

GIS analysis of cropland needs in 2040 and 2060 in Kenya, Uganda, and Tanzania



(FAO, 2023)

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Abstract

Low precipitation and low food production potential in portions of East Africa create a higher chance of vulnerability to food insecurity (Lokuruka, 2021). Therefore, developing accurate prediction models for population growth and future cropland needs is essential. This research uses geographic information systems (GIS) to analyze cropland needs in 2040 and 2060 based on current population growth rates between 2000-2020 in Kenya, Uganda, and Tanzania. ArcGIS Pro 3.1 (ESRI, 2023) was used to process and clarify topography, CRU precipitation, population, and land use datasets. It is predicted that to meet 2040 cropland needs, all forests and some savannas may need to be converted to croplands. However, even these maneuvers will not be enough to meet 2060 cropland needs, thus regional sustainable development plans should also focus on intensification of agricultural yields within existing croplands. These results have applications in natural resource governance, urban planning, and agricultural policy in Kenya, Tanzania, and Uganda.

Keywords: CRU, applied climatology, precipitation, population growth, cropland

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1. Introduction

Africa has the fastest-growing population globally and is predicted to reach 2.5 billion by 2050 (Nieves et al., 2017). This growth, paired with food insecurity (Lokuruka, 2021), disruptions to food systems due to COVID-19 (Cochrane, 2021), and low precipitation in areas such as northern Kenya and the Karamoja Region of Uganda, have lowered food production potential and made the continent more vulnerable to food insecurity (Lokuruka, 2021). Natural resource management is essential in addressing the population growth and food security in Uganda, Kenya, and Tanzania.

The study area of this analysis lies within the boundaries of Uganda, Tanzania, and Kenya.

The three aims of this study are:

Aim 1: Calculate statistics that describe the data. Visualize the area, land use, protected zones, precipitation, topography, and population statistics of each country.

Aim 2: Combine datasets to calculate statistics about relationships between croplands and topography, between forest areas and protected areas, and between precipitation and croplands.

Aim 3: Predict population growth and change. Explore the impacts of population growth and change on cropland area per capita. Spatially illustrate how to meet 2040 and 2060 needs for croplands.

The results of this analysis have applications in natural resource governance, urban planning, and agricultural policy in Kenya, Tanzania, and Uganda. This research project was developed to be used by sustainable development initiatives, such as The Africa Union Agenda 2063 and African Development Bank's Feed Africa Strategy 2025 (AfDB, 2016), that address food security and increasing populations in Uganda, Tanzania, and Kenya.

2. Methodology

This section describes the methodology for this spatial analysis project using ArcGIS Pro 3.1 (ESRI, 2023).

The following datasets were used:

1. Administrative Boundaries - a shapefile of the administrative boundaries of the world.
2. Population 2000 - a Tag Image File Format containing population values from 2000 of the hemisphere containing the African continent.
3. Population 2020 - a Tag Image File Format containing population values from 2020 of the hemisphere containing the African continent.
4. Precipitation - an American Standard Code for Information Interchange text file containing average precipitation values throughout a series of months over the African continent from September 2022.
5. Land use - a band sequential file containing land use data of the African continent.
6. Landcover Lakes - a shapefile of lake areas from the hemisphere containing the African continent.
7. two elevation files - two digital elevation model files containing elevation data for East Africa.
8. Protected areas - a shapefile of protected areas on the African continent from September 2022.

Details of the metadata of datasets used are available in the Appendix.

2.1. Pre-analysis data processing

Administrative boundaries file: Data was reprojected to Lambert, a new projected coordinate system created for this analysis. Next, only areas within the study area were extracted, selecting by expression in the attribute table. Lake areas were removed using the tool Erase.

2 elevation files: The two files were combined using Mosaic To New Raster. This new file was reprojected to Lambert using the tool Project Raster. Then, the file was clipped to the study area using Raster Calculator.

Land use file: To import the .bsq file as a GRID ESRI file, a text (.hdr) file was created that contained details for conversion. Then, the file was projected as Lambert Azimuthal Equal Area with sphere Sphere_ARC_INFO using the tool Define Projection. Next, it was reprojected to Lambert using the tool Project Raster and clipped to the study area using Clip Raster.

2 population files: The two files were reprojected to Lambert using the tool Project Raster, then clipped to the study area using the tool Clip Raster.

CRU precipitation file: Data was converted from a ASCII .txt file to a raster file. Then, it was projected to GCS_WGC_1984 using Define Projection. Next, it was reprojected to Lambert using Project Raster and clipped to the study area using Clip Raster.

Lakes file: Data was reprojected to Lambert using Project. Lake Malawi was removed from the dataset by selecting all other lakes in the attribute table and extracting a new layer. From this new layer, areas within the study area were extracted by intersecting with the administrative boundaries file using the tool Select Layer By Location.

Protected areas file: Data was projected to Lambert using Project, then clipped to the study area using Intersect.

2.2. Aim 1: Calculate statistics that describe the data.

2.2.1. Aim 1a: Calculate areas of administrative boundaries and land use classes.

Duplicates were deleted in the administrative boundaries file using Aggregate. Then, population by country and subdivision were found using the Zonal Statistics As Table. The resulting tables were extracted to Excel using Table To Excel and visualized into graphs.

In the land use file, all forest classes were combined and all cropland classes were combined by renaming them in the attribute table.

Statistics of the area and area percentage of each class per country were calculated using Zonal Histogram. The resulting table was exported using Table To Excel. In Excel, columns were added to calculate the area percentage of each class. Additionally, cropland per capita per country was calculated in Excel in an added column.

Protected forest areas per country were found using Zonal Histogram. The resulting table was exported using Table To Excel. In Excel, a new column was calculated to find the protected forest area percentage of each country. The distribution of land use classes within protected areas was calculated using Extract By Mask.

The distribution of land use classes within protected areas was calculated using Extract By Mask.

2.2.2. Aim 1b: Population measures

Attribute tables were added to the two population files using Build A Raster Attribute Table. In the attribute tables, a new field called “population density” was calculated. Using the administrative boundaries file, the population density was divided by country using the tool Copy Features.

