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# Spatiotemporal Changes in Actual Evapotranspiration, Soil Moisture, the Normalized Difference Vegetation Index, and Land Use/Land Cover in the Gedeo Coffee–Based Agroforestry System of Southern Ethiopia

Tedla Getahun[1] Girma Mamo[2] Getahun Haile[1] Daniel Markos[3] Gebremedhin Tesfaye[1]

**ABSTRACT** Mapping and quantifying changes in land use/land cover (LULC) and their drivers guides the identification of areas vulnerable to change and the design of sustainable land management strategies. In the Gedeo zone of Southern Ethiopia, policies and strategies are required to protect coffee-based agroforestry from the destabilizing effects of climate change, a declining resource base, and unplanned changes in land use. Accordingly, this study analyzed trends in LULC, soil moisture, actual evapotranspiration, and the normalized difference vegetation index (NDVI) over the preceding 30 years by using remote sensing, geographic information systems, and secondary data. Using Landsat images from the years 1993, 2008, and 2023, we mapped six major LULC types: wetlands, grassland, settlements, bare land, forest land, and cultivated land including crop lands and agroforestry systems. The NDVI exhibited a significant decreasing trend in the regions of Dilla, Raphe, and Wonago, indicating hot spots of LULC changes. Cultivated land and forest land underwent the most extensive LULC changes, with rates of 45.1% and −22%, respectively. LULC types with high environmental importance, namely grassland and wetlands, decreased annually by 10.8% and 4.3%, respectively. Settlements increased by 12.2% at the expense of coffee-based agroforestry systems, which have been the backbone of the local economy. The preceding three decades have seen rapid urban growth and development at the cost of sustainable quality coffee production in and around the study area. The root causes underlying LULC changes have been urbanization, climate change, population growth, and a lack of public awareness regarding the consequences of LULC changes. LULC changes, including the conversion of wetlands to cultivated land and uncontrolled settlements along the finest coffee belt, have threatened food and income security and have undermined ecological sustainability initiatives, as evidenced by the decreasing NDVI throughout the study period. These observed trends run counter to the standards of protecting land of agricultural significance from urban and periurban encroachment. Accordingly, the drivers of LULC changes must be regulated; otherwise, scarce natural resource bases will soon be unavailable to contribute to sustainable ecosystem services and the livelihoods of small holder farmers.
***Key Words:*** Agroforestry, Coffee, Normalized difference vegetation index, Land use, Settlement.

## INTRODUCTION

Ethiopia is Africa's largest coffee producer and the world's fifth largest exporter of *Arabica* coffee (FAOSTAT, 2023). In Ethiopia, coffee has been produced in 685294 ha of land with average productivity of 6.654 t/ha mostly using indigenous knowledge of the growers, low-input production systems and organic farming (FAOSTAT, 2023; Tadesse, 2002; Degefa, 2016). Moreover, country's small holder coffee production possesses maximum biodiversity, environmental sustainability and ecological services (Alo-Sora and Guji, 2021). The crop is Ethiopia's number one source of export revenue generating about 30-35 percent of the country's total export earnings (USDA, 2023a) involving more than 20% of the economically active population (Meskela and Teshome, 2014). This was because the country's Arabica coffee was of a single-origin with highest grade organically produced commodity differentiated by its superior flavor claiming premium prices (Daviron and Ponte, 2007). Due to this, the country remained prized on the international specialty coffee market for its high quality and unique characteristics. However, the coffee production of the country in general and Gedeo in particular has been affected by unplanned land use changes across years (Kebede *et al.,* 2019; Kebede, 2018; Hettig*et al.,* 2016; Bunn *et al.*, 2015).

Land use studies showed that land use changes have short and long - term potential economic, social, and environmental impacts with various levels of effects to agriculture and rural communities (Wu, 2008) with consequent losses in biodiversity and ecosystem services which has aggravated rates, extents and intensities in the changes (Mariye *et al.,* 2021; Dirzo *et al*., 2014). Some authors associated land use changes to global warming, degradation of soils, reduced watershed hydrology and even human well-being (Lambin *et al.* 2001). Studying such dynamics of land use provides basic information that may be needed for planning interventions, reduces risks and ensures sustainability required in the system. Because the land resources

〔1〕Dilla University, Department of Natural Resource Management for Sustainable Agriculture, P.O.Box, 419, Dilla, Ethiopia.
〔2〕Ethiopian Institute of Agricultural Research, P.O.Box-2003, Addis Ababa, Ethiopia.
〔3〕Hawassa Agricultural Research Center, P.O.Box-06, Hawassa, Ethiopia.
*

were limited, there couldn't be a condition to meet the increasing demand for multiple land use types. However, lands are the backbone of agricultural sector providing substantial economies and social benefits, which calls for land administrators to reserve productive farm lands to prioritized agriculture like coffee based agroforestry farming. Moreover, there was a need to understand the costs associated with land use changes in order to minimize the risks for sustainability of agriculture and livelihoods. Especially the scarcity of arable land and increases in land degradation necessitate the need for prioritization of land uses through series of studies to allocate a kind of land for certain type of land use (United Nations Human Settlements Program, 2018). However, it was well noted that excessive land use control may hinder the function of market forces.

In places where coffee was dominant vegetation, land use has been determined by soil suitability, terrain and distance to market (Hettig *et al.,* 2016). Moreover, soil moisture available to coffee plants directly affects its growth and performance; however, vegetation cover in tern governs processes like evapo-transpiration (Eagleson, 2002). In fact, the differential absorption of red and near-infrared spectral bands of photosynthetically active radiation absorbed by vegetation was measured by normalized difference vegetation index (NDVI) which was recognized as an indicator of vegetation productivity (Rhee and Im, 2017; Wang *et al*., 2003; Tucker *et al*., 1985). NDVI had immense spatial and temporal variability across locations, scales, and time with a decreasing trend in southern Europe (Julien*et al*., 2006), South America and Africa (Liu *et al.,* 2015). An increasing trend of NDVI has been reported in China (Meng *et al*., 2011) and Australia (Fensholt *et al*., 2012). Increases in NDVI were attributed to the increases in the growing season due to warmer temperatures that increase plant photosynthesis (Slayback *et al*., 2003) in humid areas. Some studies found no link, while others reported a negative relationship between NDVI and rainfall (Guo *et al*., 2014). Several studies used satellite-based NDVI to monitor the variation on land covers (Liu *et al.,* 2015; Guo *et al.,* 2014; Meng *et al*., 2011). According to Pieallu *et al.* (2019), low temperatures, soil water regime, soil nutrition nitrogen availability and pH limit greenness, whereas soil water reserve and temperatures limit vegetation dynamics (Piedallu *et al.,* 2019; Walker *et al*., 2003). However, assessing the environmental drivers of the vegetation dynamics at different scales and over different periods of the year, using a spatial approach helps to investigate the effects of climate and soil conditions on the land use dynamics.

