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Original Research Article

Soil Moisture Content Suitability for Coffee Growing under Climate Change Scenarios in Uganda

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Abstract: ***Background***: Previous studies have looked at suitability of Arabica coffee with less emphasis on Robusta coffee. Secondly, they looked at coffee suitability in terms of temperature and rainfall. ***Methods:*** This study examined the effect of climate change on soil moisture content for coffee growing in Uganda, using historical (1990-2022) and projected (2025-2050) data from Terraclimate and eight Global Climate Models (GCMs). Soil moisture was analyzed in relation to coffee crop moisture thresholds at the root zone to simulate historical and future coffee suitability under two scenarios: Shared Socio-economic Pathways (SSPs) 245 and 585. ***Results:*** Soil moisture content in Uganda was characterized by high variability in highland areas during the March to May season among years. Furthermore, there were both decreasing and increasing trends averaging at ±1mm/Month. The future was on the other hand dominated by increasing trends over the western region and eastern-northern regions under SSP245 and SSP585 respectively averaging at 0.2mm/Month. Suitability analysis for 1990-2022 revealed that 71% of Uganda was highly suitable for coffee, while future predictions indicated an increase in suitable areas to 74% under SSP245 and 81% under SSP585. ***Conclusion:*** Generally, the higher moisture content associated with climate change will result in increased suitability of coffee by 10%, however, characterized by shifting area suitability especially for the mid-northern and south western regions where a reduction and gain in suitability is expected, respectively. This study highly the importance of identification and adaptation of site-specific soil moisture conservation practices, especially in the unsuitable areas.

Keywords: Robusta coffee, Arabica coffee, Trends, Projections, Climate variability, CMIP6.

INTRODUCTION

Climate change is predicted to have devastating impacts on the agricultural sector globally (Gokavi & Kishor, 2020). In Uganda, where Robusta coffee accounts for 80% of total coffee exports and supports the livelihoods of 9 million Ugandans, the impact of climate change will be felt more (Kagezi *et al.*, 2021). Depending on the rate of future greenhouse gas emissions, the Intergovernmental Panel on Climate Change (IPCC) has predicted that the global surface temperature will rise by an additional 0.3 to 1.7 °C (0.5 to 3.1 °F) in a moderate scenario or by as much as 2.6 to 4.8 °C (4.7 to 8.6 °F) in an extreme scenario during the 21st century (Gokavi & Kishor, 2020). This will cause an increase of certain pests (eg coffee berry borer *(Hypothenemus hampei*) and coffee stem borer (*Monochamus leuconotus*) and diseases (eg coffee leaf rust (*Hemileia vastatrix*) as temperature rises. The coffee trees' metabolism will be affected by the increased temperature, which will lead to early ripening and lower yields (Muller *et al.*, 2009; Filho *et al.*, 2012; López-Bravo *et al.*, 2012; Kyamanywa *et al.*, 2012; Agegnehu *et al.*, 2015; Kagezi *et al.*, 2018). According to a Brazilian study, prospective coffee yields could decrease by roughly 25% by the end of the twenty-first century (Tavares *et al.*, 2018). Temperatures in Uganda are predicted to increase by 2^0C over the next few decades (Zake, 2015), with a mere one degree increase in the mean temperature found to result in a loss of 116 kgha^{-1} of green coffee (Craparo *et al.,* 2012). It has been projected that the sustainability of the coffee industry faces significant challenges by 2050 (IPCC, 2022; Gruter *et al.*, 2022; Kath *et al.*, 2022). The shift of coffee-producing regions will be accompanied by

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changes in the suitability of coffee species. Climate-wise, other regions (in Africa, Asia, and South and Central America) will become less favorable for growing Arabica coffee and more suitable for growing Robusta coffee (Bunn *et al.*, 2015). According to Magrach and Ghazoul (2015), at least 83% of the entire potential coffee-growing region satisfies the requirements for Robusta cultivation, whereas only 17% (±6%) satisfies those for Arabica. In order to mitigate potential hazards and guarantee the sustainability of coffee production over the long term, prompt and efficient agronomic adjustments are necessary (Poitronieri & Rossi, 2016).

In addition, Rojas (2012) predicted that raising temperature and altered rainfall patterns will affect coffee growing and production. These will in turn reduce availability of water for production (Bunn *et al.,* 2019). Also, evapotranspiration and, consequently, water deficiency are expected to increase as result of climate change (Pinto & Assad, 2008; Bunn *et al.,* 2019). Water affects the phenology of the plant, which in turn effects the success of coffee cultivation (Silva *et al.*, 2019). Most coffee farmers in Uganda depend on rain water for production which is expected to be erratic and thus, lead to water stress (MAAIF, 2010; BMAU, 2018; Sridharan *et al.*, 2019). Coffee plants require both an adequate water supply and an ideal temperature, which are considered to be the most important environmental variables. This is because limitations on water and temperature have a negative impact on growth, yield, and productivity (Damatta & Ramalho, 2006; Camargo, 2010). One of coffee plants' first responses to a water scarcity is stomatal closure, which aims to reduce water loss through transpiration flow. But in doing so, it immediately lowers the amount of CO_2 that is available in the chloroplasts, which lowers photosynthetic rates (Damatta & Ramalho, 2006). Thus, systematically developing and putting into practice mitigation and adaptation measures would aid in overcoming upcoming challenges (Gokavi & Kishor, 2020).

Numerous studies have predicted the effects of climate change on rainfall and temperature as noted by King'uyu *et al.,* (2000), but information on the effect of climate change on other variable such soil moisture is still limited (Nsubuga & Rautenbach, 2018). Also, scientific research on the effect of climate change on the suitability of coffee growing areas in Uganda has predominantly been conducted on only Arabica coffee (Läderach & van Asten, 2012; Markandya *et al.,* 2015). The most often used prediction for Robusta comes from Simonett (1989), who provided maps illustrating a sharp reduction in Uganda's suitable growing area due to a 2% increase in temperature. This map was created in 1989. The most recent one was carried out in central Uganda by Mulinde *et al.,* (2022). Moreso, these Robusta suitability studies were based on rainfall and temperature yet, these do not exclusively represent the dynamics and status of water in the rootzone. On the other hand, a climate change projection for Robusta coffee in Uganda suggests that the crop would retreat to higher elevations in the southwest of the country, near Rwanda and partially in Tanzania. However, this seems to be speculative since no scientific study has been conducted (Haggar & Schepp, 2012). This study therefore aimed at predicting the effect climate change on soil moisture content in Uganda so as to bridge this information gaps.

