Wagisho et al,2013 and Cheng et al,2008) carried out the analysis of annual and seasonal trends at a national level by using observed data with record length less than 50 years, while this study is based on long data record (1901 to 2016). In Ethiopia Temam et al., (2019) evaluated drought trends for three different seasons (Bega, Belg,and Meher) in Ethiopia.
Seasonal trends are useful to assess variations across a hydrologic year it can tell which season is facing greatest threat, Seasonal trends correlate well with crop productivity and economic output and seasonal trends when viewed in unison can point to some mechanistic climatic shifts that lead to observed drought behavior. Seasonal trends however do not tell us how the droughts are changing within the season and which months within the season are seeing major shifts Therefore, evaluating seasonal and intra seasonal effects of meteorological and agricultural drought is useful for understanding which part of the crop growth cycle is affected the most and droughts during growth season is more sensitive than those occurring at later times when plant water need is minimum. There is no comprehensive study focused on assessing intra-seasonal droughts in Ethiopia using Seasonal Mann Kendal Test.

5.3 Methodology

5.3.1 Description of study area

Ethiopia's geography is diversified with high and rugged mountains, deep gorges, flat-topped plateau, plains, and river valleys. The altitude ranges from the highest peak at mountain Ras Dashen (4398 meters above sea level), around Gondar to the Danakil depression of Afar (189 meters below sea level) which is one of the lowest dry land points on the earth next to the dead sea. Ethiopia is located in the tropics between 3°and 15° N of latitude and 33^0-48^0 E of longitude and it constitutes a major portion of the horn of Africa.

The inter-tropical convergence zone mainly controls the climate of Ethiopia and associated atmospheric circulation and complex topography of Ethiopia have a role on climate variability because temperature is function of elevation. Ethiopia's diversified climate range from semi-arid desert type in the low lands to warm and humid type in the south west, cool and moderate in mountainous parts of country.

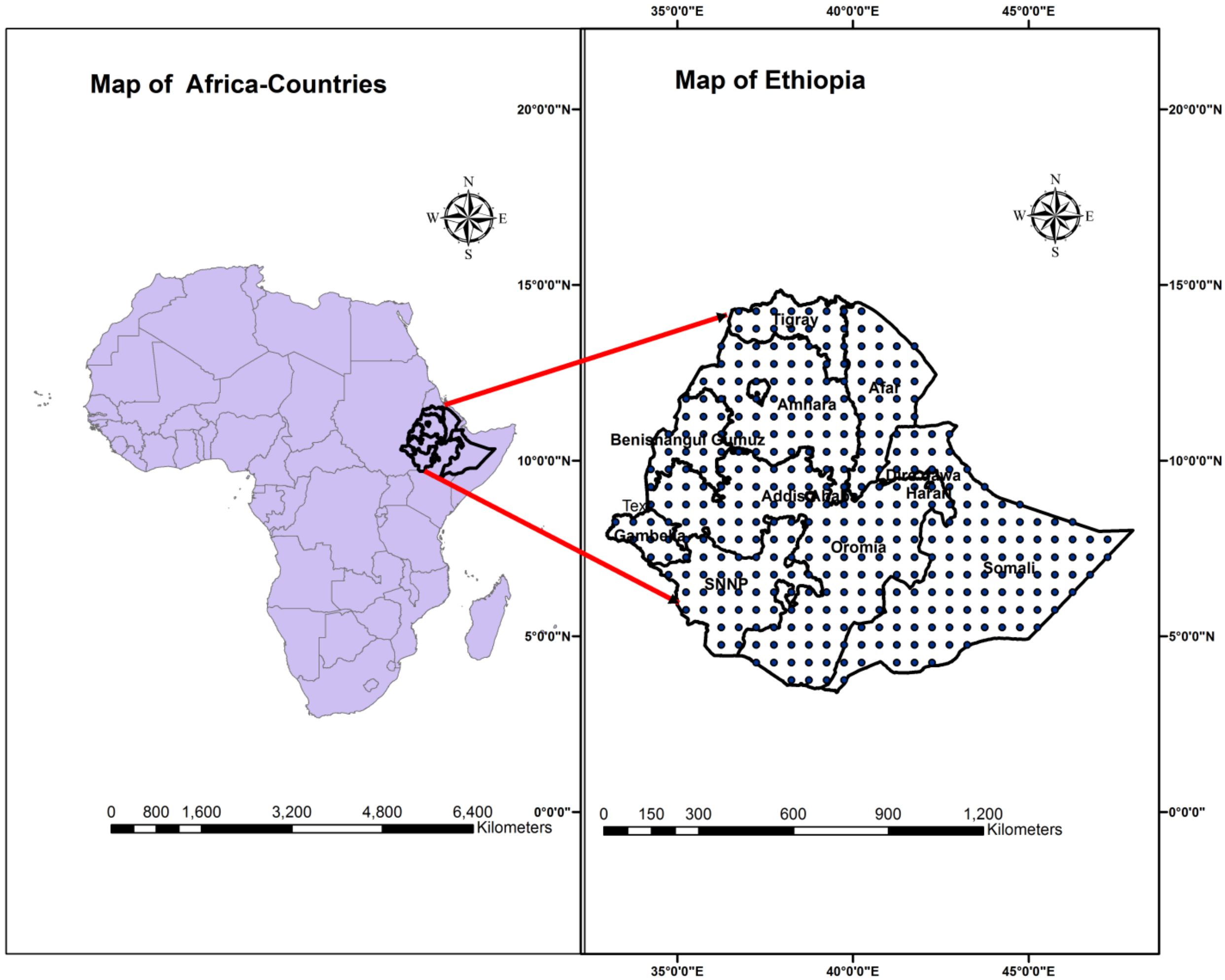


Figure 5.1 Map of Study area

Mean annual rainfall distribution has ranges from 2400 mm over the South-western parts of country and 300 mm over South-eastern and North-eastern lowlands. The mean annual temperature ranges from 15^{o} C to 25 ^{o}C over the highlands and the lowlands respectively (Kassa Fekadu, 2015).

5.3.2 Datasets

In Ethiopia it is difficult to get long period of recorded climate data. However, Asfaw et al., (2018) used and recommended that gridded data sets are vital source of climate data when meteorological stations are unevenly distributed, limited, and have large missing data under such condition gridded climate data serve as very important alternative source of data to use. Gridded dataset can improve the intensity of data because of high spatial coverage, for this reason so many studies have made use of this datasets (Asfaw et al,2018; Collins, J.M,2011; Wagesho et al,2013; Addisuet al,2015; Pingale et al,2016)

Precipitation Data obtained from Global Precipitation and Climatology Center (GPCC) Dataset with gridded resolution of 0.5^{o} x 0.5^{o} resolution based on over 80000 stations. For this study 377 grid locations extracted as shown in figure 2. The precipitation dataset covered a period ranging from January 1891 – December 2016 (Ziese et al., 2014).

Monthly time step temperature data was used from Climate Research Unit (CRU TS 4.21). The temperature data set covers a period ranging from 1901 – 2017 but for analysis we used common period of both GPCC precipitation and CRU temperature datasets (January 1901–December 2016). The CRU Climate Dataset was produced by the Climate Research unit and it is gridded at a resolution of 0.5 x 0.5 over the land mass; the CRU dataset is also based on observations from several thousand stations worldwide (Teweldebirhan et al., 2019).

The R-Statistical Software version 3.4.1 was used to analyze the climate data and the Geographic information system (GIS) software was also used for mapping and estimating corresponding areas for each grid point.

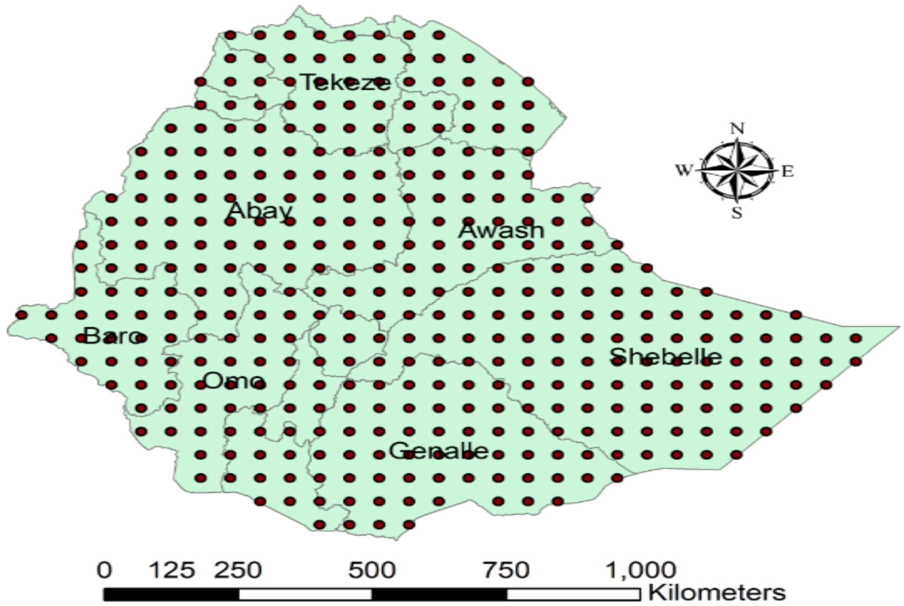


Figure 5.2 All grid station points in study area

5.3.3 Seasonal Mann Kendall Test

The importance of the Seasonal Mann- Kendall (SMK) test as described by (Gilbert 1987, Hirsch, Slack and Smith 1982, and Helsel and Hirsch 1995) is to test for a monotonic (increasing or decreasing) trend of the variable of interest for one or more months. The existence of seasonality indicates that the data have different distributions for different seasons (e.g., months) of the year. For instance, a monotonic increasing trend may exist over years for December but not for July. Hirsch, Slack and Smith (1982) proposed The Seasonal Mann-Kendall test for use with 12 seasons (months). The SMK test might also be used for other seasons, for example, the four quarters of the year and the 52 weeks of the year.

Computing the Seasonal Kendall Test described in the following steps;

a) List the data obtained for the i^{th} month in the order in which they were collected over time,$X_{i1}, X_{i2},..., X_{in}$, which represent the measurements obtained for month i for years 1, 2, …, n, respectively.

b) Determine the sign of all $n_i (n_i-1)/2$ possible differences $X_{ij}-X_{ik}$ for the i^{th} month, where j>k. These differences are

$X_{i2} - X_{i1}, X_{i3} - X_{i1} . . . , X_{ini} - X_{i1}, X_{i3} - X_{i2}, X_{i4} - X_{i2}. . . , X_{ini} - X_{i,ni-2}, X_{ini} - X_{i,n-1}$

c) Let sgn $(X_{ij}-X_{ik})$ be the indicator function for month i. This function has the values 1, 0, or -1 based on the sign of $X_{ij}-X_{ik}$; that is,

$$\text{sgn}(X_{ij} - X_{ik}) = \begin{cases} 1 \; if \; X_{ij} - X_{ik} > 0 \\ 0 \; if \; Xij - Xik = 0 \\ -1 \; if \; Xij - Xik < 0 \end{cases}$$

$X_{ij} - X_{ik} > 0$, that means that the observation for year j in month i, denoted by X_{ij}, is greater than the measured concentration for year k in month i, denoted by X_{ik}. Then we compute S_i as follows;

$$S_i = \sum_{k=1}^{n_i - 1} \sum_{j=i+1}^{n_i} \text{sgn}(X_{ij} - X_{ik}), \qquad (1)$$

This indicates the number of positive differences minus the number of negative differences for the i^{th} month. If S_i is a positive number, observations made in month i in later years tend to be larger than those made in month i in earlier years. If S_i is a negative number, then observations made in month i in later years tend to be smaller than those made in month i in earlier years.

We can compute the variance of Si as follows:

$$\text{VAR}(S_i) = \frac{1}{18} [\![n_i(n_i - 1)(2n_i + 5) - \sum_{p=1}^{gi} t_{ip}(t_{ip} - 1)(2t_{ip} + 5)] \qquad (2)$$

Where g_i is the number of tied groups for the i^{th} month and t_{ip} is the number of data in the p^{th} group for the i^{th} month. When there are ties in the data due to equal values or non-detects, the variance is adjusted by a tie correction method described in (Helsel, 1995).

$$S^! = \sum_{i=1}^{m} S_i \qquad (3)$$

$$\text{VAR}(S^!) = \sum_{i=1}^{m} VAR(S_i) \qquad (4)$$

Where m is the number of months for which data have been obtained over years. For example, if data were obtained over years for each month of the year, then m = 12.

To compute the SMK test statistic Z

$$Z = \begin{cases} \frac{S^{!}-1}{\sqrt{VAR(S^{!})}} if S^{!} > 0 \\ = 0 \; if S^{!} = 0 \\ \frac{S^{!}+1}{\sqrt{VAR(S^{!})}} \; if S^{!} < 0 \end{cases} \quad (5)$$

A positive or negative value of Z indicates that the data tend to increase or decrease over time.

H0: Null Hypothesis: There is no seasonal trend

Ha: Alternative Hypothesis: There is a trend (two-tailed)

Null Hypothesis of No seasonal trend was rejected when the absolute value of |Z| > Z-critical.

We choose SPI, SPEI, PDSI and its Z-index from different drought indicators and the accumulation period of interest is seasonal or intra-seasonal. As the study focuses on Meteorological and agricultural droughts SPI and SPEI were computed for each month and Mann Kendall tests performed for each month and then aggregating them over seasons.

The Z-Index represents short-term (monthly) soil moisture dynamics as it factors out the long-term effects embedded within PDSI (Dai, 2011). The Palmer Drought severity Index (PDSI) can be described as follow to drive Z-Index. The $PDSI_t$ (at any time, t) is a weighted sum of previous month $PDSI_{t-1}$ value which indicates climate spell and the moisture anomaly, Z_t which measures the dryness (or wetness) over the current month, t.

$PDSI_t$=$pPDSI_{t-1}$ +qZ_t-- (6)

qZt=$PDSI_t$ – $pPDSI_{t-1}$---(7)

Where, p and q are duration factors at any given location (Wells et al., 2004).

As the Z-index it is a useful indicator of intra season (short-term) droughts and it removes the effects of previous months.

The PDSI and Z-index are derived using a soil moisture/ water balance algorithm that requires a time series of daily air temperature and precipitation data, and information on the available water content (AWC) of the soil. Soil moisture storage is handled by dividing the soil into two layers

(Heim, 2002). The top layer has a field capacity of 25 mm, moisture is not transferred to the second layer until the top layer is saturated and runoff does not occur until both soil layers are saturated (Alley, W.M., 1984).

Palmer Drought Severity Index (PDSI) is Two-layer bucket model and another widely used meteorological drought indicator. It is known to correlate well with hydrological and agricultural droughts. Although both the *Z*-index and the PDSI are derived using the same data, their monthly values are quite different. The *Z*-index is not affected by moisture conditions in the previous month, so *Z*-index values can vary dramatically from month to month. On the other hand, the PDSI varies more slowly because it depend antecedent moisture conditions

5.4 Results and Discussion

5.1.1 Monthly and Seasonal Trends across Ethiopia during Bega season

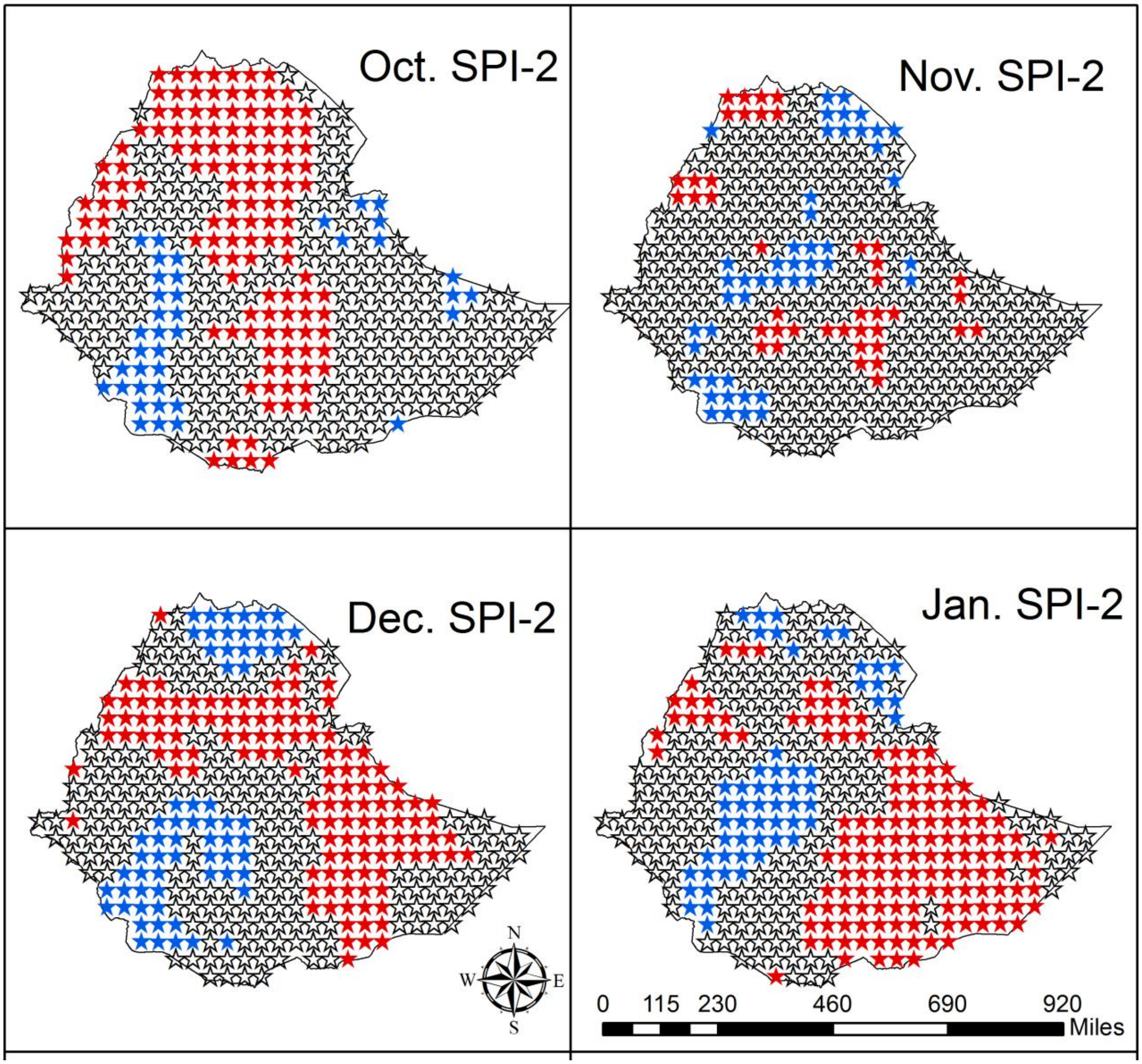


Figure 4.1.1 Intra-seasonal trends of meteorological drought (SPI-2) across Ethiopia during Bega season (Red: Drying trend, Blue: Wetting trend, and, Black – No statistical trend)

Bega is the cool and dry season in Ethiopia that runs from October to January and the weather during the period is sunny at the day time and associated with cold nights and early mornings. However, there is a small rainy season for southern area bordering Kenya, south-eastern lowlands with limited rainfall. In this season harvest and post-harvest activities are the main practices over most parts of Ethiopia were Meher is the primary growing seasson. Therefore, it is important to see which months within the season are seeing major shifts. Figure 5.1.1 indicates the century-scale drought trends within Bega months across Ethiopia. Short-term (intra-season) meteorological drought trends within Bega season explained using Oct SPI-2, NovSPI-2, DecSPI-2 and JanSPI-2. In October SPI-2 Indicates that there is no meteorological trend in south eastern and south western parts of country however, there were declines in precipitation (increased meteorological droughts) that can be seen in central and northwestern portion of the country. SPI-2 in November many parts of the country either have no or exhibit drying trends. In a similar way, there are greater number of drying trends noted with Dec SPI-2 and JanSPI-2 at North central and South eastern parts of Ethiopia as it shown in Figure 5.1.1. Drying of meteorological droughts trend are more sensitive during Oct. SPI-2 especially in- comparison to the Dec., Nov. SPI-2 and Jan.SPI-2 during Bega season. However in Nov. SPI-2 drought trend is not detected in some parts of the country and wetting trends observed in south west and north endways in December. Bega season is crop harvesting (colleting) time for both long cycle and short cycle crops. The Comparison of monthly inter-seasonal trends with seasonal aggregate analysis (Figure 5.1.4) for SPI-2 indicates that a south east central part of country is decreasing in precipitation (meteorological drought). Intra-seasonal trends and spatial variability (Sen's Slope) maps for SPI-6, SPEI-6 and PDSI are attached in Annex.

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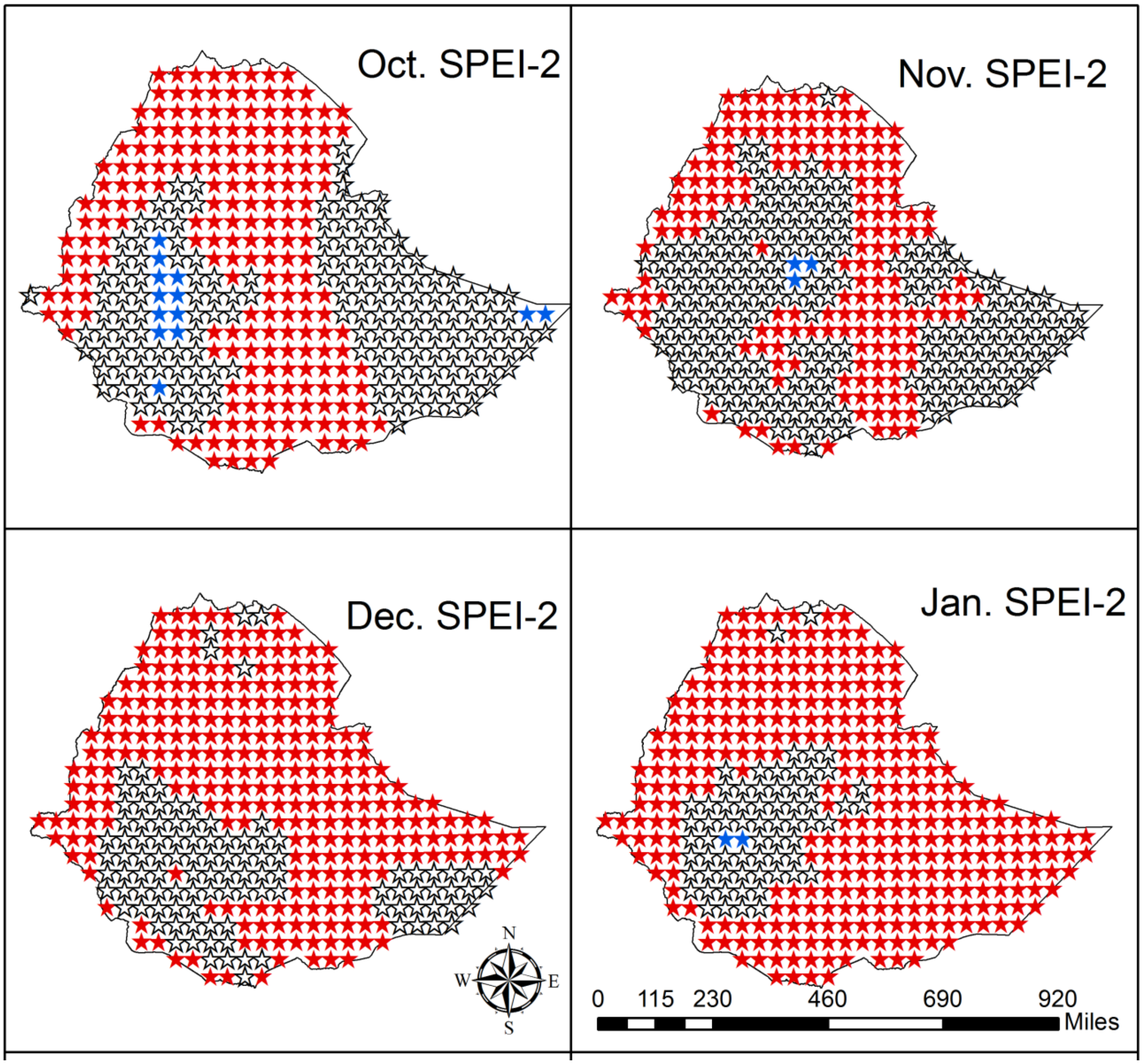

Figure 5.1.2 Inter Seasonal trends of agricultural drought (SPEI-2) across Ethiopia during Bega season

Many meteorological drought studies have been carried out using SPI However, the SPI is based on precipitation only, it has a limitation in evaluating agricultural drought (Dai, A., 2011). As indicated by (Vicente et al., 2010), Standardized Precipitation Evapo-transpiration Index (SPEI) was developed in consideration of meteorological drought for evaluating agricultural drought.