Three separate shapefiles were created for the administrative boundaries of Uganda, Tanzania, and Kenya by selecting data points of each country in the attribute table of the administrative boundaries file and exporting the selections.

Population change statistics by country were extracted by clipping both population files to each of the three countries using Extract by Mask. The resulting six tables were put in Compute Change Raster to acquire statistics about population change.

2.2.3. Aim 1c: Climate and topography statistics

Precipitation values per country were found using Zonal Statistics as Table. Precipitation values on all land use classes were found using Zonal Histogram.

Reclassify was used to export only cropland areas from the IGBP file. This new croplands layer was used in Zonal Histogram to find statistical data on precipitation in croplands.

2.3. Aim 2: Obtain new knowledge by combining different types of geographical data.

Elevation per country was found using Zonal Statistics as Table.

Elevation of all land use classes was found using Zonal Histogram.

Elevation of cropland areas was found using Zonal Histogram and Extract By Mask.

2.4. Aim 3: Predict future populations.

The 2020 population layer was transformed into an integer type using Int, then an attribute table was added using Build Raster Attribute Table. Then, data from the 2020 population raster was divided into three separate files of each country using Extract By Mask. Each of these three files was manipulated in its attribute table. A new field was calculated using the formula $!Value! * (1+r)^{**1}$ to get populations for 2040 and 2060 for each country.

In Excel, 2060 & 2040 populations were multiplied by current cropland per capita ratios to predict future cropland area needs in 2040 and 2060.

Protected and unprotected forest areas per country were subtracted from cropland needs to determine whether conversion of forest area would meet the cropland needs of 2040 and 2060.

3. Results

3.1. Aim 1: Calculate statistics that describe the data.

3.1.1. Aim 1a: Calculate areas of administrative boundaries and land use classes.

Tanzania and Uganda are, in many ways, opposites among the three countries of the study area (Fig. 1). Tanzania has the largest total area, both excluding water bodies (887,966 sq km) (Table 1) and including (940,885 sq km) (Table 2). It also has the highest percentage of cropland areas, with 38.5% of its total land being used for croplands (Table 5, Fig. 4). It also has the largest cropland area (362,375 sq km) and the largest forest area (252,670 sq km), with 26.9% of its total county area forested (Table 5).

Uganda, on the other hand, has the smallest total area, both including (Table 2) and excluding water bodies (206,633 sq km) (Table 1). It is notable that Uganda has less cropland (Table 7) compared to Tanzania (Table 6, Fig. 4) and Kenya (Table 8, Fig. 6) with only 80,719 square kilometers of croplands making up 34.7% of its total country area (Fig. 5). It is also the only country in the study area that contains wetlands (Fig. 2, Table 4).

Administrative boundaries of study area in Uganda, Kenya, and Tanzania



Fig 1. Administrative boundaries of study area in Uganda, Kenya, and Tanzania.

Table 1. The areas, excluding water bodies, of Kenya, Uganda, and Tanzania. Tanzania has the largest area while Uganda has the smallest.

country	area (sq km)
Kenya	572,089
Uganda	206,633
Tanzania	887,966

Table 2. The areas, including water bodies, of Kenya, Uganda, and Tanzania. Tanzania has the largest water area and Uganda has the smallest.