MATERIALS AND METHODS

Study area

The study was carried out in all Robusta and, Arabica coffee growing areas as well as the non-traditional coffee areas of Uganda (Figure 1). The majority of Uganda is located between 900 and 1500 meters above sea level (Bamutaze, 2010). Robusta coffee is grown in low lying regions of Central, Eastern, Western and South Eastern Uganda between 900 and 1,500 masl (UCDA, 2019- Hand book). Conversely, Arabica coffee is produced at high elevations of more than 1400 meters above sea level in the highland regions of Uganda on the slopes of Mount Elgon in the eastern, Mt. Rwenzori and Mt. Muhavura in the south-western, and West Nile regions (Bunn *et al.*, 2015; Jassogne *et al.*, 2013; Ovalle-Rivera *et al.*, 2015). In the south of Uganda, there are two distinct rainy seasons, or a bimodal cycle, which results in more rainfall from March to May and September to November. In the north, a prolonged single rainy season that spans the seasons makes a unimodal cycle (one rainy season) more evident. Not much rain falls in Uganda's far northeast in any month of the year. Rainfall is moderate to relatively abundant, typically ranging between 500 and 2800 millimeters per year. Uganda experiences annual temperatures of about 21°C. The lowest monthly temperature is 15°C in July, while the highest temperature is 30°C in February (Irish Aid, 2017). The majority of Uganda's agricultural soils are composed of Ferrasols and Nitisols, which are nearing the end of their weathering process and consequently have relatively little nutrient stores (Eswaran *et al.*, 1997; Henao and Banaante, 1999; Stocking, 2003; NEMA, 2009).

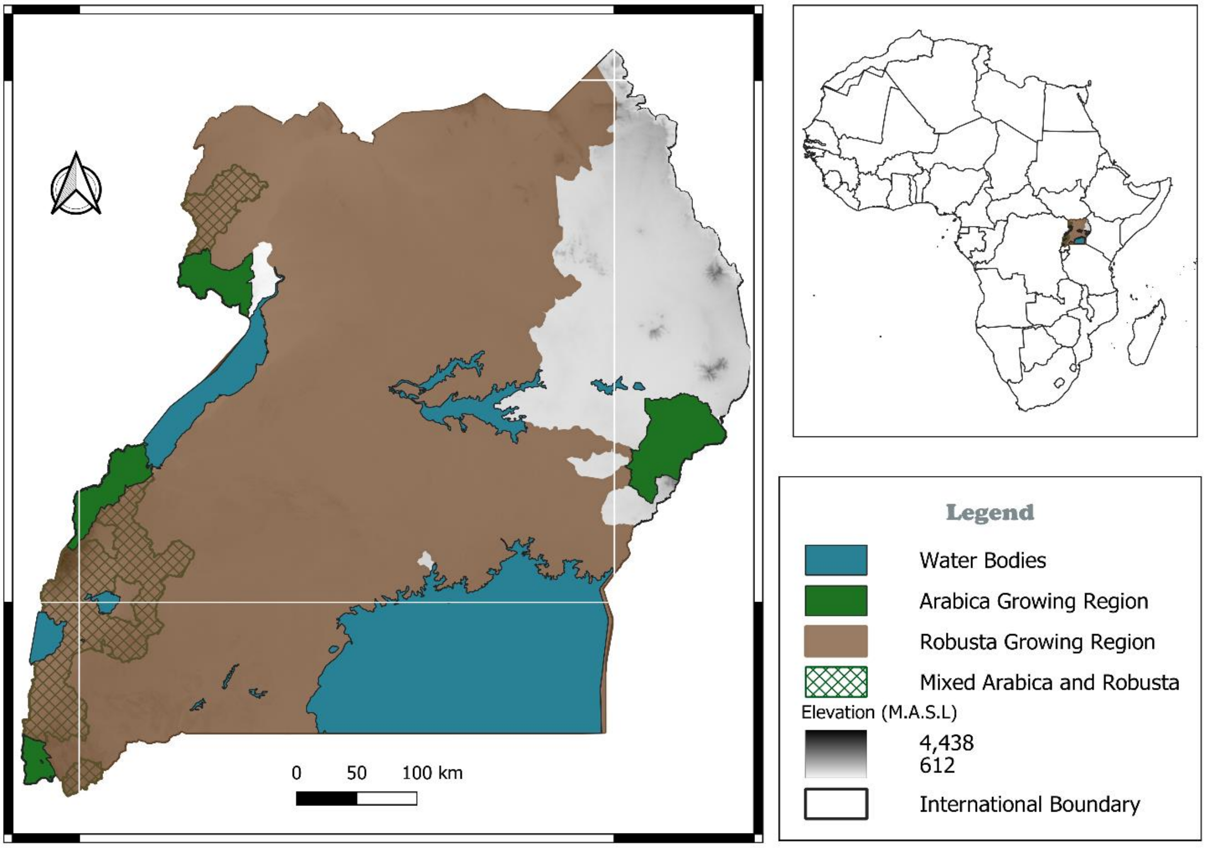

Figure 1: Location of Uganda and it's coffee growing regions

Data acquisition and analysis

Soil moisture Thresholds

Soil moisture thresholds data (Field capacity, permanent wilting point and saturation) were obtained from https://www.isric.org/explore/soilgrids (Accessed on 24.10.2023). These datasets were selected because of high resolution and consistency. Coffee Maximum allowable Depletion (MAD) was taken as 40% of the available water capacity in the rootzone (Allen *et al*., 1998).

Historical (1990-2022)

Terraclimate data (Abatzoglou *et al.*, 2018) at ~4km spatial and monthly temporal resolutions were used as historical soil moisture content data obtained from UofI TERRA CLIMATE's Webpage (northwestknowledge.net) (Accessed on 05.1.2024) for a period of 1990-2022. The historical soil moisture was corrected to the coffee root zone depth of 0.4m using in situ soil moisture that was collected at field sites in Mukono and Mubende. Quality control was done using root mean square error (RMSE) over two sampled points of Uganda including Mukono and Mubende districts. Soil moisture was collected at both sites using Diviner 2000 from Jan 2022-Dec 2023. RMSE was determined using this observed soil moisture and the terraclimate soil moisture content data. The results showed that the difference between observed soil moisture and the terraclimate data was 5mm in Mubende while in Mukono, it was 2.80mm. The Normalized root mean square error (NRMSE) was determined by dividing RMSE by range of observed soil moisture. Based on the Scatter Index, the errors (Mukono=3.41% and Mubende=4.41%) were relatively low hence warranting our adoption of the dataset. Soil climatology was done using MATrix LABoratory (MATLAB) (The MathWorks Inc., 2019) live scripts and a set of climatology functions in Climate Data Toolbox (CDT) tool box (Greene *et al.*, 2019) that include seasonality, climatology, trend among other methods. These methods are powered by the Mapping Toolbox which includes as set of spatial interpolation, overlay, masking, Re-projection, spatial integration among other GIS functions (Fig. 2). The monthly data were further divided into four seasons of Dry (JF i.e., January, and February), Wet (MAM, i.e., March, April, and May), Dry (JJA, i.e., June, July, and August), and Wet (SOND, i.e., September, October November and December). Spatial and temporal analysis was carried out using Spatio-Mann Kendall method in MATLABR2023b. Mann-Kendall (Yue and Wang, 2004) approach intends to identify potential trends of meteorological components without requiring data to fit into a certain statistical distribution. Also its insensitivity to outliers common in climatology data. Thus, it is frequently employed in trend analysis (Kahya and Kalayci, 2004).