For Bega season SPEI-2 shows greater declining trends and drying effects are prominent as shown in Figure 5.1.2. Dec. SPEI-2 is more sensitive than Oct-SPEI-2, Nov. SPEI-2 and Jan.SPEI-2.

Monthly Dec. SPEI-2 and Jan.SPEI-2 shows drying trend when it compare with seasonal aggregate of SPEI-2 as indicated at in Figure 5.1.4

Bega rain fall is common in south east margin of country particularly, for Afar regional state but, in December and January this area getting dry and that affects pastoralist. .

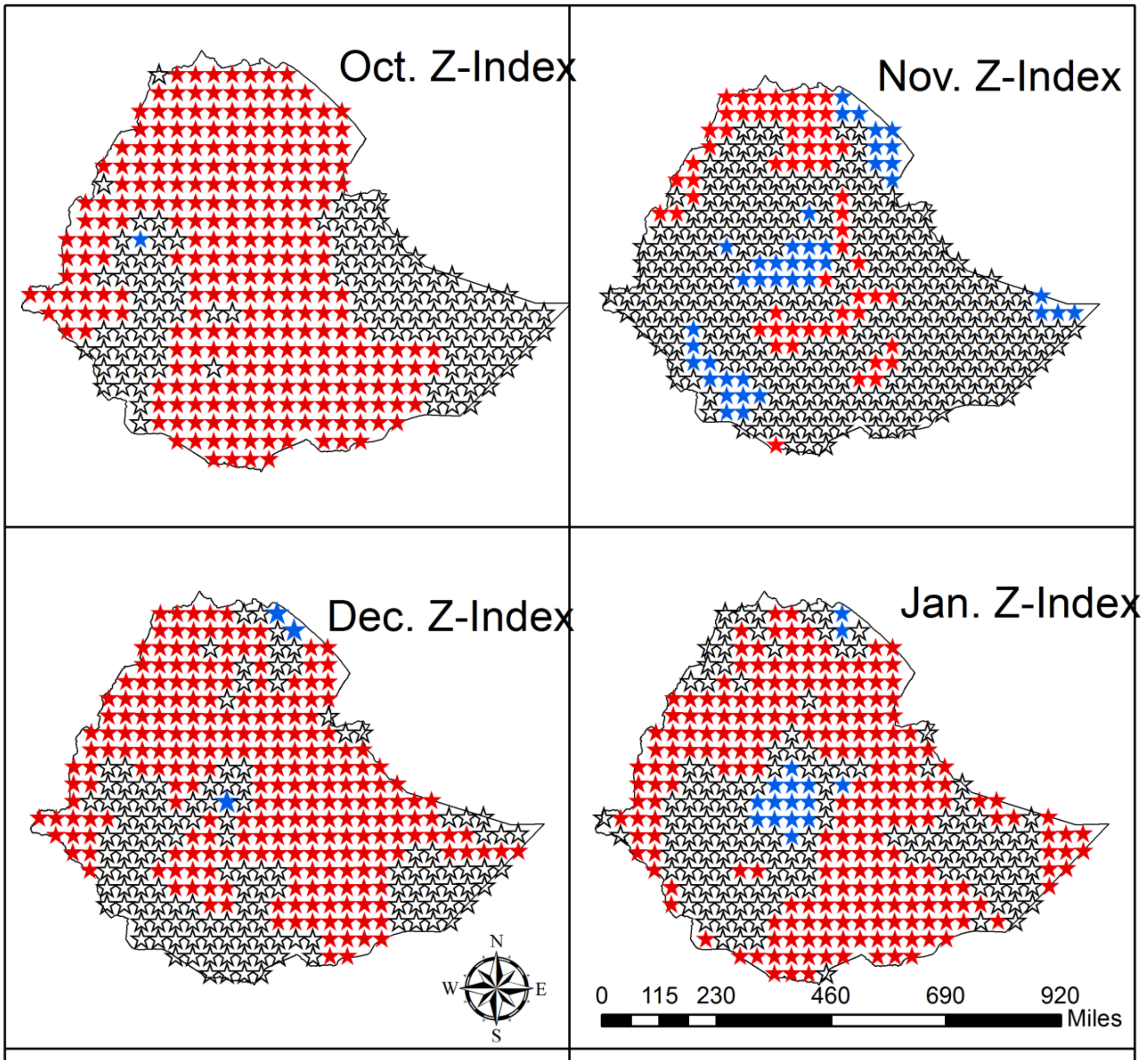

Figure 4.1.3 Intra-Seasonal trends of agricultural drought (Z-Index) across Ethiopia during Bega season

Another important indicator to evaluate intra-seasonal (short term) agricultural drought is Z index (Moisture Anomaly Index) and its trend pattern in each season shown by Figure 5.1.3 it is a function of Palmer Drought Severity Index and it is much responsive to short term moisture deficiencies than PDSI. During Bega season rain benefiting areas getting moisture particularly in

Nov. Z- Index and the remaining parts of country has increasing agricultural drought trend at Oct. Z- Index and Dec. Z- Index. In Jan. Z- Index except central parts of country another parts getting drought. Figure 5.1.3 shows both increasing moisture deficit and increasing with soil moisture trends and no trend as well. In agreement with this result finding Demeke et al., (2013) indicated that in Abay basin trends are not detected during Bega season.

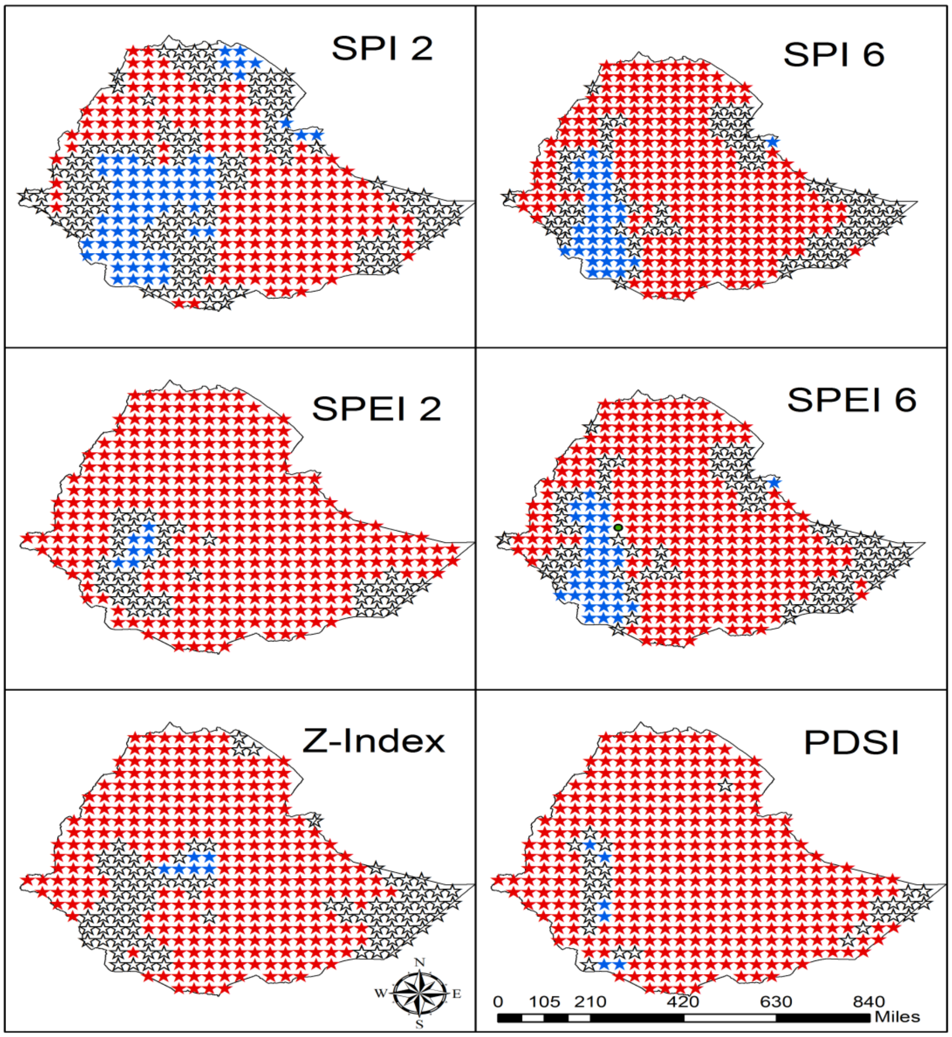

Figure 5.1.4 Seasonal trends of meteorological and agricultural drought across Ethiopia for Bega Season

As indicated in Figure 5.1.4 seasonal aggregate of months shows that SPEI-2, Z-Index shows that increasing drought trends while SPI-2, SPI-6 and SPEI-6 shows getting wet or no trend in the south west of the country during Bega season and in agreement with result, Liebmann et al.,

(2014) reported that over the whole horn of Africa region there is an increasing October–December rainfall. PDSI shows more drying trends in the long-term compared to SPEI 6 and SPI 6. Drought trends are consistent in portions where Bega rains are high particularly parts of Afar region and red sea coastal plains.

The comparison of Mann Kendall tests after seasonal aggregate and before seasonal aggregate for Bega season, before seasonal aggregate (performing Mann Kendall tests for each month and then aggregating them over seasons) shows increasing drought trend per all indicators during Bega season.

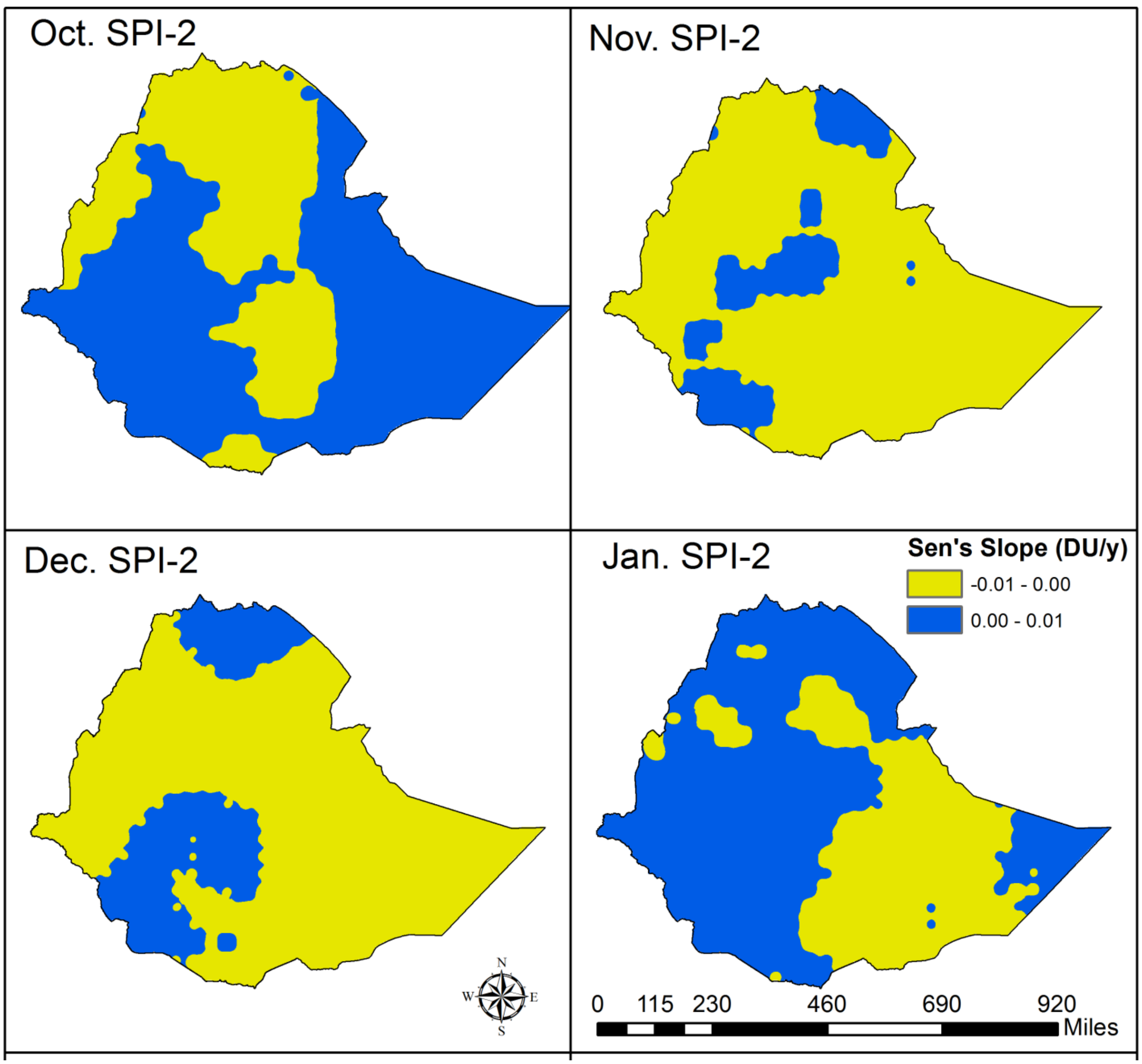

Figure 4.1.5 Variability of Sen's Slope for Intra- Seasonal meteorological (SPI-2) drought trends across Ethiopia

As it is indicated in the Figure 4.1.5 above, the magnitudes of wetting and drying trends show considerable spatial variability within season. During Bega season Nov SPI-2 and Dec SPI-2 shows drying trends in northwest and south east parts of country's region. No significant meteorological trends observed in western and eastern parts of country in Oct SPI-2 and there is no significant trend changes observed in Jan SPI-2 as well.

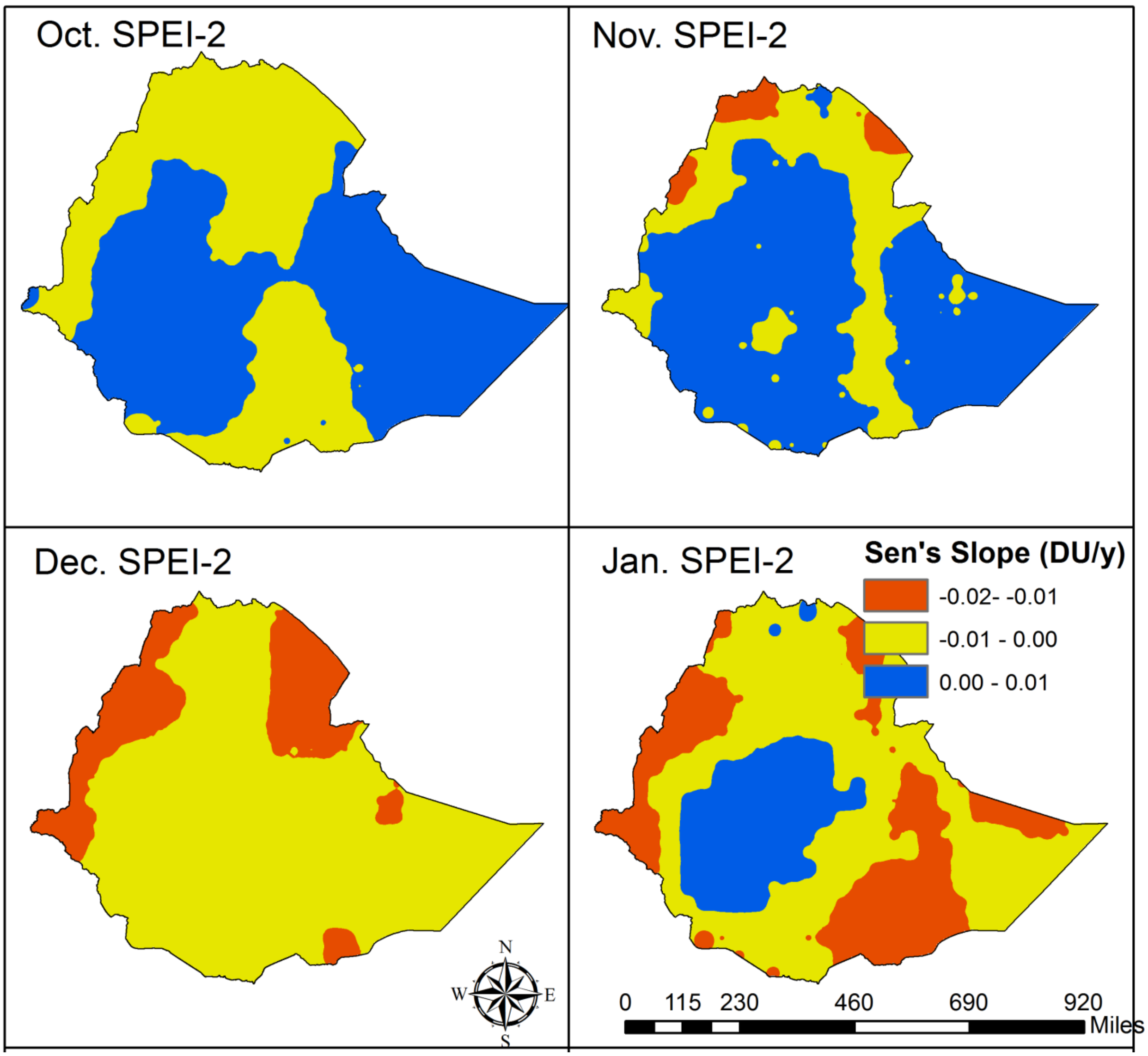

Figure 4.1.6 Variability of Sen's slope for Intra-Seasonal agricultural (drought) trends across Ethiopia

During Bega season the Sen's slope shows more increasing dry trend in Jan. SPEI-2 and Dec. SPEI-2 than Oct. SPEI-2 and Nov. SPEI-2. Dec SPEI-2 is aggressive drought period During Bega season as it illustrated in Figure 5.1.6 above. Except Central and south-west of country there is increasing agricultural drought throughout country for accumulation period of Jan SPEI-2. The magnitude of change in Sen's slope for SPEI-6 shows increasing by 0.01DU/y and decreasing by -0.01DU/y this is due to moisture accumulation for long term scale.

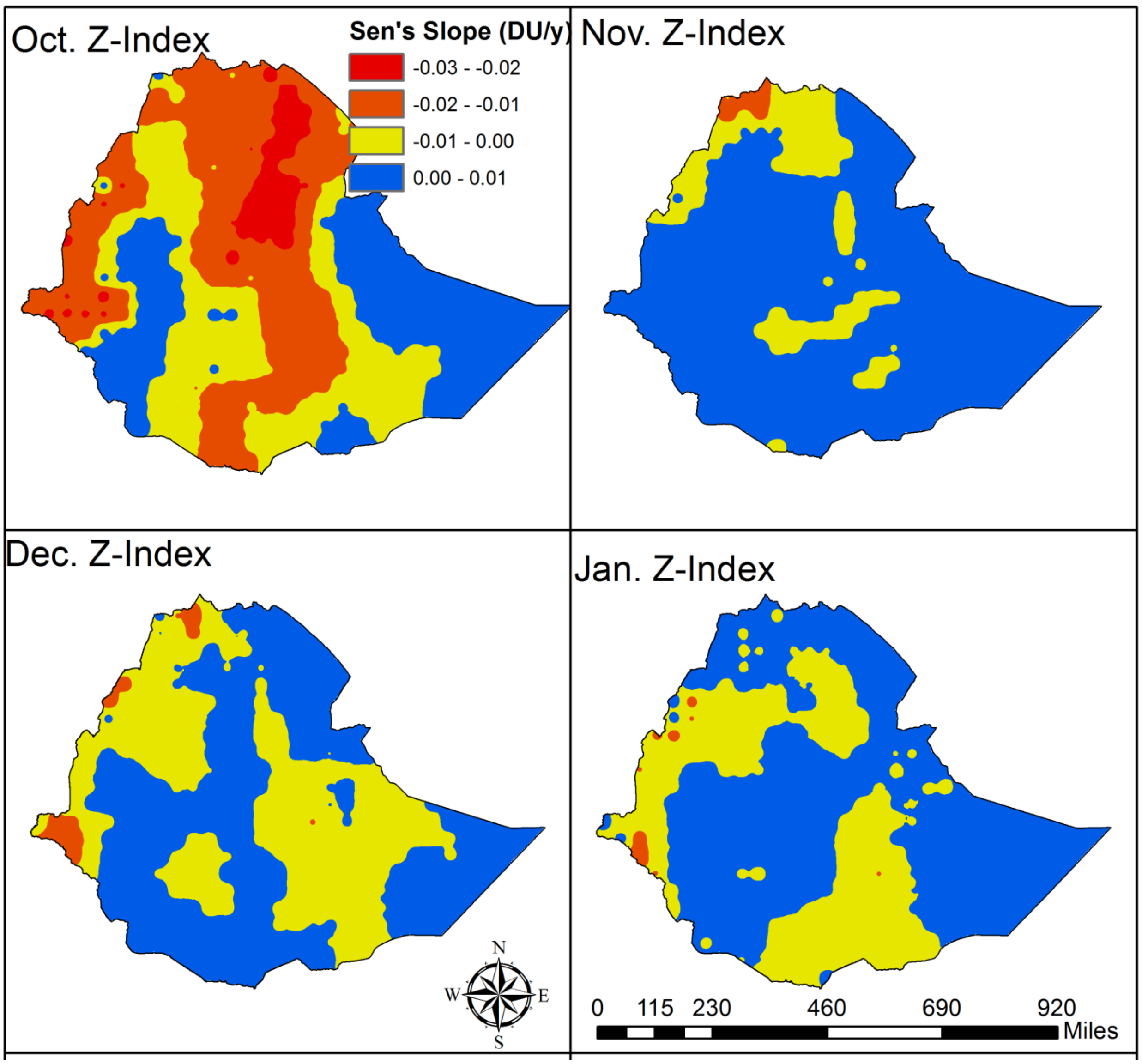

Figure 5.1.7 Variability of Sen's slope for Intra-Seasonal agricultural (Z-Index) drought trends across Ethiopia

During Bega season the magnitude of drying trends increasing in October (Oct. Z-Index) in different parts of country as it shown in Figure 5.1.7 for example, Gambella, Tigray, Oromia, Amhara regional state and western parts of Somalia region and its magnitude varying from -0.03 to -0.01DU/y. There is no significant change in soil moisture in Nov. Z-Index, Jan. Z-Index and Dec. Z-Index.