For authors like coffee production has increased in Ethiopia in response to climate change (Bunn *et al.,* 2015). Other authors reported that climate change affected coffee farmers negatively leading to late harvests due to lack of rainfall and lack of knowledge and technology to implement climate smart agriculture practices, opposing the previous finding (USDA, 2023b). According to the later report, many coffee farmers were abandoning coffee in favor of more resilient crops with higher short-term value (USDA, 2023b). Very low prices paid to farmers during the 'price crisis' of 1999 and 2004, resulted in the drop of producers' revenues, which forced alteration to food crop cultivation after uprooting coffee plants (Gole *et al*., 2002). Other authors indicated that Ethiopia's coffee farms have been modified in response to population growth, markets and cultural factors (Kebede *et al.,* 2019; Kebede, 2018). In this regard, complex interactions of population pressure, market demand, climate change and public policies operating at different scales of space and time have been transforming land uses across the globe (Wu, 2008; Lambin *et al.* 2001). Most recently, food security issues, renewable energy and emerging carbon markets were creating pressures for the conversion of agricultural land to other uses (Metternicht, 2017). Some authors argued the geographic (rugged topography) and demographic situation (900 persons/km$^2$) of the Gedeo landscape led to the traditional agroforestry system which was commonest land use in the area (Tadesse, 2002); however, the vulnerability of agro-biodiversity and agroforestry settings to climate change has also been reported recently with a reduction in average rainfall pattern in most of the stations and an increase in temperature within the employed time range (Markos *et al*., 2022; Fikadu and Azene, 2022) resulting in the change of proportion of land use and land cover from agroforestry system to other land uses. The areal reduction would be a big challenge for the biodiversity of the ecosystem and indicates ecological degradation (Markos *et al*., 2018; Jakson *et al.,* 2007).

Recently, wrong perceptions of agroforestry productivity, erosion of indigenous knowledge, and expansion of monocrops driven by market forces have challenged the agroforestry based coffee production of the area (Degefa, 2016). Adane and Bewket (2021) reported decreasing forest coffee at a rate of 1.02% per year and increase of semi-forest coffee at the rate of 0.9% per year in Yirgacheffe area and associated it to the increasing demand for coffee in the global and national market. However, the newly developed land use options should not only improve economic opportunities based on sustainable management of land resources but also reconcile with conservation and development objectives (Metternicht, 2017). These requires integrating both the social and environmental dimensions of land use together with the structure, processes, and outcomes in each subsystem, and calls for care full planning and informed decision at all levels through implementation of land use science that improves the observation, monitoring, understanding, modeling, and sustainability of land use systems and their change (Robinson *et al*., 2018). Although some researchers reported decreasing rate of coffee based forests (Degefa, 2016; Adane and Bewket, 2021), there wasn't a policy or strategy designed for controlling the land use that supports the livelihoods and economy of the farmers. Results of past studies did not also show LULC changes across the whole Gedeo area, the information required for holistic planning of intervention measures at higher administrative scale. Hence, the objectives of this study were to map, assess and quantify the land use land cover categories and patterns of land use dynamics over the last 3 decades from 1993 to 2023, and study the derivers behind the dynamics of dominant land use changes and suggest possible strategic options that were pertinent to enhance desirable land use land cover in Gedeo Zone.

# MATERIALS AND METHODS

## 1. Description of the Study area

The study was conducted at all districts of Gedeo zone. The zone is located geographically between $38^{0}0'0''$ E to $38^{0}50'0''$E and $5^{0}50'0''$ to $6^{0}20'0''$N. Gedeo zone is located 385 km and 90 km far from Addis Ababa and Hawassa cities, respectively. Representative villages were selected from highland, midland and lowland areas of each district. The study was conducted on 18 village's. According to Gedeo Zone Plan and Development annual statistical data (2021), the major crops of the area were coffee and enset. Fruit and cereals production takes the 3rd and 4th level, respectively. The agro-ecology of the zone is categorized into three classes; 26% is highland, 71.5% is mid-altitude areas and 2.5% is low lands. The total coverage of the zone is 135, 247 $km^2$. The topography of the land ranges from moderate sloppy feature to extremely sloppy mountainous topography.

## 2. Thematic sketch of the research process

To understand the dynamics, we employed step by step procedure of knowing the ETa, NDVI, soil moisture and satellite imagery as shown below in the flow chart (Fig 2).