Future (2025-2050) under two Shared Socio-economic Pathways

Soil moisture was projected for the present to near future (2025-2050) period. This study period was selected so as to contribute towards the implementation of vision 2040 of Uganda. The future climate projections for the years 2025-2050 were derived from eight global climate models (GCMs) under two emission scenarios of future shared socio-economic pathways (SSPs), 245 and 585, from the Coupled Model Inter-comparison Project phase 6 (CMIP6) (https://esgf-node.llnl.gov/search/cmip6/) (accessed on 16.1.2024). A new set of emissions and land use scenarios created using integrated assessment models (IAMs) based on the Representative Concentration Pathways (RCPs) and the Shared Socioeconomic Pathways (SSPs) were used in these climate projections (Oneill *et al.*, 2016). The SSPs outline alternate future societal evolutions that do not rely on climate change or climate policy. Two integrated scenarios were examined in this study: the combination of SSP2 with RCP4.5, as described by SSP245, and the combination of SSP5 with RCP8.5, as defined by SSP585. The reason CMIP6 was chosen was its improved understanding of past, current, and future climate change resulting from unforced variability in nature or from variations in radiative forcing within the framework of several models (Eyring *et al.*, 2016). The climate forecasts for CMIP6 will also be different from those for CMIP5 because of a new generation of climate models, a different start year for the future scenarios (2015 for CMIP6 vs. 2006 for CMIP5), and a new set of scenarios pertaining to emissions, concentrations, and land use (Oneill *et al.,* 2016). According to SSP2, there exists a center channel wherein trends maintain their historical patterns without significant deviations. According to Oneill *et al.*, (2016), SSP5 predicts rather positive trends for human development, including significant investments in health and education, quick economic growth, and well-functioning institutions. According to Riahi *et al.*, (2011), RCP 4.5 depicts a modest level of greenhouse gas reduction, leading to some changes in worldwide climate patterns. In contrast, RCP 8.5 indicates substantially less mitigation, leading to significantly bigger global climate changes. Given the bulkiness of global datasets from CMIP6 models, climate variables are provided in individual years at a global scale. As such, projected soil moisture datasets per GCM were concatenated using CDO-command lines in Linux Environment to form a composite time series of the entire study period in NetCDF format. Regridding and remapping was done using the conservative first- and second-order remapping methods (Zhang *et al.,* 2011) in Linux to cater for variations in model grid spacing. Multi-model ensemble approach (Christensen & Lettenmaier, 2007) was used to combine the data from eight different CMIP6 models namely: BCC-CSM2-MR, CMCC-CM2-SR5, CMCC-ESM2, CNRM-CM6, GDFL-ESM4, CNRM-CM6-1-HR, NorESM2-MM and CNRM-CM6-1 . This is due to the fact that a single climate model cannot sufficiently capture the dynamics of climate change. Based on the fundamental presumptions that all models are fairly independent, equally plausible, and distributed around reality, moisture prediction employed the averaging or combining of results from multiple models to reduce uncertainty (Sanderson *et al.,* 2015; Knutti *et al.,* 2017). These data were equally used to perform climatological and trend analysis for the future period using methods explained in the previous subsection.

Coffee Suitability Mapping

Both historical and future coffee-suitability based on soil moisture was done using a suite of rootzone adjusted historical and future soil moisture data, and soil moisture thresholds over Uganda at uniform grids. Suitability maps were created in MATLAB using the Mamdami Fuzzy inference system (FIS) (Akgun *et al.,* 2012). The rationale behind the use of FIS was that it addresses the subjective uncertainty (fuzziness, vagueness, and imprecision) present in the way experts approach their problems, enables the explicit expression of system knowledge via fuzzy "if-then" rules, and combines numerical and categorical data (Alvarez Grima, 2000). Four suitability classes were considered; 1) High suitability (between Total Available Water Holding Capacity (TAW) and Field capacity), 2) Average suitability (between Field capacity and Permanent Wilting Point), 3) Low suitability (Above Saturation) and 4) unsuitable (Below MAD).

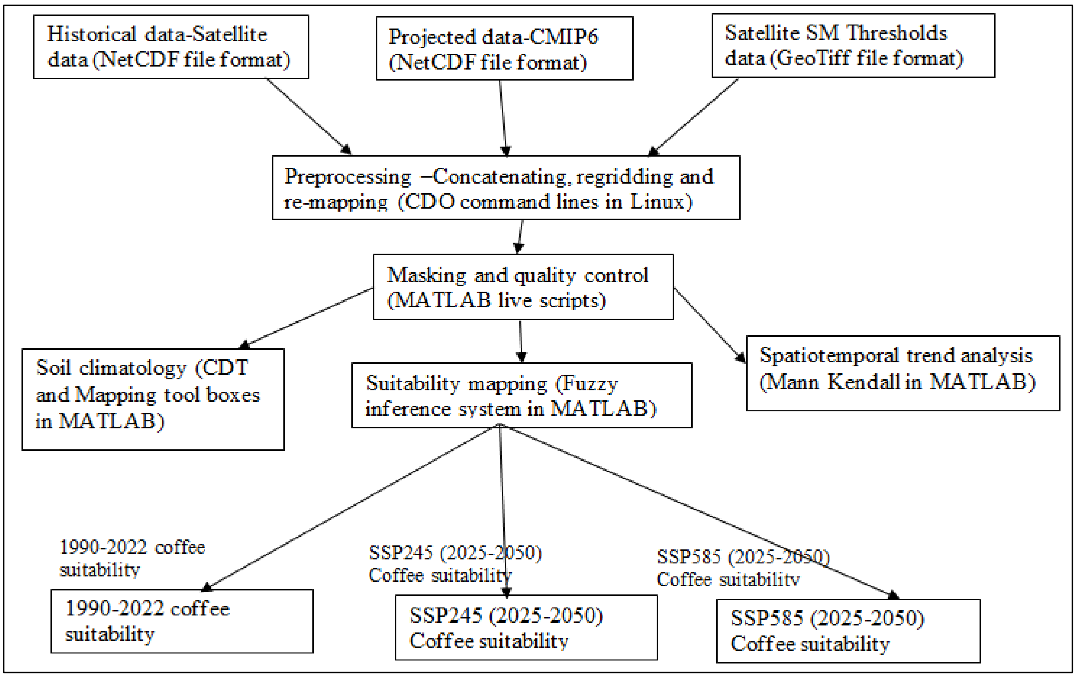

Figure 2: Flow chart of preprocessing and data analysis

Results and Discussion

Evaluating the spatio-temporal distribution of historical soil moisture climatology