5.1.2 Monthly and Seasonal Trends across Ethiopia during Belg season

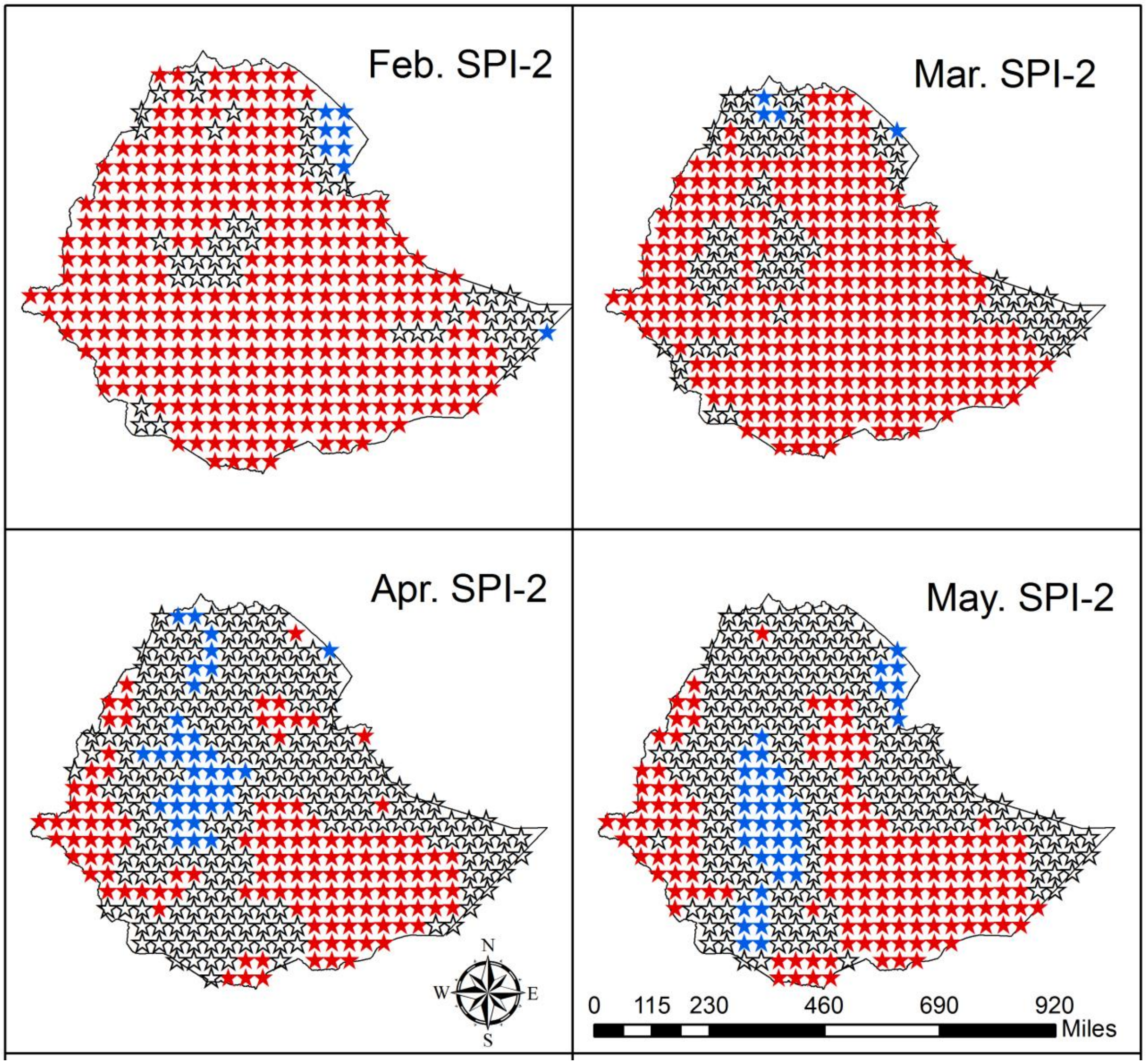

Figure 5.1.8 Intra-Seasonal trends of meteorological (SPI-2) drought across Ethiopia during Belg season (Red: Drying Trend, Blue: Wetting trend and Black No-statistical trend)

Belg is the small rainy season and lasting from February to May. The rainfall amount and distribution during the Belg season has significant effect on the performance of long cycle crops. For Ethiopia in which majority of communities are agrarian, Belg rain fall is vital due to different reasons. The Belg rainfall saves livestock of Pastoralist. Land preparation for Mehir planting should be undertaken ahead of time during the belg rain that makes the task so easy. Moreover, farmers are using the Belg rainfall to plant long season crops like maize and sorghum which need longer growth period for harvesting. Changes in meteorological drought during Belg (February–May) season have been analyzed over the entire Ethiopia.

Belg season rainfall makes a significant contribution to agriculture in the northeast, North West and central portions of Ethiopia especially in April and May as indicated by figure 16 that means April-SPI-2 and MaySPI-2 are very important for agricultural activities. Furthermore, meteorological drought indicators predict wetting trend in the northeast, northwest and central portions of Ethiopia during April-SPI-2 and MaySPI-2 accumulation period. Meteorological drought are prevalent in Mar SPI-2 and April SPI-2 when it compared with seasonal SPI-2 (Figure 5.1.11) during Belg season. Adequate rains in March may have helped farmers to complete belg season planting of short cycle crops, such as barley, wheat and teff. For this season the equatorial easterlies provide rain to the highland of Somalia regional state and to the central and southeastern lowlands and highlands of Ethiopia and during Belg the southern and southeastern parts of the country enjoy their main rainy season (Kassa Fikadu, 2015).

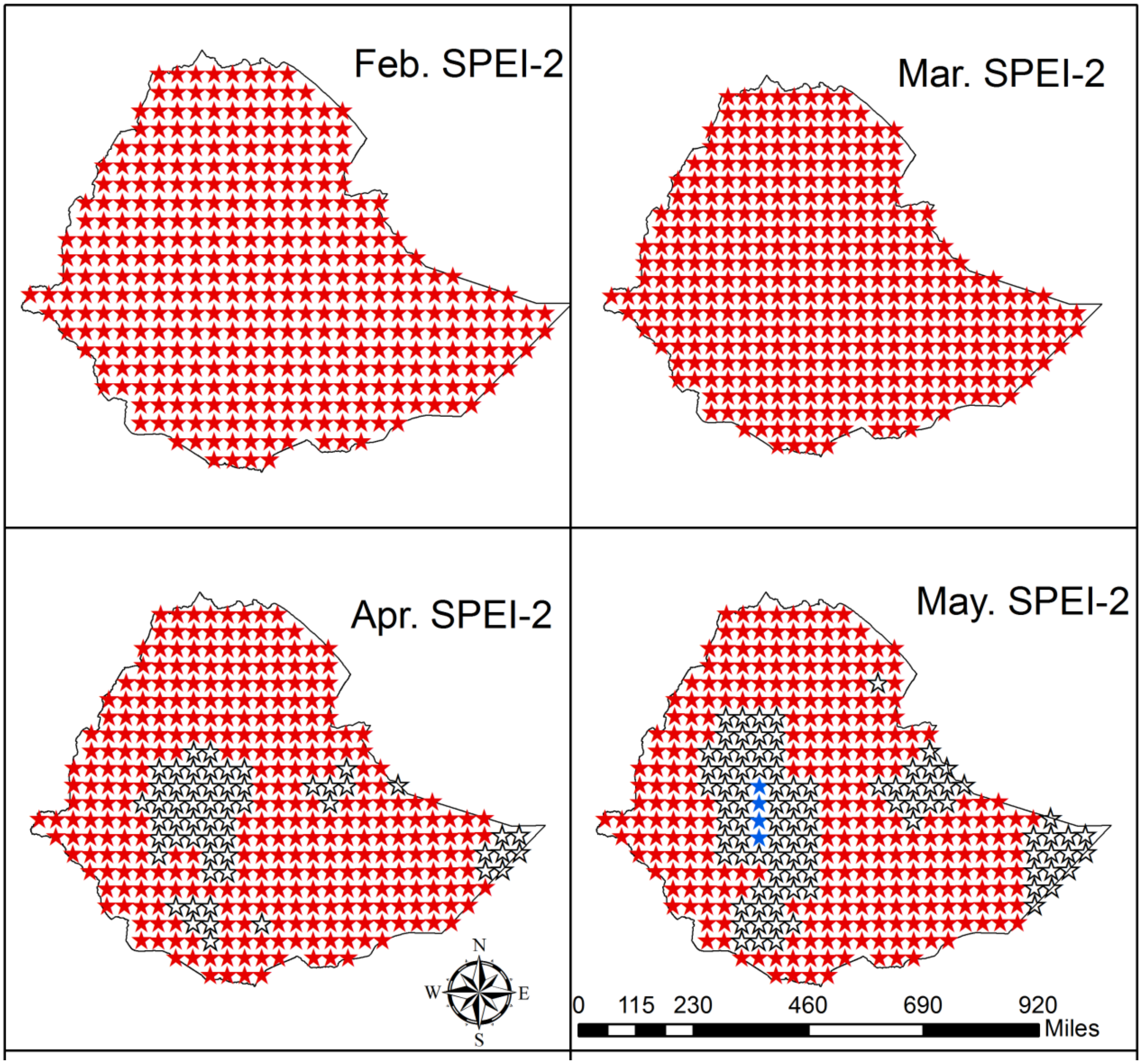

Figure 5.1.9 Intra- Seasonal trends of agricultural drought (SPEI-2) across Ethiopia during Belg season

During Belg season Feb-SPEI-2 and Mar SPEI-2 are getting dry due to increased evaptranspiration. When we look at figure 5.1.8 there is no significant drought trend for Feb-SPI-2 and Mar SPI-2 but, Feb-SPEI-2 and Mar SPEI-2 have significant drying trend as illustrated in Figure 5.1.9 and seasonal SPEI-2 aggressive as well. During the Belg intra-season, Apr SPEI-2 and May SPEI-2 have extreme events mostly observed over north -west extending towards the eastern part of the country and north-eastern parts of country. In the Belg agricultural drought had significantly affects pastoral and agricultural areas of southern, southwestern and parts of northeastern low lands for the accessibility of pasture and drinking water.

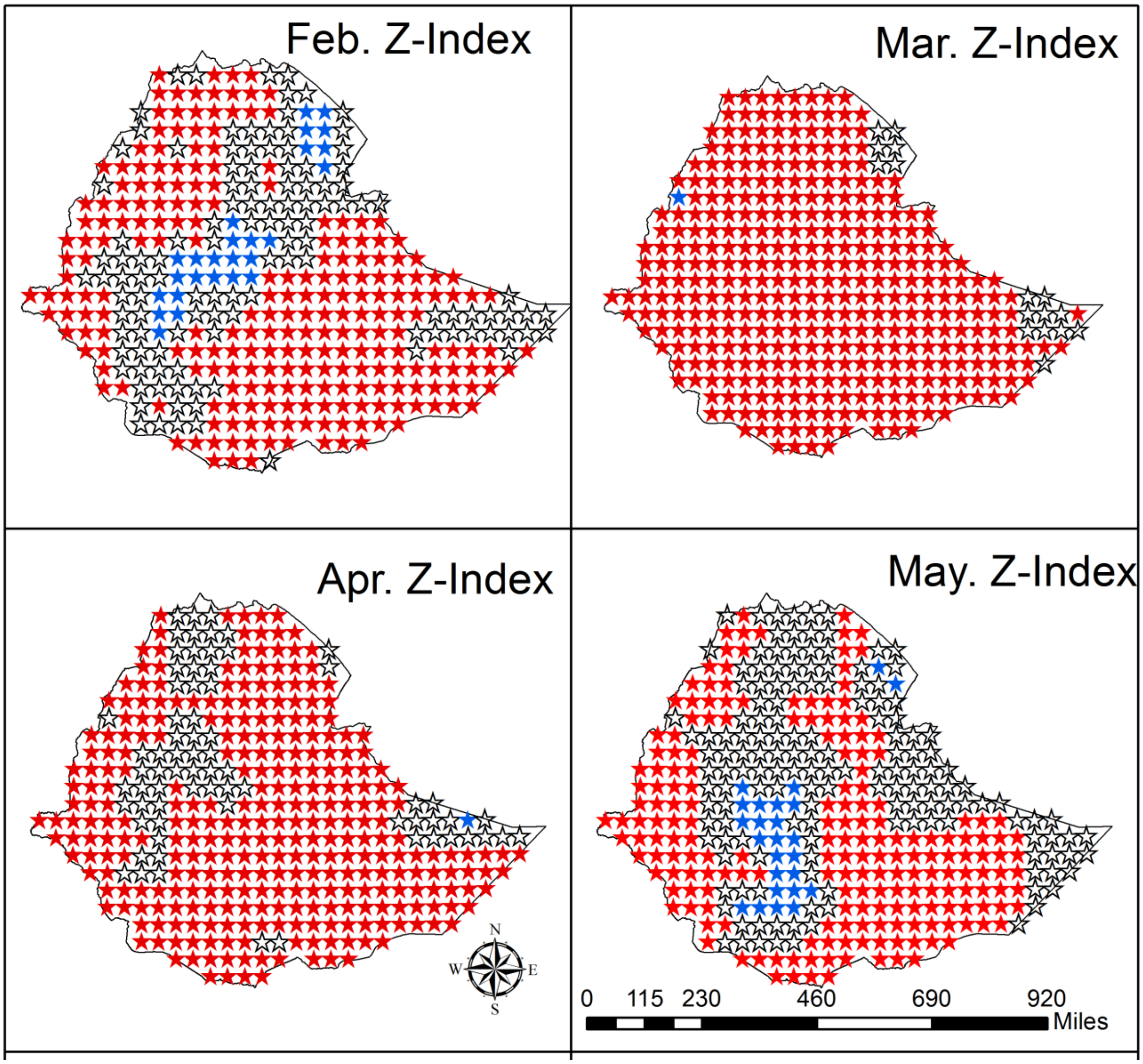

Figure 5.1.10 Intra-Seasonal trends of agricultural drought (Z-Index) across Ethiopia during Belg season

Within Belg season except southern and southeastern low lands of Ethiopia for most parts of country it is the small rainy period. This season covers the period from February to May. As it is shown in Figure 5.1.10 in the Mar. Z-Index and Apr. Z-Index in Belg season agricultural drought was strengthened in amount and distribution over entire country. A Seasonal Z-Index during Belg season show drying trend over all country except eastern part of Afar and Somalia (see Figure 5.1.11). At this month crop growth is highly dependent on short-term moisture conditions, and affects long cycle crop like Maize and Sorghum in which it plated during this months. Z-

Index is the most sensitive indicator for detecting agricultural drought trend and it doesn't depend on antecedent soil moisture condition.

For intra-seasonal droughts, PDSI, shows drying trends throughout months during Belg seasons with similar pattern. In south east margin of Somalia regional state and south west central parts of country drought trends are not detected. PDSI in any given month is determined by antecedent conditions (previous PDSI values), only one-third of its value is dependent on the precipitation and temperature in the current month (Steven et al., 2003).

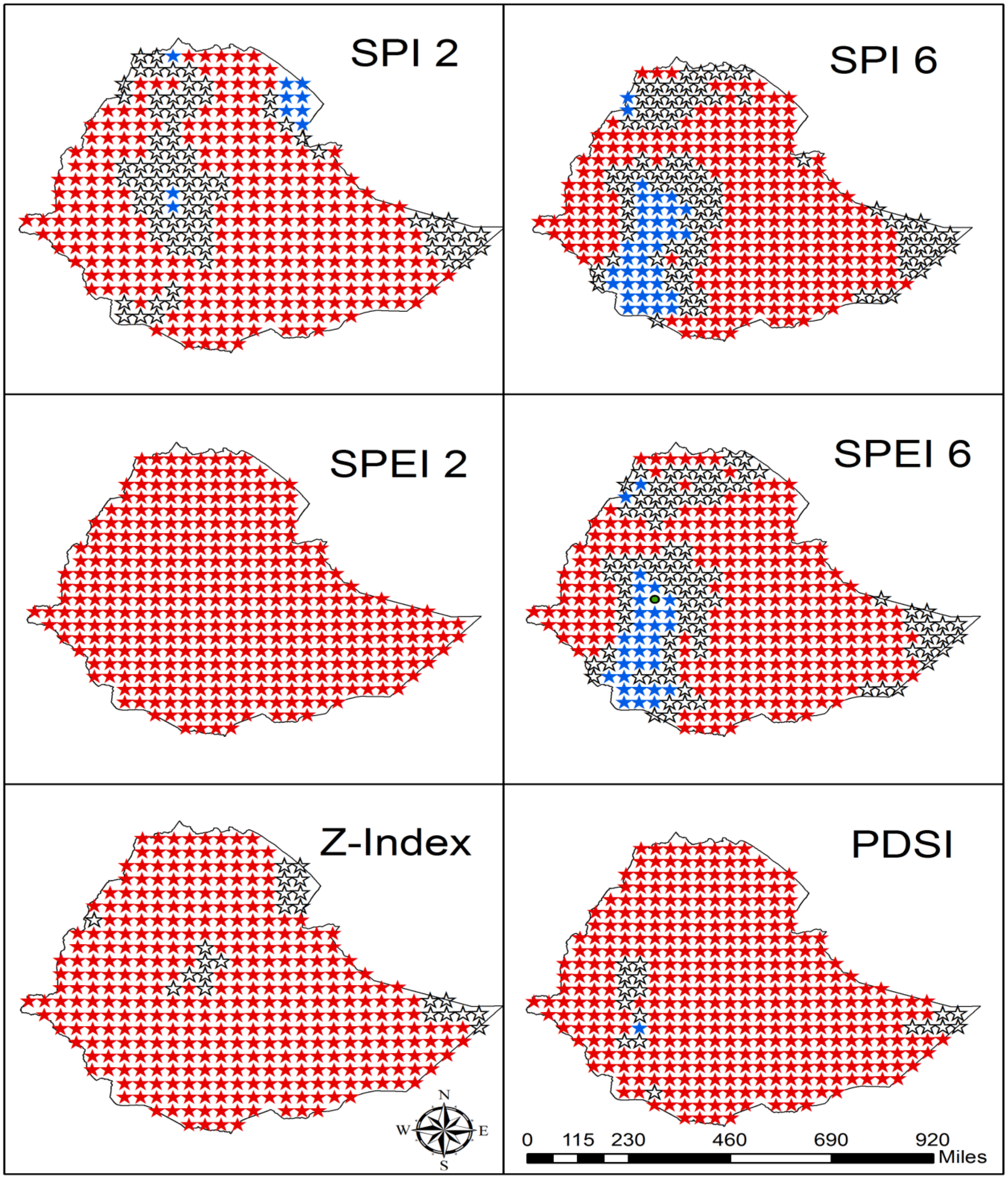

Figure 5.1.11 Seasonal Trends of meteorological and agricultural drought across Ethiopia during Belg Season

Seasonal Mann Kendall Tests maps shows more increasing drought trend than seasonal maps during Belg season. The Belg season is facing greatest threat when it is compared to Bega and

Meher season. Figure 5.1.11 above shows the worse drying trend for SPEI-2, PDSI and Z-Index and increasing temperature however; null hypothesis is not rejected for SPI-2, SPI-6 and SPEI-6 at central parts of Ethiopia. Asfaw et al., (2018) reported that the palmer Drought severity index shows intensively increasing drought trend which is in agreement with the results. Then again, Belg rain which is important not only just for the Belg crops (accounting for 5–15% of the national food crop) but also for improving pasture for livestock, and for the planting of long-season crops as well as useful for land preparation for Meher production.

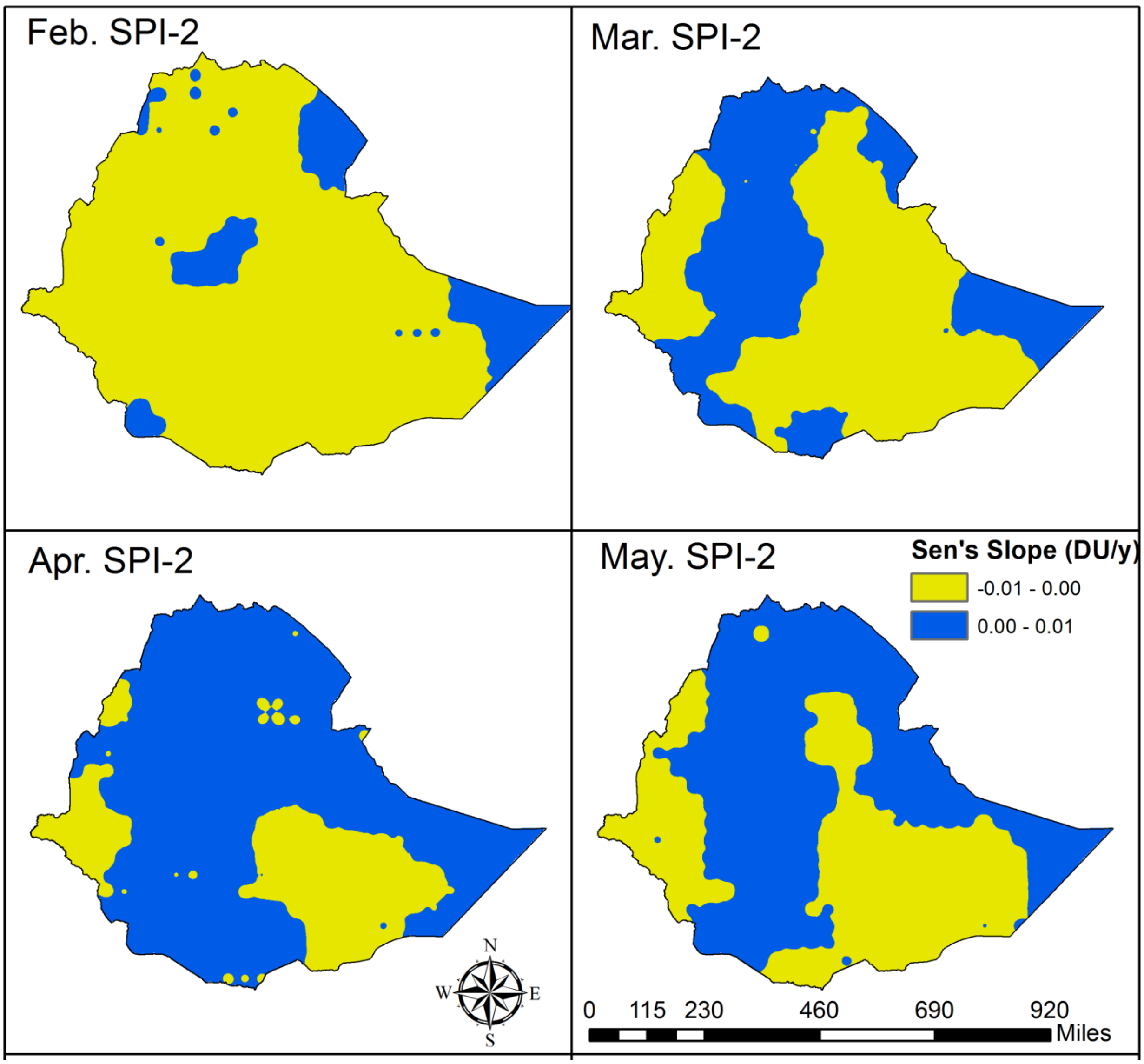

Figure 5.1.12 Variability of Sen's slope for Intra-Seasonal meteorological (SPI-2) drought trends across Ethiopia

The variability of Sen's slope for SPI-2 meteorological drought indicator within Belg season is shown in Figure 5.1.12. The Belg rainfall has a crucial importance for social and economic benefits. The magnitude of Sen's Slope shows both positive trend (wet) changes by 0.01DU/y and negative trend (dry) -0.01DU/y

