EXCELLENCE IN AGRONOMY
ADAPT INTENSIFY GROW

A FRAMEWORK TO MONITOR

CROP-SPECIFIC DROUGHT AND FLOOD IMPACTS USING REMOTE SENSING DATASETS.

CGIAR
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CGIAR Initiative on Excellence in Agronomy

The Excellence in Agronomy Initiative forms a part of The CGIAR's new research portfolio, delivering science and innovation to transform food, land, and water systems in a climate crisis. EiA delivers agronomic gain for millions of smallholder farming households in prioritized farming systems, with emphasis on women and young farmers for measurable impact on food and nutrition security, income, water use, soil health and climate resilience. CGIAR Excellence in Agronomy Initiative

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Summary

Weather triggered hazards such as drought and flooding have negative impacts on society and agriculture. Drought can lead to reduced access to drinking water, lower agricultural productivity, and conflicts over water resources. Flooding causes loss of agricultural production, damages infrastructure, and leads to socio-economic losses. The report aims to develop a guiding framework to create a Combined Drought and Flood Index (CDFI) for monitoring crop-specific agricultural drought and flood conditions. The proposed framework for monitoring crop-specific agriculture drought and flood conditions includes meteorological, agricultural, and hydrological indices. The framework uses remote sensing datasets to monitor drought and flood impacts. The cross-referencing of these indices helps reduce the probability of false alarms during monitoring floods and droughts. It is crucial having a uniform methodology that countries can apply to monitor drought and flood conditions for specific crops. The 5-step standardized methodology was applied for the case study country in Ethiopia, where wheat, sorghum, and teff crops are the major crops. The findings show, flooding occurred in the northern and central part of the country in 2016, causing reduced respiration in the soil root zone of crops affecting mid-season phenological growth of sorghum, wheat, teff, and barley. Likewise, the study revealed, in 2015 moderate to severe drought impacted the phenological growth of sorghum due to the El Nino Phenomenon. The framework aims to provide valuable insights for policymakers, decision-makers, and agricultural practitioners. The coarse resolution of the rainfall and soil moisture datasets applied in the study might be limitations of this method however, it still provides a valuable oversight for agricultural drought and flood monitoring.

1. INTRODUCTION

1.1. General Background on Agricultural Drought and Flood Condition

Excellence in Agronomy (EiA) is an initiative of the Consultative Group on International Agricultural Research (CGIAR) that aims to deliver an increase in productivity and quality per unit of input (agronomic gain) for millions of smallholder farming households in prioritized farming systems by 2030, with an emphasis on women and young farmers, showing a measurable impact on food and nutrition security, income, resource use, soil health, climate resilience and climate change mitigation. The EiA Initiative, which started in 2020, brings together the public and private sectors in the Global South to encourage cross-learning and better collaboration to make the agrifood systems more sustainable, inclusive, and resilient. EiA seeks to build climate adaptation and increase productivity for smallholder farmers sustainably by deploying a wide range of agronomic interventions across different agro-climatic regions by leveraging big data and advanced analytics interventions such as engagement on women and young farms and an emphasis on food and nutrition security, profitability, soil health, and climate resilience (International Rice Research Institute (IRRI), 2020). One of the ongoing efforts of EiA is monitoring and accessing drought and flood impacts on agriculture and working with different agencies to minimize their impacts on crop production, food security, and sustainable agriculture.

One of the most significant impacts of the ongoing anthropogenic climate crisis is the increase in the severity and frequency of natural disasters over a significant geographic area (Thomas & López, 2015). According to a report by the Food and Agriculture Organization (FAO), between 2006 and 2016, 83% of damage or loss in the agricultural sector in the 53 developing countries occurred due to drought. Likewise, volcanic eruptions, storms, and flooding accounted for 30%, 23%, and 17% of the losses, respectively. Among the components of the agricultural sector, crops were the most vulnerable, with 49% being destroyed during these disasters. While floods may have ranked fourth in the overall statistics, the 2010 flood in Pakistan was the most catastrophic event, resulting in a staggering $4.5 billion in damages. It was followed by the 2008-2011 drought in Kenya, which caused significant losses totaling USD 1.5 billion.

Agricultural Flooding is rainfall induced hazard accompanied by water logging and characterized by reduced light, oxygen depletion in soil and altered microbial activity(Wang et al., 2022). Whereas, drought is a recurrent and temporary phenomenon that arises from a prolonged lack of precipitation (Patel & Yadav, 2015). Agricultural drought is prolonged period of dryness characterized by decrease in crop productivity caused by inconsistent rainfall patterns and insuficient soil moisture in the root zones where crops grow (Gidey et al., 2018).The erratic weather pattern results into extreme rainfall or no rainfall triggering the rainfall induced disasters.Consequently, this may exacerbate the frequency of landslides, and the severity of flash floods in some areas.. The rising in temperature may increase in water evaporation and transpiration. In return, this could lead to increase the occurrence of extreme rainfall event, rainfall amount as well as the intensity. Consequently, may exacerbate the frequency of landslides, and the severity of flash floods in some areas. The significant increase in frequency of climate triggered hazard has increased the vulnerability of agricultural sector. Their severity of consequences on both natural and human systems depend on how long each event lasts, what crops are being grown, and what agronomic and best management practices are in place.

The impacts of weather triggered hazard ranges from scarcity of drinking water and increased risk of wildfires to a decline in agricultural productivity due to crop failure in subsequent season. Moreover, droughts can have a range of profound negative impacts on society, including reduced access to drinking water, lower agricultural productivity, loss of livelihoods, and an increased risk of wildfires. In some cases, drought can even lead to conflicts over water resources for agriculture (Gill, 2023). In developing countries, where many people depend on farming for a living and may not have access to good water storage and distribution systems, drought can have very bad effects (Keller et al., 2000). Similarly, flooding also causes loss of agricultural production as it makes soil harder to get nutrients and changes how soil microbes work. An excessive amount of flooding leaves fields with standing water, slows plant development and even kills plants (an anaerobiosis condition). Floods can also damage infrastructure and facilities on farms, which costs farmers and land managers more money.

Floods in agriculture can lead to significant socio-economic losses by damaging crops, and infrastructure, and disrupting livelihoods (Xie et al., 2019). Such events often result in decreased agricultural productivity and increased financial burdens on affected communities, exacerbating poverty and food insecurity (Mishra and Khan, 2019). Droughts are generally categorized into three broad categories (Wilhite, 2000): meteorological, agricultural, and hydrological. Based on the decreasing level of water availability, the progression begins with meteorological, then moves to agricultural, and finally to hydrological drought. Figure 1.1 illustrates the progression of drought types.

In the context of floods, whose progression depends on the amount of rainfall, the timeline for flood progression can be different from the timeline for drought progression. In this report, the discussion pertains to the types of floods—meteorological, agricultural, or hydrological—based on the amount of rainfall affecting the amount of water in the soil but not about the timeline of the flood.

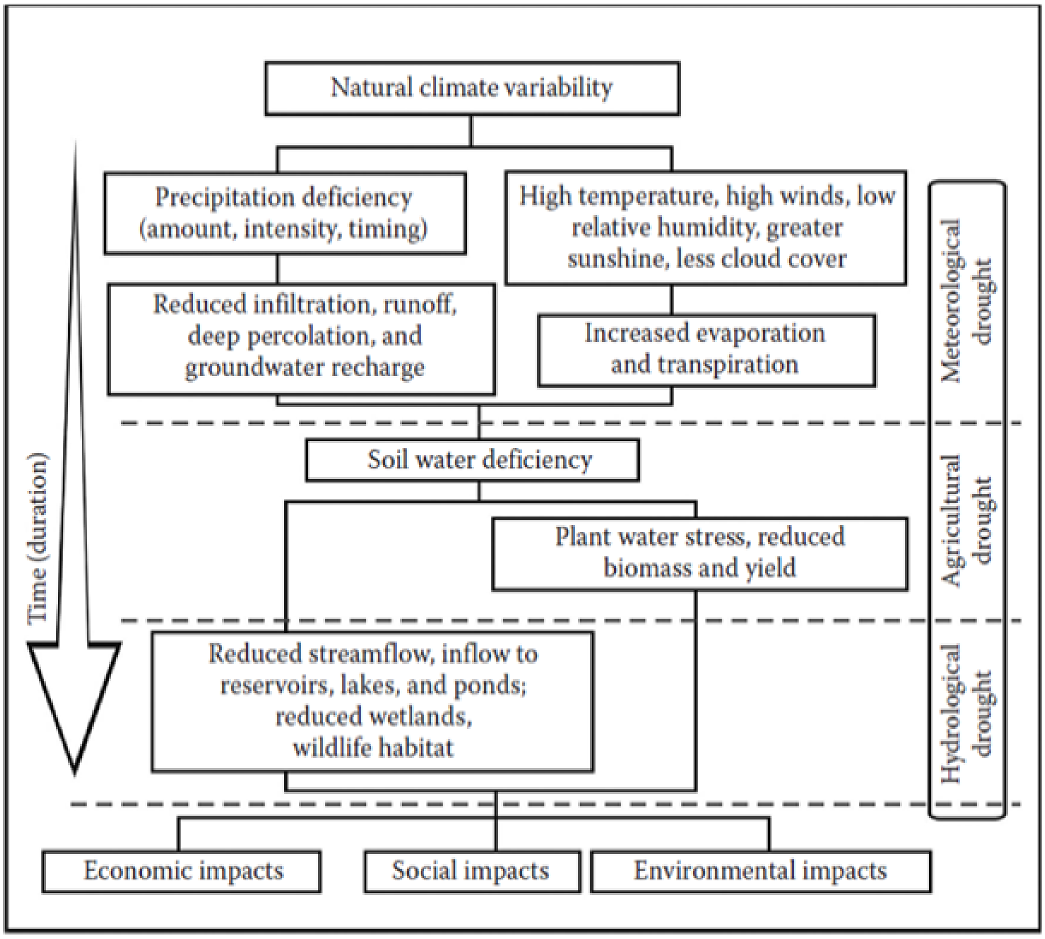

Figure 1.1: *Progression of Drought Types with Decreasing Water Availability (Wilhite, 2000)*

1.2. Problem Statement

Countries and regions use different methods to keep track of droughts and floods that affect agriculture. Most of these methods rely on deriving indices from either weather stations or remote sensing images. Often, it is complex to link these indices directly with the crop state impacted by floods or droughts. There is a need for crop-specific standard protocols or frameworks for assessing drought and flood impacts that can be implemented at a sub-national level. In agriculture, drought and flood conditions can be tracked and evaluated with the help of weather stations, soil sensors, groundwater observation wells, remotely sensed satellite data, and gridded climate data. In some countries, drought and flood conditions are tracked by looking at rainfall data from weather stations that aren't very close to each other. So, there needs to be a standardized method with steps for the standardization process that countries could follow to keep track of drought and flood conditions for specific crops.

In addition to monitoring the current drought and flood conditions, which are increasing in both frequency and severity with time, this much-needed standardized methodology could be applied to access and analyze the possible impacts of future climate change on agriculture around the world consistently. There is a growing need to determine the future risk of climate change in agriculture. By accessing the climate projection data and analyzing the severity of drought and flood conditions and their possible impacts on agriculture in the future, adaptive strategies could be developed and implemented to combat the future impacts of climate change and secure crop production. Therefore, there is a need for a standardized methodology to determine the future impacts of climate change on agriculture around the globe in a consistent manner.

1.3. Research Objectives and Tasks

The goal of this research is to develop a guiding framework for developing a Combined Drought and Flood Index (CDFI) for monitoring crop-specific agricultural drought and flood conditions. The framework will consist of standardization steps for utilizing different types of available climate and biophysical data, selecting and applying appropriate indices, and deriving crop specific CDFI. The standardization process steps should account for a wide range of agro-climatic conditions in which the EiA use cases are implemented, incorporate widely available datasets, and ensure the process complexity doesn't hinder application by the EiA use case teams.

The specific objectives of this research are outlined below:

- Review existing types of drought indices and select widely accepted **meteorological, agricultural, and hydrological indices** suitable for monitoring drought and flood impacts on crops.
- Integrate the three indices and create a CDFI leveraging the advantages of each in monitoring the drought's progression.
- Implement and evaluate the CDFI framework in Ethiopia for selected crops.