country	area (sq km)
Kenya	583,359
Uganda	232,627
Tanzania	940,885

Spatial distribution of land use classes in Kenya, Uganda, and Tanzania

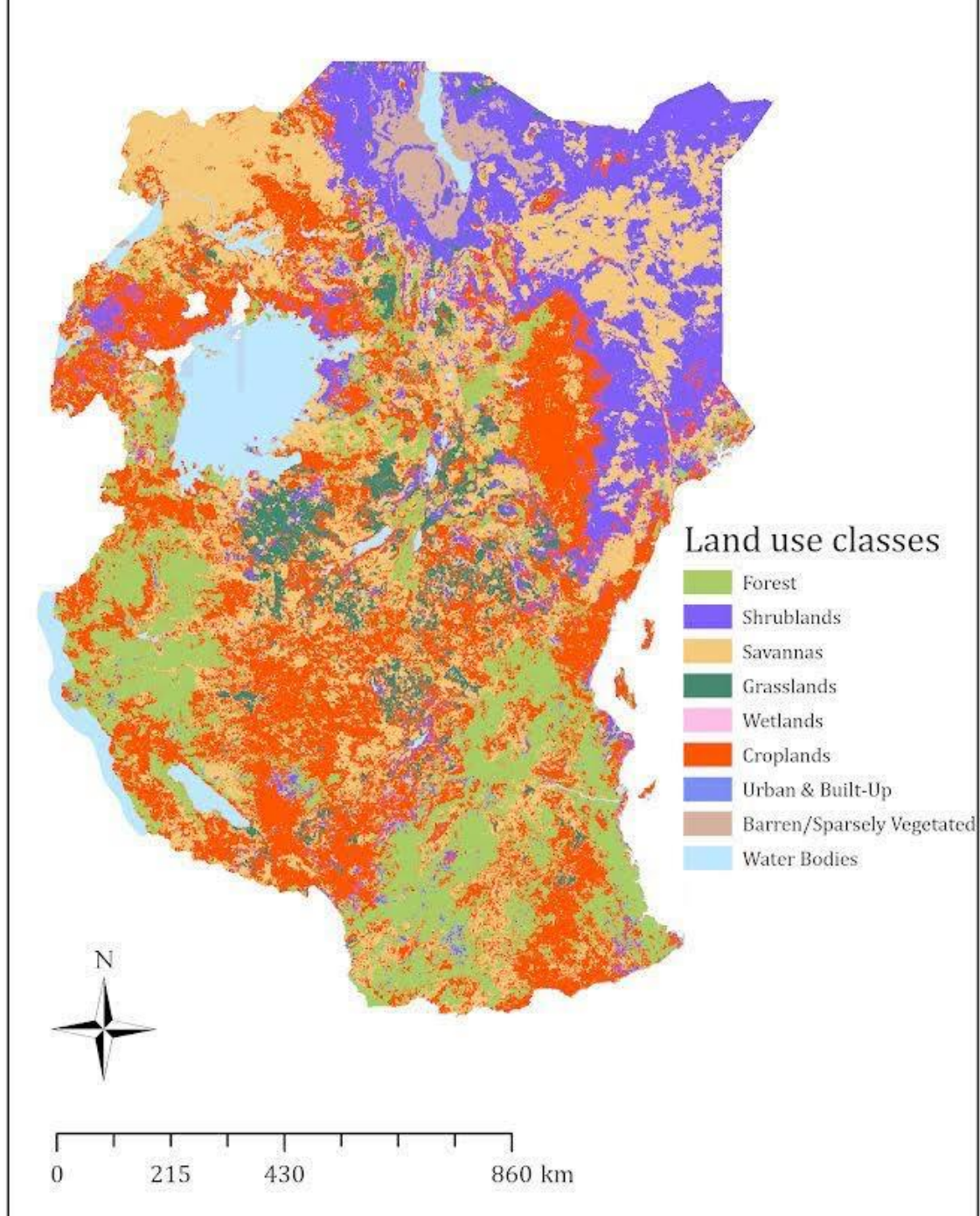


Fig 2. The spatial distribution of the land cover types.

Wetland areas and urban and built-up areas in the total study area are too small to be shown as a percentage of the study area. The study area contains 42 square kilometers of wetlands and 396 square kilometers of built-up areas (Table 4).

Table 4. Areas and percentages of areas of land use classes in the total study area.

Land use class	area (km sq)	% of total study area's land surface area including water bodies	% of total study area's land surface area excluding water bodies
Forest	289,890	16	18
Shrublands	257,689	15	16
Savannas	409122	23	25
Grasslands	86642	5	5
Wetlands	42	0	0
Croplands	559351	32	34
Urban and Built-Up	396	0	0
Barren or Sparsely Vegetated	41361	2	3
Water Bodies	112639	6	7

Table 5. Areas of land use classes (sq km) and percentages of total country area.

Land use type	Uganda	% of country	Tanzania	% of country	Kenya	% of country
Forest	8869	3.8	252670	26.9	28342	4.9
Shrublands	11440	4.9	25976	2.8	220266	37.8
Savannas	90423	38.9	167577	17.8	151098	25.9
Grasslands	2857	1.2	64517	6.9	19265	3.3
Wetlands	42	0	0	0	0	0
Croplands	80,719	34.7	362375	38.5	116221	19.9
Urban & Built-Up	107	0.05	112	0	176	0
Barren/ Sparsely Vegetated	2296	1	4408	0.5	34635	5.9
Water Bodies	35874	15.4	63250	6.7	13356	2.3

Cropland has the largest total area among all classes in the study area, making up 31.8% of the total area (Fig. 3).

Land use distribution in total study area

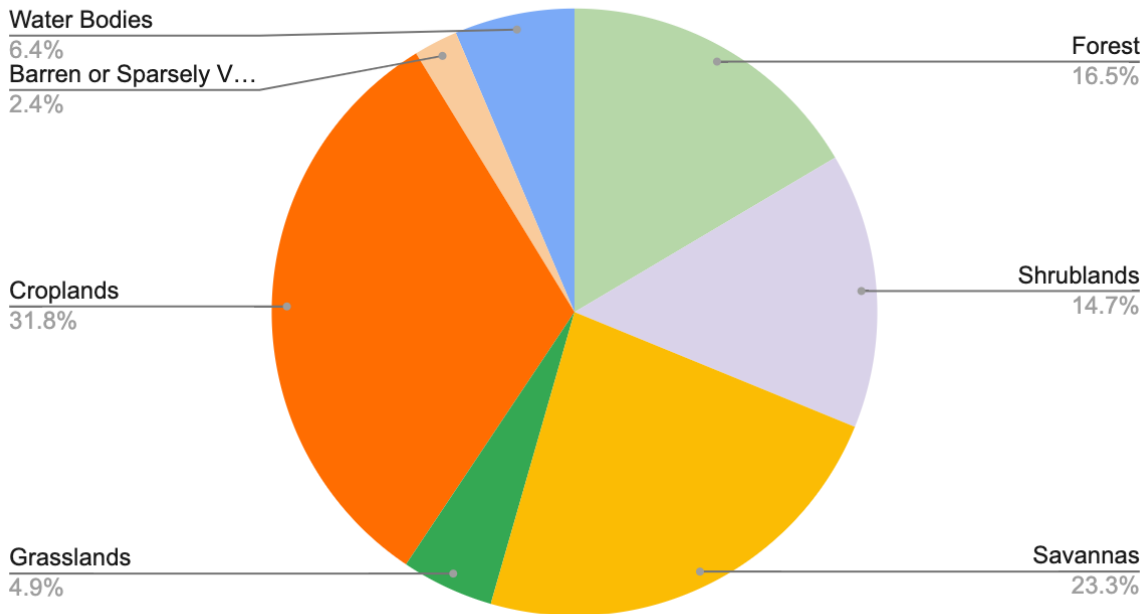


Fig 3. Land use distribution in the study area including water bodies.

Table 6. Land use classes area (sq km) and their percentages of the total country area in Tanzania.

Land use class	area (km sq)	% of total study area's land surface area including water bodies	% of total study area's land surface area excluding water bodies
Forest	262,950	24	26
Shrublands	60,710	6	6
Savannas	201,788	18	20
Grasslands	72,625	7	7
Croplands	423,773	39	41
Urban and Built-Up	216	0	0
Barren or Sparsely Vegetated	4,887	0	0
Water Bodies	64,198	6	6