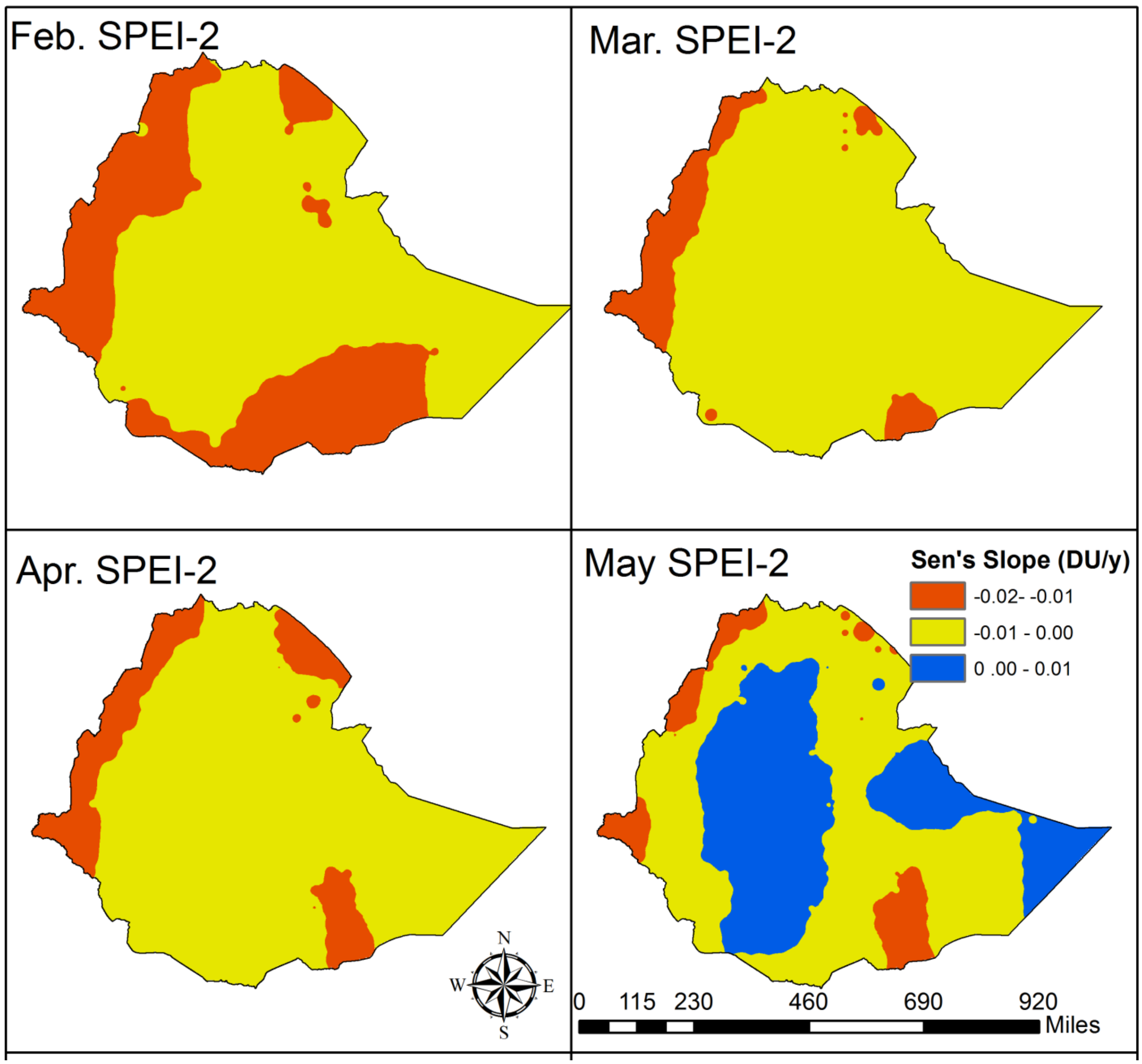

Figure 5.1.13 Variablity of Sen's slope for Intra-Seasonal agricultural (SPEI-2) drought trends across Ethiopia

Except May SPEI-2, all Belg months namely Feb. SPEI-2, Mar. SPEI-2 and Apr.SPEI-2 have negative (dry) trend changing from -0.01 - -0.02 DU/y. As indicated in Figure-6 Feb SPEI-2, Mar SPEI-2 April SPEI-2 variability of Sen's slope shows drying trend due to increased temperatures are important in characterizing agricultural droughts.

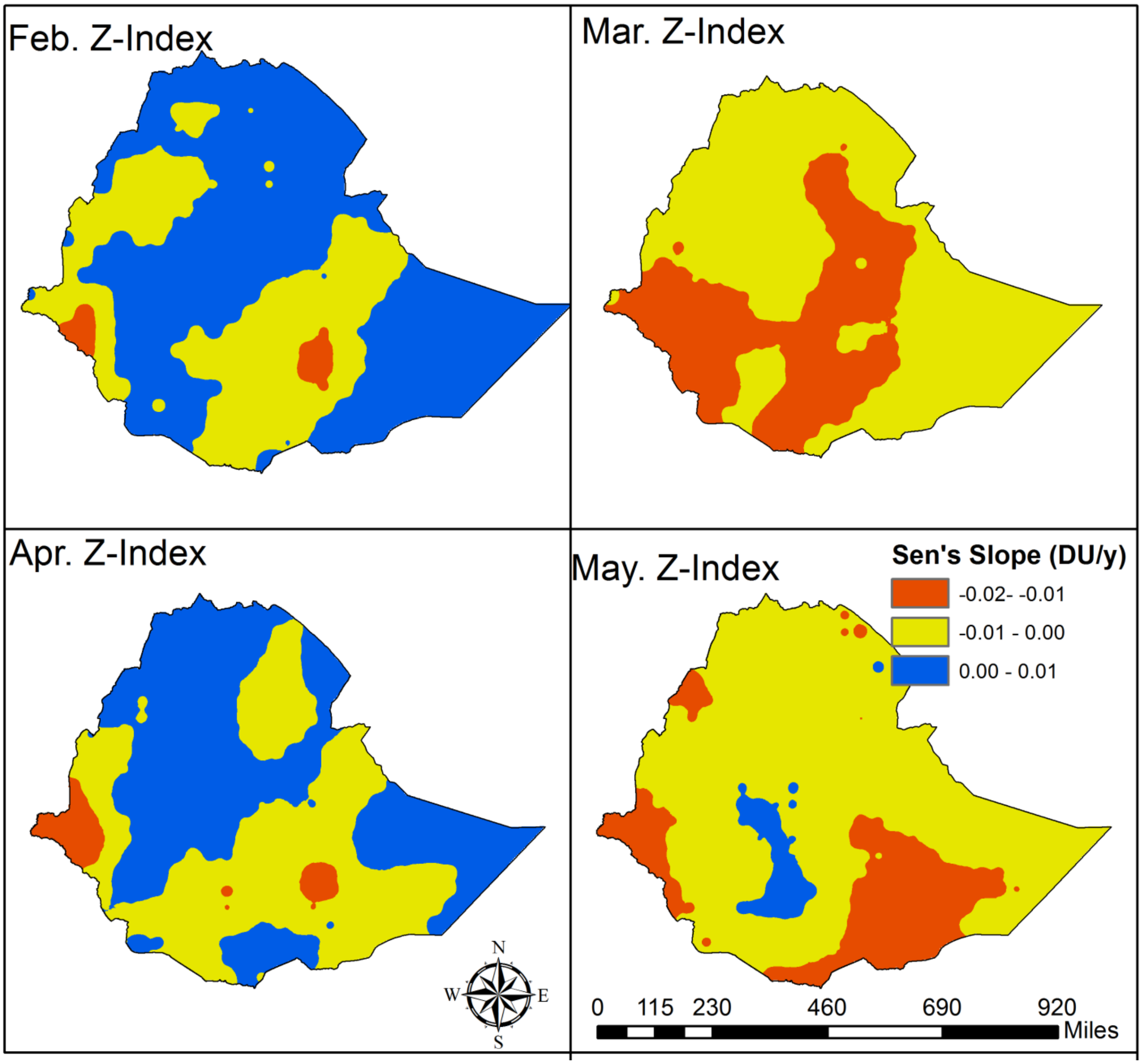

Figure 5.1.14 Variability of Sen's slope for Intra-Seasonal agricultural (Z-Index) drought trends across Ethiopia

Figure 5.1.14 the magnitude of sen's slope shows significant increasing in Agricultural drought during month of March (Mar. Z-Index) and May (May.Z-Index) in all parts of the country. Wetting trend observed in northern and central parts of country in February and April. Figure 5.1.14 shows aggressive deficit in soil moisture observed in March which has negative impact on long cycle crops and it has ~ -0.02DU/y.

5.1.3 Monthly Seasonal Trends across Ethiopia during Meher season

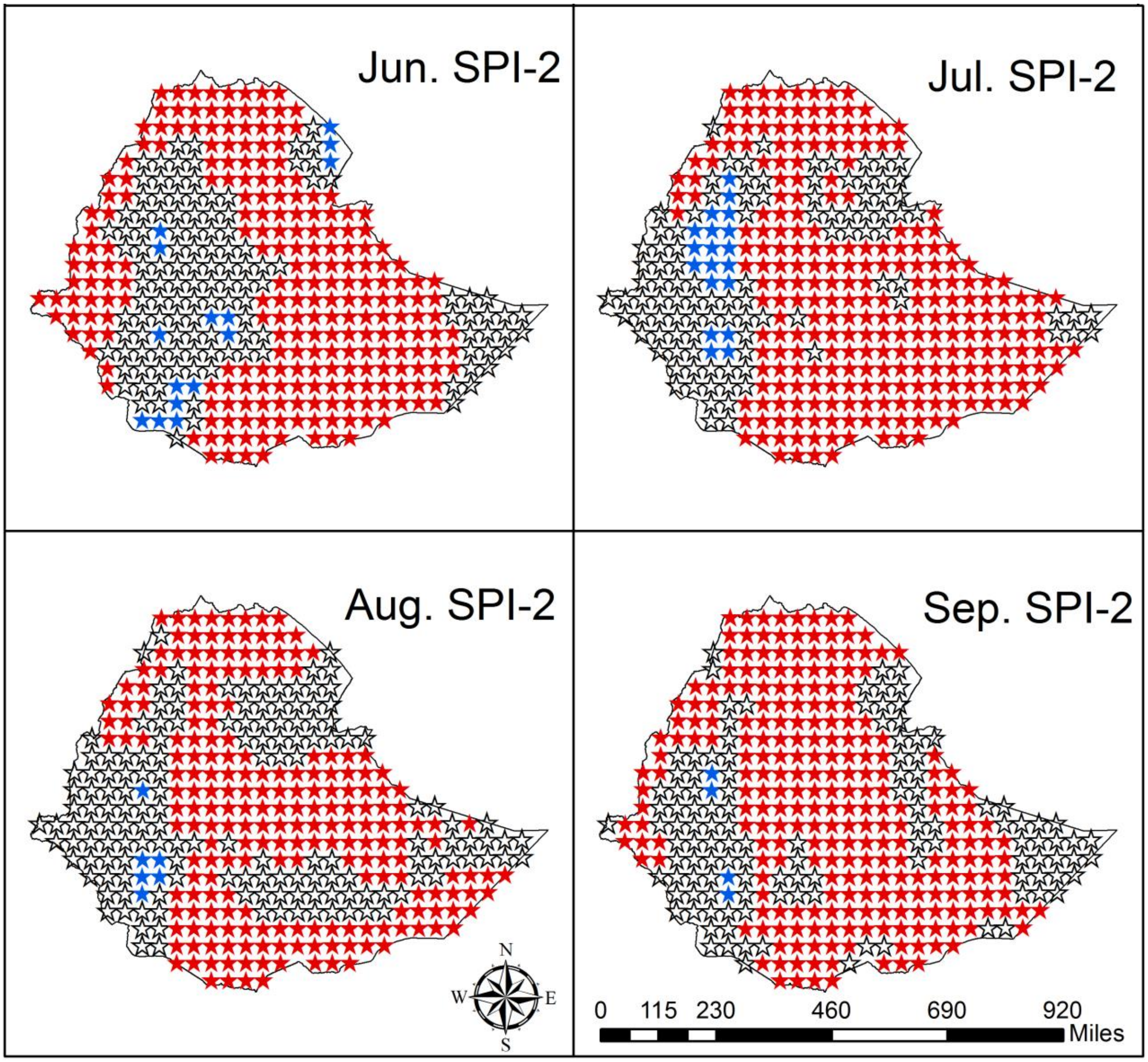

Figure 5.1.15 Intra-Seasonal Trends of meteorological drought (SPI-2) across Ethiopia for Meher season (Red: Drying Trend, Blue: Wetting Trend, and Black: No statistical Trend)

Meher is the main rainy season in Ethiopia, lasting from June to September. This season is caused by the convergence of low-pressure systems of inter tropical convergence zone (ITCZ). From Meher seasonal rainfall that illustrated in Figure 5.1.15, the south and southeast portions of the nation are seeing increasing meteorological drought trend in June and July however, southwest, west, north, central and mid-east regions of Ethiopia getting increase in drought trend Aug in SPI-2 and Sep SPI-2. In general during Meher season decline in precipitation observed this result agree with Cheung et al., (2008) they reported that there was a significant decreasing trend for Meher (June-September) rainfall for some watersheds over the period from 1960 to 2002 in Ethiopia. The intra-seasonal rainfall variability also shows significant differences variation across the lowlands and Rift Valley regions. Sep SPI-2 shows significant drying trends compared to June SPI-2, SPI-2 and Jul SPI-2. The aggregate seasonal SPI-2 which is shown in Figure 5.1.18 shows except south-west central parts of country precipitation decreasing in all parts of country.

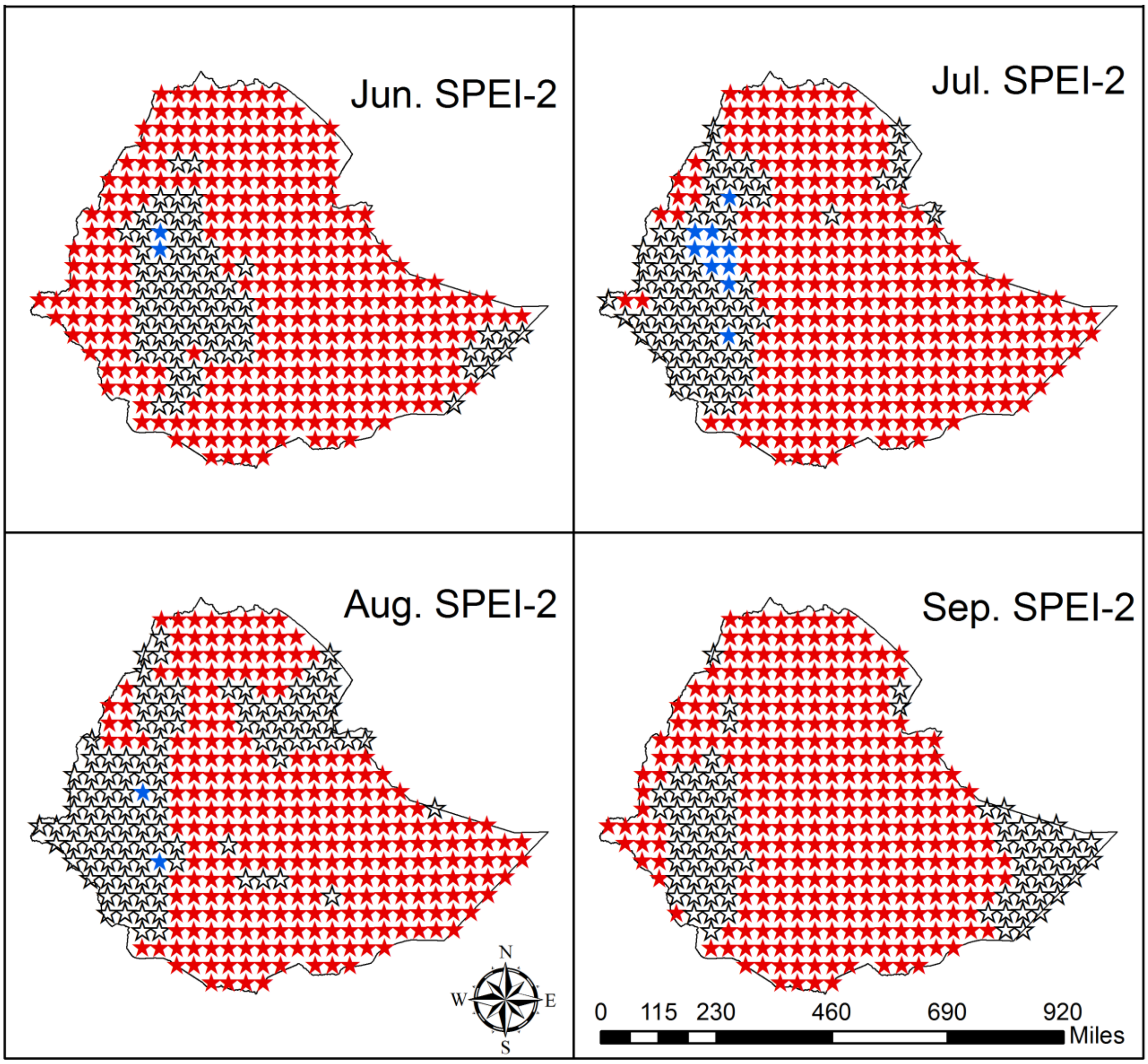

Figure 5.1.16 Intra-Seasonal Trends of agricultural drought (SPEI-2) across Ethiopia during Meher season

Mehir(June-September) is the season that satisfies the crop water requirement for long -term crops like maize and sorghum that are planted in the months during Belg season and for Meher crops that achieve maturity at start at late September which is part of Bega season (NMA, 2018). In Ethiopia during Meher, moisture condition all over the months benefited drinking water over pastoral and agro-pastoral areas and Meher agricultural activities. However, late onset of Meher rain and insignificant moisture stress observed over some parts of low lands of eastern half and central parts of the Ethiopia (NMA, 2018). During this season increasing agricultural drought trend observed in northern, southern and south-eastern parts of country in Jun. SPEI-2 and Jul. SPEI-2. Increases in precipitation also observed for Aug-SPEI-2 at south western parts of nation. During Meher season precipitation is decreasing in Sept. SPEI-2 relative to Jun. SPE-2, Jul. SPEI-2 and Aug.SPEI-2 as it is shown in Figure 5.1.16. The aggregate SPEI-2 also shows increasing drought trend in many parts of country as it indicated in Figure 5.1.18.

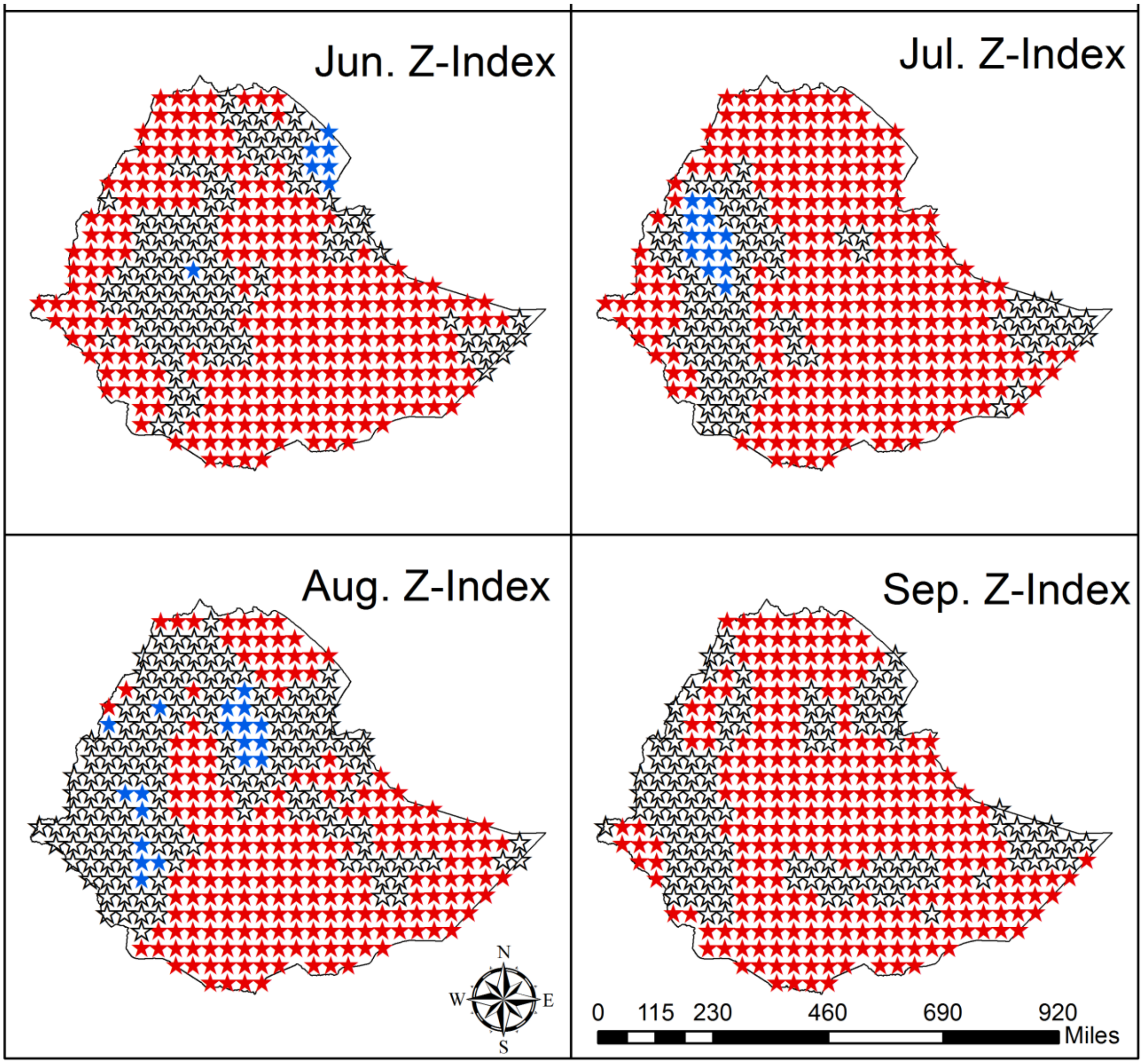

Figure 5.1.17 Intra -Seasonal Trends of meteorological drought across Ethiopia during Meher season

In July except south-west parts of country others exhibit deficit of moisture. From Meher season September (Sep. Z-Index) shows decline in soil moisture (agricultural drought) due to decreasing rain fall during Meher season.