The inclusion of the hydrological index depends on whether agricultural fields are irrigated or rain-fed (non-irrigated). If the agricultural fields are rainfed, only the meteorological and agricultural indices will be applied, whereas if they are irrigated, then the hydrological index will also be included (***Figure 1.2***). This index will be used only in the context of irrigated agriculture systems. For example, if the value of the hydrological index is very low in the rainfed agriculture area or during the non-growing crop season, it should not trigger a drought.

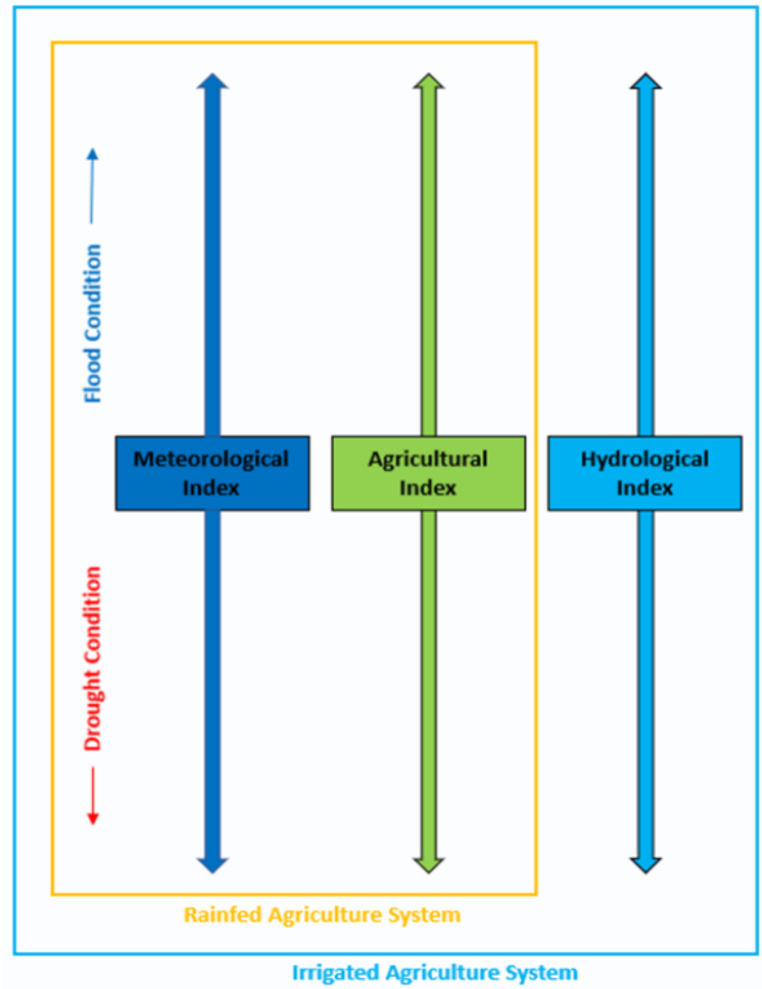

Figure 1.2: *Framework of the CDFI for rainfed and irrigated agriculture systems*

2. PROPOSED STANDARDIZATION PROCESS

The proposed method for standardizing the way drought and flood conditions in croplands are tracked consists of five steps. It starts with learning about a country's climate and farming system and goes all the way to making a crop-specific CDFI. Figure 2.1 shows a simplified version of the five steps involved in the standardization procedure.

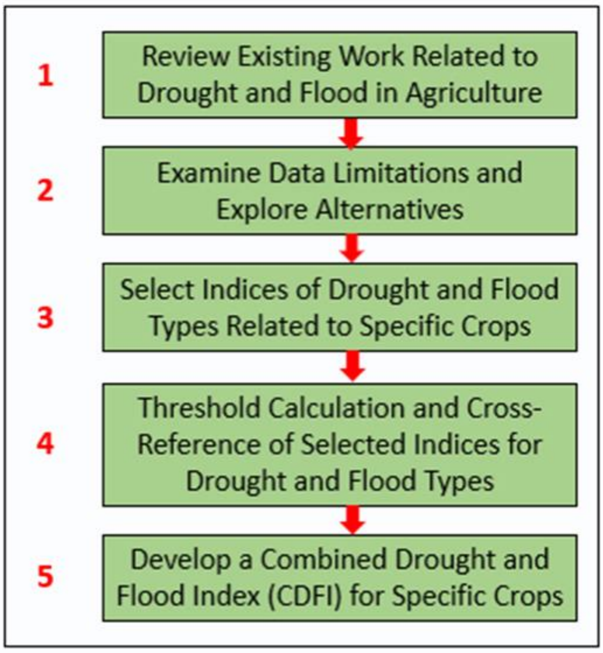

Figure 2.1: *Proposed Steps of Standardization Process for Crop-Specific Monitoring of Drought and Flood Impacts*

2.1. STEP 1:
Review Existing Work Related to Drought and Flood in Agricultural systems or sector

In the first step, the region's climate, and farming conditions in the past and present should be looked at. To understand the region's setings, information such as the climate regime, precipitation and temperature patterns and trends, major crops, growing seasons, and past drought and flood conditions should be analyzed. A thorough review is required of what is currently being done to monitor agricultural drought and flood conditions in the country. Similarly, a thorough review is needed of the different available techniques for monitoring droughts and floods in the region since multiple regional or global monitoring systems providing the same indices might be available. If specific indices are used in the country or region of interest, they should be checked to see if they can be used to keep track of drought and flood conditions for specific crops.

A list of resources that could be used as references to start with in Step 1 is given below. This list is by no means exhaustive.

- Handbook of Drought Indicators and Indices (2016)
  https://www.droughtmanagement.info/literature/GWP_Handbook_of_Drought_Indicators_and_Indices_2016.pdf

- Agricultural Drought Indices – Proceedings of an Expert Meeting (2010)
  https://www.droughtmanagement.info/literature/WMO_agricultural_drought_indices_proceedings_2010.pdf

- FAO Irrigation and Drainage Paper No. 56 (1998)
  https://www.fao.org/3/x0490e00.htm

- Water Requirement Satisfaction Index (2004)
  https://iridl.ldeo.Columbia.edu/documentation/usgs/adds/wrsi/WRSI_readme.pdf

- A review of drought indices: predominance of drivers over impacts and the importance of local context (2021)
 https://nhess.copernicus.org/preprints/nhess-2021-152/nhess-2021-152.pdf

- European Drought Observatory: Combined Drought Indicator (2019)
https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_combinedDroughtIndicator.pdf

- SPEI global drought monitor
https://spei.csic.es/map/maps.html#months=1#month=1#year=2023

- The Famine Early Warning System Network
https://fews.net/

- Global Flood Awareness System
https://www.globalfloods.eu/

2.2. STEP 2:
Examine Data Limitations and Explore Alternatives

In the second step, different types of data related to the analysis of drought and flood conditions in agriculture should be explored. For the monitoring mechanism, types of data that should be explored include precipitation, temperature, soil moisture, stream flow, lake and reservoir levels, and groundwater elevation through time. There are two main criteria that should be followed during the data selection process: 1) The data should have a long period of records (>= 30 years) for good statistical analysis, and 2) the data should have good, and acceptable accuracy.

In the case of limited data availability, freely available remotely sensed and gridded global/regional datasets should be explored and utilized. Most of the global remote sensing-based datasets on precipitation, temperature, and others cover a 30-year period. While selecting the gridded global climate datasets, consideration should be given to the accuracy of the data, and information related to the uncertainty data should be reviewed thoroughly to make a decision on its usability. If data from a weather station is available, it should be used to validate the global or regional gridded products, and, if needed, corrections should be made to the gridded products. The gridded environmental data should be compared to local ground truth (weather station) data and bias-corrected to better represent extreme events. A list of freely available satellite and model-based geospatial climate data categorized based on meteorological, agricultural, and hydrological indices is given below, which could be used as a reference to start with while in the process of selecting appropriate datasets.

DATASETS RELEVANT FOR METEOROLOGICAL INDEX

- Global Time-Series Precipitation Data
Climate Hazards Group, CHIRPS – 5km spatial resolution, daily and monthly temporal resolution:
https://www.chc.ucsb.edu/data/chirps

- Global Time-Series Land Surface Temperature Data
University of California Merced, TerraClimate – Climatology Lab – 5km spatial resolution, daily and monthly temporal resolution:
https://www.climatologylab.org/terraclimate.html
https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE#:~:text=TerraClimate%20is%20a%20dataset%20of,varying%20data%20from%20CRU%20Ts4.

DATASETS RELEVANT FOR AGRICULTURAL INDEX

- Global Time-Series Soil Moisture Data
National Aeronautics Space Administration, SMAP – 9 km spatial resolution, and 3 hr temporal resolution:
 https://nsidc.org/data/spl4smlm/versions/5

- Digital Soil Map of the World
Food and Agriculture Organization (FAO):
https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/446ed430-8383-11db-b9b2-000d939bc5d8

DATASETS RELEVANT FOR HYDROLOGICAL INDEX

- Global Time-Series Water Level Data of Lakes, Reservoirs, and Rivers
  Copernicus Global Land Service:
  https://land.copernicus.eu/global/products/wl

- Global Time-Series Water Level Data of Groundwater System
  Global Groundwater Information System:
  https://ggis.un-igrac.org/view/well-and-monitoring-data#/

- Global Time-Series Water Level Change Data of Groundwater System
  National Aeronautics Space Administration, GRACE Tellus:
  https://grace.jpl.nasa.gov/applications/groundwater/

2.3. STEP 3:
Select Indices of Drought and Flood Types Related to Specific Crops

In the third step, after a thorough review, meteorological, agricultural, and hydrological indices should be chosen to track drought and flood conditions. First, we should look at the indices that are already being used to track drought and flood conditions in weather, agriculture, and water. The logic and justification behind the selection of these indices should be reviewed and analyzed to see if they are appropriate for monitoring crop-specific drought and flood impacts. Current indices suitable for monitoring crop-specific agriculture's drought and flood impacts should be retained and used in conjunction with other selected indices. Some of the important criteria that should be considered while selecting the indices are:

- There should be appropriate logic, thoughts, and justification for the selection of an index for a specific crop in the country or region;

- Index should not be complex, but easier to understand, calculate and implement;

- Index should be selected that meets the user's resources availability (time, work hours, and servers/computers).

When making the standardized process steps, different meteorological, agricultural, and hydrological indices were looked at, and indices that were good for monitoring crop-specific drought and flood conditions were found and chosen. Figure 2.2 illustrates the selected indices for monitoring crop-specific drought and flood conditions. These selected indices are discussed briefly in sub-sections.

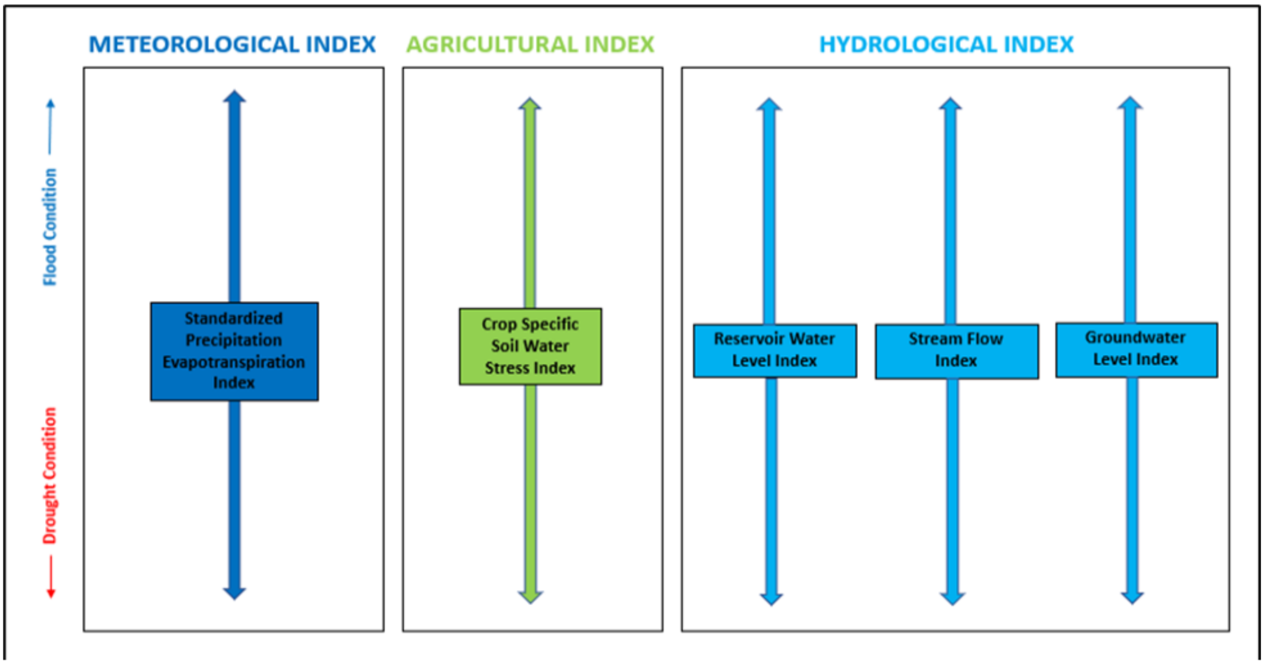

Figure 2.2: *Selected Indices Representing Meteorological, Agricultural, and Hydrological Indices*

The proposed indices for monitoring crop-specific agriculture drought and flood conditions are the Standardized Precipitation Evapotranspiration Index (SPEI), the Crop-Specific Soil Moisture Index, and an index derived from water body data (stream flow, reservoir levels and flows, and groundwater level data), representing the meteorological, agricultural, and hydrological indexes, respectively.