Root zone soil moisture content was more (115-143mm) in the Lake Victoria basin especially the northern districts of Mpigi, Wakiso and Mityana, Kibaale, Mt Rwenzori subregion and Mt Elgon areas in the districts bounding the bounder of Kenya (Fig 3). These results are in line with those of Jury (2015) who found out that rainfall around Lake Victoria exceeded 2 m/yr in comparison to other areas of around 1.5 m/yr. GOU (2007) also indicated that the wetter areas of Uganda, around the Lake Victoria basin and the east are tending to become wetter, indicating an increase in rainfall in these areas. Furthermore, according to UNESCO (2020) and the NBI (2020), the regions east of the Lake Victoria and Lake Kyoga basins are exhibiting positive trends in wetting tendencies; this could also account for the landslide incidents that have been occurring in the Lake Kyoga basin around Mount Elgon region and the current rise in lake levels.

In contrary, areas of north-eastern Uganda, Isingiro, Kiruhura and Rakai in south-western had the least soil moisture content of less than 30mm. These results are consistent with other studies that show Karamonja region which is located in the northeastern part of Uganda was most vulnerable to drought and worst hit by climate change (USAID, 2017; Kakumba, 2022). The northeast of Uganda has the lowest soil moisture levels since it experiences the elevated irradiance boosting evapotranspiration and the least amount of rain throughout the year (CDKN, 2015). The soil's moisture content decreases when evaporation rise and precipitation levels fall (Afolabi *et al.*, 2009; Omona, 2023). Indeed, studies have demonstrated a strong and positive relationship between soil moisture content and precipitation, as well as a negative relationship between soil moisture content and imbalance in radiative budget such as increasing latent heat and air temperature (e.g. Findell and Eltahir 1997; Eltahir, 1998; Dai *et al.*, 2022) which drive evaporation. Additionally, regions in the country's northeast and southwest were found to be water stressed, according to WRMD (2004). It should be noted that these regions are part of the Cattle Corridor, which spans diagonally from southwest to northeastern Uganda and accounts for approximately 35% of the country's land area. The corridor has several semi-arid characteristics, including low and irregular rainfall and protracted droughts (Nimusiima *et al.*, 2013; Mayanja *et al.*, 2020).

On the other hand, results showed that soil moisture content has been significantly increasing per month in Karamojonja regions, Manafa, Tororo by 1.5mm while in Mukono, Buikwe, Jinja, Bugiri, Busia, Kiruhura and Lyantonde districts by 0.5mm and significantly decreasing in the rest of the country. A study by Diem *et al.*, (2014), reported a significant decrease in seasonal rainfall in western and central regions of Uganda during the period 1983-2012. While a study by Mubialiwo *et al.*, (2020) and Nsubuga *et al.*, (2014) reported significant increased trends in annual rainfall in the Mpologoma catchment in Eastern Uganda for the period 1948-2016. This therefore suggests increased water availability in the area (Kilama Luwa *et al.*, 2021). Goulden (2008) indicated high percentage increases in rainfall for historically dry seasons for many parts of Uganda.

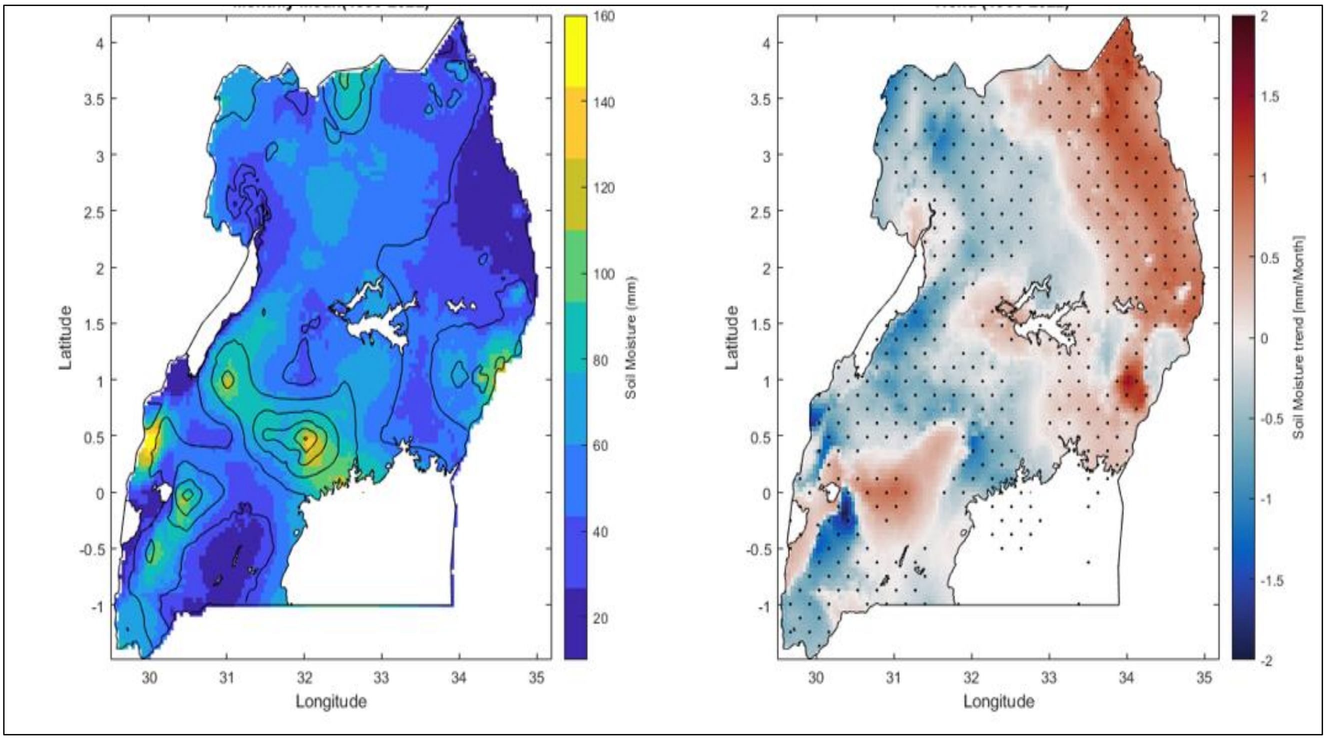

Figure 3: Root zone Soil Moisture monthly climatology (left) and Trends (right) for the period 1990-2022. (Stipples indicate where the trend was significant at 5% level of significance.)