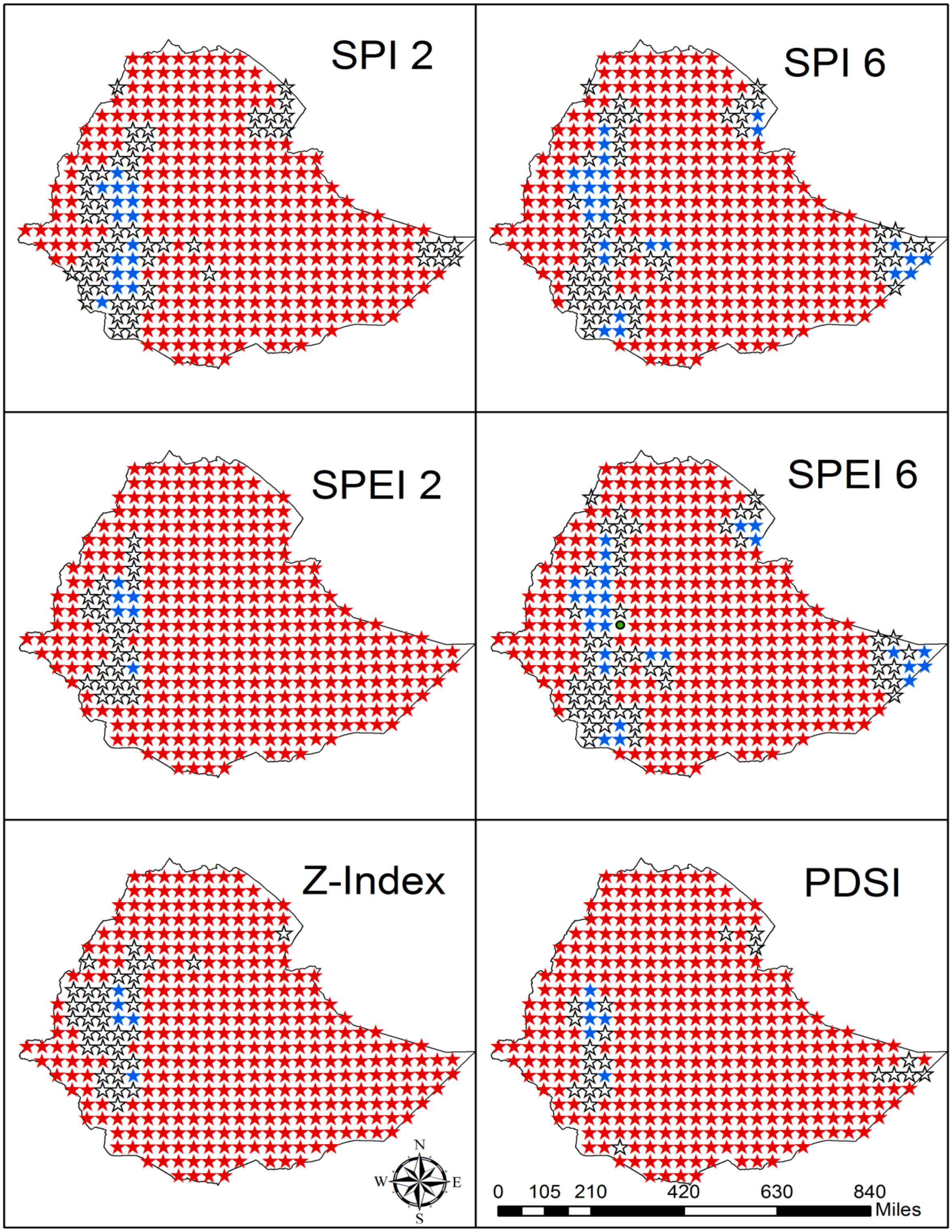

Figure 5.1.18 Seasonal Trends of meteorological and agricultural drought across Ethiopia for Meher season

The Seasonal Mann Kendal Test maps shows more drying trend than seasonal maps (maps formed by aggregating monthly data into seasons first and then performing Mann Kendall test) however, both show nearly same drying trend in Northern, central, south eastern parts of the country. As it shown by Figure 5.1.18 Seasonal Mann Kendal Test map indicates in south western parts drought trends are not detected and some parts getting wet. In general there is declining precipitation all over the country except south west central parts of Ethiopia. The Meher season generally decreasing in rain fall (increasing drought) this result is agree with finding of Temam et al.,(2019), Asfaw et al.,(2018) and Wagisho et al.(2013). Meher rain account for 50–80% of annual rainfall totals in Ethiopia and has high contribution to agricultural productivity and major water reservoirs. Hence, the most severe droughts in Ethiopia are usually related to a failure of the Meher rainfall to meet the agricultural and water resource needs.

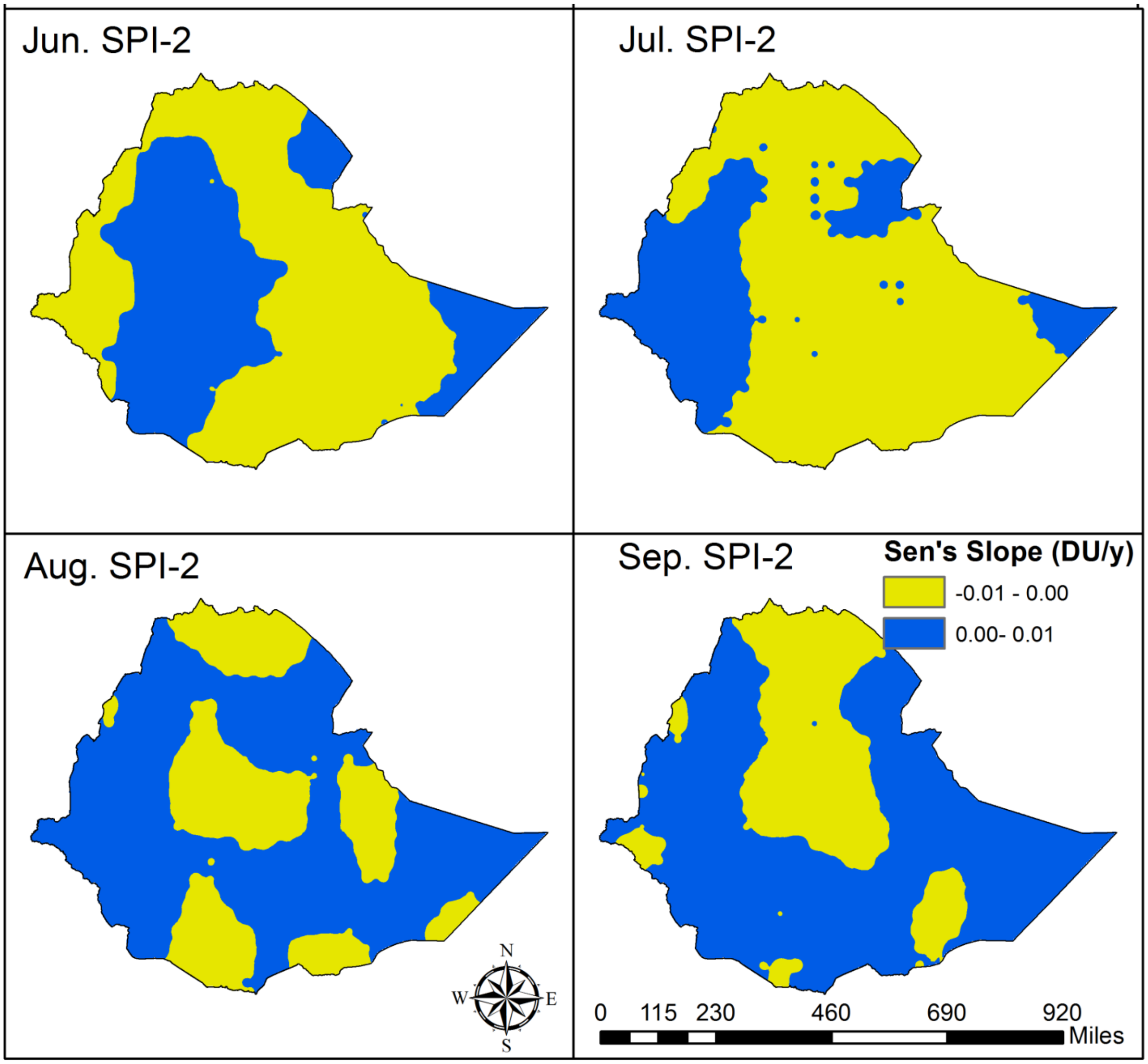

Figure 5.1.19 Variability of Sen's slope for Intra-Seasonal meteorological (SPI-2) drought trends across Ethiopia

Aug. SPI-2 and Sep. SPI-2 shows positive (wet) trends in many parts of country and Jun. SPI-2 and Jul. SPI-2 indicates negative (drying) trend and have -0.01DU/y.

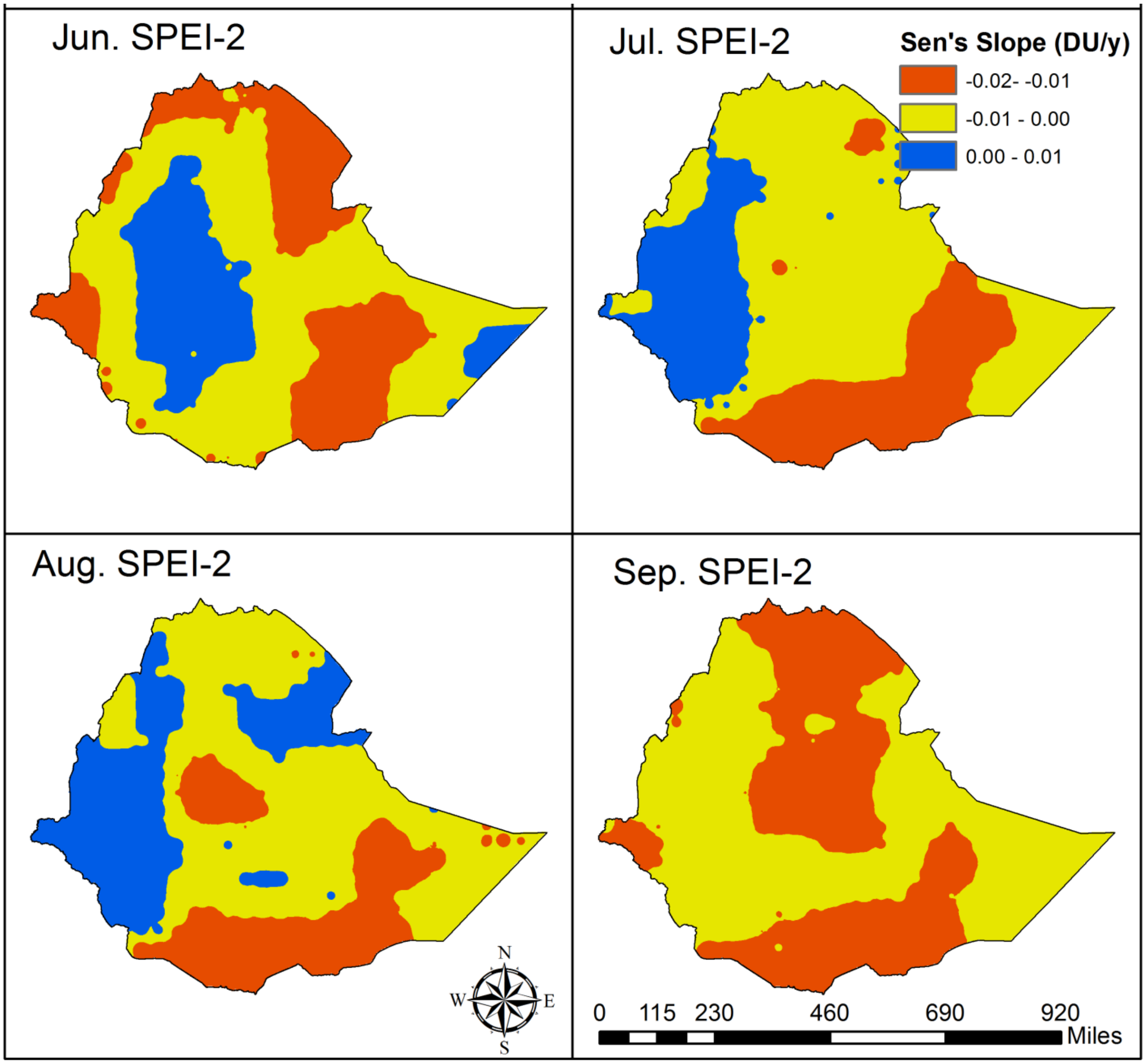

Figure 5.1.20 Variability of Sen's Slope for Intra-Seasonal agricultural (SPEI-2) drought trends across Ethiopia

The variability of Sen's slope have seen in Meher season (June- September) changes in drying trends noted due to precipitation declines and temperature increases in the central , south eastern and northern parts of country in Jun SPEI-2, July SPEI-2 and Aug SPEI-2. From Meher season September shows significant drying trend ~ -0.02DU/y.

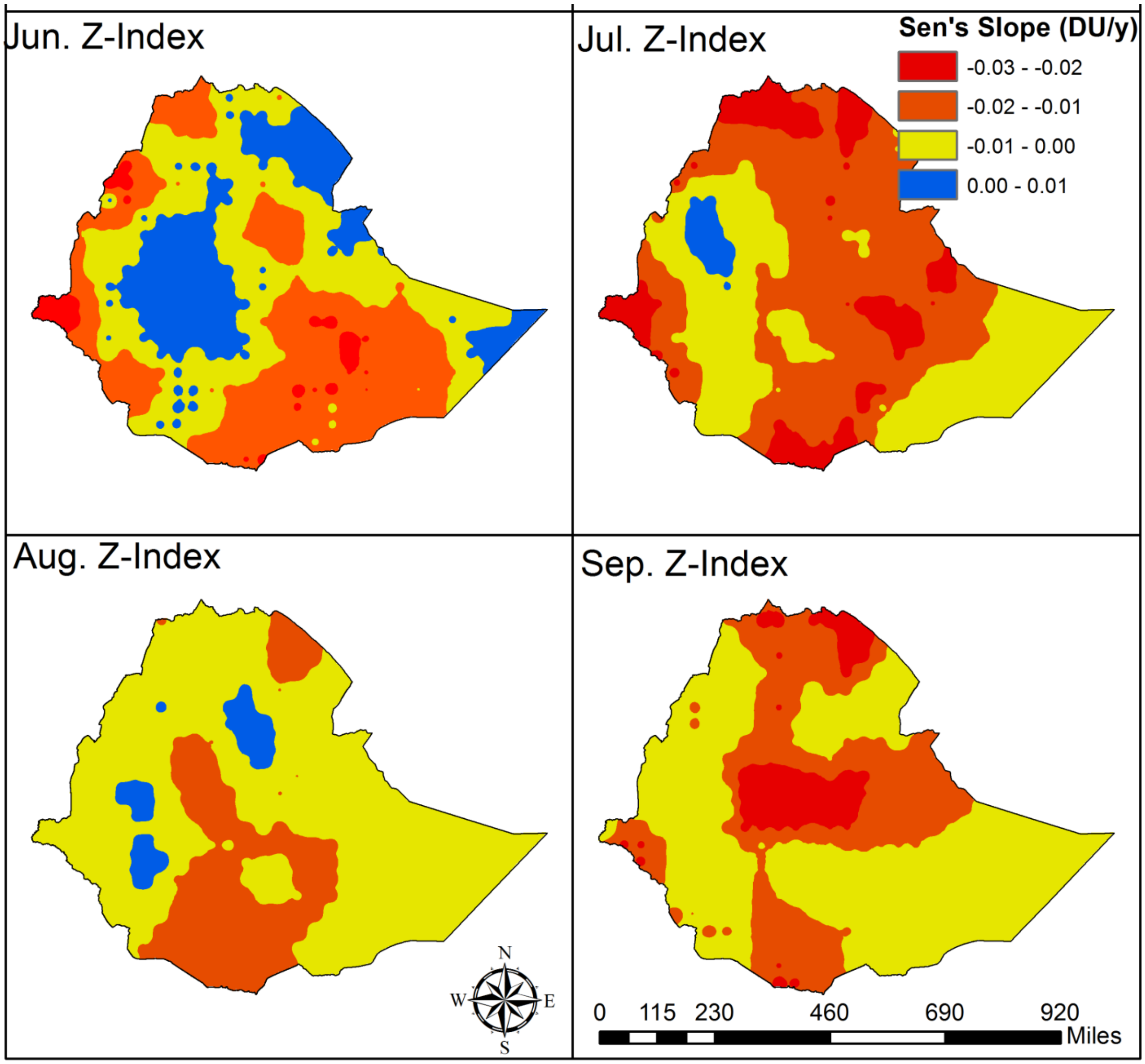

Figure 5.1.21 Variability of Sen's Slope for Intra-Seasonal agricultural (Z-Index) drought trends across Ethiopia

As to be expected, the magnitudes of wetting and drying trends are varying during Meher season (June –September). In June north-east, central and south-west parts of country there is increasing wet trend. The Figure 5.1.21 above shows intra-seasonal agricultural drought increasing during months of Jul. Z-Index, Aug. Z-index and Sept. Z-index throughout the whole parts of the country. As part of agricultural drought index Z-index shows drying trends which affects both long cycle crop and Meher season crops that achieve maturity during Bega season. Mostly drying trend observed in Sep. Z-index relative to another Meher Months and its changing magnitude is ~ -0.03DU/y

Conclusion

Agriculture is the main economic sector that influenced by agricultural drought. Understanding the effects of drought within season is essential to identify drought indicators response for each month within season because drought at growth stage affects more than maturity stage. This study mainly focuses to see the intera-seasonal effects of meteorological and agricultural drought trends using Seasonal Mann Kendall Test and for both meteorological and agricultural drought indicators and it evaluates trends of meteorological and agricultural drought within Bega, Belg and Meher using SPI, SPEI, PDSI and Palmer Z-index (Z-index). The study showed that in which month meteorological and agricultural drought trend adversely impacting.

For Bega season, seasonal Mann Kendall test shows that increasing, decreasing and no trends in some parts of country. Drying trends are consistent in where Bega common. The Belg season season is facing greatest threat due to increasing temperature and deficit in soil moisture. SPEI-2 was the most sensitive indicator for detecting trends during Belg season among short term drought indicator, while PDSI is the most sensitive for long term drought indicator. The Meher season generally decreasing in rain fall (increasing drought) and accounts 50 - 80% of annual rain fall that is why the most severe droughts in Ethiopia are usually related to a failure of the Meher rainfall.

As part of meteorological droughts indicator Dec. SPI-2 trend was more sensitive than Oct. SPI-2, Nov. SPI-2 and Jan. SPI-2. The comparison of Mann Kendall tests after seasonal aggregate and before seasonal aggregate for Bega season, before seasonal aggregate (performing Mann Kendall tests for each month and then aggregating them over seasons) shows increasing drought but, the pattern of increasing is nearly similar.

Drying trend most pronounced during Belg season. In this season increasing meteorological drought is observed in Feb. SPI-2 and Mar. SPI-2 but Feb. SPI-2 is the prevalent during Belg season than Mar SPI-2, April SPI-2 and May SPI-2 rain in this season is very important for agricultural activities. The Comparison of monthly inter-seasonal trends with seasonal aggregate analysis for SPI-2 indicates that a south east central part of country is decreasing in precipitation (meteorological drought).

Intra-seasonal rainfall variability also shows significant differences variation across the lowlands and Rift Valley regions during Meher season. Sep. SPI-2 shows significant drying trends compared to another Meher months namely; Jun. SPI-2, SPI-2 and Sep. SPI-2. The magnitude of trend change is both positive trend (wet) changes by 0.01DU/y and negative trend (dry) -0.01DU/y. The Seasonal Mann Kendal Test maps shows more drying trend than seasonal maps (maps formed by aggregating monthly data into seasons first and then performing Mann Kendall test) However, both show nearly same drying trend in Northern, central, south eastern parts of the country during Meher season.

The pattern of the agricultural drought within each season shows variability in trend change. Jan. SPEI-2 is getting dry trend relative to another Bega months. During the Belg season, Apr. SPEI-2 and May SPEI-2 have extreme events mostly observed over north –west extending towards the eastern part of the country and north-eastern parts of country. Meher season shows decreasing precipitation in Sep. SPEI-2 and at higher precipitation accumulation levels meteorological and agricultural drought indicators exhibited greater similarity.

Z index (Moisture Anomaly Index) is best indicator to show short term soil moisture deficit and it didn't depend on previous soil condition. During Bega season Z-index is more sensitive in October due to decreasing in precipitation. In March within Belg season agricultural drought was strengthened in amount and distribution over entire country and from Meher season September (Sept. Z-Index) show decline in soil moisture (agricultural drought). The magnitude of trend change varies from 0.01DU/y to -0.03DU/y.

Agricultural systems are affected by intra-seasonal effects of drought. Therefore, it is recommended that the federal and regional governments, the nation's farming community and other stake holders should make themselves ready for the challenge of reoccurring and related problems by implementing the mitigation and adaption measures.

5. Chapter- Five: General Conclusions and recommendation

5.1 Conclusions

Agriculture is the primary economic driver in Ethiopia. Droughts can cause major economic, environmental, and sociopolitical disruptions in Ethiopia because the country rainfall-dependent. Understanding how meteorological and agricultural droughts propagate through agro-hydrological systems has paramount importance to cope up effects of drought. In Ethiopia, there have been some studies that have evaluated regional trends by using meteorological drought indicators. However, in addition to rainfall, soil dryness (agricultural droughts) can be caused by increased temperatures and evapotranispiration. To quantifying agricultural droughts, it is better to use drought indicators that account both rainfall and temperature effects instead of using rainfall alone. In this study, the standardized precipitation evapotranspiration index (SPEI), the Palmer drought severity index (PDSI), and the associated Zindex are used to characterize short-term (two-month accumulation) and long-term (six-month accumulation) droughts during the three major seasons Bega (Octotober - January), Belg (February - May), and Meher (June-August) in Ethiopia. Furthermore, the response of these indicators evaluated to see the trend shifts within seasons.

Meteorological and agricultural drought indicators exhibited greater similarity at higher precipitation accumulation levels because rainfall in other seasons that accumulates in the longer-term droughts help buffer intraseasonal changes. The result shows that, PDSI was noted to be the most assertive drought indicator for long-term droughts, indicating that noted precipitation and temperature declines create delayed but more prominent changes in hydrologic and soil moisture dynamics.

For characterizing short-term droughts SPEI-2 (two-month accumulation) was the most aggressive drought indicator, indicating surficial drying due to increased temperatures are important in characterizing intraseason droughts over much of the country. Intraseasonal droughts over much of the country exhibited declining trends when evaluated on a century-scale data. Winter temperatures had a major influence on Bega droughts. Temperature increases further exacerbated soil dryness caused by rainfall declines during Belg, during which many crops are grown for internal food consumption. Declining trends were also noted during Meher but were largely attributable to changes in rainfall more so than changes in temperature. Even small changes in the magnitude of rainfall has a greater impact, as this is the major rainy season over much of the country.

Drying trends are most prevalent during Belg season especially for two-month accumulation. Belg rainfall results from easterly and southeasterly winds which bring considerable rainfall to eastern and southeastern parts of the country. The increased dryness coupled with exponential population growth places an enormous stress on the agricultural systems of the country. As Tef grown during Belg is mostly consumed internally, an agricultural drought during Belg has profound implications to the food security and livelihoods of Ethiopia as it is discussed by (Rossel and Holmer , 2007). Furthermore, if the production of Tef is shifted to the longer Mehir season, the growth of high valued crops comes under threat affecting the economic viability of the nation which depends extensively on agricultural production.

Agricultural systems are affected by short-term soil drying during increased temperatures. Hydrologic changes caused by precipitation declines and temperature increases act slowly but affect soil moisture availability over the growing season The result of Seasonal Mann-Kendall test shows inter-seasonal trend analysis during Bega (dry), Belg (short-rainy) and Meher (long-rainy) seasons that SPI shows significant drying trends (meteorological droughts) and it is most rampant during December in Bega season, February during Belg season, and in July during Meher respect. SPEI indicates drying trend in December, March and September. Z-index shows moisture deficit (agricultural drought) in October, March and September during Bega, Belg and Meher season respectively. This affects both long cycled and short cycled crops.

The results of the study infer that climate has changed considerably over the last century in Ethiopia, which in turn has affected the drought characteristics. This study focused on assessing long-term and short term trends and changes in drought intensities. Chowdhury et al., (2019) reported that In addition to changes in intensities, the patterns of wet–dry spells and transitions between these climate states is also important to fully understand drought characteristics.