METEOROLOGICAL INDEX: STANDARDIZED PRECIPITATION EVAPOTRANSPIRATION INDEX (SPEI)

The SPEI index includes precipitation and temperature, allowing the index to account for the effect of both rainfall and temperature on drought development. The output of this index is applicable to all climate regimes. This index is derived from the product, which is the difference between precipitation and potential evapotranspiration in the atmosphere. Potential evapotranspiration can be calculated by applying the temperature data.

The SPI index relies solely on rainfall data for its calculation. In our investigation of agricultural-related drought and flood conditions, we delved into the SPEI index, which incorporates both rainfall and temperature data to calculate potential evapotranspiration, making it more pertinent to agriculture. The accessibility of both rainfall and temperature data is a key advantage of employing the SPEI index within the agricultural context.

On its intensity scale, both positive and negative values can be used to figure out whether an event will be wet or dry. Monthly SPEI estimates allow it to be used operationally (WMO, 2016).

AGRICULTURAL INDEX: CROP-SPECIFIC SOIL MOISTURE INDEX

This index was developed based on the Food and Agriculture Organization (FAO) Irrigation and Drainage Paper No. 56 (1998), which has crop-specific values of agriculture parameters to analyze the response of different crops (in different soil type setings) to different soil moisture availability conditions (FAO, 1998). Figure 2.3 illustrates a schematic diagram of the monitoring of drought and flood conditions with the crop-specific soil moisture index.

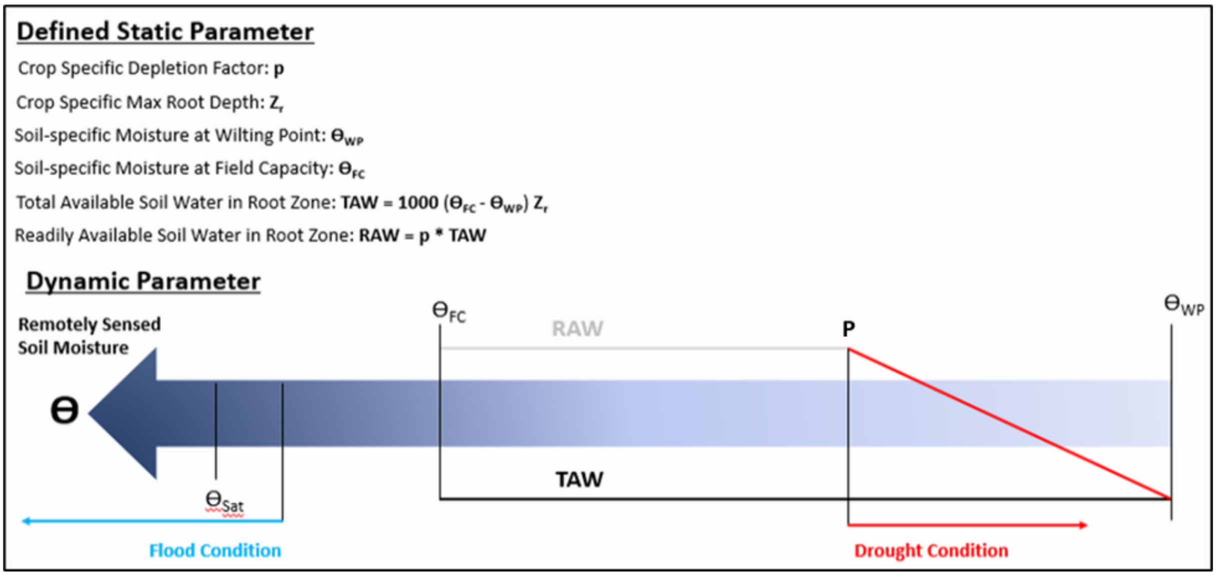

Figure 2.3: *Crop-Specific Soil Moisture Index for Monitoring Drought and Flood Condition*

When the level of root zone soil moisture begins to increase or decrease from the point that is optimum for the crop's phenological growth due to either flood or drought conditions, it reaches levels at which it starts to inhibit crop growth. There are two threshold levels for flood and drought conditions where crop growth starts to get stressed, which are:

- **Flood condition threshold level** at which anaerobiosis starts to develop due to higher levels of soil moisture. At this point, the root zone will have decreased oxygen levels, which suppresses the plant's respiration process. This is the level that starts at five percent less than the level of soil moisture in the saturated condition.

- **Drought condition threshold level** at which crop growth starts to get affected due to low soil moisture available for plant uptake. This level is called p value which is illustrated in ***Figure 2.3.***

HYDROLOGICAL INDEX: STREAM FLOW, GROUNDWATER, AND RESERVOIR LEVEL INDICES

Hydrological index is more related to the irrigated agriculture system which depends on water availability in the basin to feed water storage systems. Therefore, data related to water sources for irrigation during the growing season will be analyzed. Historical data records from the sources listed below related to the irrigated agriculture system will be analyzed, and an index will be calculated.

- Water level and release flow data of reservoirs
- Streamflow data
- Water level data of the groundwater system

If canal diversion data for an irrigated area is available, it will be utilized to develop an index and be included in the hydrological index. When observation data from reservoirs is not available or accessible, remotely sensed satellite data could be used to access hydrological drought and flood conditions. Typically, the remote sensing data measures the surface water extents of reservoirs and other water bodies. By comparing the surface water extent from the normal year to the drought year, a measure of water availability can be estimated. If observational data on groundwater levels are unavailable, groundwater level data based on the fusion of remote sensing (the GRACE mission) and a hydrological model (GLDAS-NOAH) could be used to calculate the hydrological index for monitoring crop-specific drought and flood conditions (Shalby et al., 2023).

2.4. STEP 4:
Threshold Calculation and Cross-Reference of Selected Indices for Drought and Flood Types

For the selected indices that represent drought and flood types, thresholds for drought and flood should either be calculated, or existing published threshold values of the indices should be incorporated in this step. These thresholds of meteorological, agricultural, and hydrological indices should be identified from the perspective of specific crops' responses to water and soil moisture availability for their phenological growth. The calculated index thresholds for drought and flood categories should then be compared and validated with available field or gridded data.

The drought and flood category threshold values of the meteorological index (SPEI index) that could affect agriculture (or the threshold value that shows stress in crop growth) should be compared to the soil moisture index value of the corresponding agricultural indicator. Here, the goal is to find out how much water is in the crop root zone when meteorological index threshold values for drought or flood suggest that they might be affected. It is to confirm if the agricultural drought or flood conditions related to specific crops have started or not. Similarly, when the soil moisture index value gets very high or very low during an agricultural drought or flood condition, it should be cross-referenced to the value of the hydrological index to confirm whether hydrological drought or flood conditions have started or not. This process of cross-referencing values between indices also helps to reduce the possibility of false alarms during monitoring floods and droughts. For example, there could be a loss of crops in fields due to plant disease and not because of less precipitation or less soil moisture. This process helps to confirm these types of false alarms. ***Figure 2.4*** illustrates the process of cross-referencing threshold values between different selected indices.

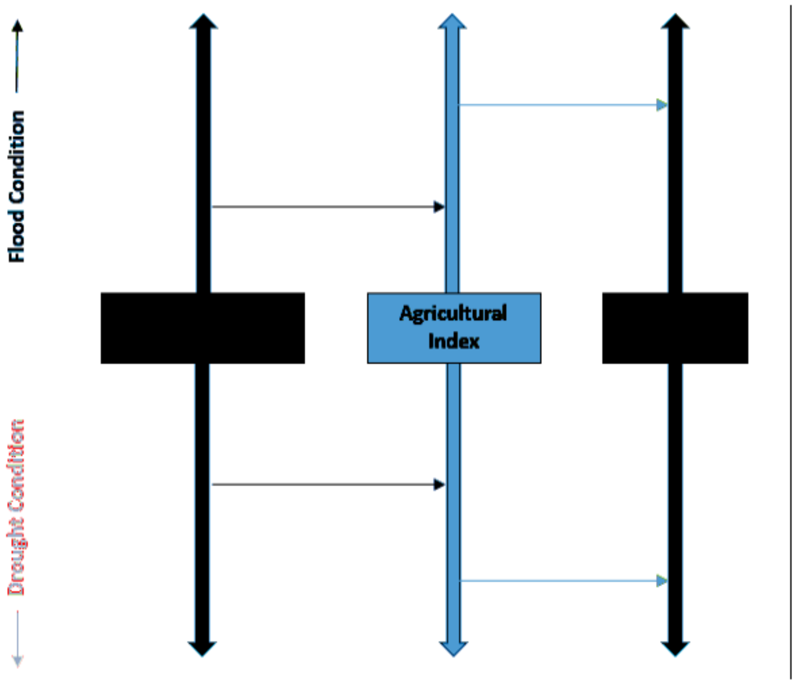

Figure 2.4: *Cross-Referencing of Threshold Values between Different Selected Meteorological, Agricultural, and Hydrological Indices*

2.5. STEP 5: Develop a Combined Drought and Flood Index (CDFI) for Specific Crops

This last step is the development of a final product, CDFI, based on the outcomes of previous steps in the process. In this step, a good standard way to make CDFI that can be used to keep track of drought and flooding conditions for each type of crop should be found. A simple, easy-to-understand tool for decision-makers for drought and flood monitoring and management should be developed, which would be a compiled version of different indices with lower threshold values for drought and flood categories that point out CDFI and different important levels of drought and flood conditions related to crop-specific agriculture. Figure 2.5 illustrates the crop-specific CDFI, which is the final product to be implemented for monitoring crop-specific drought and flood conditions.

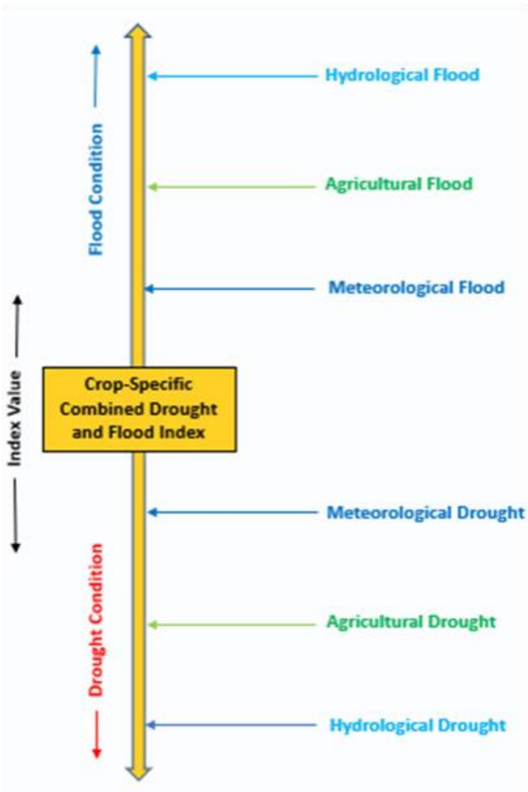

Figure 2.5: *Crop-Specific Combined Drought and Flood Index*

3. APPLICATION OF STANDARDIZED PROCESS STEPS IN USE-CASES COUNTRY

3.1. STUDY AREA

The developed methodology of the standardized process was applied in the use-case country of Ethiopia, where wheat, sorghum, and teff crops are the major crops and are affected by floods and droughts. Figure 3.1 shows the location of Ethiopia on the African continent.