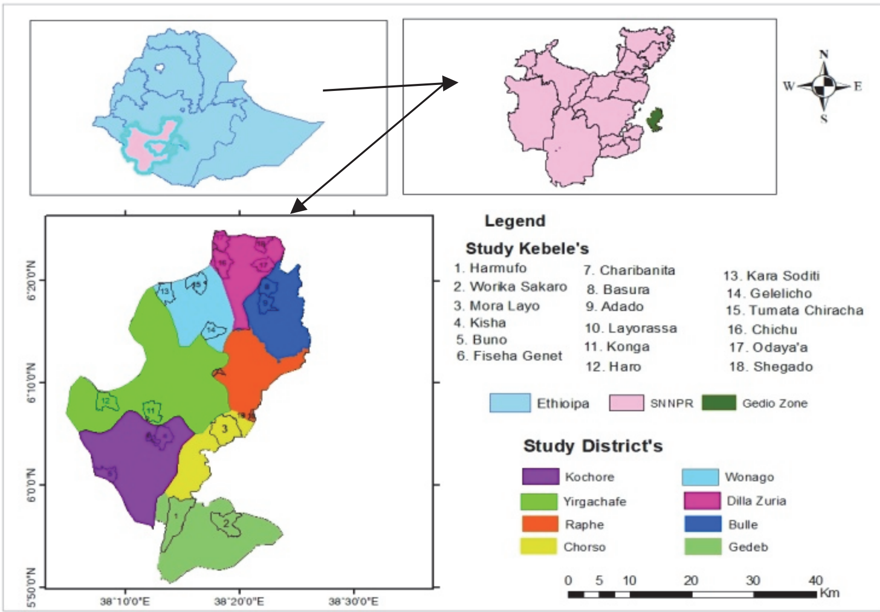


**Fig.1 Geographic map of the study area**

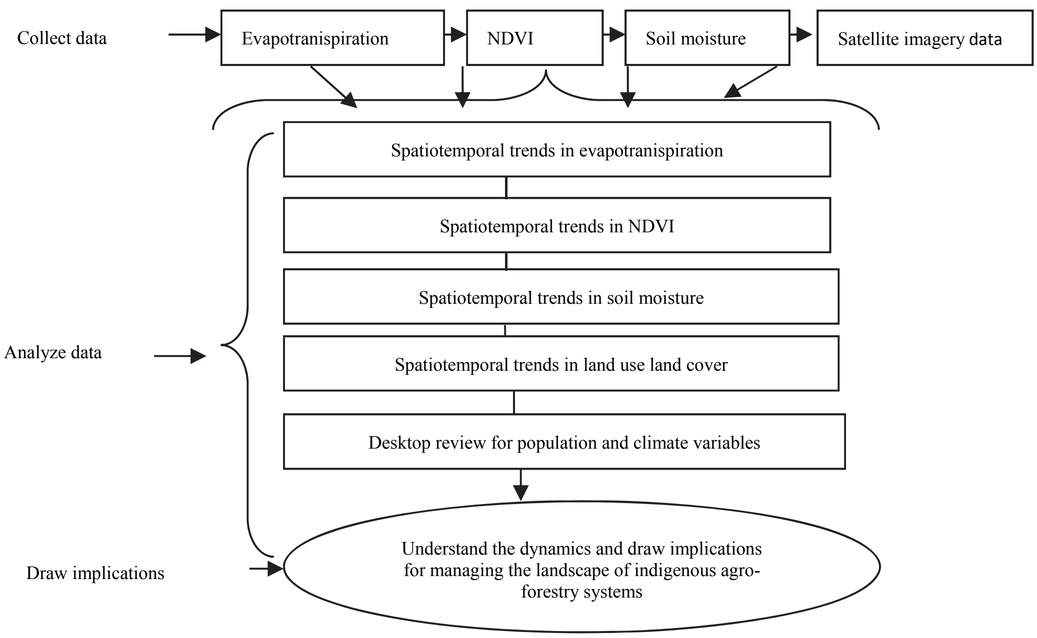


**Fig.2 Framework showing the research processes**

## 3. Data acquisition

Landsat 8OLI/TIRS C1 Level 1, Landsat 7ETM+C1level 1 and Landsat 4-5TM C1 level-1 images were acquired from USGS. The cloud free Landsat imageries of 1993, 2008 and 2023 were downloaded from the USGS website (https://earthexplorer.usgs.gov/) based on availability of data. The acquired image was geo-referenced to the World Geodetic System (WGS_84 datum) and Universal Transverse Mercator Zone 37 North coordinate system. Population data was collected from secondary data sources including zonal planning and economic development department and CSA (Gedeo zone plan and development annual statistical abstract, 2021). Temperature data of contrasting multi-model ensembles of 20 Global Climate Models (GCMs) were accessed using Coordinated Regional Climate Downscaling Experiment (CORDEX) (Giorgi *et a*l., 2009) which had been downscaled to 44 km horizontal resolution for the Africa domain (available at https://esgf-node.llnl.gov/search/esgf-llnl/). Rainfall data was captured from Climate Hazards Group Infra-Red Precipitation Stations (CHIRPS) satellite rainfall data (https://data. chc.ucsb.edu/ products/CHIRPS-2.0/) (Markos *et al.,* 2023) were used. Subsequently, seasonal and annual time series data were computed as required for variability and trend examination.

We also used a series of MODIS Terra 16-day composite images (MOD13Q1 collection 5 product) at 250 × 250 m resolution, the highest provided by this satellite. The Constrained View angle - Maximum Value Composite (CV-MVC) technique was utilized by National Aeronautics and Space Administration (NASA) to generate this MOD13Q1 product. It selects the observation with the highest NDVI, soil moisture and ETa and the smallest view angle to correct cloud contamination, directional reflectance, sun angle and shadow effects, and aerosol and water-vapor effects (Huete *et al*., 2002). In this study, the spatial resolution of the NDVI monthly synthetic products was 250 m (MODIS/Terra MOD13Q1) were used to batch process data. We selected NDVI, soil moisture and ETa for periods 2013-2022, 2013-2022 and 2013-2022, respectively. Adaptive Savisky-Golay algorithm using TIMESAT software has been applied to correct noise in the NDVI, soil moisture, and ETa data series (Jönsson and Eklundh, 2004). Normalized difference vegetation index (NDVI) measures the greenness and the density of the vegetation captured in a satellite image. Healthy vegetation has a very characteristic spectral reflectance curve which we can benefit from by calculating the difference between two bands – visible red and near-infrared. NDVI is that difference and it is calculated as a ratio between the red (R) and near-infrared (NIR). In this manuscript, learn how to apply the NDVI Formula and calculate vegetation patterns (Gandhi *et al*., 2015) in equation 1.

NDVI = (NIR-Red) / (NIR+Red) Eq. 1

where NIR is near-infrared light and Red is visible red light. NDVI defines values from -1.0 to 1.0, where negative values were mainly formed from clouds, water and snow, and values close to zero are primarily formed from rocks and bare soil. Very small values (0.1 or less) of the NDVI function correspond to empty areas of rocks, sand or snow. Moderate values (from 0.2 to 0.3) represent shrubs and meadows, while large values (from 0.6 to 0.8) indicate temperate and tropical forests (Huete *et al*., 2002).