Soil moisture is affected by surficial drying and other hydrological processes (e.g., deep percolation, Evapotranspiration) that remove water from the soil. Overall, it is clear that climate change has been significantly affecting the trend patterns of drought. Therefore, it is recommended to; The meteorological network of the country must be expanded to provide better nationwide coverage and operated to collect data at higher frequencies (i.e., daily timescale) with little to no downtime to avoid large data gaps as they currently exist to further improve drought assessments and better characterize the impacts of trends and wet–dry spells, the creation of a national-scale soil moisture sensing program and improving agriculture resilience through irrigation should be top priorities for sustaining the agricultural-dependent economy of Ethiopia and the federal and regional governments, the nation's farming community and other stake holders should make themselves ready for the challenge of reoccurring and related problems by implementing the mitigation and adaption measures.

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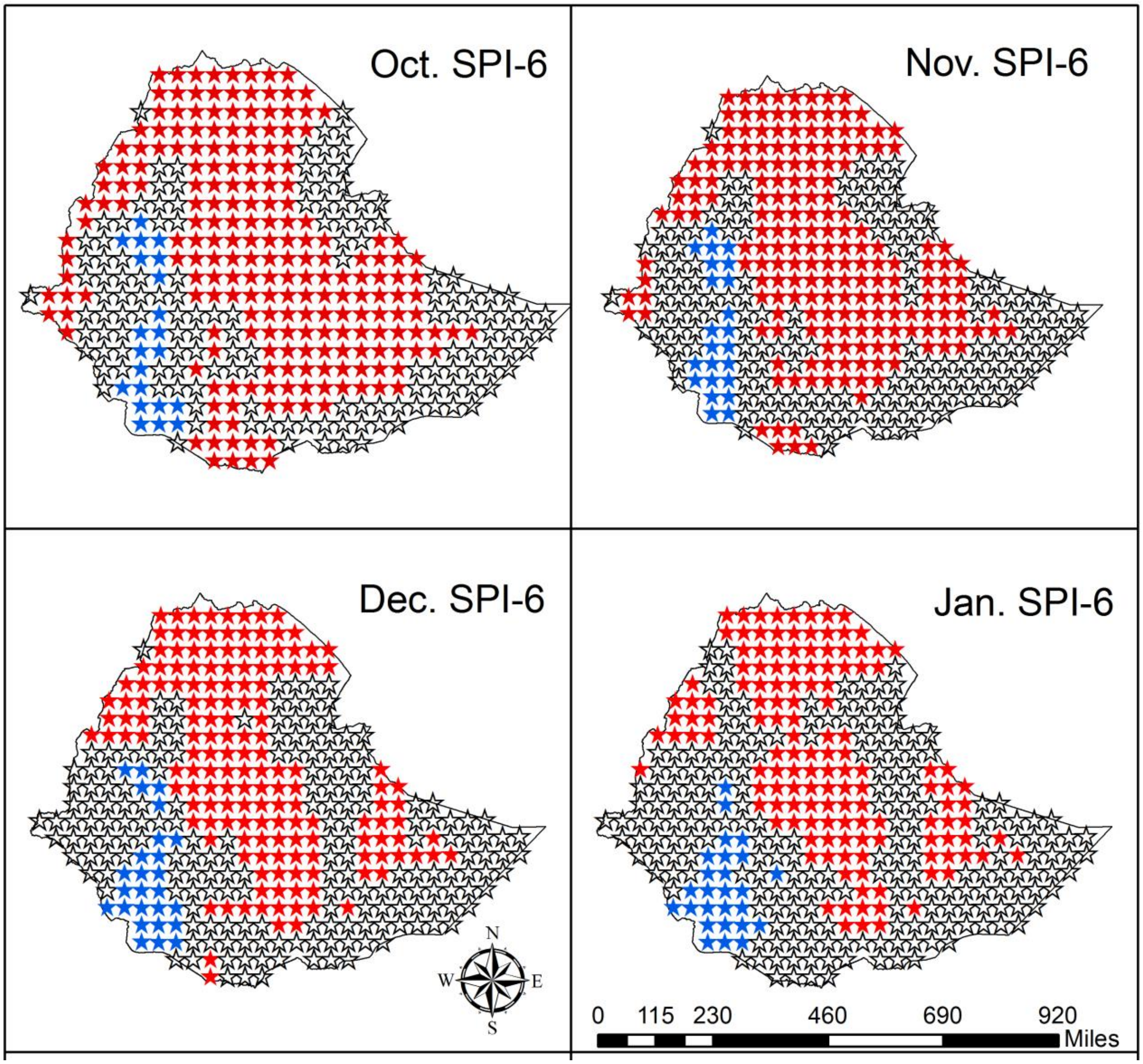
Annexes



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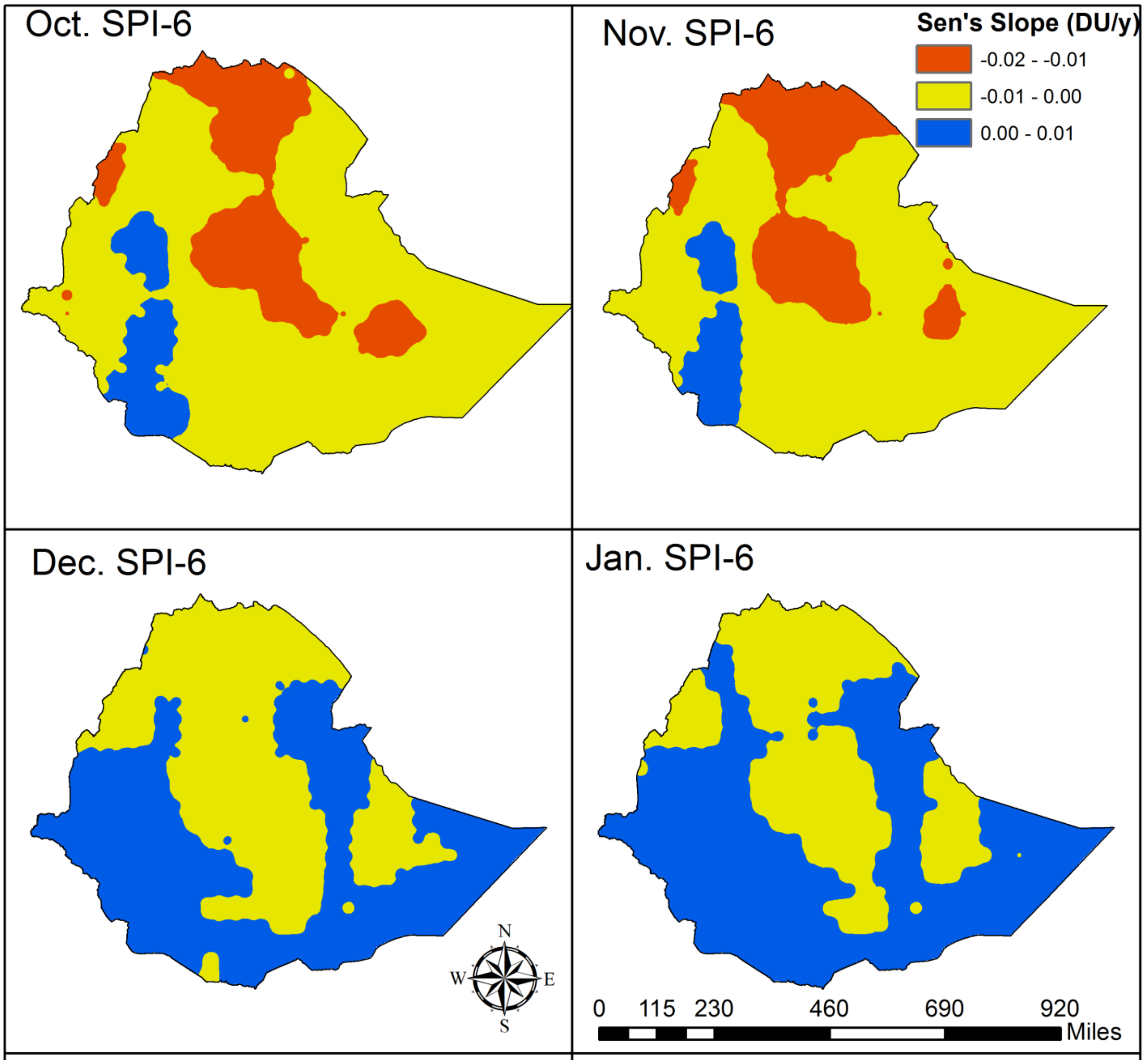
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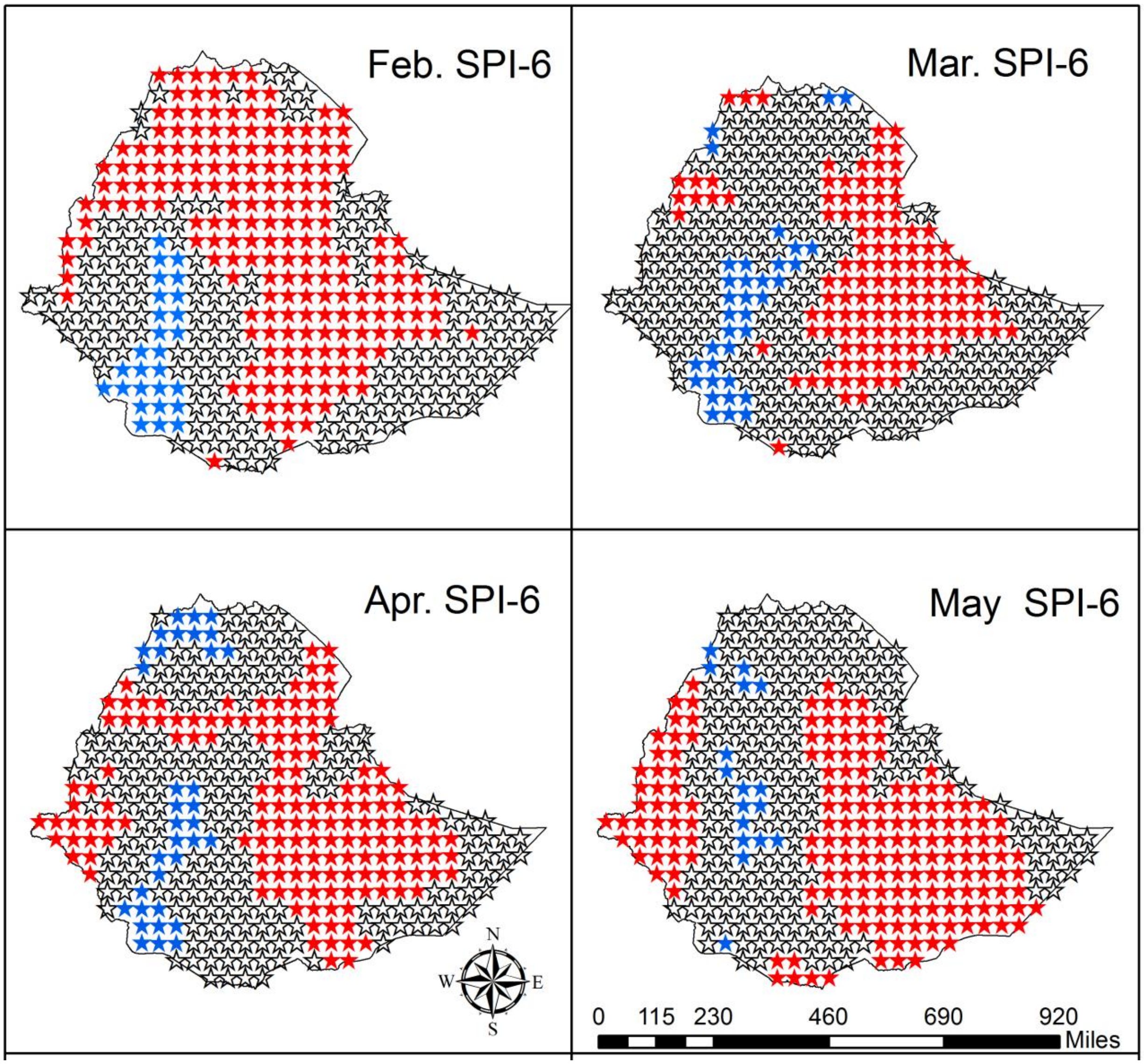
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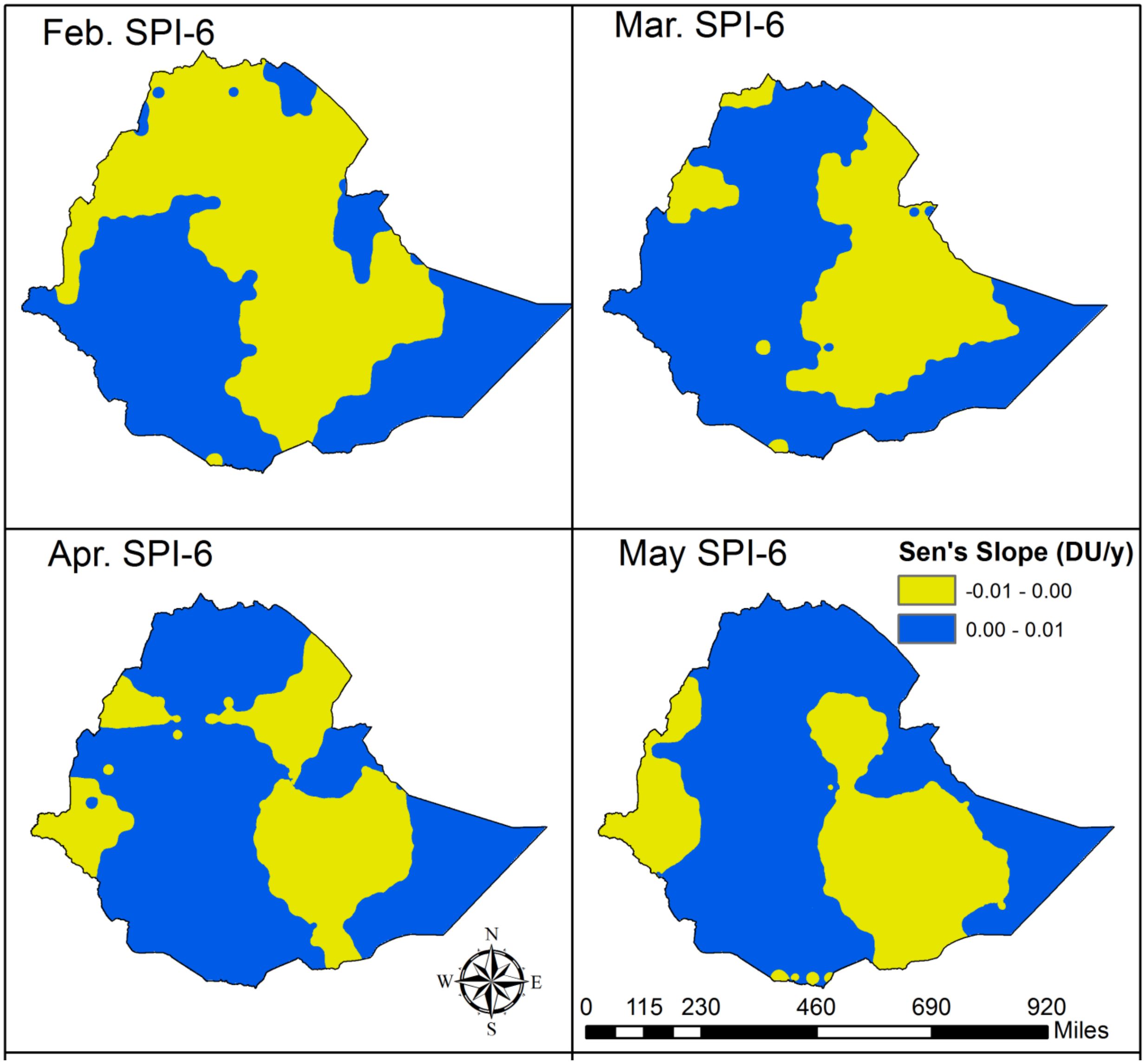

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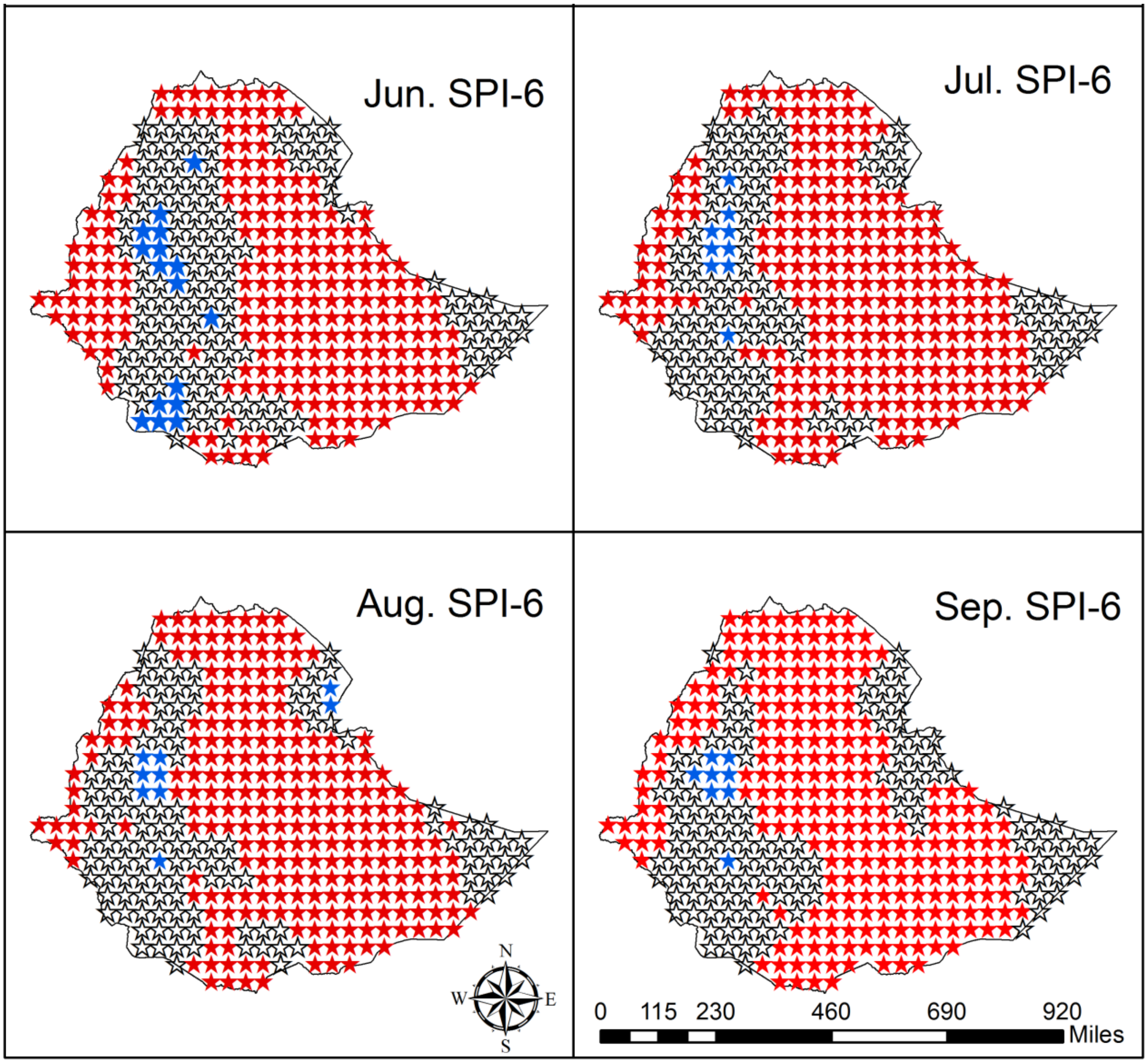
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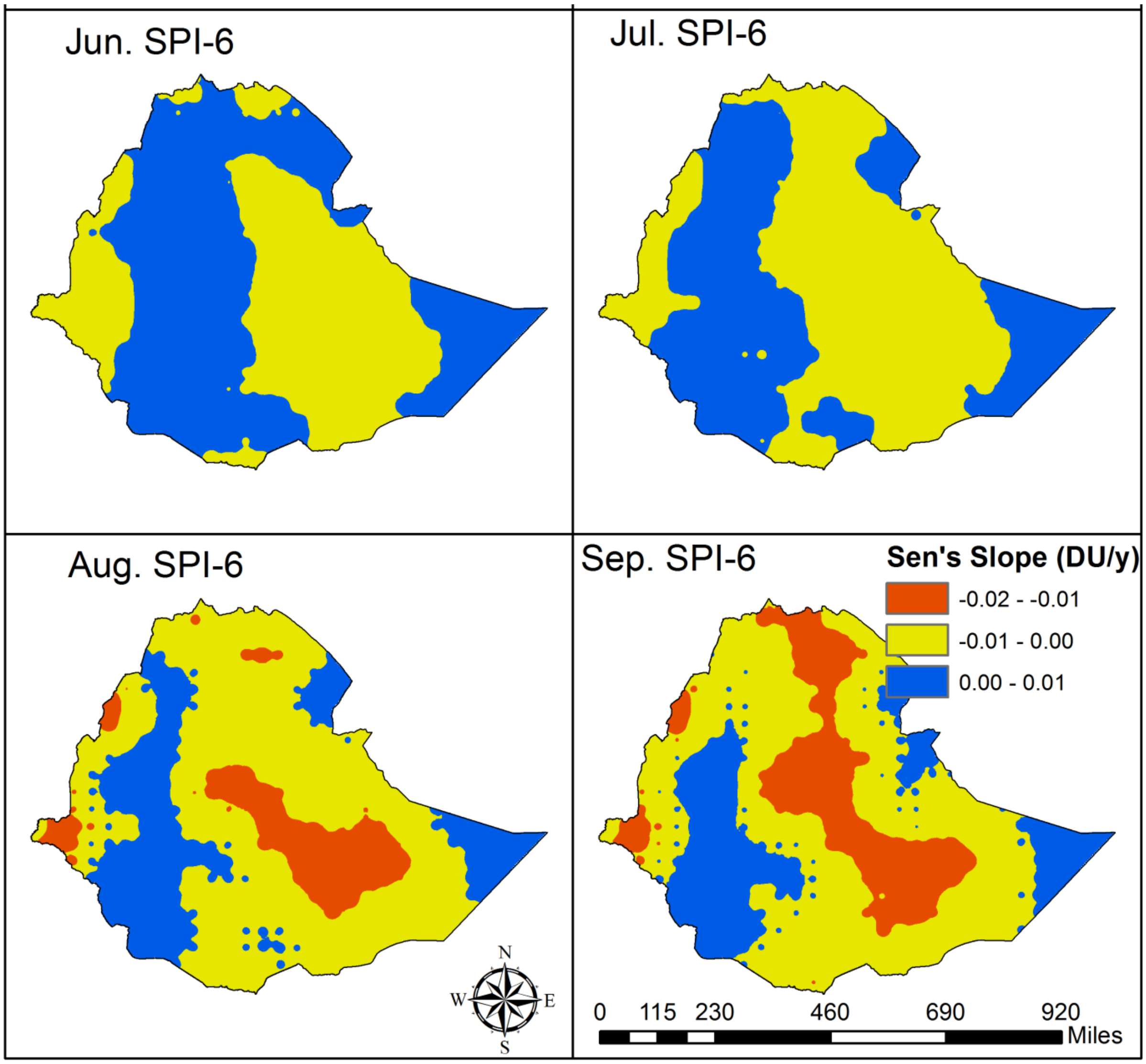