Land use distribution of Tanzania

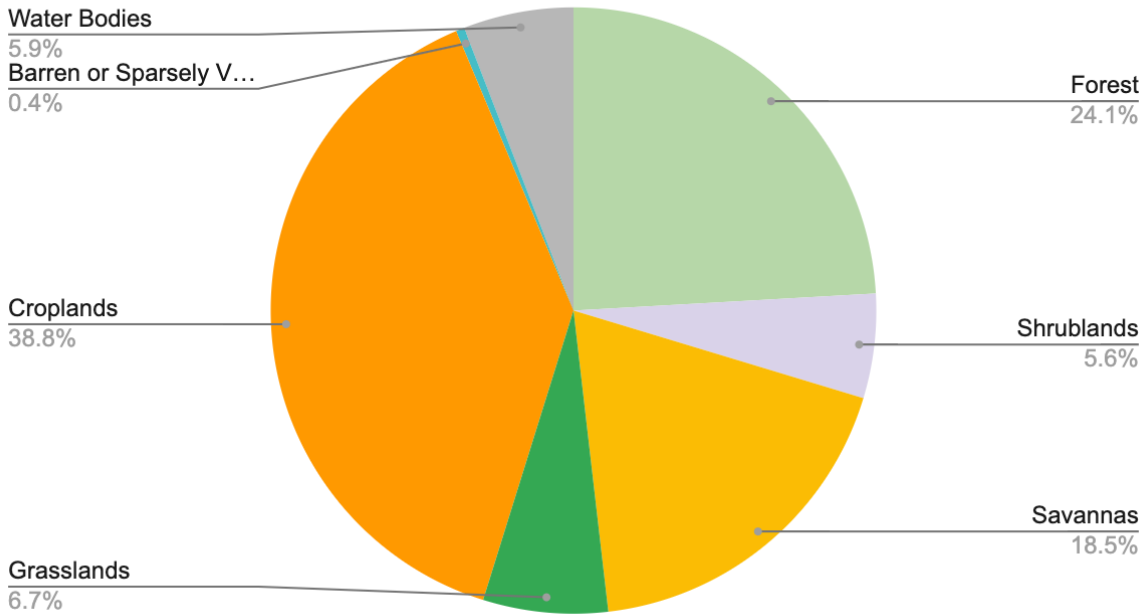


Fig 4. Land use distribution of Tanzania, including water bodies.

Table 7. Land use classes area (sq km) and percentage of total country area in Uganda.

Land use class	area (km sq)	% of total study area's land surface area including water bodies	% of total study area's land surface area excluding water bodies
Forest	15,060	5	6
Shrublands	29,725	10	12
Savannas	98,072	33	40
Grasslands	3,877	1	2
Wetlands	42	0	0
Croplands	95,762	32	39
Urban and Built-Up	134	0	0
Barren or Sparsely Vegetated	2,953	1	1
Water Bodies	53,241	18	22

Land use distribution of Uganda

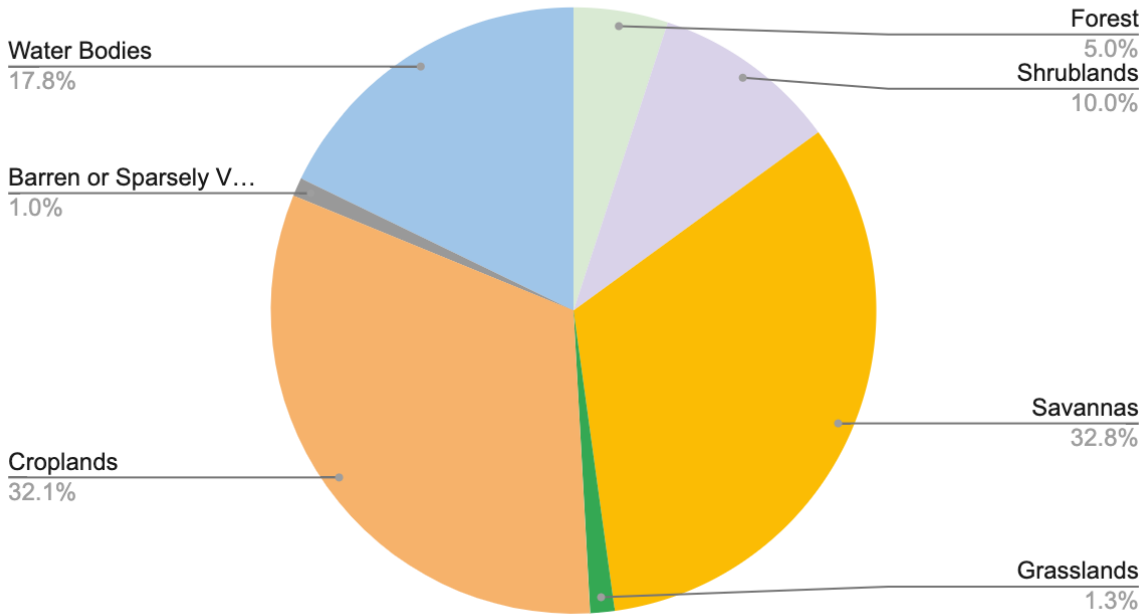


Fig 5. Land use distribution in Uganda including water bodies.

Table 8. Land use classes area (sq km) and percentage of total country area in Kenya.

Land use class	area (km sq)	% of total study area's land surface area including water bodies	% of total study area's land surface area excluding water bodies
Forest	44,366	6	6
Shrublands	232,875	31	32
Savannas	205,469	27	28
Grasslands	48,308	6	7
Croplands	172,140	23	23
Urban and Built-Up	219	0	0
Barren or Sparsely Vegetated	35,736	5	5
Water Bodies	17,488	2	2