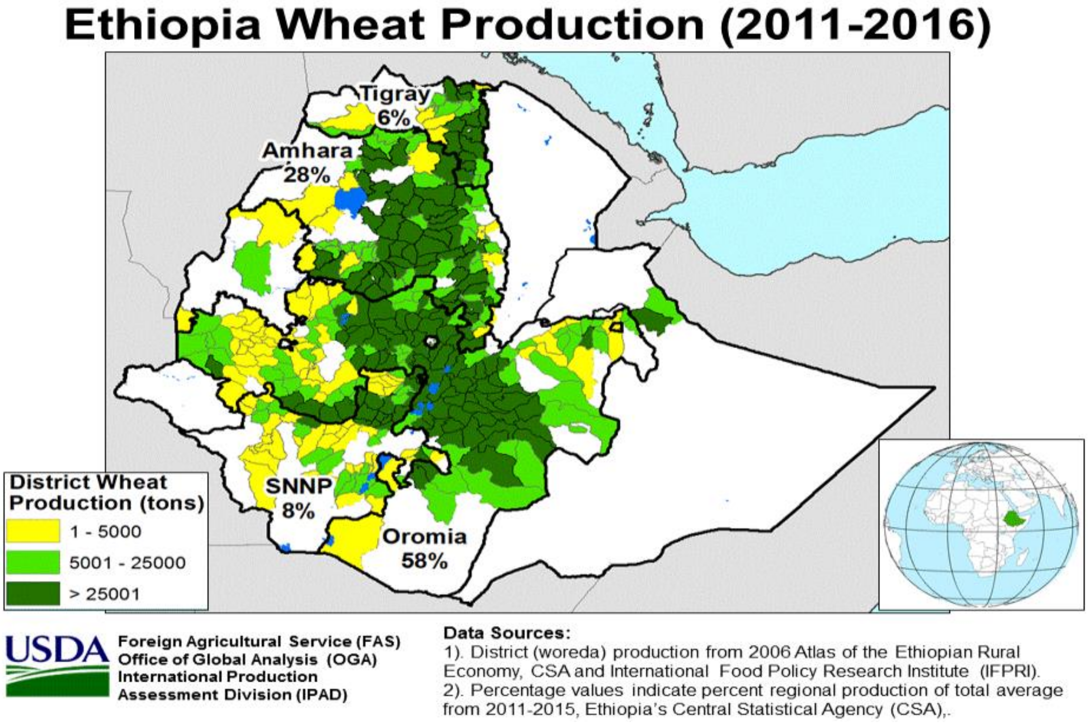

Figure 3.1: *Wheat production map of Ethiopia (Source: USDA, 2023)*

3.2. Application of Proposed Five Steps

Using the steps of the standardization process, a combined drought and flood index for specific crops was developed. The application process in the Ethiopia use case is described in the proposed five steps below:

STEP 1: REVIEW EXISTING WORK RELATED TO DROUGHT AND FLOOD IN AGRICULTURE

The south-eastern and north-eastern lowlands of Ethiopia have a tropical climate, while the large central highlands of the country are much cooler. The average annual temperature in high-altitude regions is around 15-20 oC and 25-30 oC in the lowlands. The mean annual temperature has increased by 1.3 oC between 1960 and 2006, an average rate of 0.28 oC per decade (USAID, 2016). Ethiopia's rainy seasons are mostly caused by the movement of the Intertropical Convergence Zone (ITCZ). Most of Ethiopia experiences one main wet season (called "Kiremit") from mid-June to mid-September (up to 350 mm per month in the wettest regions) when the ITCZ is at its northernmost position. Parts of northern and central Ethiopia also have a secondary wet season of sporadic and considerably lesser rainfall from February to May (called the "Belg"). The southern regions of Ethiopia experience two distinct wet seasons, which occur as the ITCZ passes through this more southern position. The March to May "Belg" season is the main rainfall season, yielding 100–200 mm per month, followed by a second rainfall season in October to December called "Bega" (around 100 mm per month). The easternmost corner of Ethiopia receives very little rainfall at any time of year. In Ethiopia, there is no statistically significant trend in the amount of rain that is seen in any season (USAID, 2016). The movements of the ITCZ are sensitive to variations in Indian Ocean sea-surface temperatures and vary from year to year; hence, the onset and duration of the rainfall seasons vary considerably interannually, causing frequent droughts (USAID, 2016).

Ethiopia has experienced several droughts, most notably in 1983-1985, 1988, 2000, 2002–2003, 2006, 2011, and now in 2015. The identified historical flood event years (1988, 1996, 1998, 2006, 2010, 2012, and 2016) in the country were also known as “La Niἡa” (Mamo et al., 2019). Scientists have done a number of studies on watershed basin scales in different parts of the country to track drought conditions, although this work done on a national scale is inaccessible to the general public (AICCRA, 2022; FAO and UN, 2021). Commonly, these La Niἡa events in Ethiopia were preceded by the drought effects of El Niἡo events (Mamo et al., 2019).

In the process of figuring out how to track crop-specific drought and flood impacts in Ethiopia, different drought and flood indices were looked at. This was done based on the level of complexity and availability of environmental data.

STEP 2: EXAMINE DATA LIMITATIONS AND EXPLORE ALTERNATIVES.

Various freely available climate geospatial data that are suitable for the development of indices were reviewed. Three types of data were selected in this step, which are:

1. **CHIRPS Rainfall Data:**
   It is a global time-series precipitation data set developed by the Climate Hazards Group that incorporates and blends both remotely sensed (satellite-based) and weather station data. This precipitation data is available in an 5-kilometer grid size and in daily and monthly time steps. The timeframe of this data that was available was from 1981 to 2021.

2. **TerraClimate Temperature Data:**
   It is a global time-series temperature data set (minimum and maximum temperature), developed by TerraClimate, the Climatology Lab at the University of California, Merced. This temperature data is available in a 5-kilometer grid size and in monthly time steps. The timeframe of this data that was available was from 1958 to 2021.3.

3. **SMAP Soil Moisture Data:**
   It is a global time-series root zone (100 cm depth) soil moisture data set developed by the National Aeronautics and Space Administration (NASA). This soil moisture data is available in a 9-kilometer grid size and in 3-hour time steps. The timeframe for this data that was available was from March 31 of the year 2015 to the present.

STEP 3: SELECT INDICES OF DROUGHT AND FLOOD TYPES RELATED TO SPECIFIC CROPS

METEOROLOGICAL INDEX

For the meteorological index, the Standardized Precipitation Evapotranspiration Index (SPEI), a widely accepted meteorological index for monitoring drought and flood conditions, was selected. It reflects the evapotranspiration of vegetation by including temperature data during the conditions index calculation, which is suitable for monitoring drought and flood conditions related to agriculture. The SPEI index was calculated on a monthly basis using daily gridded CHIRPS precipitation data (a blend of remotely sensed and local weather station data) and monthly averaged TerraClimate minimum and maximum temperature data. Data from 2015 to 2021 were used in the SPEI index calculation process. Figure 3.2 shows the time-series box plot of monthly SPEI from April of 2015 to December of 2021 for the cropland area of Ethiopia. SPEI threshold values for different stages of flood and drought conditions are also labeled in the figure. Table 3.1 and Table 3.2 presented in Step 4 have a detail explanation about these thresholds values.

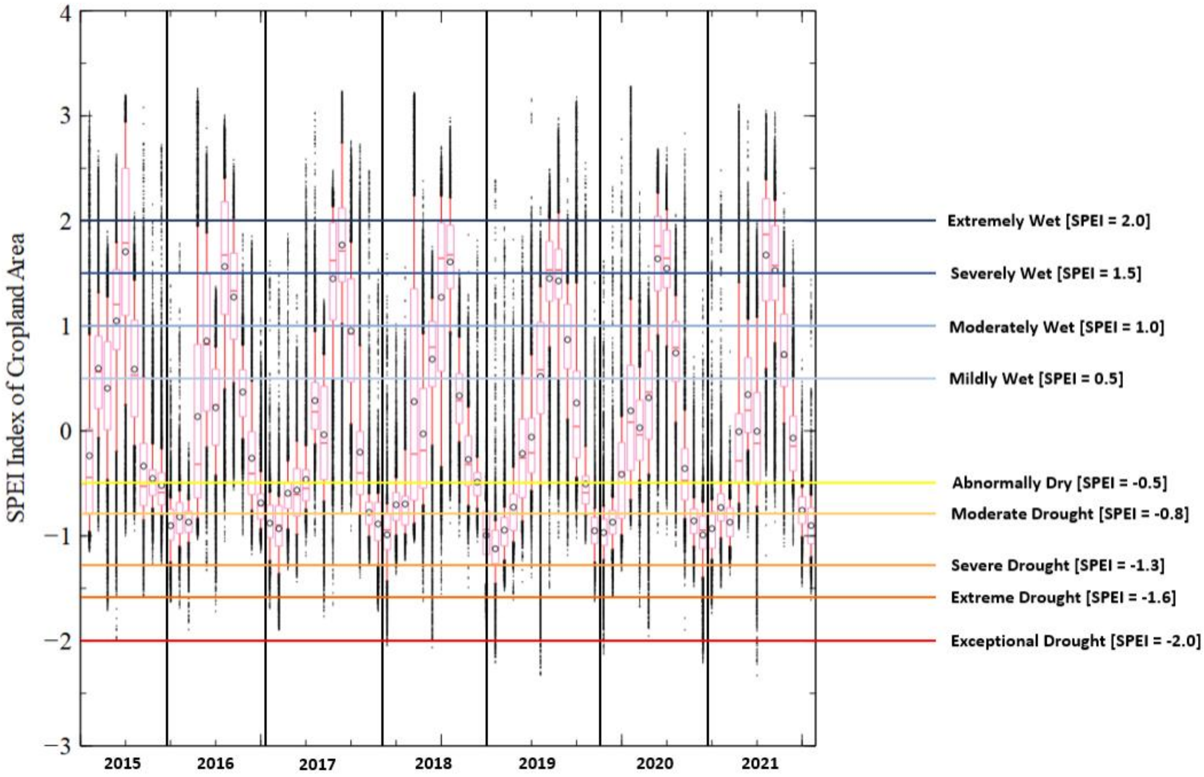

Figure 3.2: *Box plot of Monthly SPEI of Cropland Area in Ethiopia*

AGRICULTURAL INDEX

The Agricultural Index was calculated by looking at how wheat, sorghum, and teff crops did in different types of soil. The depletion factor is the level of soil moisture below which a plant will start to sense that it needs more water for its growth.

Similarly, the threshold values of soil moisture for an anaerobic condition were calculated for different soil texture types. It is the level of soil moisture that is five percent by volume below the level of saturation. Tables presented in Step 4 show the calculated values of thresholds for the depletion factor and anaerobiosis conditions. 10-day interval is considered appropriate to measure root zone soil moisture related to crop health. Figure 3.3 shows the box plot of 10-day average soil moisture from April of 2015 to December of 2021 for Ethiopia. It shows the pattern in which soil moisture in the root zone changes over time.