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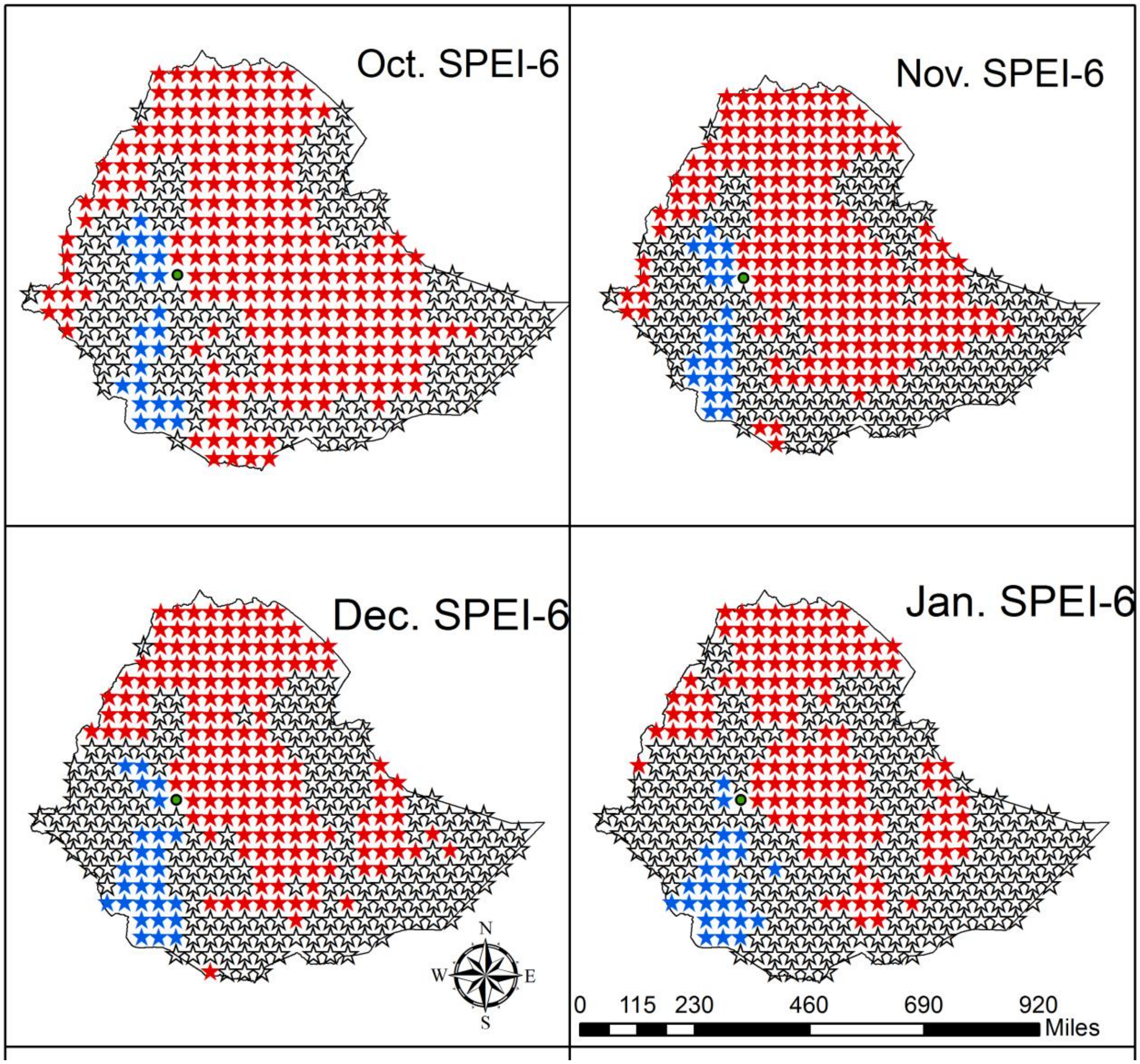
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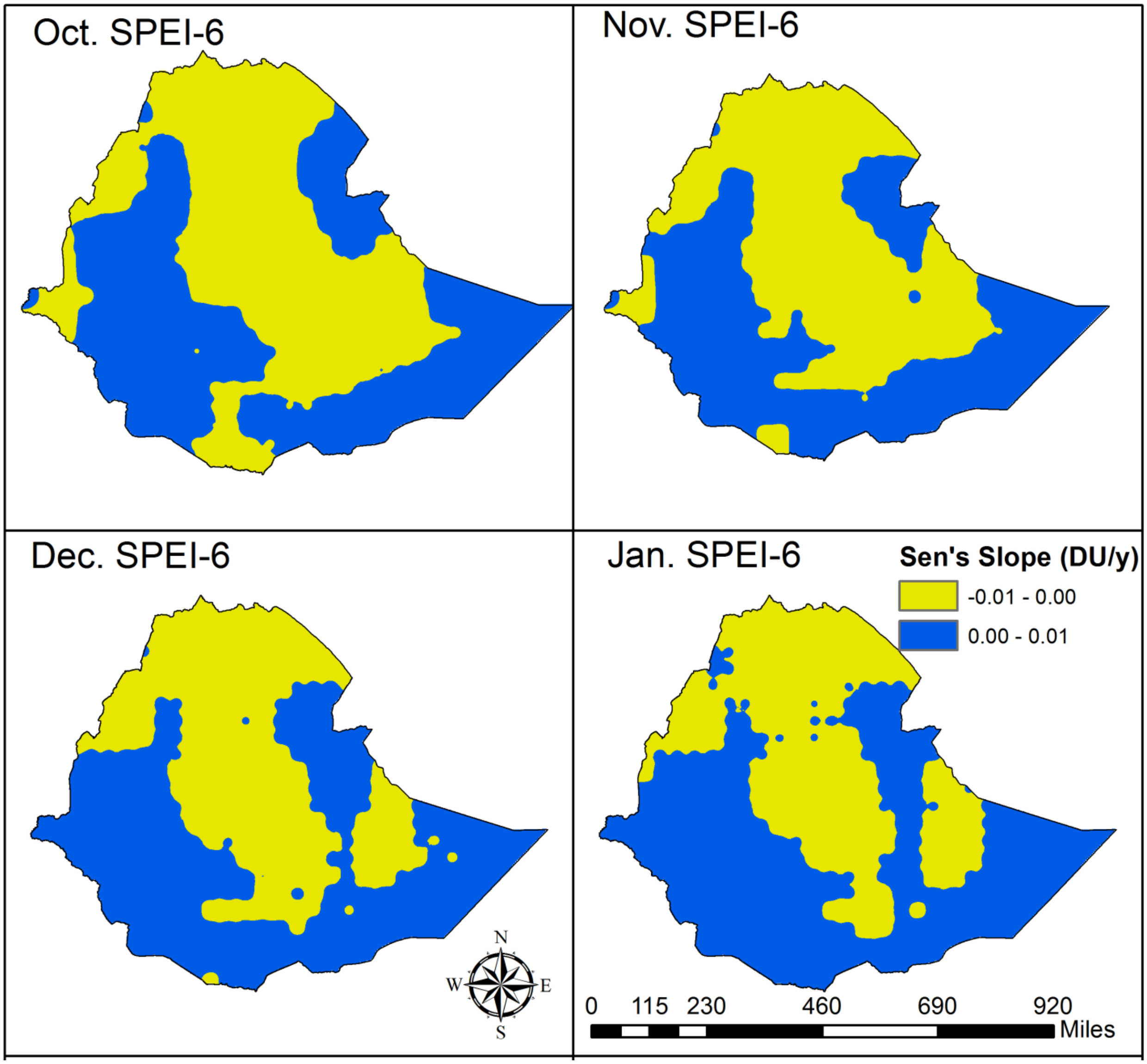
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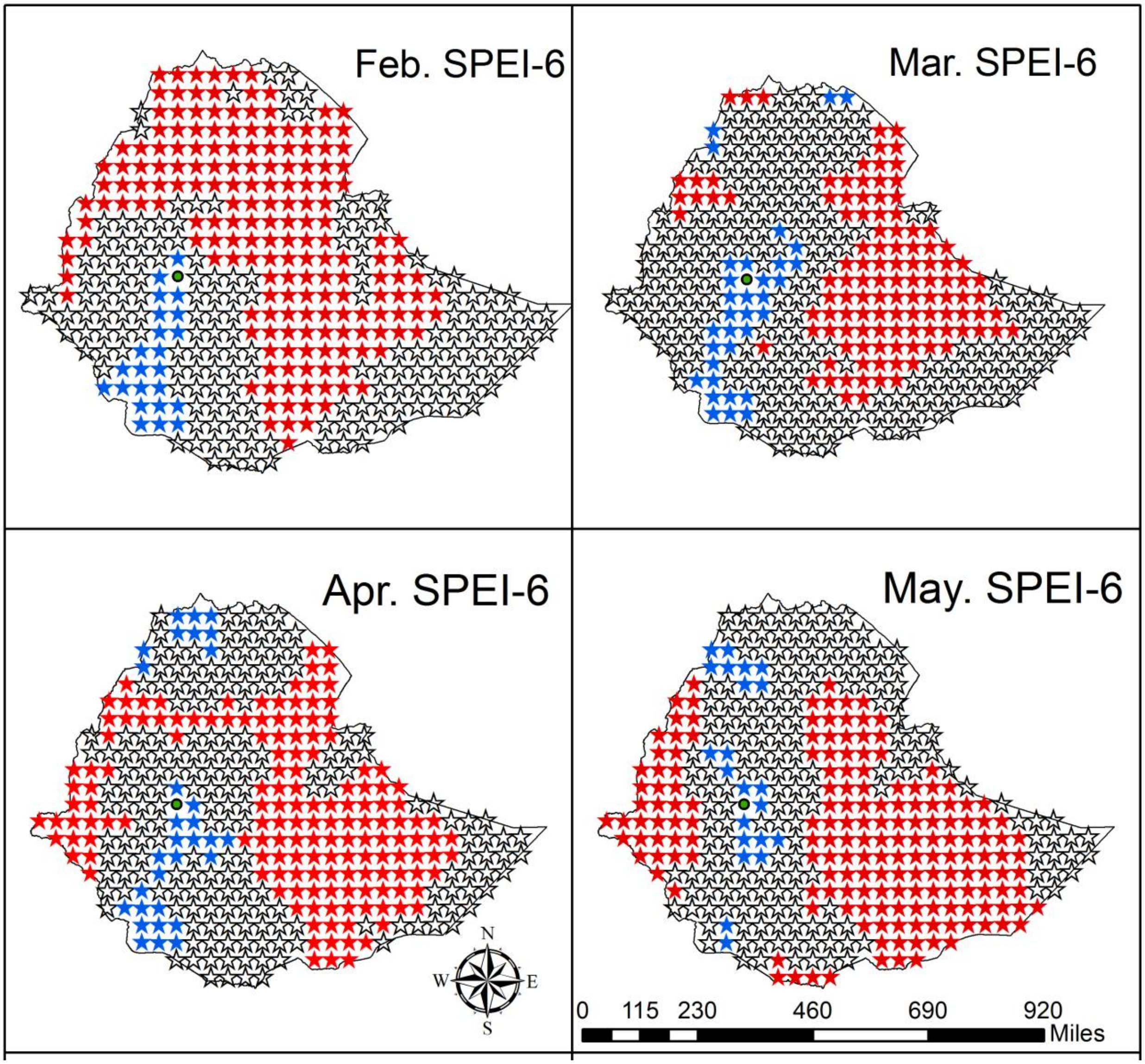

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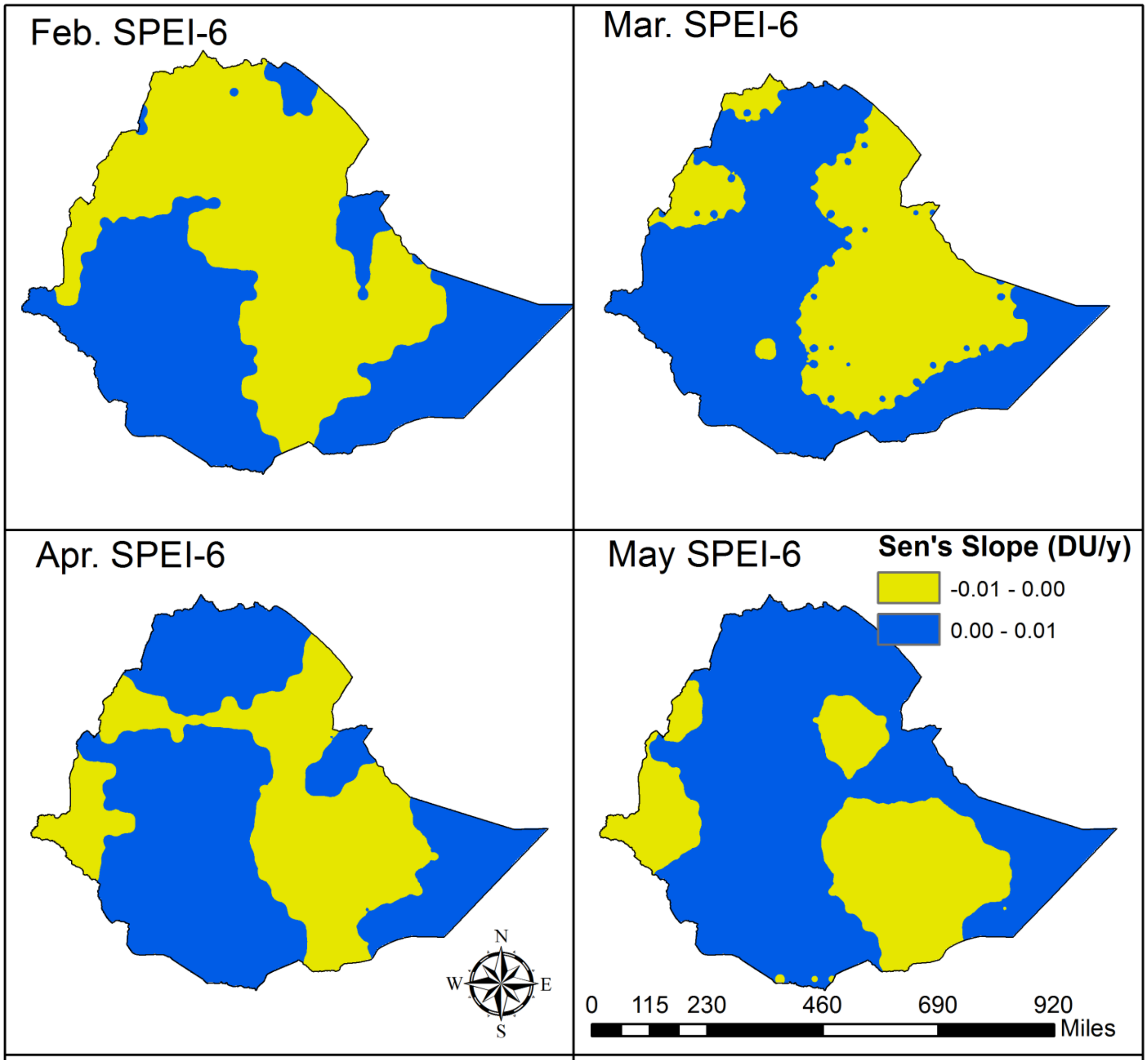
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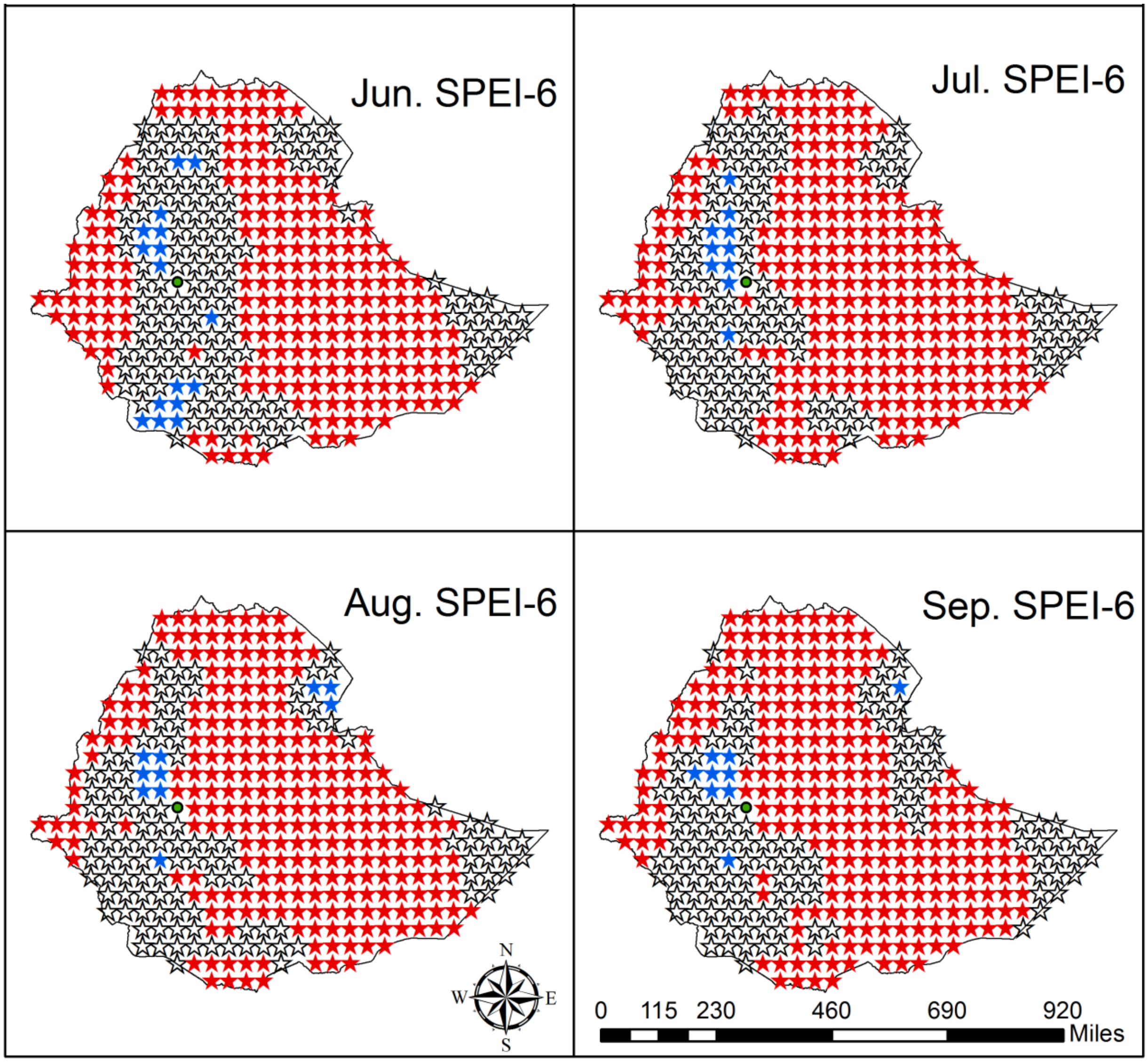
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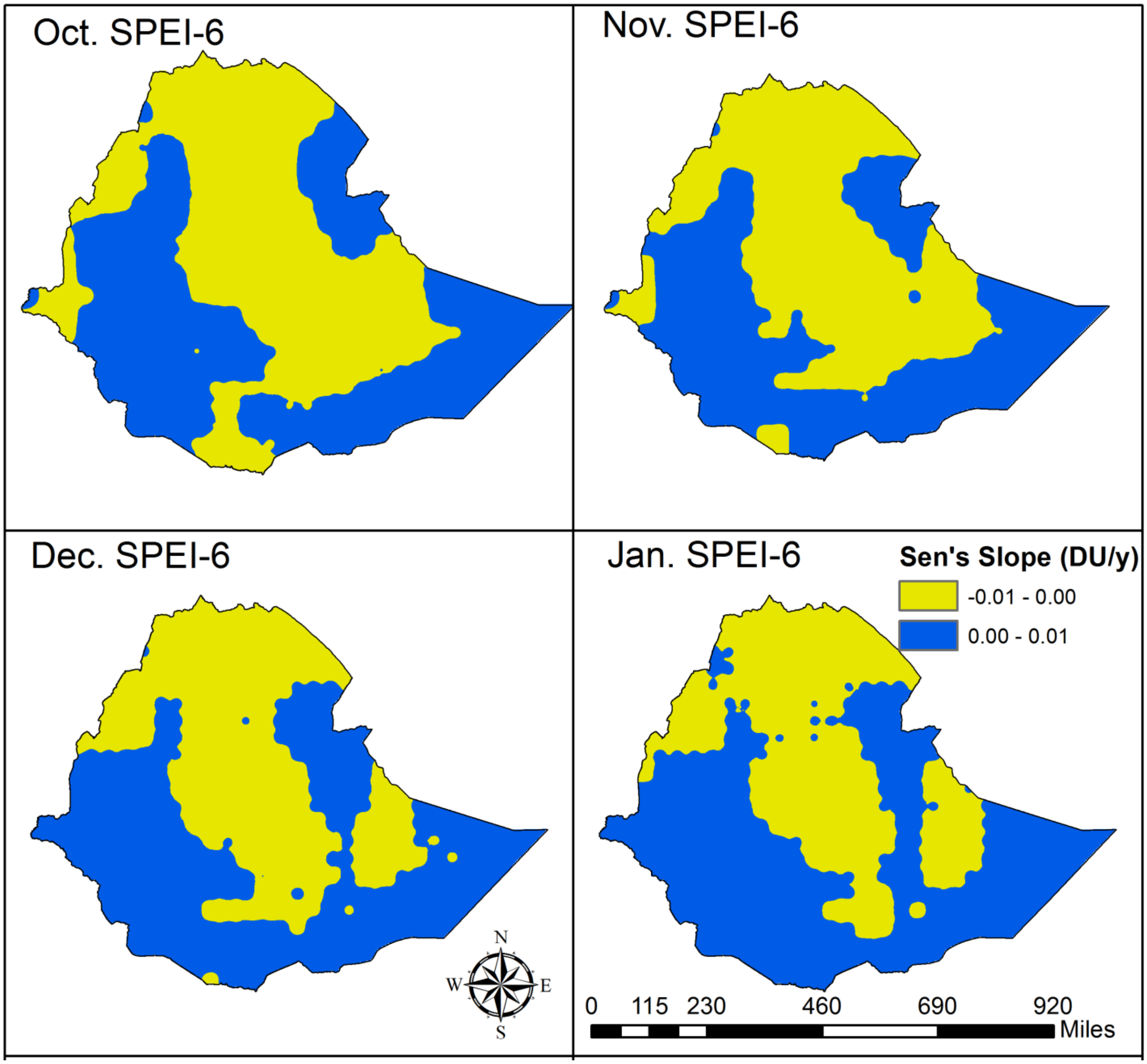