Land use distribution of Kenya

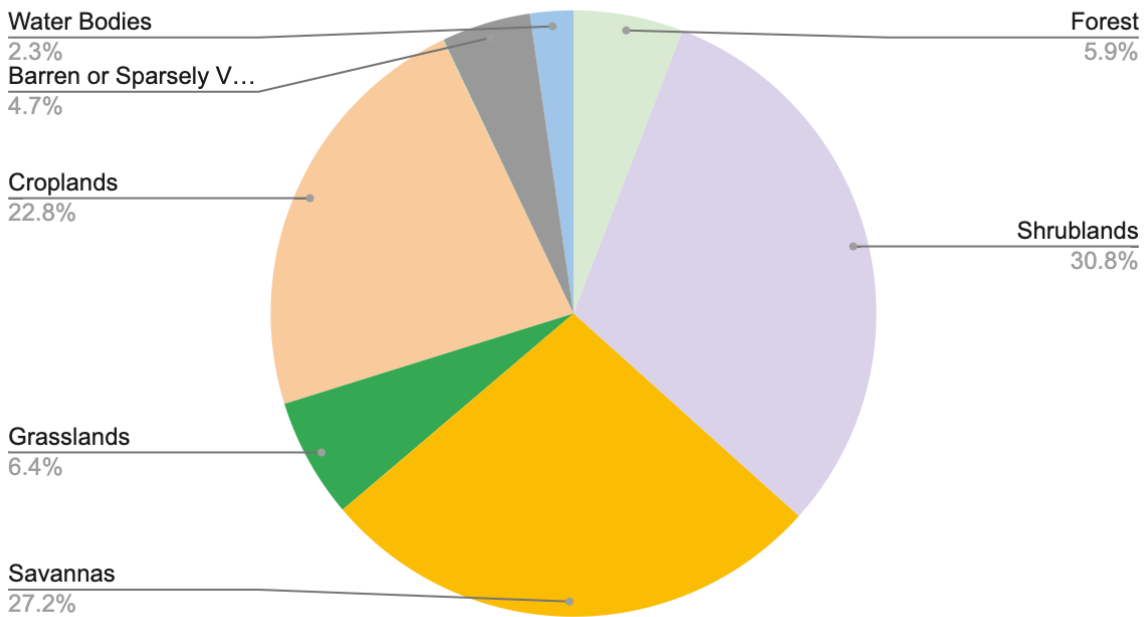


Fig 6. Land use distribution in Kenya including water bodies.

Croplands are the class with the largest area within Kenya and Tanzania's protected zones (Table 9). In Uganda, savannas are the class with the largest area in its protected zones. Tanzania also has a large protected forest area (Fig. 7).

Table 9. Protected areas (sq km) and distribution of land use classes in protected areas.

Land use class	Kenya	Tanzania	Uganda
Forest	6837	114280	2367
Shrublands	26343	7798	2819
Savannas	26198	65102	17039
Grasslands	3635	21777	894
Wetlands	0	0	42
Croplands	27116	148222	10752
Urban & Built-Up	5	1	16
Barren/Sparsely Vegetated	955	1269	236
Water Bodies	634	2653	1363

Land use distribution in protected areas of Kenya, Uganda, and Tanzania

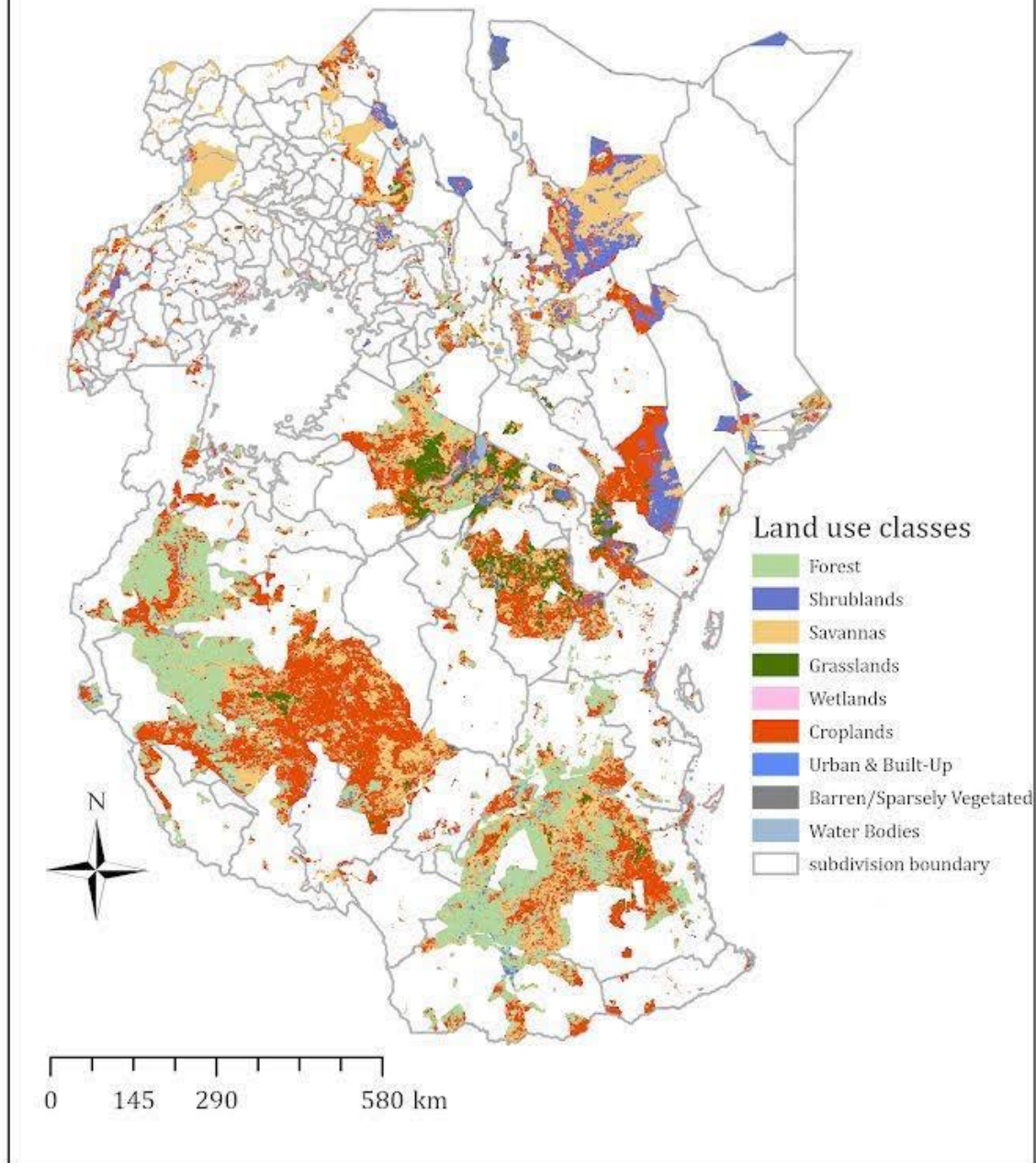


Fig 7. The land cover distribution throughout protected areas in Kenya, Tanzania, and Uganda. Uganda has the smallest area of protected zones while Tanzania has the largest.

3.1.2. Aim 1b: Population measures

Population values in Kenya, Uganda, and Tanzania have nearly doubled between 2000 and 2020 (Table 10, Fig. 8).