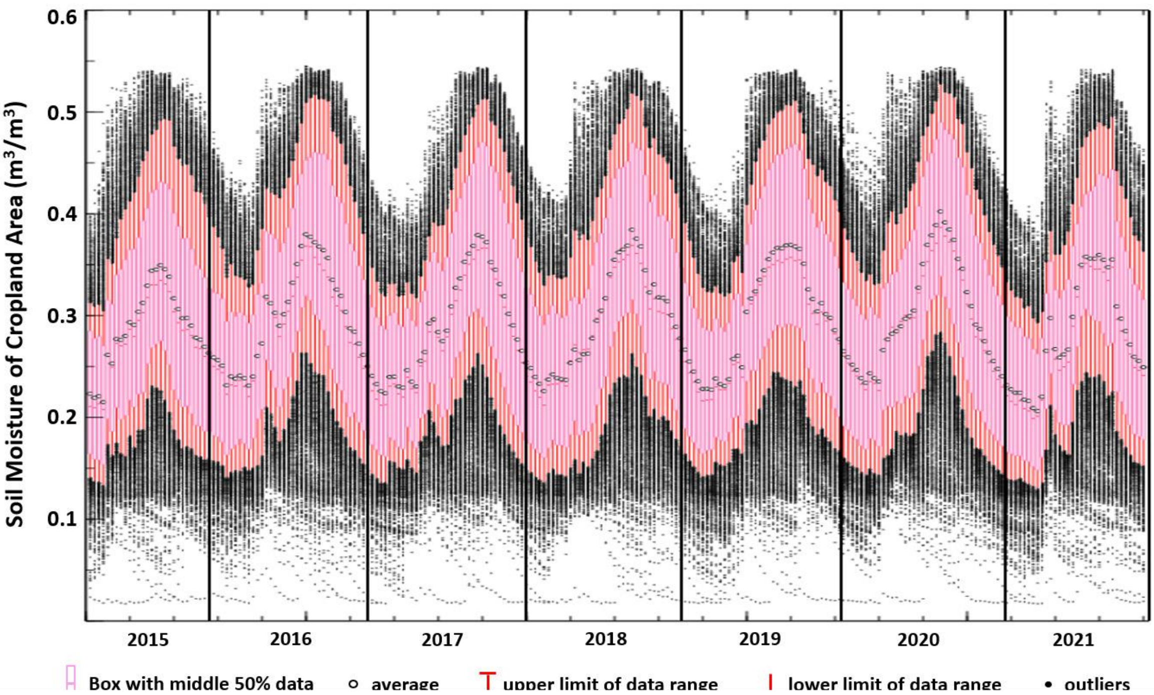

Figure 3.3: *Box plot of 10-day soil moisture of Cropland Area in Ethiopia*

In the box plot of Figure 3.3, box represents the interquartile range (IQR) of soil moisture value, which is the middle 50% of the data. The top and bottom edges of the box represent the 75th percentile (Q3) and the 25th percentile (Q1) value of soil moisture, respectively. The length of the box shows the spread of this middle 50% of the soil moisture value data. The whiskers in red color extend to the minimum and maximum values within a range. The lower whisker extend to the 9th percentile, and the upper whisker extend to the 91st percentile, indicating the range within which the majority of the data falls.

HYDROLOGICAL INDEX

Because the crops in use cases in Ethiopia are all rainfed crops, the hydrological index is less relevant, as the goal here is to select a hydrological index that is relevant to the irrigated agriculture system. Even though agriculture would have been irrigated, a hydrological index could be chosen based on where the water for irrigation came from. If the irrigated water comes directly from a stream, a stream flow index could be chosen, and index values calculated using the stream flow data. A standardized reservoir supply index could be selected if the irrigated water is supplied from the reservoir, and a standardized groundwater level index could be selected if the source of the irrigated water is groundwater pumping.

STEP 4: THRESHOLD CALCULATION AND CROSS-REFERENCE OF SELECTED INDICES FOR DROUGHT AND FLOOD TYPES

METEOROLOGICAL INDEX

The National Drought Mitigation Center (NDMC) has defined different threshold levels of the SPI and SPEI indexes related to drought categories and their possible impacts on agricultural crops (NDMC, 2023). This published list of threshold values for drought categories related to agriculture was incorporated into the selected SPEI index, which is summarized in Table 3.1.

Range of SPEI Index	Description	Possible Impacts to Crops
-0.5 to -0.7	Abnormally Dry	• Going into drought with short-term dryness slowing crop growth • Coming out of drought with some lingering water deficits, and crops not fully recovered
-0.8 to -1.2	Moderate Drought	• Some damages to crops • Low levels of water in streams, reservoirs and wells
-1.3 to -1.5	Severe Drought	• Crop losses likely • Water shortages common
-1.6 to -1.9	Extreme Drought	• Major crop losses • Widespread water shortages
-2.0 or less	Exceptional Drought	• Exceptional and widespread crop losses • Water emergencies due to shortages of water in reservoirs, streams, and wells

Table 3.1: *Threshold Values of SPEI Index for Different Drought Categories related to Agriculture (Source: NDMC)*

For the threshold values related to flood conditions, a widely used threshold value of the SPEI index for categorizing different levels of wet conditions was incorporated and is given in Table 3.2. While the SPEI index has been used to map extreme flood events, it is from a climatological perspective (Ayugi, 2020). Even if the rainfall event is extreme, its conversion into a flood condition in agricultural areas depends on a number of factors, such as the shape and size of the catchment area, which also need to be considered.

Range of SPEI	Flood Category
2.00 or more	Extremely Wet
1.50 to 1.99	Severely Wet
1.00 to 1.49	Moderately Wet
0.50 to 0.99	Mildly Wet

Table 3.2: *Threshold Values of SPEI Index for Different Flood Categories*

AGRICULTURAL INDEX

Table 3.3 shows the calculated value of the depletion factor, p value, which is the minimum soil moisture (in units of m3/m3) below which crops will experience water stress (the start of a drought). Cereal crops (wheat, sorghum, and teff) are the major types of crops found in Ethiopia, and the soil moisture at p value of cereal crops for different soil textures are listed in the table.

Soil Type	Soil moisture (m^3/m^3) at p value of Cereal Crops
Loamysand	0.1060
Sandyloam	0.1490
Loam	0.1880
Siltyclay	0.3575
Clay	0.4178

T***able 3.3:*** *Crop-specific Soil Moisture at p Value in Combination with Different Soil Textures*

Similarly, soil moisture threshold values for anaerobiosis conditions (during flood conditions) of different soil textures were calculated from the literature (FAO, 1998). The threshold value of soil moisture for anaerobiosis is calculated as 95 percent of the soil moisture volume in saturated conditions. Table 3.4 lists these threshold values of soil moisture for anaerobiosis (flood) conditions in different soil textures.

Soil Type	Threshold Value of Soil Moisture (m^3/m^3) for Anaerobiosis Condition
Loamy sand	0.375
Sandy loam	0.404
Loam	0.442
Siltyclay	0.494
Clay	0.518

Table 3.4: *Threshold values of soil moisture for anaerobiosis condition of different soil textures*

This study was done to check if the results of the indices matched the causes while monitoring drought and flood conditions using the Combined Drought and Flood Index. In the Results and Discussion section, we talk about what we learned from validating these indices and comparing them to each other.

STEP 5: DEVELOP A COMBINED DROUGHT AND FLOOD INDEX (CDFI) FOR SPECIFIC CROPS

A Combined Drought and Flood Index based on threshold values of meteorological and agricultural indices was developed for the cereal crop i.e. wheat, sorghum, and teff. Furthermore, as part of incorporating information regarding sensitive growth stages of crops into the CDFI for monitoring drought and flood conditions, the crop calendar of Ethiopia was referenced, and months of the growing season, which include sensitive stages of flowering and grain filling, were noted for wheat, sorghum, and teff. Figure 3.4 shows the months in which the growing season of wheat, sorghum, and teff falls (FAO, 2022). The sensitive stages of growth for wheat and teff crops fall in the months from July to October, whereas for sorghum they fall in the months from mid-May to September. When the reduced root zone soil moisture reaches the p value threshold, or anaerobiosis condition threshold value, due to excessive soil moisture in the root zone during the sensitive stages of crops, there is a high chance of crop failure, resulting in a decrease in crop yield. This information was included as part of the CDFI's development since it is important to consider while monitoring crop-specific drought and flood conditions.

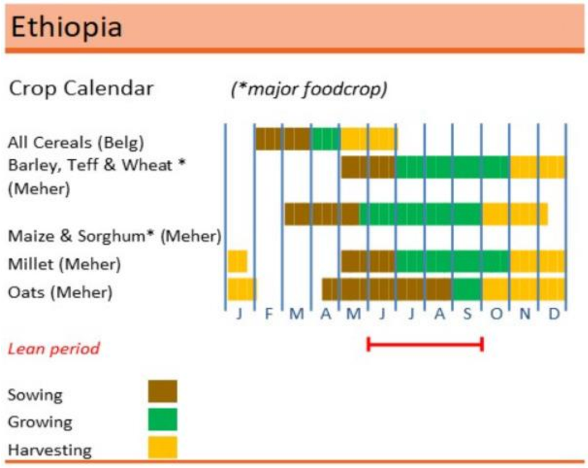

Figure 3.4: *Crop Calendar of Major Crops in Ethiopia (USDA, 2022)*

The spatial distribution map of soil textures was referred (Berhanu, 2013) to access the major types of soils in Ethiopia, especially in the agricultural region. Figure 3.5 shows the spatial distribution of soil texture in Ethiopia. From the figure, it is clear that Siltclay is the major soil texture in the agricultural region of Ethiopia. Soil moisture related to p-value thresholds and anaerobic conditions related to only these soil textures were considered important enough to include in the CDFI during its development for cereal crops.

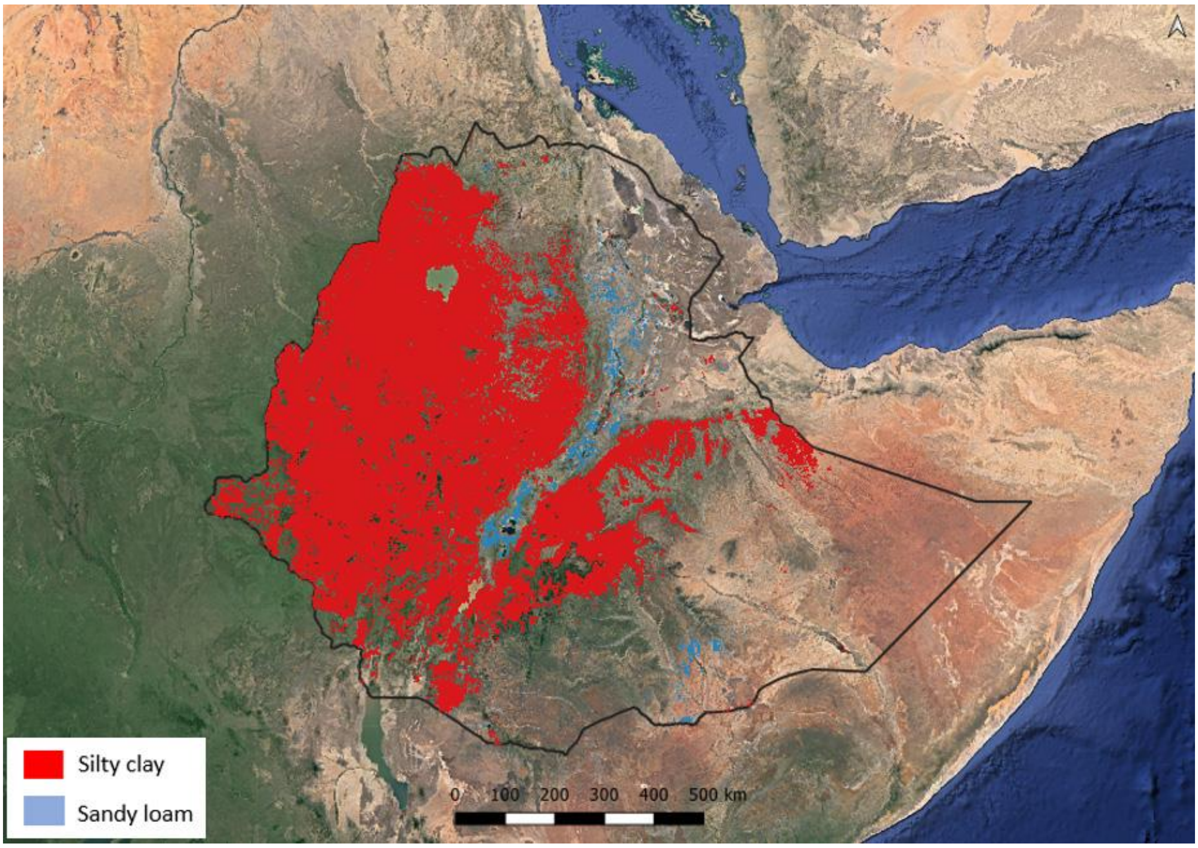

Figure 3.5: *Spatial Distribution of Soil Textures in Ethiopia*

The spatial distribution map of cropland area was referred (Buchhorn et al., 2020) to access the area of agricultural land in Ethiopia. Figure 3.6 shows the spatial distribution of cropland area in Ethiopia.