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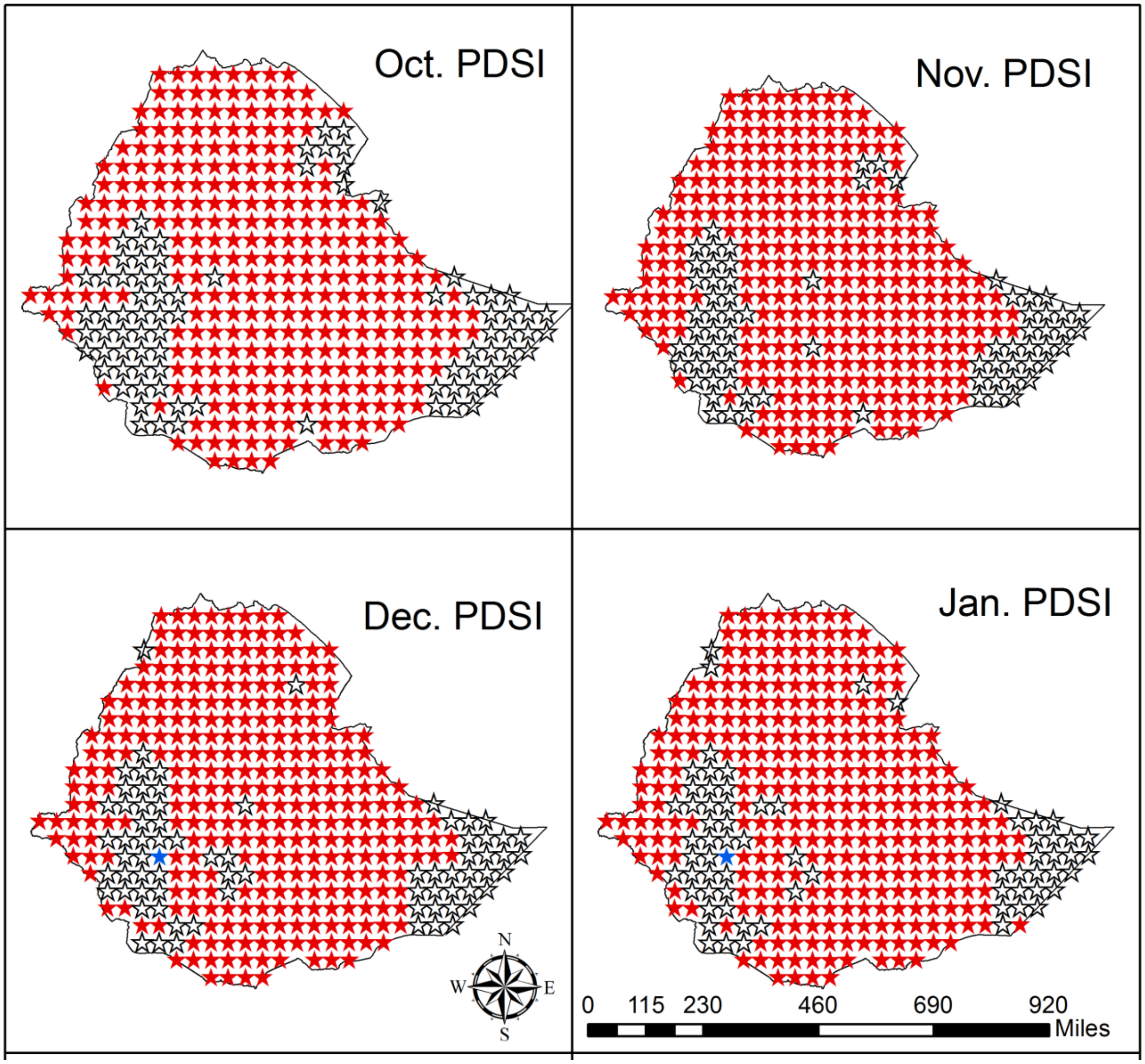
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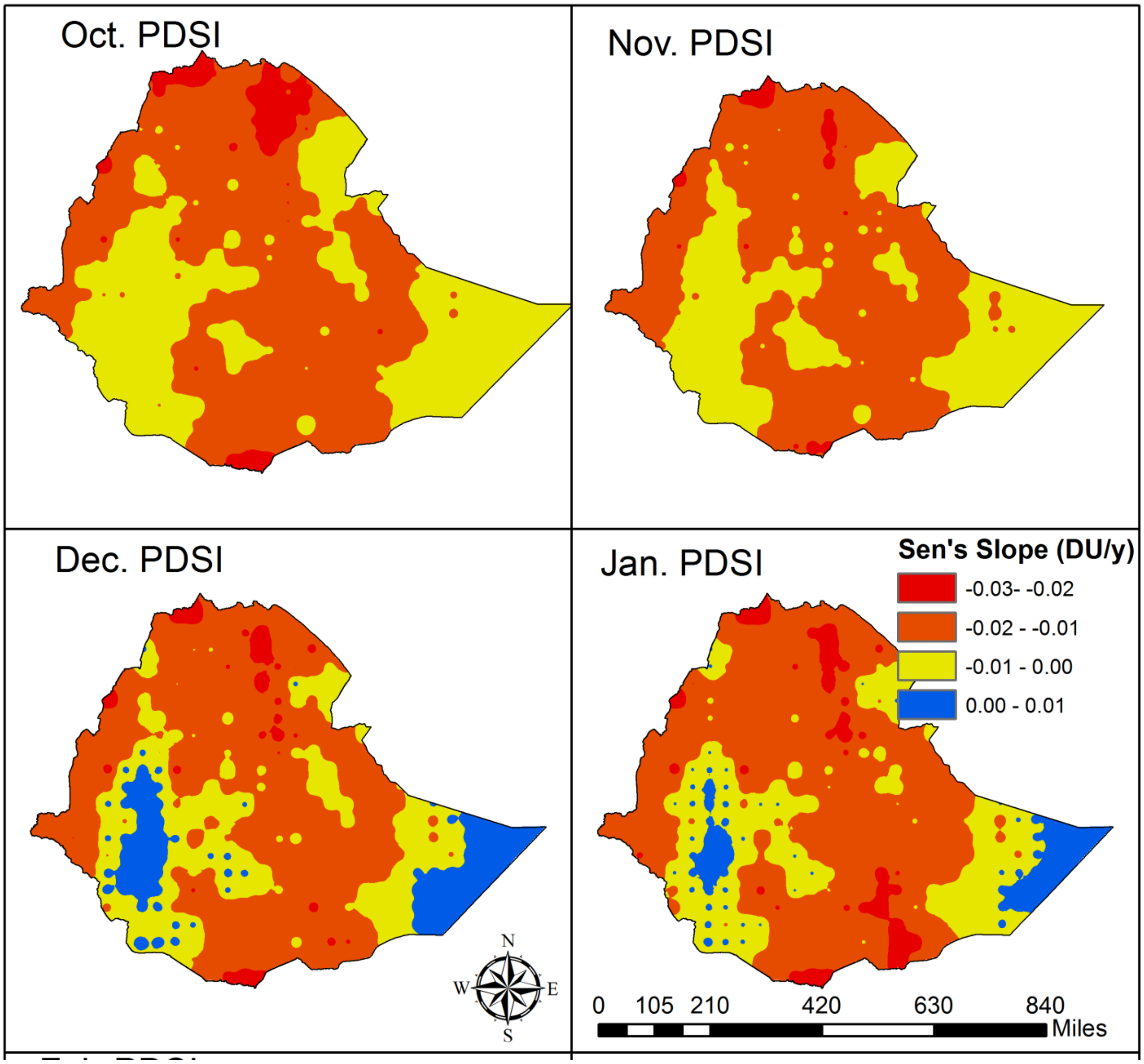
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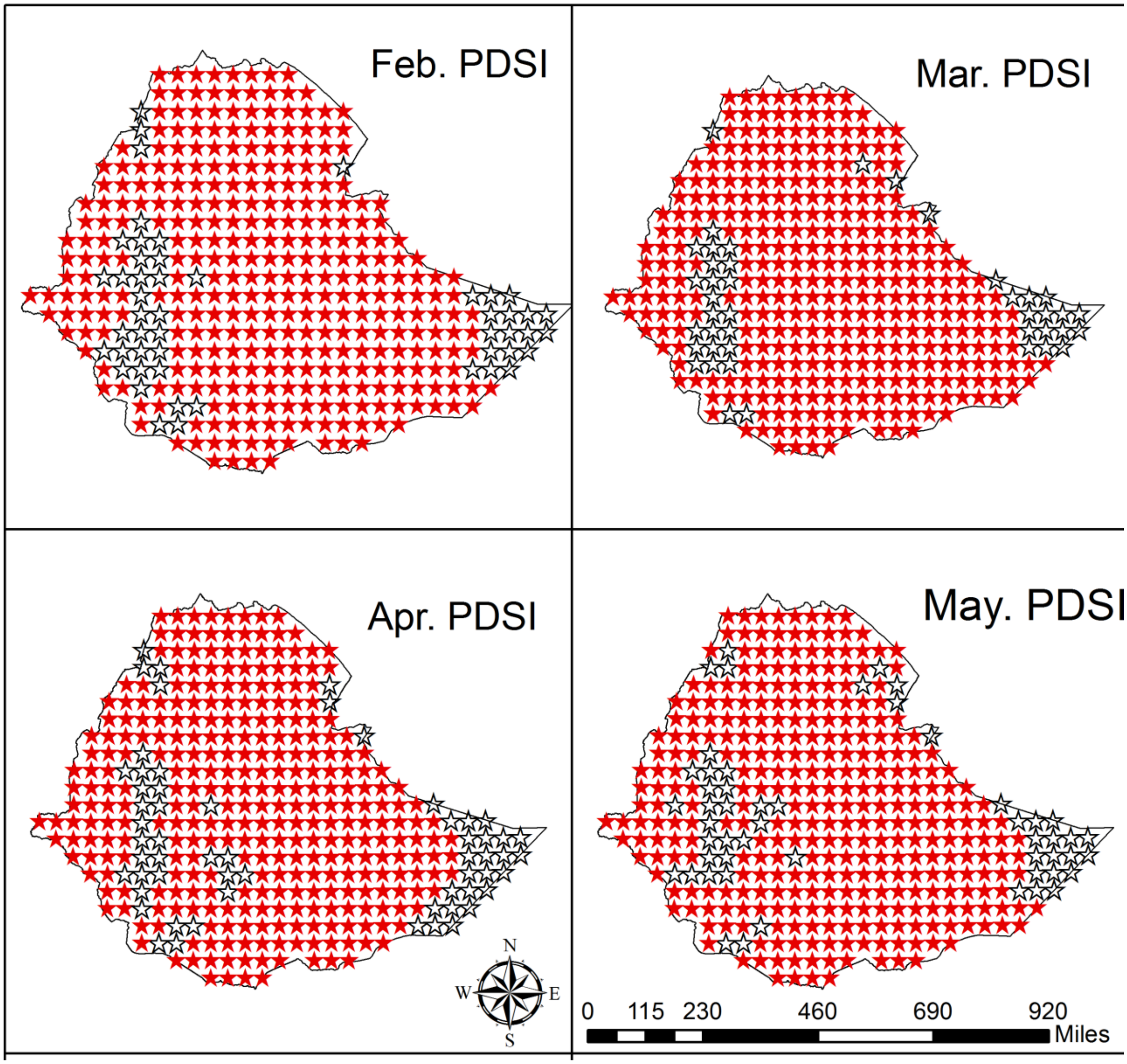
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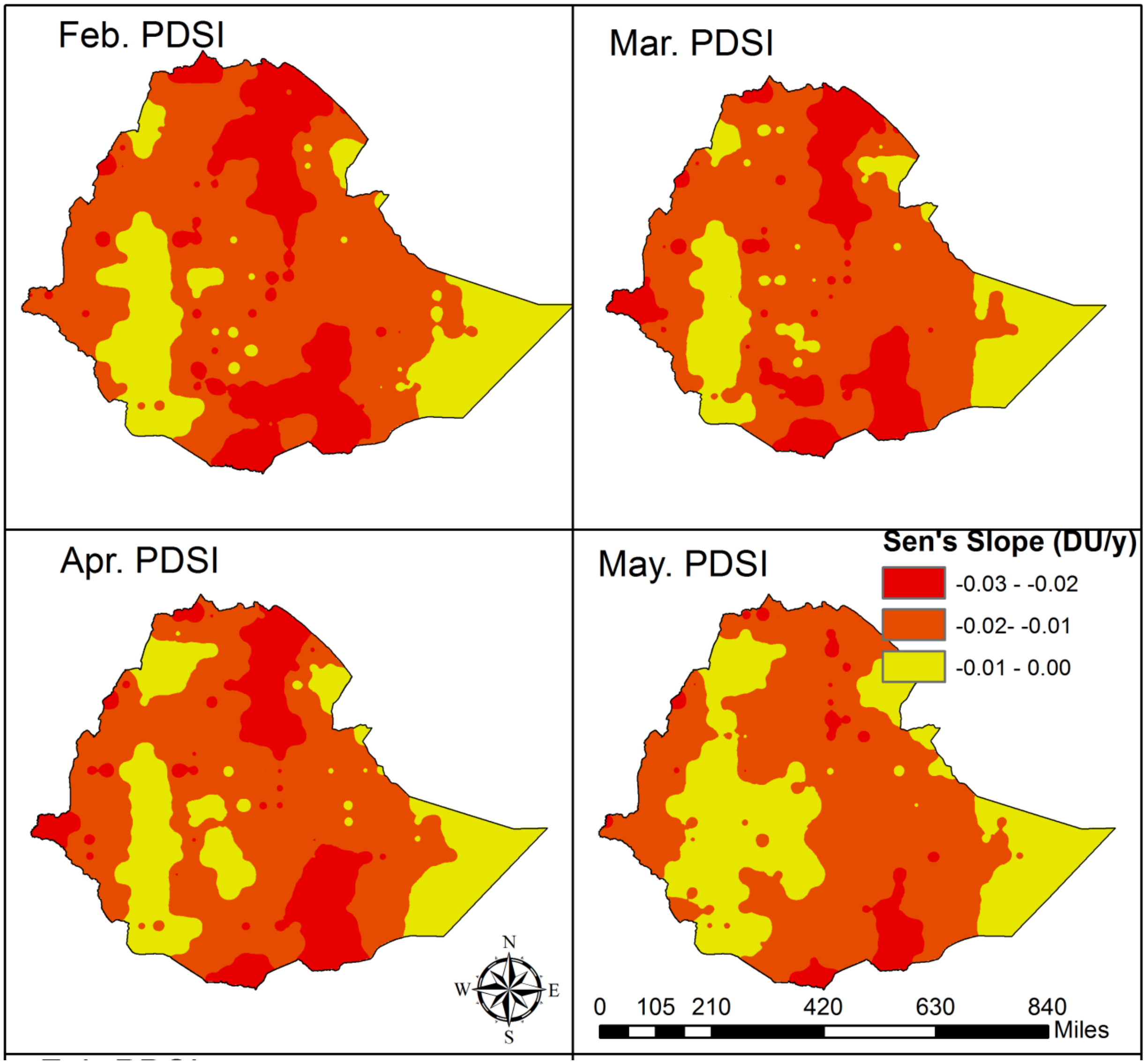
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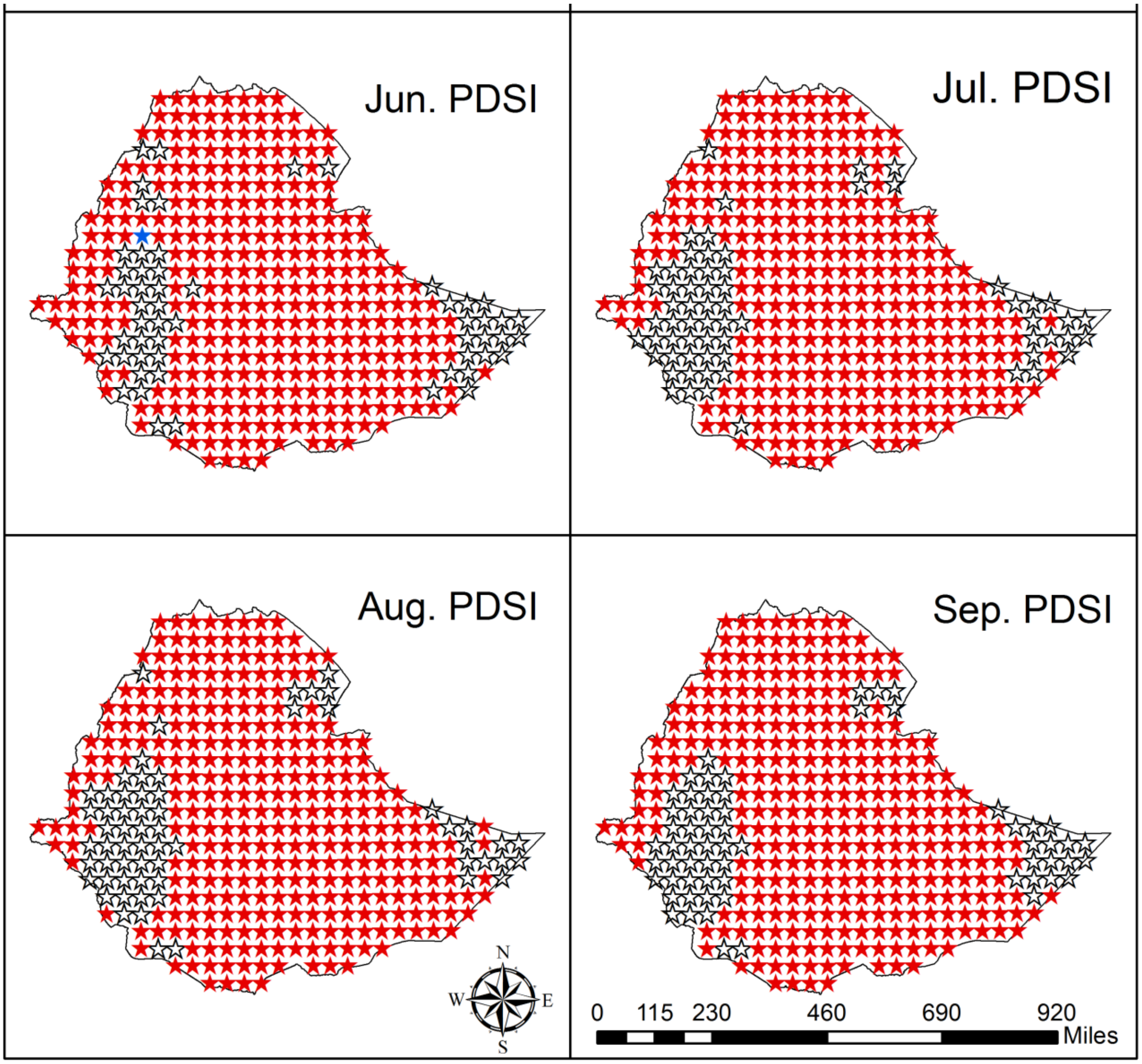
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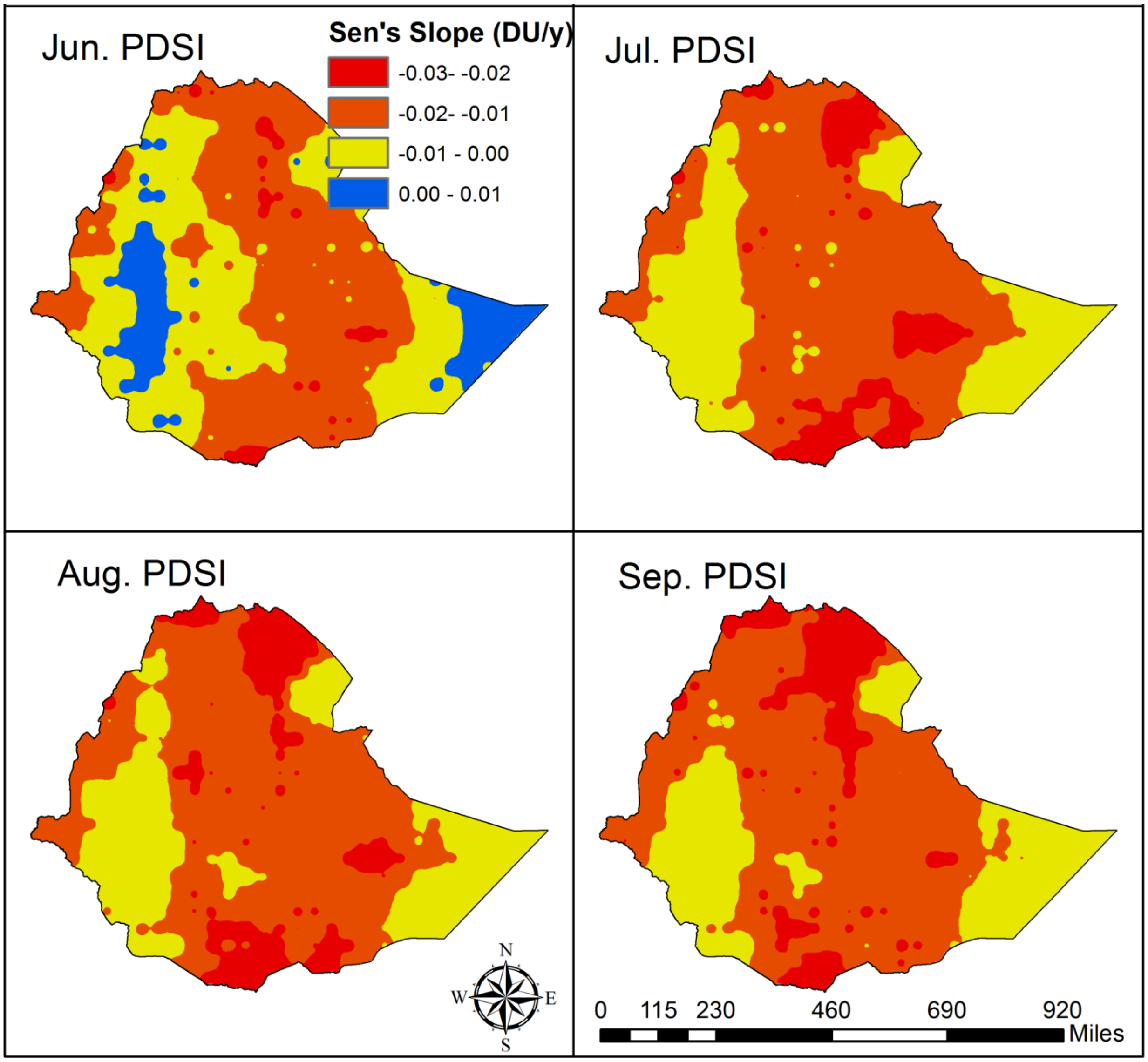
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Author‘s curriculum vitae

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	Email:	dawdtemam16@@gmail.com
	Field of specialization	Sustainable Water Resource Engineering
	Academic Rank	Lecturer
	Position	Ph.D. candidate in Sustainable Water Resource Engineering , Jimma Institute of Technology, School of Civil and environmental engineering
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	Department	Hydraulic and water resource Engineering

Educational Background

Tertiary Education

Period (dd/mm/yy)	Name of Institution	Name of studies	Type of diploma/Award
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September, 2012 – November, 2014	Arbaminch University	MSc in Hydrology and water resource Engineering	MSc
2007 – 2009 GC	Arbaminch University	BSc in water resources and irrigation engineering	BSc

Primary and Secondary school

Period (dd/mm/yy-dd/mm/yy)	Name of Institution	Address	
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2003-2006	Goro Comprehensive secondary school	Wolkite	Grade 9 -12

Research interests

- Evaluation of drought trend analysis
- Analysis of land use land cover on stream flow
- Climate change

Publications

1. Wajira Takala, Tamene Adungna and Dawd Temam Temporal varablity of hydrological proceses on Gilgel Gibe Basin. IJST, 8, 239-248.

2. Effects of land use land cover change on stream flow on Wabe watershed; Omo gibe basin, Ethiopia. LAMBERT

3. Temam, D; Uddameri, V.; Mohammadi G; Hernandez, E.A.; Ekwaro-Osire, S. Long-Term Drought Trends in Ethiopia with Implications for Dryland Agriculture. *Water* **2019**, *11*, 2571

4. Multi-scale, Intera seasonal Drying and Wetting Trends in Ethiopia using SPI and SPEI. For possible publication in Environmental Earth Science.

participation

1. **Seminar presentation** was held in Jimma University on February 2017, on the title ‘’**Flood management: A Case Study’’**
2. International Workshop presentation in Sustainable water resources organized by Texas Tech University and Jimma University which was held in Jimma University on April 25th and 26th 2017.
3. **Research Seminar** by Dave A.R. Louis, Ph.D. Associate Professor of College of Education at Texas Tech University, USA. Organized by Texas tech and Jimma University in Uni-Bremen, Germany from 11-19/07/2017 on Proposal Writing, Professional Presentations and Publications.
4. **International Conference on Engineering Innovations in Ethiopia**, Sustainable water resource in March 11-12, 2019, Jimma University. ‘’Seasonal Evaluation agricultural drought trend in Ethiopia’’**.**