Table 10. Population changes in 2000-2020 in Kenya, Tanzania, and Uganda.

country	population 2000	population 2020	population change 2000-2020
Kenya	35,954,906	67,255,381	31,300,475
Uganda	26,616,045	47,863,676	21,247,631
Tanzania	39,512,493	68,137,469	28,624,976

Large cities experienced the largest population increase between 2000-2020 while rural areas experienced the smallest (Table 11). Population densities are highest at or around the largest cities, Dar es Salaam, Wakiso (3,573,000), and Nairobi (6,032,000). Dar es Salaam (7,698,000), Wakiso, and Nairobi continue to be hotspots in 2020 (Fig. 10), experiencing continued population density increases between 2000 and 2020 (Fig. 11). Wakiso is a district that partially encircles Kampala, so experiences population overflow from Kampala. Unlike Kampala and Nairobi, Dar es Salaam does not experience much population overflow outside of its borders (Fig. 11).

The route between Kampala and Nairobi experiences higher population densities (Fig. 9, Fig. 10) and increased population densities between 2000 and 2020 (Fig. 11).

Table 11. The most and least populated subdivisions per country. The subdivision per country with the greatest and smallest population increase.

country	most populated subdivision & population (2020)	least populated subdivision & population (2020)	subdivision with greatest population increase (2000-2020)	subdivision with smallest population increase (2000-2020)
Kenya	Nairobi City, 6,032,000	Lamu, 168,500	Nairobi City, 3,193,832	Lamu, 74,475
Uganda	Wakiso, 3,573,000	Kalangala, 35,400	Wakiso, 2,550,176	Moyo, -97,200
Tanzania	Dar es Salaam, 7,698,000	Kusini Unguja, 187,300	Dar es Salaam, 5,185,264	Kusini Pemba, 49,605

Population changes between 2000 and 2020 in Kenya, Uganda, and Tanzania

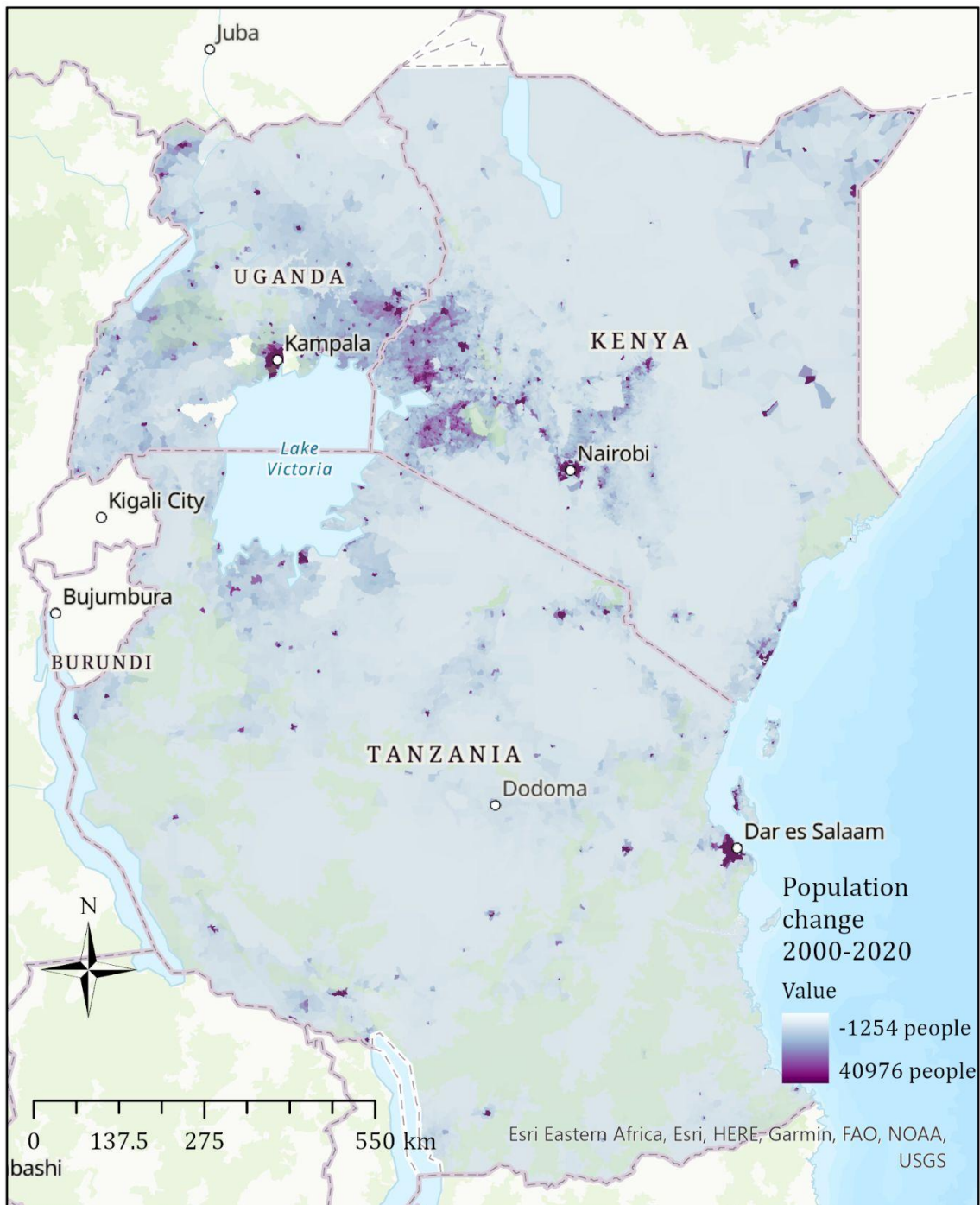


Fig 8. Population changes between 2000 and 2020 in the study area.