## 4. Data analysis

(1) Image processing techniques

After data acquisition from landsat 5, the study used four digital image processing techniques. These would be image enhancement (IE), maximum likelihood classification (MLC), accuracy assessment (AA) and change detection (CD) techniques. IE would be one of the image processing methods of this study. It would be applied to image data to be more effectively display or record the data for subsequent visual interpretation (Lillesand *et al.*, 2014). MLC was another image processing techniques that will be used in this study. It was one of the most commonly used classification algorithms that dependent upon the probability distribution of the feature classes (Liu and Mason, 2013). In this algorithm, the normal probability distributions of each spectral class was demarcated using a covariance matrix by selecting a sufficient number of pixels in each spectral class as training sample for the classification algorithm (Richards and Jia, 2006). Images were arranged in false color composite (FCC) band order and a general case of color was displayed (Liu and Mason, 2013). After the image arrangement and the actual colors was displayed, ArcGIS 10.8 was used to carry out MLC by taking broad land cover classes based on their representativeness in the image for study area (Masood and Takeuchi, 2012). This was based on training sets. The sample points collected during fieldwork were used for validating classification results. A focal majority filter in Arc GIS was used for smoothing the classification results. After the land use classification process, accuracy assessment techniques were carried out to pin and quantify mapping. It was carried out by method of a confusion matrix generated through a simple cross tabulation of the mapped class label against that observed in the ground or reference data. The employment was for a sample of cases at specified locations (Koukoulas and Blackburn, 2001; Canters, 1997). The image classification accuracy was assessed by calculating the Kappa coefficient ‘k’. The kappa statistics was used to estimate measure of overall agreement between image data and the reference (ground truth) data.

The coefficient of Kappa statistics (K) typically could fall on the scale between 0 and 1, where the latter indicates complete agreement, and was often multiplied by 100 to give a percentage measure of classification accuracy. Kappa values were also be characterized into 3 groupings: a value greater than 0.80 (80%) represents strong agreement, a value between 0.40 and 0.80 (40 to 80%) represented moderate agreement, and a value below 0.40 (40%) represented poor agreement. Eventually, change detection technique was used to assess the change in LULC pattern within ten year (Lunetta *et al*., 1999).

During comparison, if the corresponding pixels lied in the same class label, the pixel was changed. To quantify the change, the study used ERDAS model of analysis as Pixel values of 0 represented no change; decrease and increase was represented by change in pixel values, either negative change or positive change. Image processing and classification was carried out using ERDAS Imagine 2014 software. Documentation and statistical analysis were accomplished using MS office 2010 word and Microsoft excels software. The software's used and specific applications were summarized in Table1.

**Table 1 Software packages and materials used with their respective application**

| No. | Softwares and material | Application |
|---|---|---|
| 1. | ArcGIS 10.8 | Database creation, dataset preparation, raster calculation, Displaying and viewing spatial data and map lay out preparation. |
| 2. | ERDAS 2014 | Land sat 8 image pre-processing, LULC classification, Post Classification Change Detection and map layout preparation. |
| 3. | MS office 2010 | Documentation, statistical analysis and presentation |
| 4. | GPS (Garmin 72) | Used to mark LULC sample sites. |

In this study three years imageries of 1993, 2008 and 2023 namely; land sat 4-5 TM, land sat 7ETM+ and land sat 8OLI/TIRS were analyzed to determine with respect to LULC change within 15 years interval (Table 2). The pre-processing, classification and accuracy assessment were undertaken. The LULC classification in 1993 assumes change of ruling government under Ethiopian condition and prevalence of satellite images acquisition that started in 1990s.

**Table 2 Main characteristics of imageries used in the study**

| Image | Acquisition year | Path/Row | Spatial resolution |
|---|---|---|---|
| Landsat 4-5TM C1 level-1 | 1993 | 168/55 | 30m x30 m |
| Landsat 7ETM+C1level 1 | 2008 | 168/55 | 30m x30 m |
| Landsat 8OLI/TIRS C1 Level 1 | 2023 | 169/55 | 30m x30 m |

(2) Image pre-processing

The cloud free Landsat imageries of 1993, 2008 and 2023 were downloaded from *(https://earthexplorer.usgs.gov/)*. The acquired image was geo-referenced to the World Geodetic System (WGS_84 datum) and Universal Transverse Mercator Zone 37 North coordinate system. An intensive pre-processing such as geo-referencing, enhancement, layer-stacking and sub setting based on area of interest (AOI) were made. The satellite image had original format in TIFF. They were exported to .img format in ERDAS Imagine 2014 software using layer stack function. Then, Gedeo zone image was extracted from the stacked image the by clipping with respect to the zonal shape file using ArcGIS 10.8 software. In order to interpret and discriminate surface features clearly, all satellite images were composed using Red Green Blue (RGB) color composition. False Color Composites (FCC) of satellite imageries were prepared using band 4 (NIR), band 3 (Red), and band 2 (Green) combination.

(3) Image classification

At the study area six (6) land use land cover classes such as cultivated land, bare land, settlement, grass land and forestland were considered as training areas in image classification based on field observation and information obtained from Gedeo zone Agriculture and Natural Resource Development office (Table 3). The overall KAPPA coefficient was 0.85 or 84.6%.This value indicates that the image were classified in a good manner because the value is near to 1(one).

**Table 3 Land use land covers classes**

| No. | LULC class | Description |
|---|---|---|
| 1 | Cultivated land | Covers both crop land and areas covered with coffee or enset based agroforestry |
| 1.1 | Crop land | Land covered by enset based agroforestry system and annual crops |
| 1.2 | Coffee based agroforestry | Fields covered with coffee based agroforestry system. |
| 2 | Forest land | The land covered by natural and plantations in open and closed area. |
| 3 | Bare land | Stony or rocky areas, eroded lands and soil exposed without any cover. |
| 4 | Settlement | Urban areas, schools and health centers, any organizational buildings and rural homesteads. |
| 5 | Grass land | Land covered by grasses and suited for grazing livestock. |
| 6 | Wetlands | Area coved by water including river, pond and streams. |

These, major land use and land cover types were identified by using the field data and original Landsat image. In ERDAS Imagine 14 software, the signature editor was created for identified classes. Each class on the signature editor was created with the help of Google earth pro connected with ERDAS Imagine 14 and collected field data by adding a number of pixels. In decision making phase the maximum likelihood algorithm was selected because of the advantage of considering the center of the clusters together with shape, size and orientation. The methods used to identify the key drivers of Land Use/Land Cover (LULC) changes were based on the secondary data from zonal and district level agriculture offices. Field observation and farmers discussion was also made to identify the drivers of land use land cover change at the study area. Table 3 shows the implication of each land use land cover classes used in classification.