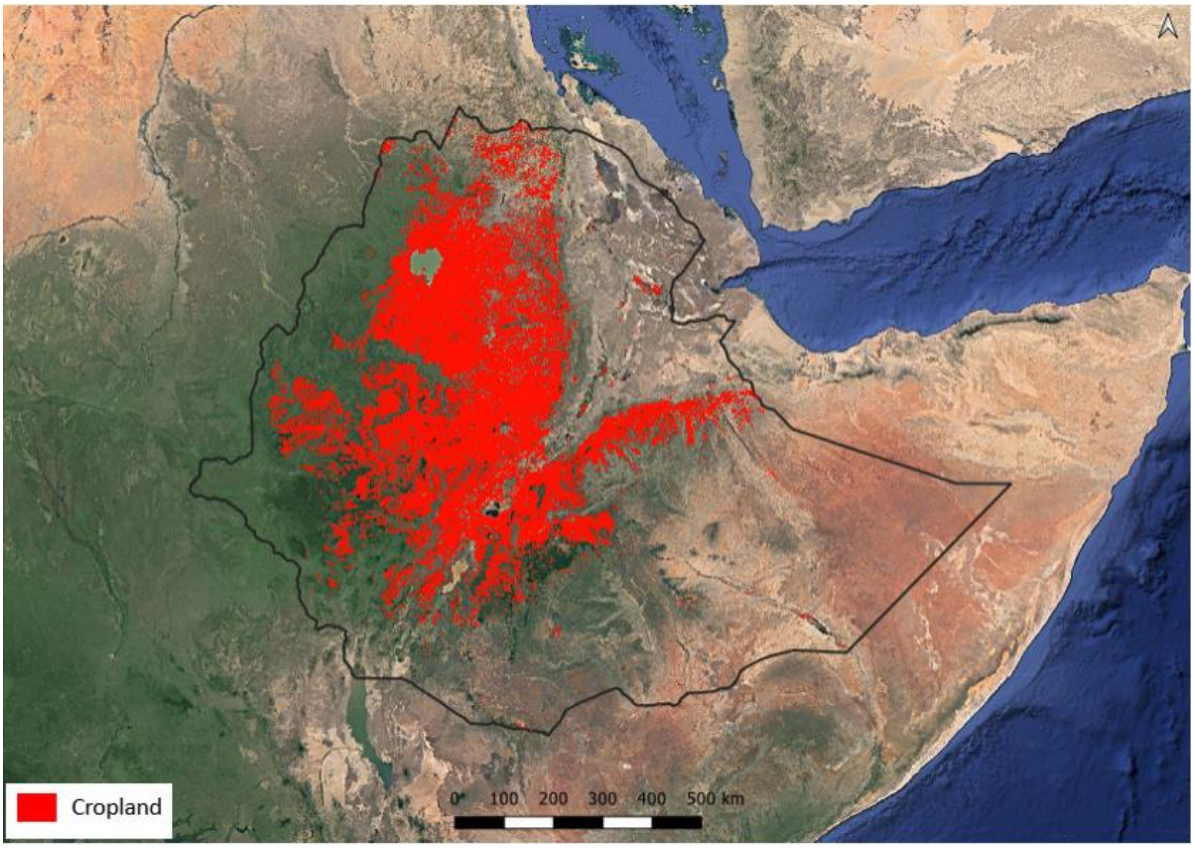

Figure 3.6: *Spatial Distribution of Cropland Area in Ethiopia*

By compiling the threshold values of indices and information related to the sensitive stages of crop growth, the CDFI was developed for cereal crops which is presented in Tables 3.5.

First-stage Index		Second-stage Index	
		Loamysand Anaerobiosis Condition	$\Theta = 0.375\ m^3/m^3$
Extremely Wet	SPEI = 2.0	Sandyloam Anaerobiosis Condition	$\Theta = 0.404\ m^3/m^3$
Severely Wet	SPEI = 1.5	Loam Anaerobiosis Condition	$\Theta = 0.442\ m^3/m^3$
Moderately Wet	SPEI = 1.0	Siltclay Anaerobiosis Condition	$\Theta = 0.494\ m^3/m^3$
		Clay Anaerobiosis Condition	$\Theta = 0.518\ m^3/m^3$
Normal	SPEI = 0.99 to -0.79		
		Soil Moisture at p value for Cereal Crops:	
Moderate Drought	SPEI = -0.8	Loamysand	$\Theta = 0.1060\ m^3/m^3$
Severe Drought	SPEI = -1.3	Sandyloam	$\Theta = 0.1490\ m^3/m^3$
Extreme Drought	SPEI = -1.6	Loam	$\Theta = 0.1880\ m^3/m^3$
Exceptional Drought	SPEI = -2.0	Siltyclay	$\Theta = 0.3575\ m^3/m^3$
		Clay	$\Theta = 0.4178\ m^3/m^3$

Notes:
1. While monitoring the SPEI index for meteorological condition, check the corresponding soil moisture value for agricultural condition.
2. Sensitive stages of wheat is in months from July to October.
3. Sensitive stages of sorghum is in months from mid-May to September.
4. Sensitive stages of teff is in months from mid-May to September.

Table 3.5: *Combined Drought and Flood Index of Cereal Crops (wheat, sorghum, and teff)*

4. RESULTS AND DISCUSSION

4.1. Latest Flood and Drought Conditions in Ethiopia and Assessment of Selected Indices

After selecting the meteorological index (SPEI) and agricultural index (soil moisture) for monitoring crop-specific flood and drought conditions, the SPEI index was calculated on a monthly basis for more frequent monitoring of the condition (calculation of the SPEI index within a shorter time interval was not recommended). Similarly, average soil moisture was calculated over a 10-day time interval (suggested to align with crop growth stages). After retrieving remotely sensed gridded data and calculating the SPEI index and 10-day average soil moisture, these results were compared to the latest recorded flood and drought conditions to access the performance of the selected indices and find out whether the indices are sensitive and capture the historical conditions (validation process).

First, the SPEI and 10-day average soil moisture maps were generated to visualize the effect of the flood conditions of year 2020. Figure 4.1 shows the spatial distribution of SPEI in Ethiopia during the month of July 2020. A SPEI index value above 2.0, i.e., an extremely wet condition, is evident in the northern and central parts of the country.

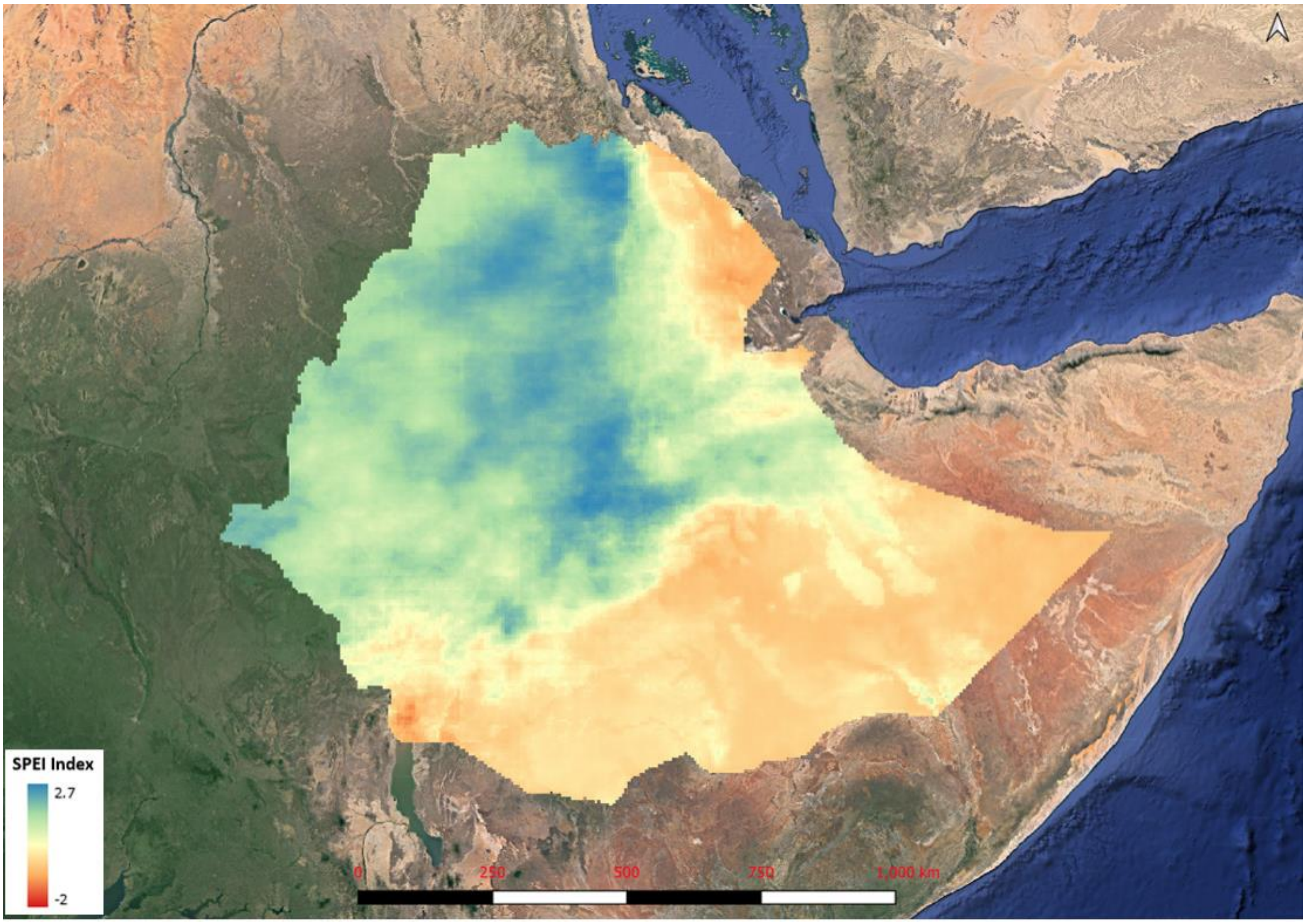

Figure 4.1: *Spatial Distribution of SPEI Index in Ethiopia for the Month of July, 2020*

Figure 4.2 shows the spatial distribution of 10-day average soil moisture in Ethiopia during early August of 2020.

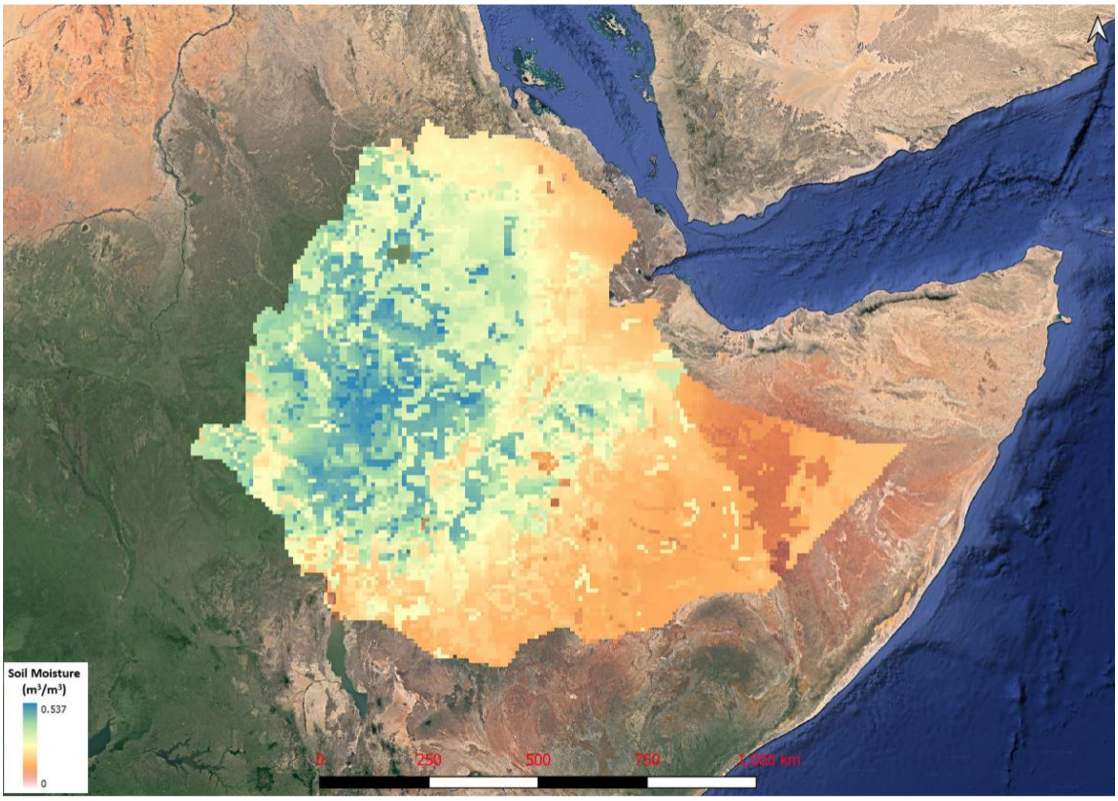

Figure 4.2: *Spatial Distribution of Root Zone Soil Moisture in Ethiopia in Early August, 2020*

The soil moisture map of early August of the year 2020 shows the development of an anaerobic condition in the soil root zone. This implies that the phenological development in mid-season (sensitive stages of flowering and grain filling) of sorghum, wheat, teff, and barley was affected due to reduced respiration in the soil root zone of crops.