Population density in 2000 in Kenya, Uganda, and Tanzania

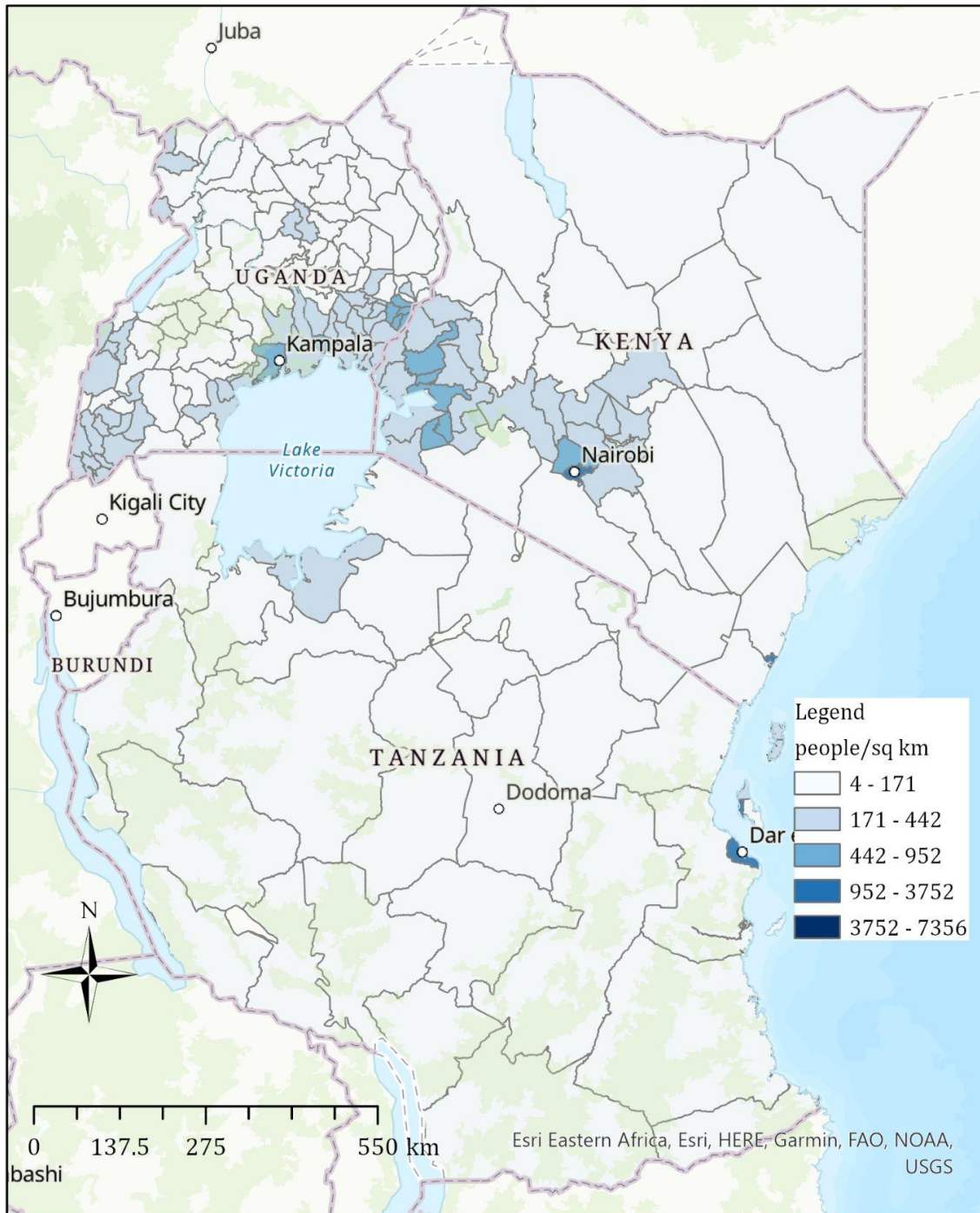


Fig 9. Population density in 2000 (people per km) in the study area. Population densities are highest at or around the largest cities, Dar es Salaam, Kampala, and Nairobi. The route between Kampala and Nairobi coincides with higher population densities.