# RESULT AND DISCUSSION

## 1. Monthly evapotranspiration: spatial and temporal variation in the study area

As shown below in Figure 3, the average monthly actual evapotranspiration of Gedeo zone ranged between 22.94 - 31.11 mm month$^{-1}$ based on remote sensing dataset. However, there were variations across agro-ecological zones. For instance, the actual monthly evapotranspiration was 22.94 – 26.21 mm month$^{-1}$ in highland areas of Raphe and Bule but the actual monthly evapotranspiration was 29.48-31.11 mm month$^{-1}$ in lower mid altitude areas of Yirgachefe and Dilla zuria. The actual monthly evapotranspiration was 29.48-26.21 mm month$^{-1}$ in intermediate mid altitude areas of Gedeb, Wonago, Yirgachefe and Kochore. Thus, areas like Yirgachefe and Dilla showing very high monthly actual evapotranspiration, call for particular attention by researchers and water resource managers in agriculture and water resources management for subsequent planning and decision making for crops growing in the area. As reported in table 5, monthly actual evapotranspiration showed increasing trend at Kochore, Gedeb, Dilla and Bule areas of Gedeo (Table 5), which could be attributed to increasing temperatures (Table 6) arising from conversion of grazing lands to coffee farms and wetlands to *Eucalyptus* mono crops (G/Hiwot and Maryo, 2015). However, actual evapotranspiration showed a significantly ($P<0.05$) decreasing trend at Chorso, Yirgachefe and Wonago areas. At Raphe, the trend of monthly evapotranspiration showed no clear trend. The current findings at Chorso, Yirgachefe and Wonago areas agreed with the findings of Savenjje, who reported vegetation reductions resulting in an increased albedo and reduced evapotranspiration in the Sahel, which might have exacerbated drought occurring in these regions (Savenije, 1995).

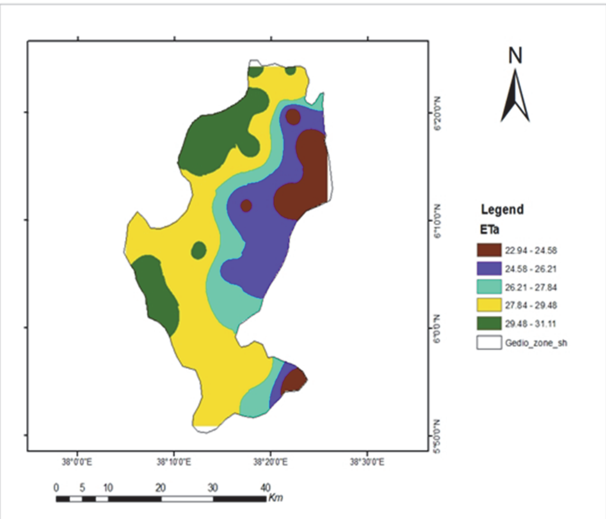


**Fig.3 Mean monthly evapotranspiration map for**

## 2. NDVI: Spatial and temporal variation of in Gedeo Zone

As reported in Figure 4, the NDVI values ranged from 0.59 (lowest) to 0.79 (highest), which means the values were large enough to indicate the greenness of vegetation in the study area. The lowest NDVI was observed in Bulle and Raphe districts (Fig 4), which were places known for enset-based agroforestry system with barley and wheat composing the cereal component. But the higher NDVI values were observed in Gedeb, Kochore and Wonago districts. Chorso, Yirgachefe and Dilla zuria district have intermediate NDVI values. Higher than 0.75 NDVI (normalized difference vegetation index) was reported in Kochore, Gedeb, Yirgachefe, Dilla and Wonago. These later areas were typical known for throughout the country. In Raphe and Bule, the NDVI values were below 0.7 (Table 5). Though relatively lower, the NDVI in Raphe and Bule areas was still high, which were due to greenness of enset, barley, faba bean and wheat crops that were the dominant food security crops of the areas. But some of these are annual crops, which would lead to occasionally lowered greenness during maturity and harvesting thereby lading to lower greenness. In highland areas of Raphe and Bule, coffee production has been limited by higher altitude, colder temperature and higher relative humidity, The higher NDVI in Gedeb, Kochore and Wonago districts could be due to greenness arising from dense coffee -shade tree associations or stands throughout the year, which were in tern due to the use of full coffee productivity package through extension system to enhance yields including planting of 250 – 1500 coffee seedling ha$^{-1}$ year$^{-1}$ (Zinabu *et al.*, 2017). The index values of these later districts also indicated healthy agroforestry or forestry cover, which was the high reflection of the healthy plants in the wavelengths of the infrared band and its low reflection in the presence of the red band of the electromagnetic spectrum (Hesketh *et al.*, 2014).

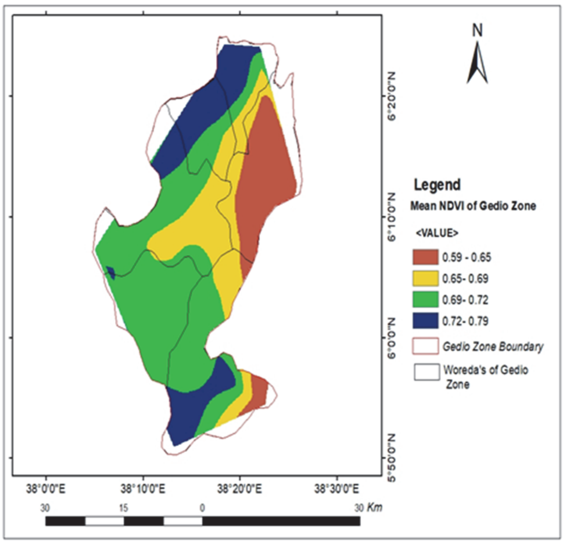


**Fig.4 NDVI map for Gedeo zone**

Considering the temporal trends between the years 2012-2023 (Table 4), NDVI showed a decreasing trend across the whole districts of Gedeo except Kochore. The decreases were strong at Dilla (S=23), Gedeb (S=15), Raphe (S=13) and Wonago (S=13) compared to Chorso, Yirgachefe and Bule (S=7). The magnificent decreases in NDVI at Dilla, Wonago and Yirgachefe were related to lowered greenness of vegetation, which was in tern due to increased build-up/settlement at the expense of indigenous coffee based farming system, which was in tern dictated by increasing population and faster urbanization. Additionally, the highland areas of Gedeb, Raphe and Chorso were known for a culture of highland cereals and pulses that would show a decreasing trend of greenness of vegetation due to increasing soil acidity over years (Endalew *et al*., 2014). This finding was in harmony with reports of Zewdie *et al*. ( 2017) that state changes in NDVI could be related to anthropogenic factors linked to land use changes and associated management practices, which in turn affects the temporal variations in $CO_2$ fertilization (Fensholt *et al*., 2012) or response of vegetation to climate changes (Luo *et al*., 2016).