Evaluating the spatio-temporal distribution of future soil moisture climatology

SSP245 and SSP 585 showed that soil moisture (119-135mm) will be high in Kigezi sub region, with high variability between years (Fig. 4 and 5 respectively) . There will also be high soil moisture in Rwenzori sub-region, however it will not vary among years. A study conducted by Ngoma *et al.,* (2022) showed that as projected by SSP245, rainfall in the country's western and southern regions will rise by up to 8 mm by the end of the century. This partly explains the observed upward trends in soil moisture in these regions. SSP245 projections also showed that soil moisture will decrease around Lake Victoria as well as Kisoro and Kabale area by 0.02-0.06mm and increase in the rest of the country. The highest increase being observed in Rwenzori sub-region and Kitgum by 0.08mm. In line with this, Jury (2024) predicted an increasing trend in rainfall in Rwenzori subregion attributable to a faster Hadley circulation driving more equatorial and less subtropical rainfall. SSP585 showed that soil moisture will increase in the country with the highest being Moroto and Amudat by 0.2-0.25mm per month and almost no change around Lake Victoria, Kisoro and Kabale. In line with the results, Mininstry of foreign Affairs (2018) reported that rainfall will increase in the north of the country and a decrease in the southeast. According to earlier rainfall forecasts, most of the nation will see a modest decline in annual precipitation overall, with somewhat wetter circumstances expected in the west and north-west under RCP 4.5 and RCP 8.5, respectively. Rainfall is expected to drop by -20mm around Lake Victoria (Markandya *et al.,* 2015).

Seasonal characteristics of historical soil moisture

Historical data (1990-2022) showed that soil moisture content in the root zone was high (100-150mm) across all seasons in the areas of Mt Elgon, Rwenzori subregion, Mpigi, Mityana, Mubende, Kibaale and Bushenyi. Soil moisture was lowest (less than 33mm) in Karamoja subregion, Isingiro, Rakai, Pakwach, Nebbi and Ntoroko in all the seasons (Fig. 6). This is in line with previous study by Basalirwa (1995) that predicted an increase of about 10-20% in rainfall for high ground areas, and more drying conditions for low areas such as Uganda's cattle corridor. Low soil moisture in Karamonja sub-region, Isingiro, Rakai, Pakwach, Nebbi and Ntoroko in all the seasons is because these regions received low rainfall and experienced a high temperature and evaporative demand (Nimusiima *et al.,* 2013; Mayanja *et al.,* 2020). Long term dynamics of soil moisture droughts are mainly driven by precipitation and evapotranspiration (Dai *et al.,* 2022; Lui *et al.,* 2022), land use land cover changes as well as the soil's capacity to hold water. Ogwere (2021), however, demonstrated that the annual and seasonal soil moisture content generally decreased across all soil depths in Uganda's various regions. MAM shows high variability of soil moisture content among years in most parts of the country. This could be influenced by high interannual rain deviations in April (Jury, 2015).

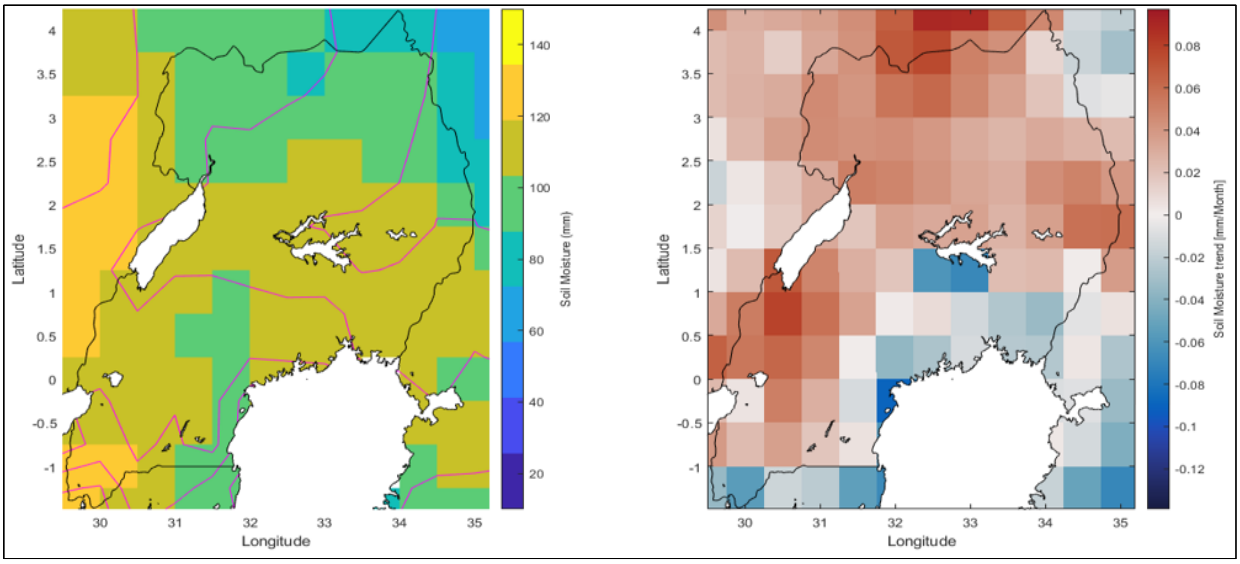

Figure 4: Future climatology (Left) and trends (Right) of soil moisture under SSP245 over Uganda

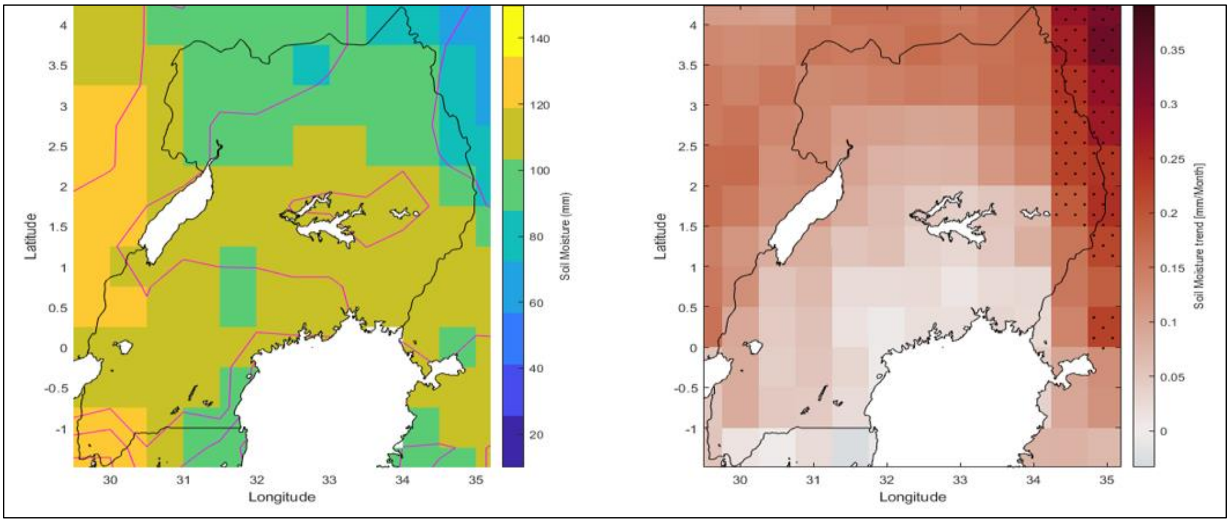

Figure 5: Future climatology (Left) and trends (Right) of soil moisture under SSP585 over Uganda. (Stipples indicate where the trend was significant at 5% level of significance.)