Similarly, the SPEI and 10-day average soil moisture maps were generated to visualize the effect of the drought conditions of 2015. Figure 4.3 shows the spatial distribution of SPEI in Ethiopia during the month of April 2015. A SPEI index value of lower than-1.0 up to-1.35 in the northern and central parts of the country indicates moderate to severe drought conditions with possibilities of crop damage or crop loss. This drought conditions this year was caused by the strong El Nino phenomenon (Funk et al., 2016).

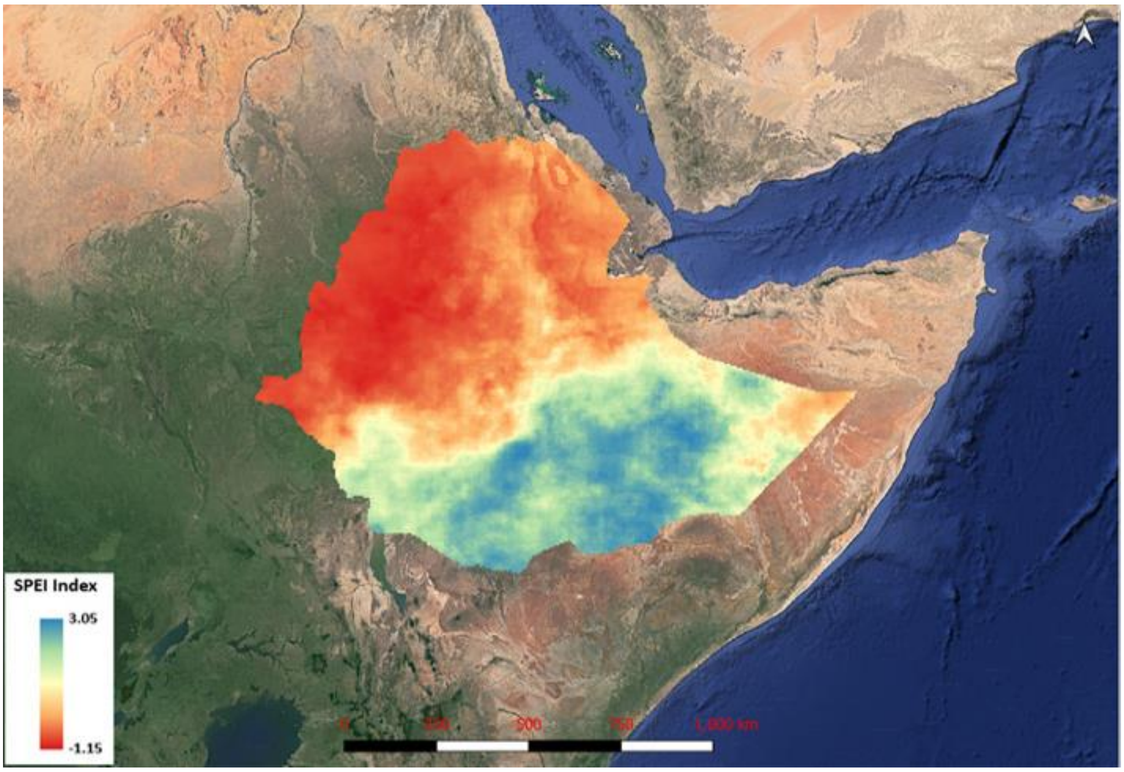

Figure 4.3: *Spatial Distribution of SPEI Index in Ethiopia for the month of April, 2015*

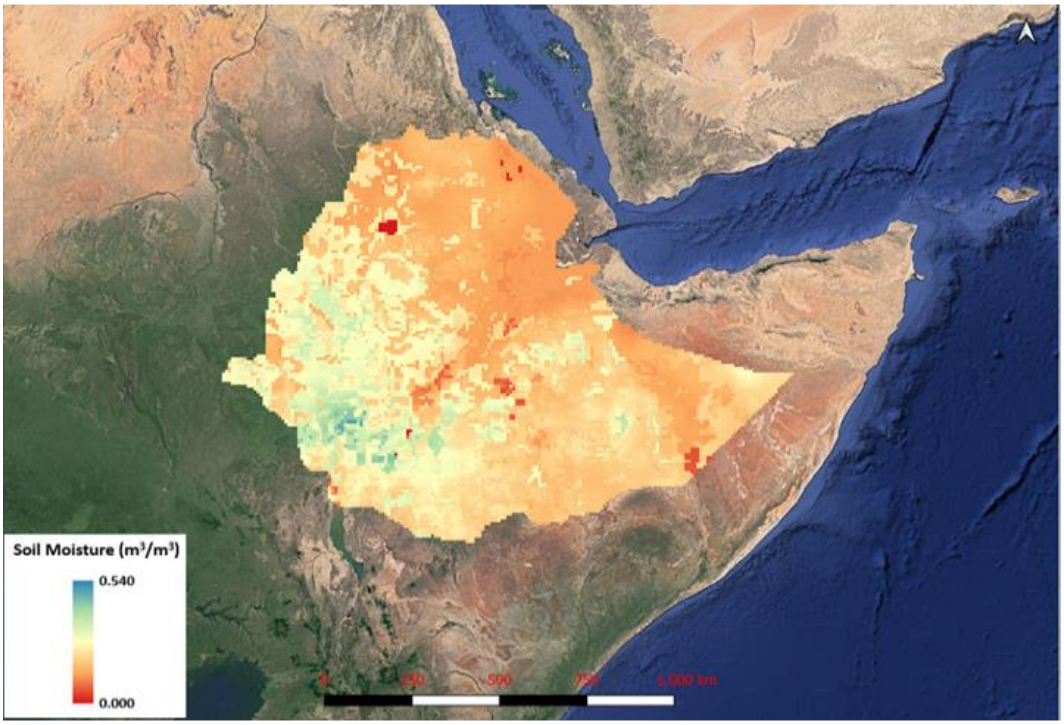

Figure 4.4: *Spatial Distribution of Root Zone Soil Moisture in Ethiopia in Early May, 2015*

The start of the mid-season of the sorghum crop, with sensitive stages of flowering and grain filling, starts in May. The lower soil moisture condition illustrated in Figure 4.4 implies that the phenological growth (sensitive stages) of sorghum was affected during the drought of 2015. Furthermore, the arid and semi-arid areas in the south and east parts of the country can be seen in wet conditions in the SPEI index map, whereas the corresponding response is not seen in the soil moisture map. The level of soil moisture is still low, which could be due to the effect of soil texture in the area, which needs to be further investigated.

Besides threshold calculation of indices, analyzing maps of indices in monthly (SPEI) and 10-day interval (average soil moisture) helps decision makers and agronomists to evaluate the conditions of flood and drought in different regions of the country.

Figure 4.5 shows the time-series plot of average SPEI index of cropland area in Ethiopia.

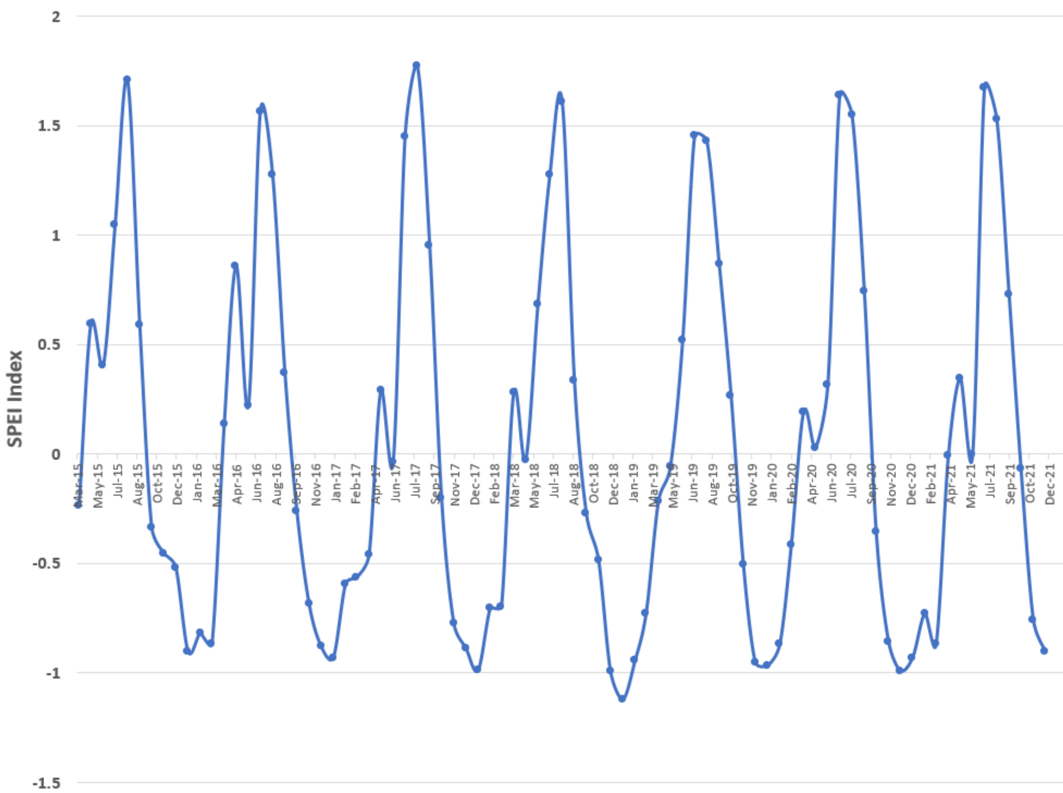

Figure 4.5: *Time-Series Plot of Average SPEI Index of Cropland Area in Ethiopia*

As a First-Stage Index, this can be applied to monitor when in crop growing season the condition of agricultural area is approaching towards either flood or drought condition. The Second-Stage Index can then be applied to access the condition of soil moisture and analyze if different crops are in stressed condition in its growing season. Figure 4.6 shows the time-series plot of average soil moisture of cropland area in Ethiopia.