**Table 4 Spatial and temporal variation in soil moisture, NDVI and ETa in Gedeo zone, Ethiopia**

| | Descriptive statistics | | | Kendall's tau | S | Var(S) | p-value | alpha | Sen's slope | Trend |
|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | | | | | | | |
| | | | | | Soil moisture (%) | | | | | |
| Chorso | 0.305 | 0.373 | 0.339 | 0.217 | 178 | 7110.3 | 0.035 | 0.05 | 4.80E-04 | Increasing |
| Kochore | 0.277 | 0.354 | 0.313 | 0.259 | 212 | 10923.9 | 0.043 | 0.05 | 6.25E-04 | Increasing |
| Yirgachefe | 0.305 | 0.372 | 0.336 | 0.266 | 218 | 6587.8 | 0.007 | 0.05 | 5.70E-04 | Increasing |
| Gedeb | 0.282 | 0.362 | 0.318 | 0.268 | 220 | 6941.1 | 0.008 | 0.05 | 6.69E-04 | Increasing |
| Bule | 0.317 | 0.388 | 0.358 | 0.076 | 62 | 7926.7 | 0.486 | 0.05 | 1.46E-04 | No trend |
| Dilla | 0.295 | 0.372 | 0.334 | 0.302 | 248 | 7926.7 | 0.005 | 0.05 | 7.04E-04 | Increasing |
| Raphe | 0.312 | 0.381 | 0.349 | 0.19 | 156 | 7926.7 | 0.08 | 0.05 | 4.02E-04 | No trend |
| Wonago | 0.306 | 0.375 | 0.339 | 0.278 | 228 | 5929.4 | 0.003 | 0.05 | 6.28E-04 | Increasing |
| | | | | | Actual evapo-transpiration (mm month$^{-1}$) | | | | | |
| Chorso | 22.3 | 27.0 | 25.0 | -0.289 | -13 | 50.7 | 0.092 | 0.05 | -0.054 | Decreasing |
| Kochore | 28.4 | 31.7 | 30.1 | 0.022 | 1 | 86.8 | 1 | 0.05 | 0.010 | Increasing |
| Yirgachefe | 27.6 | 30.5 | 29.1 | -0.067 | -3 | 83.4 | 0.827 | 0.05 | -0.004 | Decreasing |
| Gedeb | 25.4 | 30.3 | 28.1 | 0.022 | 1 | 125 | 1 | 0.05 | 0.008 | Increasing |
| Bule | 21.6 | 24.0 | 22.9 | 0.022 | 1 | 125 | 1 | 0.05 | 0.006 | Increasing |
| Dilla | 27.2 | 29.9 | 28.9 | 0.200 | 9 | 125 | 0.474 | 0.05 | 0.042 | Increasing |
| Raphe | 22.4 | 24.9 | 23.7 | -0.333 | -15 | 125 | 0.21 | 0.05 | -0.181 | No trend |
| Wonago | 27.9 | 31.2 | 29.9 | -0.022 | -1 | 125 | 1 | 0.05 | -0.012 | Decreasing |
| | | | | | NDVI | | | | | |
| Chorso | 0.680 | 0.740 | 0.712 | -0.156 | -7 | 39.2 | 0.264 | 0.05 | -0.003 | Decreasing |
| Kochore | 0.715 | 0.779 | 0.744 | 0.022 | 1 | 54.0 | 0.892 | 0.05 | 0.0008 | Increasing |
| Yirgachefe | 0.687 | 0.755 | 0.728 | -0.156 | -7 | 32.0 | 0.216 | 0.05 | -0.002 | Decreasing |
| Gedeb | 0.703 | 0.787 | 0.751 | -0.333 | -15 | 125.0 | 0.180 | 0.05 | -0.002 | Decreasing |
| Bule | 0.625 | 0.691 | 0.646 | -0.156 | -7 | 51.4 | 0.329 | 0.05 | -0.002 | Decreasing |
| Dilla | 0.708 | 0.754 | 0.730 | -0.511 | -23 | 125.0 | 0.040 | 0.05 | -0.003 | Decreasing |
| Raphe | 0.633 | 0.715 | 0.670 | -0.289 | -13 | 44.5 | 0.041 | 0.05 | -0.002 | Decreasing |
| Wonago | 0.714 | 0.763 | 0.739 | -0.289 | -13 | 45.5 | 0.050 | 0.05 | -0.002 | Decreasing |

*Values in bold are different from 0 with a significance level alpha=0.05*

## 3. Spatial and temporal variation in soil moisture

Soil moisture showed significant ($P<0.05$) increasing trend across Chorso, Kochore, Yirgachefe, Gedeb, Dilla and Wonago areas of Gedeo (Table 4), which could be attributed to enhanced indigenous agroforestry systems in low to mid-altitude areas as opposed to the highland areas. However, soil moisture showed a non-significant undefined trend at Bule and Raphe areas. This was a manifestation that the highland areas of Gedeo were becoming increasing undefined as far as soil moisture was considered, which could be attributed to effects of climate change in the area. This is in line with reports of Wierik and his colleagues who elaborated land-use change alters soil moisture dynamics through interactions between the soil and vegetation (micro-level) and the land surface and atmosphere (macro-level) (Wierik*et al*., 2021).

## 4. Changes in population and climate variables in Gedeo in the last three decades

In 1984, the population in Gedeo was 446, 634 with density of 329 persons per km$^2$ out of which only 7% were urban dwellers in towns like Dilla, Wonago and Yirgachefe (CSA, 1984). However, 20% of the dwellers which account for 259, 311 where urban dwellers in 2021 when zonal average population density was 959 persons per km$^2$ which is eight fold increases in 37 years. This showed expanding urban settlement in formerly rural areas and alarmingly growing population in a unit of land in Gedeo area (Table 5). The changes in climatic variables showed that there was increment in yearly minimum and maximum temperature whereas the changes in rainfall seemed unpredictable and decreasing at times (Table 5). In Gedeo, such increasing human population and urbanization was intensifying competition for limited land resources, which ultimately force unplanned land use changes by way of urban and per-urban encroachment to indigenous coffee based farming system, degradation of wetlands, deforestation of shade trees and expansion of cultivated land to previous grass lands and wetlands (Table 5 and 6).