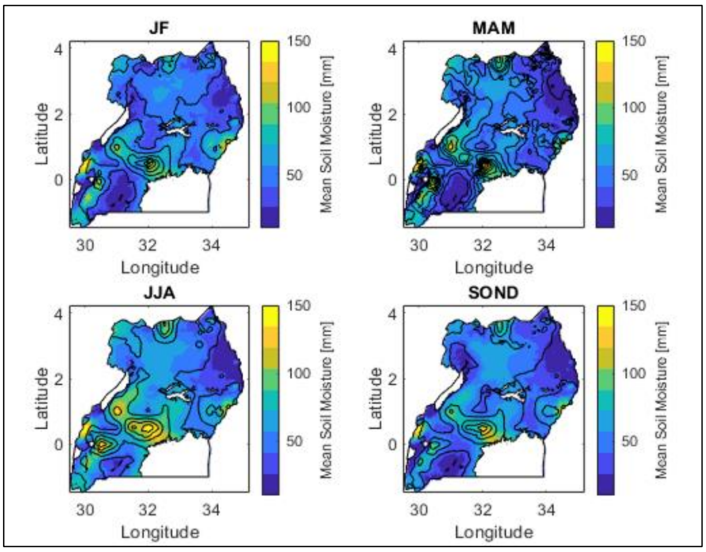

Figure 6: Mean seasonal Root zone Soil moisture and its spatiotemporal variability (1990-2022) expressed as contours
JF=January, February; MAM=March, April, May; JJA=June, July, August; SOND=September, October, November, December.

Seasonal characteristics of future soil moisture content

Under the SSP245, all seasons will have similar distribution of soil moisture content across the country with the Northern, West Nile, Karamojonga regions and a few area in Rakai having the least soil moisture (80-100mm) (Fig 7). Similar predications have been made by SSP585 except for January-February season where areas around Rakai, Sembabule, Mubende, Kiruhura, Wakiso and Luwero have more soil moisture by +20mm compared to other seasons (Fig 8). This is because rainfall is projected to increase in drier seasons by 2050 by 5 - 20% (Hulme *et al.*, 2001; IPCC, 2007). Goulden's (2008) analysis shows significant percentage increases in rainfall for historically dry seasons in many locations of Uganda. In contrast, Nandozi's (2012) prediction that precipitation will remain constant and comparable in seasonality between 2071-2100. Predictions based on SSP 245 and SSP258, showed that there will be a high variation in soil moisture content among years in areas of Kigezi sub region across all seasons.

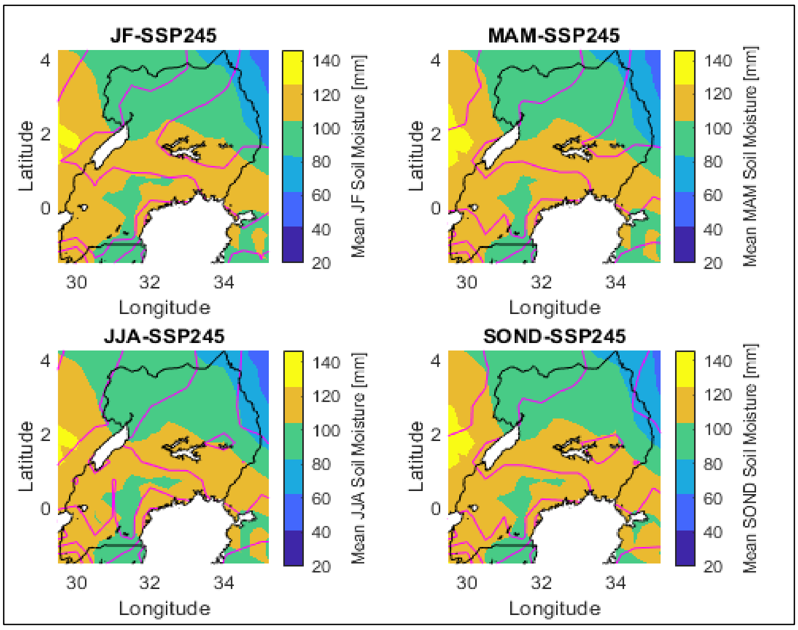

Figure 7: Future Mean seasonal soil moisture and its spatiotemporal variability (2025-2050) under SSP245 expressed as contours

JF=January, February; MAM=March, April, May; JJA=June, July, August; SOND=September, October, November, December.

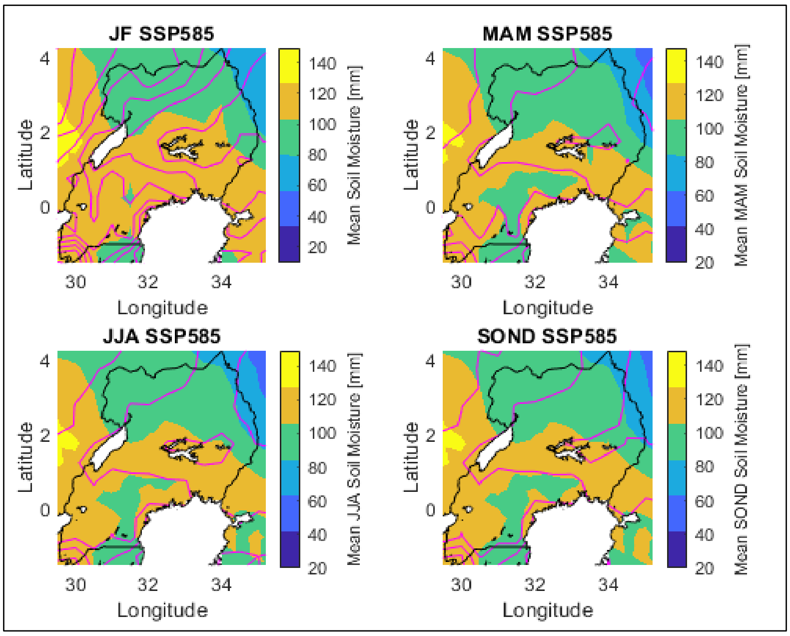

Figure 8: Future Mean seasonal Soil moisture and its spatiotemporal variability (2025-2050) under SSP585 expressed as contours

JF=January, February; MAM=March, April, May; JJA=June, July, August; SOND=September, October, November, December.