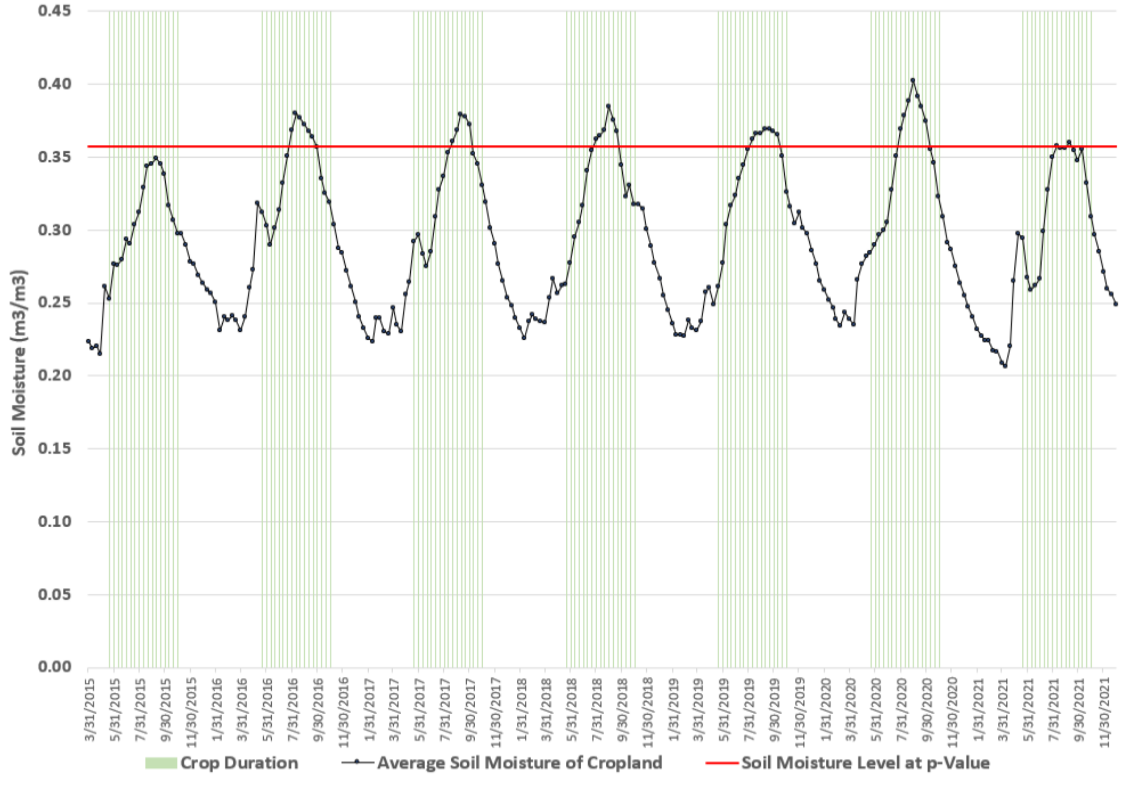

Figure 4.6: *Time-Series Plot of Average Soil Moisture of Cropland Area in Ethiopia*

It is seen in the figure that the soil moisture level of cropland area in year 2015 is well below 0.3575 m3/m3 during the growing season of cereal crops. Similarly Figure 4.7 shows the percent of cropland area in the country below the p value soil moisture condition in time-series. It is seen that the percent of cropland area in stressed state due to drought condition in growing season of cereal crops were higher in year 2015 compared to other years.

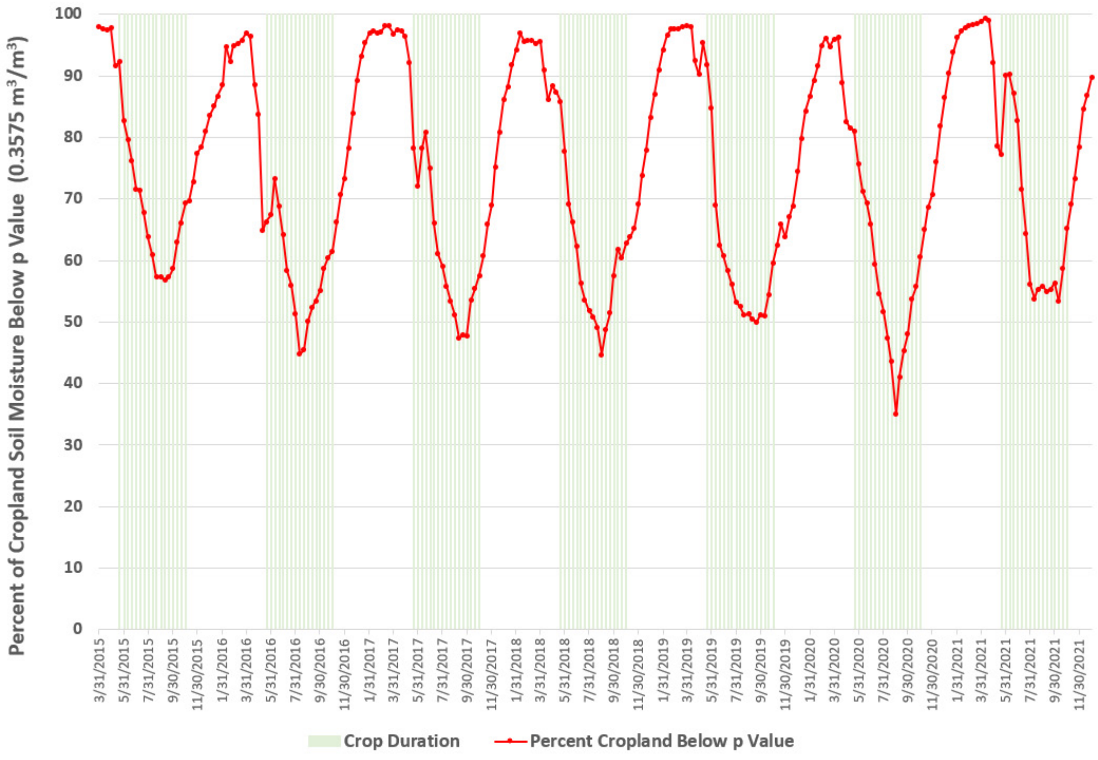

Figure 4.7: *Percent of Cropland Area Below the p Value Soil Moisture Condition in Time-Series*

Lastly, Figure 4.8 shows the percent of cropland area in anaerobiosis condition corresponding to the soil moisture values. It is seen in the figure that in around September of year 2020, 23 percent of cropland area of the country were in stressed condition due to flood event. During this period, the soil moisture level was above 0.494 m3/m3, and cereal crops were in stressed state due to anaerobic condition (flood condition).

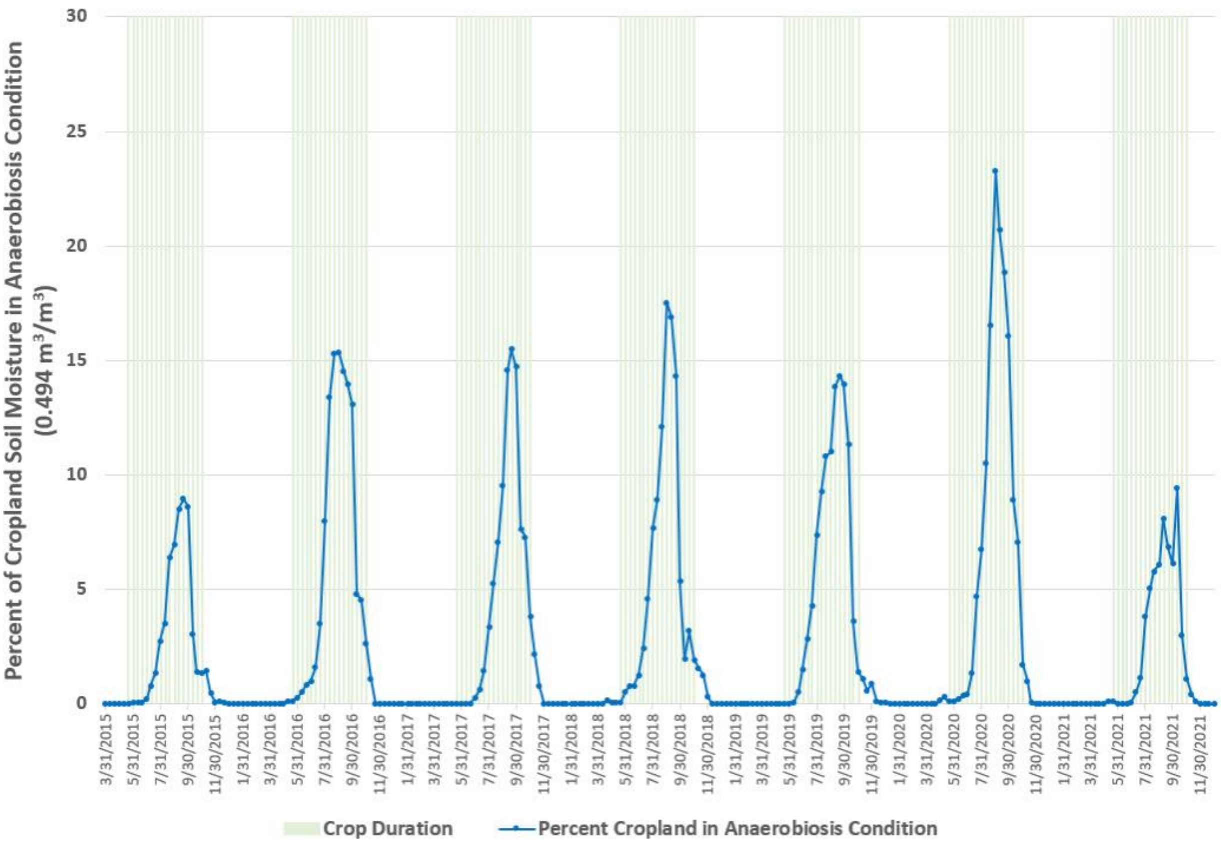

Figure 4.8: *Percent of Cropland Area in Anaerobiosis Condition (Flood Condition)*

4.2. Data Limitations and Future Work

Due to the coarse resolution (9 km) of SMAP soil moisture data, users should be mindful of how cautiously or appropriately to use this data since there are different small agro-ecological zones in different regions. If we are looking at a heterogeneous area in terms of both landscape and agriculture, we need to be aware of the issue of spatial resolution of soil moisture data. This soil moisture data has not yet been put through a performance analysis to see how well it works in drought and flood conditions that are specific to a crop at the local level. This research was done at the country level, and this coarse-resolution soil moisture data can give inaccurate results while monitoring drought and flood conditions at the local level. There are commercially available high-resolution root zone soil moisture data sets available now that utilize SMAP data, downscale it to 100 m resolution, and account for root zone soil moisture at 40 m depth (by combining 5 m of remotely sensed soil moisture with sub-surface modeling) by applying other geospatial data and machine learning algorithms (Planet, 2022).

These standardized indices can be used anywhere in the world. This means that in the future, these processes can be used in other countries, compared to historical data on floods and droughts to see if they work, and used with climate change data in the future to determine the frequency of occurrence of the droughts and floods. If spatial data with a higher resolution becomes available in the future, these indices can be recalculated for the higher resolution and tested in the field. This can help predict droughts or floods on a field-by-field level if local soil moisture or climate data is known or can be predicted. The predicted droughts or floods can act as an early warning, which will help in determining interventions to help reduce crop yield loss.

5. CONCLUSION

A five-step framework of the standardized process was proposed and developed in this research project for monitoring crop-specific agricultural drought and flood conditions. A final product of these steps was a combined drought and flood index with selected information from index thresholds and crop growth information for monitoring agriculture conditions. The index related to soil moisture data was selected as part of the agricultural index since the object of this research was to monitor conditions related to specific crops, and soil moisture is a dominant parameter in crop stages. Similarly, the SPEI index was selected since it incorporates the potential evapotranspiration component of vegetation (crops) in the meteorological index.

Geospatial climate data in time series was utilized, and the proposed steps were applied in the country of Ethiopia as a proof of concept of the proposed idea of a standardized process and as a tutorial guide to the early adopters on how to follow the steps of the framework for monitoring crop-specific flood and drought conditions. Examples of accessing the performance of selected and calculated indices with historical drought and flood conditions were also developed for early adopters to easily understand the meaning of (and relate to) the values of indices in terms of the severity of flood and drought conditions.

The standardization steps outlined in this framework address the challenges of data availability, the complexity of standardization steps, and resource requirements for implementation. Through the selection of widely accepted indices, this research provides a comprehensive approach to monitoring drought and flood conditions related to crop-specific agriculture, offering valuable insights for policymakers and decision-makers, agricultural practitioners, and other stakeholders. The five-step framework of the standardized process developed in this research has the potential to contribute to the sustainable management of water resources and agriculture and could be applied in various regions and contexts worldwide.

The coarse resolution of the rainfall (5 km) and soil moisture (9 km) datasets applied in this study was to develop the CDFI index at the country scale. Different soil moisture thresholds related to drought and flood conditions for different crops (in combination with soil types) were derived from a literature review (FAO, 1998), and SPEI index thresholds were included that are widely adopted by the scientific community. The maps of the SPEI index (5 km) and soil moisture (9 km) could be used to monitor conditions and analyze their pattern and distribution in different regions of the country. This will help the decision-makers be aware of the current situation of drought and flood conditions and the types of crops that might be vulnerable to their impacts.

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