**Table 5 Mean of population density and climate variables in Gedeo zone from 1984 - 2021**

| Year | 1984 | 1994 | 2007 | 2015 | 2021 | Sources |
|---|---|---|---|---|---|---|
| Population | 446,636 | 564,073 | 847,434 | 1079771 | 1,296,557 | CSA, 1984; 1994; 2007; Alambo and Yimam, 2019 |
| Urban (% increase) | 31, 264(7%) | 65, 374(11.6%) | 107,781(12.72%) | 213, 865(19.8%) | 259, 311(20%) | |
| Population (persons/km$^2$) | 329.0 | 418.8 | 699.8 | 853.0 | 959.0 | |
| Tmin ($^0$C) (% increase) | 11.13 (3.5%) | 11.83 (6.2%) | 13.1 (10.7%) | 13.24 (4.1%) | 13.85 (4.6%) | Giorgi *et al*., 2009 |
| Tmax ($^0$C) | 25.57 | 25.65 | 25.75 | 25.85 | 26.02 | Giorgi *et al*., 2009 |
| Rainfall (mm) | 935.3 | 1447.7 | 1507.3 | 1395.3 | 1165.9 | Markos *et al*., 2023 |

**Table 6 Changes in land use land cover across 1993, 2008 and 2023 in Gedeo Zone**

| No | LULC class | 1993 | | 2008 | | 2023 | | Changes in land use/land cover (km$^2$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Area (km $^2$) | % | Area (km $^{2)}$ | % | Area (km $^2$) | % | 2008-1993 | 2023-2008 | 2023 - 1993 | change per year | % |
| 1 | Cultivated land | 42131.5 | 31.1 | 62466.1 | 46.1 | 78535 | 58.1 | 20334.6 | 16068.9 | 36403.5 | 2426.9 | 45.1 |
| | Crop lands | 19366.8 | 14.3 | 25221.1 | 18.6 | 28354.5 | 20.9 | 5854.3 | 3133.4 | 8987.7 | 599.2 | 21.8 |
| | Coffee based AF | 22764.7 | 16.8 | 37245 | 27.5 | 50180.5 | 37.1 | 14480.3 | 12935.5 | 27415.8 | 1827.7 | 23.4 |
| 2 | Forest land | 37585.5 | 27.7 | 30012 | 22.1 | 21826 | 16.1 | -7573.5 | -8186 | -15759.5 | -1050.6 | 22.0 |
| 3 | Bare land | 10252 | 7.5 | 6928 | 5.1 | 5543 | 4.1 | -3324 | -1385 | -4709 | -313.9 | 5.6 |
| 4 | Settlement | 8878 | 6.5 | 18887 | 13.9 | 21659 | 16 | 10009 | 2772 | 12781 | 852.1 | 12.2 |
| 5 | Grass land | 20997.7 | 15.5 | 15878.8 | 11.7 | 6819 | 5 | -5118.9 | -9059.8 | -14178.8 | -945.3 | 10.8 |
| 6 | Wetlands | 15402 | 11.3 | 1075 | 0.79 | 865 | 0.64 | -14327 | -210 | -14537 | -969.1 | 4.3 |
| | Class total | 135247 | 100 | 135247 | 100 | 135247 | 100 | 0 | 0 | 0 | 0 | |

*AF stands for agroforestry*

## 5. Land use land cover change

(1) Increase of cultivated land

The coverage of cultivated land (inclusive of crop lands and coffee based agroforestry systems) was 42131.5, 462466.1 and 78515 km$^2$ in 1993, 2008 and 2023, respectively (Table 6). The area showed that the coverage of cultivated land has increased at the rate of 2426.9 km$^2$ year$^{-1}$ from 1993 to 2023 due to the expansion of coffee in the agroforestry practices of varying storey, annual crops production on wetlands, grass lands and bare lands of the area. Currently, the dominant land use in Gedeo across the past thirty years has been coffee based agroforestry followed by enset based agroforestry with respective income and food security roles in the community (Table 6). The expansion of cultivated lands could also be due to government programs that promoted production diversification as a strategy to improve local incomes and conserve environmentally beneficial multipurpose shade-trees also called agroforests. Shades trees of coffee, for example *Milletia spp.* and *Euphorbia spp.* has been introduced from midlands to highlands of Gedeo where coffee has not been produced before (Table 6). This change has been favored by increasing fuel wood demand and present day warmer temperatures than before (Table 6). In Gedeo, coffee is being grown in 134 rural kebeles out of which 116 Kebeles were specializing in coffee, which has been intensified in growth and transformation plan (GTP) in the period between 1993 to 2023 (Zinabu *et al*., 2017). Correspondingly, the coffee tree coverage were increased due to its increased plantation from 2008 to 2023. This result is in agreement with the findings of (Zemede and Tewodros, 2023), which depicted the increase of cultivated land cover instead of bare lands, shrub and grass lands from 1993 to 2020 in Bilate-Halaba watershed. The current 45.1% increase in cultivated land is over and above the projections of MEA (2005) who anticipated cultivated land increase by 18% in 2050. If this trend continues, the expected expansion of agricultural land would lead to further devastation of forests and loss of ecological services from traditional ecosystems. In return, this would boost the pressure on agricultural areas to provide a larger part of the provisioning, supporting, culturing and regulating ecosystem services deemed important for human well-being (MEA, 2005). Against the current finding, a decrease in global coffee markets forced alteration of land use to better selling of agricultural commodities as reported by Eakin *et al*.(2006). The coffee based agroforestry system of 78,535 ha (Table 6) reported in this study applying remotely sensed data as a principal data source was lower than 89,239.8 ha, which was reported by Gebrehiwot and Maryo in 2015 employing the same methodology. This could be due to expansion of settlement in rural, per-urban and urban area that was previously occupied by coffee based agroforestry species.