Current and projected coffee suitability based on soil moisture content

Historical soil moisture content data showed that areas of Isingiro, Kiruhura, Nebbi, parts of Adjumani, Aura, Bulisa, Kitgum, parts of Kabong, Kotido, Abim, Moroto, Napak, Katakwi, Nakapiripirit, Amudat, Nakasongola, Nakaseke, Kasese and Rubirizi are unsuitable for coffee growing while parts of Ntoroko have low suitability (Fig 9). Future suitability under both SSP245 (Fig 11) and 585 (Fig 12) shows that northern Uganda and Bukeda sub region will be unsuitable for coffee except for Nwoya, Apac, Gulu, Kotido and Moroto . The low soil moisture for Northern region and Teso sub-region could have contributed to its unsuitability both in the past years and the future (Moat *et al.,* 2017). According to Swaibu *et al.,* (2014), coffee production in northern Uganda is limited to one season each year due to prolonged dry spells, as opposed to two seasons in most of the country's major coffee-growing regions (UCDA, 2019-Hand book). Also, historical low soil moisture suitability in Isingiro, Kiruhura is as a result of low soil moisture in these areas due to low rainfall reported in cattle corridors by Basalirwa (1995). The increase in coffee suitability in central, western, eastern and Karamoja sub-region implies that Robusta suitability will increase in the future in these areas. Similar research was done in Uganda by Nandozi (2012), who found that 84% of the coffee-prone areas are expected to remain appropriate for coffee growth in the future based on forecasted climate data. However, Arabica which is grown in West Nile will reduce suitability and also, Robusta suitability will reduce in mid-north. This result is consistent with Von Loeben *et al.,* (2023) who stated that by the end of the century, the areas of West Nile that are at the moment suitable for Arabica coffee will become unsuitable hence farmers might need to shift to growing Robusta coffee or other more climate-resilient coffee species or varieties. These authors further reported that the Northern region will be hit particularly hard due to a projected increase in the frequency of hot days and nights, together with dramatic temperature fluctuations. This will jeopardize the Governments' initiatives and programs of increasing coffee production in Northern Uganda and other non-traditional coffee growing areas (Swaibu *et al.,* 2014; Coffee Roadmap, 2017). On a good note, Teso sub-region known for not growing coffee will increase in suitability in the future. Past research by Jassogne *et al.* (2013), Läderach & van Asten (2012), and CIAT (2013) indicates a significant decrease in regions suitable for Arabica production by 2030 and a significant increase in areas completely unsuitable for coffee producing by 2050. Simonett (1988) is the first example of an impact research that evaluates how climatic change affects the production of *C. canephora* in Uganda. Maps provided by this study demonstrate how a 2% increase in temperature has resulted in a sharp change in Uganda's coffee growing area. The map was created in 1989, though, Haggar and Schepp (2012) conclude that "it is not clear what the scientific basis is of the prediction for Uganda, so any extrapolation must also be considered speculative." Haggar and Schepp (2012) provided evidence for the increased suitability in south-western Uganda by projecting that Robusta coffee in Uganda would retreat to higher elevations in the southwest, where it borders Tanzania and Rwanda. Von Loeben *et al.,* (2023) similarly came to the conclusion that, under all scenarios, Uganda's Robusta coffee will shift away from the interior and toward the coasts of Lake Victoria. Furthermore, according to research from Kenya and Uganda, Haggar and Schepp (2012) indicated that Robusta production will shift to higher rainfall zones and the minimum altitude for Arabica production would increase by as much as 400 meters as a result of climate change. The countries that cultivate coffee may see a decline in export income if the viability of their coffee-growing regions changes (Bilen *et al.,* 2023). Due to the fact that smallholder farmers are becoming more and more dependent on coffee profits, producers in certain places will need to use soil moisture conservation practices if they want to continue growing coffee (Bunn *et al.,* 2015; Salad *et al.,* 2021; Bracken *et al.,* 2023). The areas that are highly suitable makeup 71%, low suitability, <1% while 28% of the area is unsuitable (Fig. 10). The area suitable for coffee growing will increase by 74% and 81% as predicted by SSP245 and SSP 585 respectively (Fig 13). According to Nandozi (2012), the majority of the coffee-prone areas (84%) will probably still be appropriate for coffee development in the future, based on the expected climate (evaporation and rainfall). Nevertheless, 2% of the area will be probably not be appropriate for growing coffee, and 14% of the area will be probably only marginally suitable.

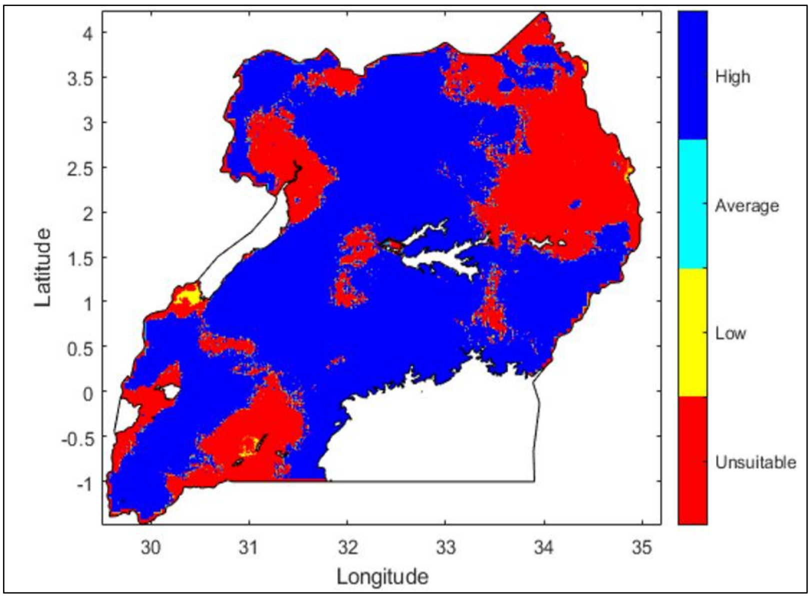

Figure 9: Coffee suitability over Uganda for the period 1990-2022

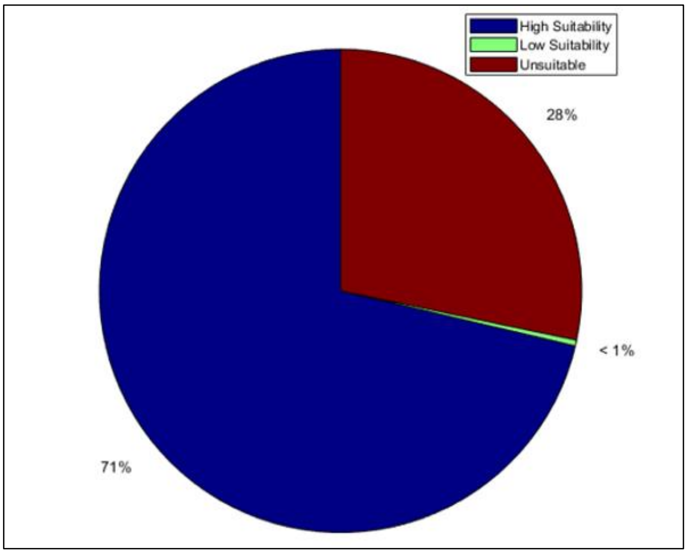

Figure 10: Percent of area suitable for coffee production (1990-2022)

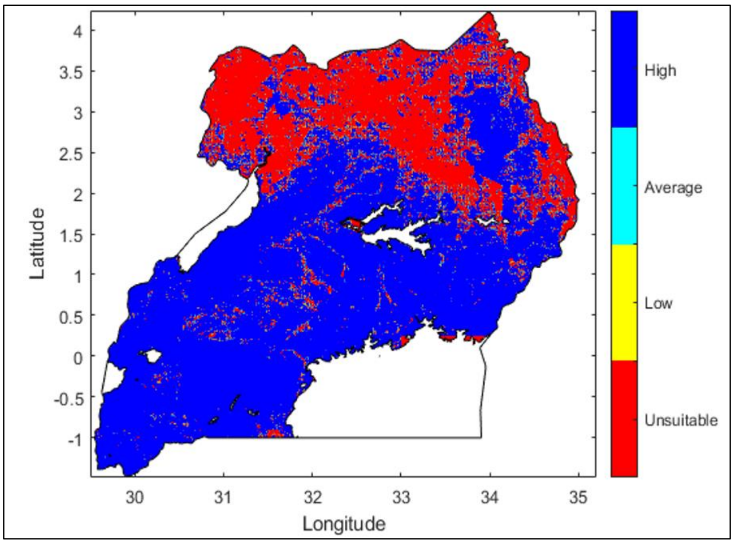

Figure 11: Future Coffee suitability over Uganda for the period 2025-2050 under SSP245

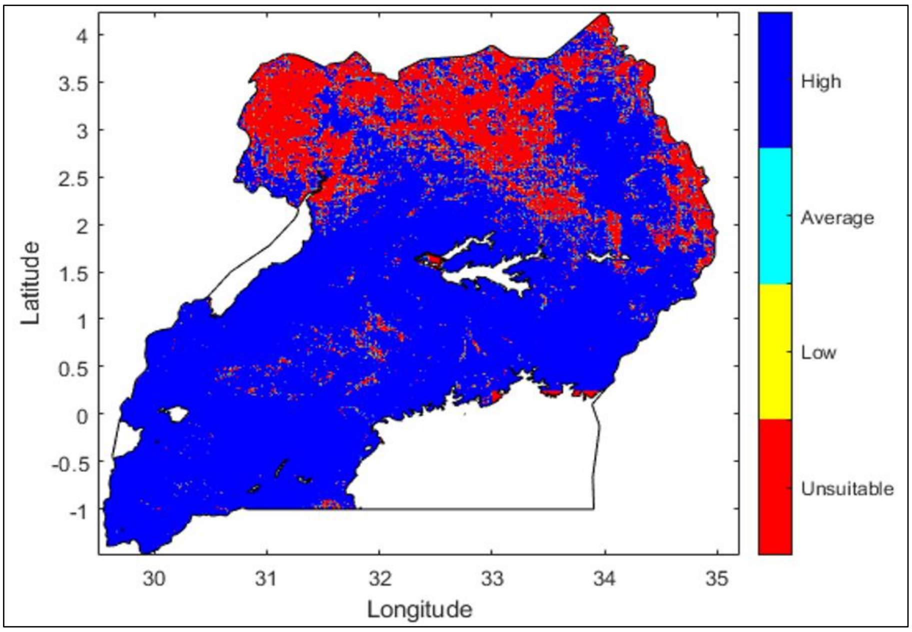

Figure 12: Future Coffee suitability over Uganda for the period 2025-2050 under SSP585

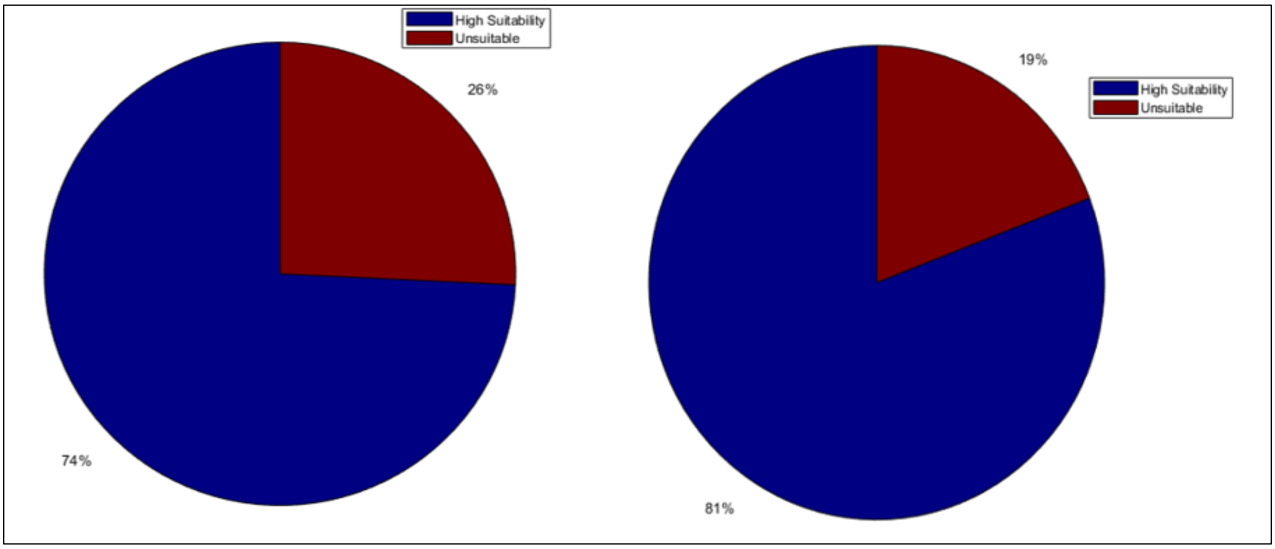

Figure 13: Percent of area suitable for Future coffee production (2025-2050) under SSP245 (left) and SSP585 (right)

CONCLUSION

Climate change will result in higher soil moisture, which will increase the suitability of coffee by 10%. This shift in suitability still requires identification and adaptation of site specific soil moisture conservation practices especially in the unsuitable areas. There is also need to determine how these changes in areas will translate to changes in coffee production.

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