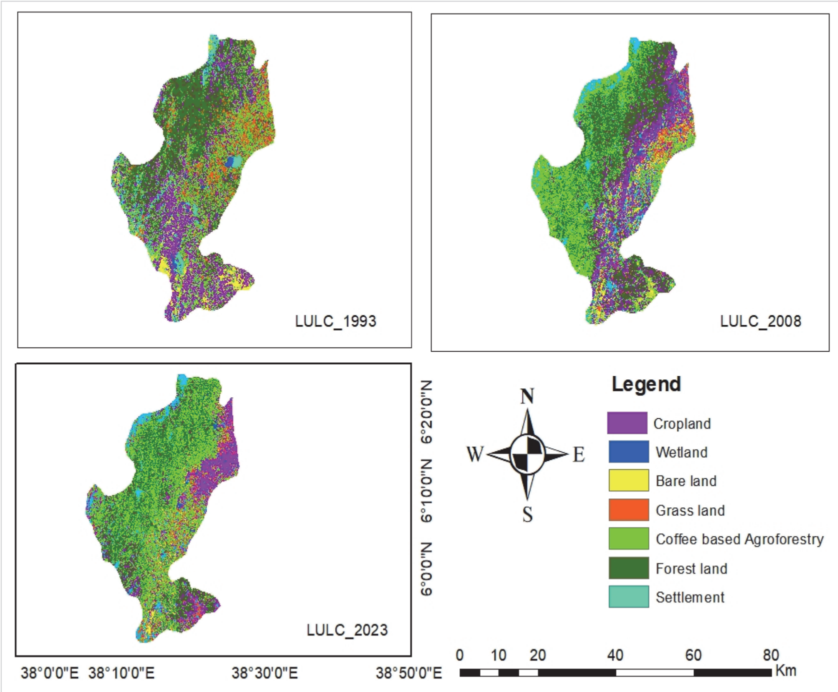


**Fig.5 Land use land cover map of 1993, 2008 and 2023.**

(2) Decrease of forest land

Forest lands include native forests of bambo and permanent preservation areas, and planted forests like forest monocultures of *Juniperous* and *Eucalyptus*. According to the above table 5, the total area coverage of forest land area decreased by 1050.6 km$^{2/}$year from 1993 to 2008 (Table 6). The decreament happened at the rate of 22% per year, which meant decreases in environmental functions like shade functions, watershed values, fuel wood uses, carbon sequestration, and habitat for fauna and flora, and could be attributed to increasing population growth and urbanization. The reduction of forest land in the past 30 years calls for a consistent land-use management that aims both production and conservation objectives from forests.

(3) Increase of built-up/settlment area

This area includes built places including urban area, established rural areas, roads and other constructions and infrastructural sites.The total area coverage of settelement has increased consistently from 1993 to 2023 by 12, 781 km$^2$ (Table 6).The average rate of incrment in settlement was 12.2%year$^{-1}$. The increment in settlment was 10, 009 km2 between 1993 and 2008 (Table 6). This agrees with findings of Regasa *et al.* (2021) who elaborated rapid variations of LULC in the last decades due to population pressure, resettlement programs, climate change, and other human- and nature-induced driving forces in Ethiopia. In mid to low lands of Gedeo, coffee enset based agroforestry changed to settlements, which is due to population increases resulting in unprecedented urbanization producing land use changes (Table 5). Urbanization in Gedeo could make housing affordable to middle– and low–income households but is happening at the cost of agricultural economies and lands available for food, feed, fuel wood and timber production. This ultimately calls for strict policies that protect agricultural land from pre-urban and urban encroachments through restriction of towns to vertical constructions.

(4) Decreases in grass lands

The area of grass land was 20997.7 km$^2$ in 1993, 15878.8 km$^2$ in 2008 and 6819 km$^2$ in 2023 showing a consistent decrease year after year (Table 6). Thus, the coverage of grass lands showed a decline as years passed. The rate of decrease in grasslands was 10.8% year$^{-1}$. The decrease is a manifestation of fierce competition for land resources and poses consistent risk in supply of feeds/forage for livestock production in Gedeo.

(5) Decreases in Wetlands

The wet lands include water slide, dams, rivers or streams, lagoons, artificial lakes or and ponds (Meneses and Sano, 2012). The area of wet land was 15402 km$^2$ in 1993, 1075 km$^2$ in 2008 and 865 km$^2$ in 2023 showing a consistent decrease year after year (Table 6). The rate of decrease in wet lands was 4.27% year$^{-1}$. Wet lands that were used for multiple ecological benefits have been invaded by local villagers through planting eucalyptus, which is uprooted after 4$^{th}$ year to leave the field for coffee lands subsequently. The decrease is a manifestation of fierce competition for wet land resources as farmers systematically expand their farm through planting of *Eucalyptus* spp. in the first few years and changing that farm to coffee fields in the subsequent years (Alo-Sora and Guji, 2021).

## Conclusion and Recommendation

This study provided soil moisture, NDVI, ETa, land use land cover changes and coffee cover dynamics of Gedeo Zone from 1993 to 2023. Land use and land cover of the study area showed visible changes over the past 30 years with dominant land uses becoming coffee and enset based agroforestry systems that meet food and income security objectives, respectively. In Gedeo, cultivated land coverage was increased at the expense of wetlands, grass lands and bare lands. As a consequence, the bare land and grass lands coverage showed a decline. Forest land coverage was decreased from 1993 to 2028, but increased 2008 to 2023, which was due to national initiatives of green legacy for tree planting. Settlement area coverage of Gedeo has expanded from 1993 to 2023, due to urbanization and infrastructures development. The drivers of these land use changes were urbanization policies, population increase, climate change, global market orientations, and national initiatives for commercialization of agriculture. Although the current coffee based agroforestry has been increasing at the rate of 23.4% (including expansion to higher altitudes, wet lands and grass lands), the most suitable area of coffee based agroforestry has been encroached by new developments and expansion of urban centers of Dilla, Wonago, Yirgachefe and Kochore.

The mean monthly evapotranspiration (ETa) was low in highlands of Bule (22.9 mm) and Raphe (23.7 mm), which could be due higher relative humidity reducing aerodynamic component of evapotranspiration. Conversely, average ETa was as high as 30.1, 29.9 and 28.9 in mid-altitudes of Kochore, Wonago and Dilla, respectively. The later areas where known for denser coffee vegetation cover and proliferation of indigenous agroforestry systems. The decreasing trends of NDVI at Dilla, Gedeb, Raphe and Wonago, and actual evapotranspiration at Chorso, Yirgachefe and Wonago areas were due to LULC changes and associated vegetation reductions. These unwanted trends should be turned back through increasing plantations of coffee and shade trees, and reduction of encroachments of urban and pre-urban areas to agricultural lands. Since coffee is a single most important cultural and cash crop of the area with regional and international economic significance, there is a need to enhance sustainable coffee production systems, which calls for restricting urban centers from encroachment of coffee farms. Therefore, we recommend that policy makers and local administrators shall promote desirable land use land cover changes but disincentivize unwanted land use changes in the area by way of protecting fertile agricultural lands and coffee fields from pre-urban and urban settlement; and protecting wetlands from invasion by farmers in order to maintain sustainable indigenous coffee based agroforestry system, profitable coffee production and efficient ecosystem services in the area.

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