Population density in 2020 in Kenya, Uganda, and Tanzania

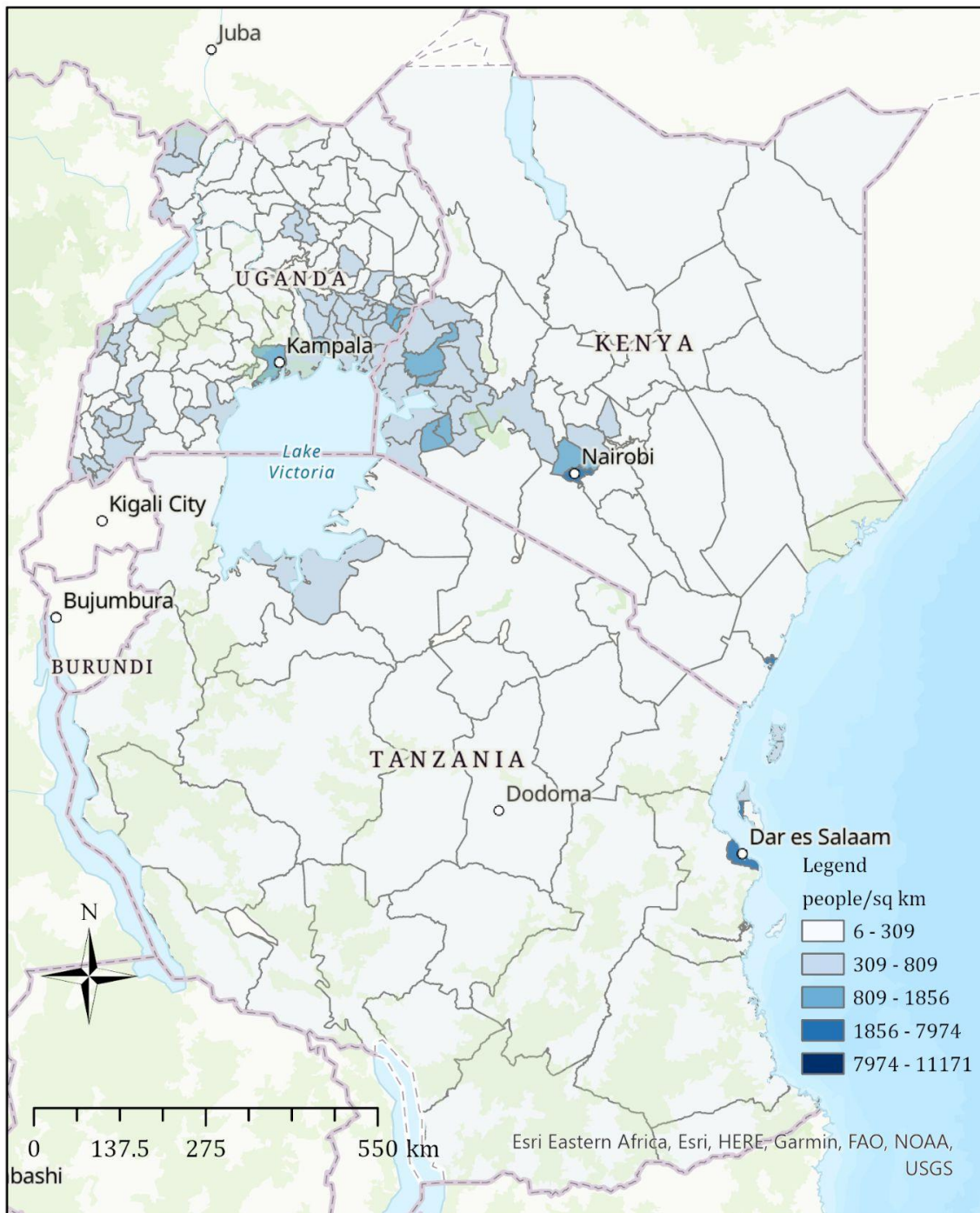


Fig 10. Population density (people per sq km) in 2020. The population density hotspots from 2000 continue to be hotspots in 2020.

Population density change between 2020 - 2020 in Kenya, Uganda, and Tanzania

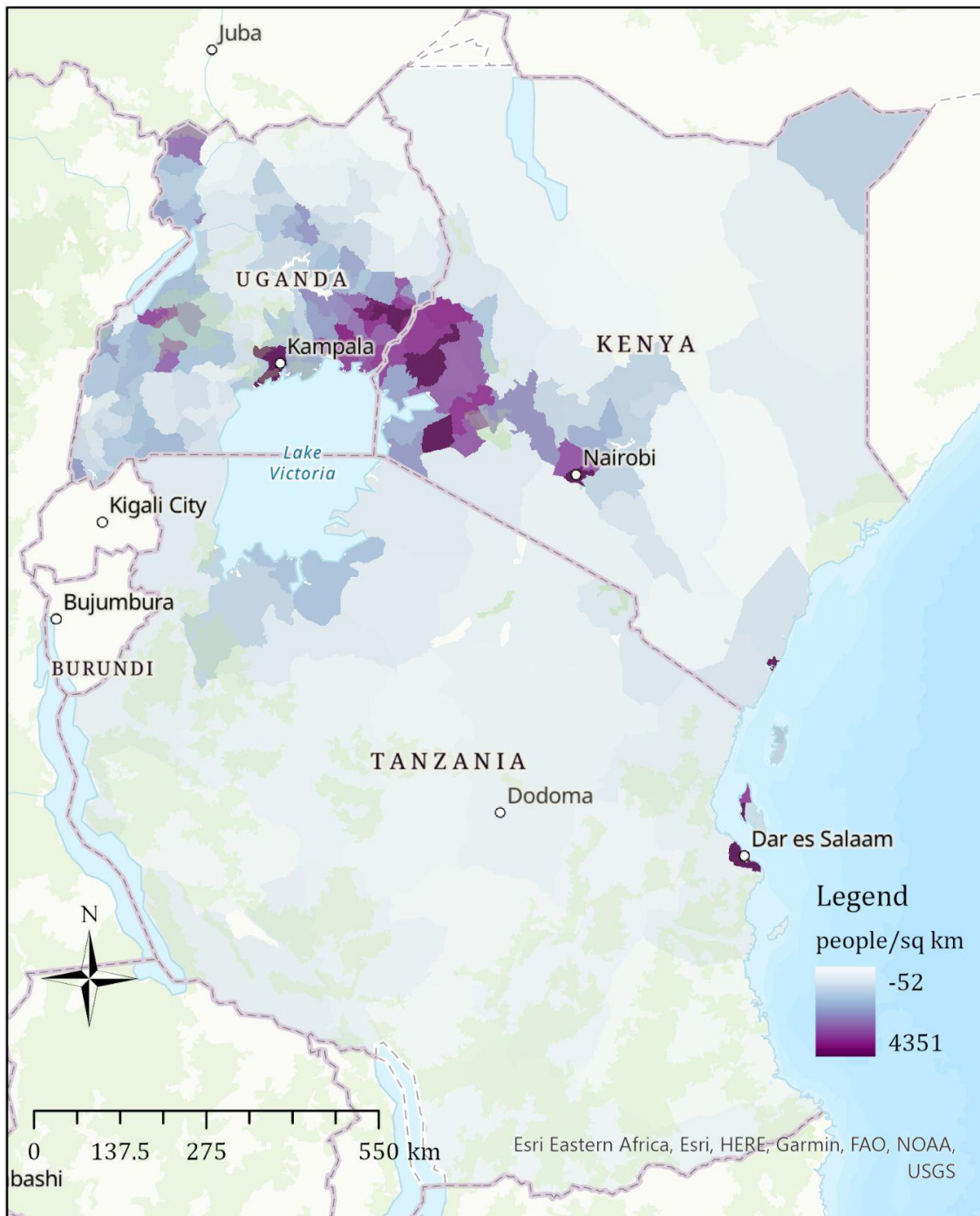


Fig 11. Population density change (people/sq km) between 2000-2020. The population density hotspots from 2000 experienced increases by 2020. The route between Kampala and Nairobi continues to have a high population density. Dar es Salaam continues to not experience population overflow outside of its subdivision.

3.1.3. Aim 1c: Climate and topography statistics

The highest precipitation values in the study area (2,064mm/month) are found around Lake Victoria (Fig. 12), where there are also relatively high elevation values. Higher elevation climate systems often receive more precipitation. The high precipitation areas of southeastern Tanzania, however, do not have high elevation values (Fig. 18).

Precipitation in Kenya, Uganda, and Tanzania

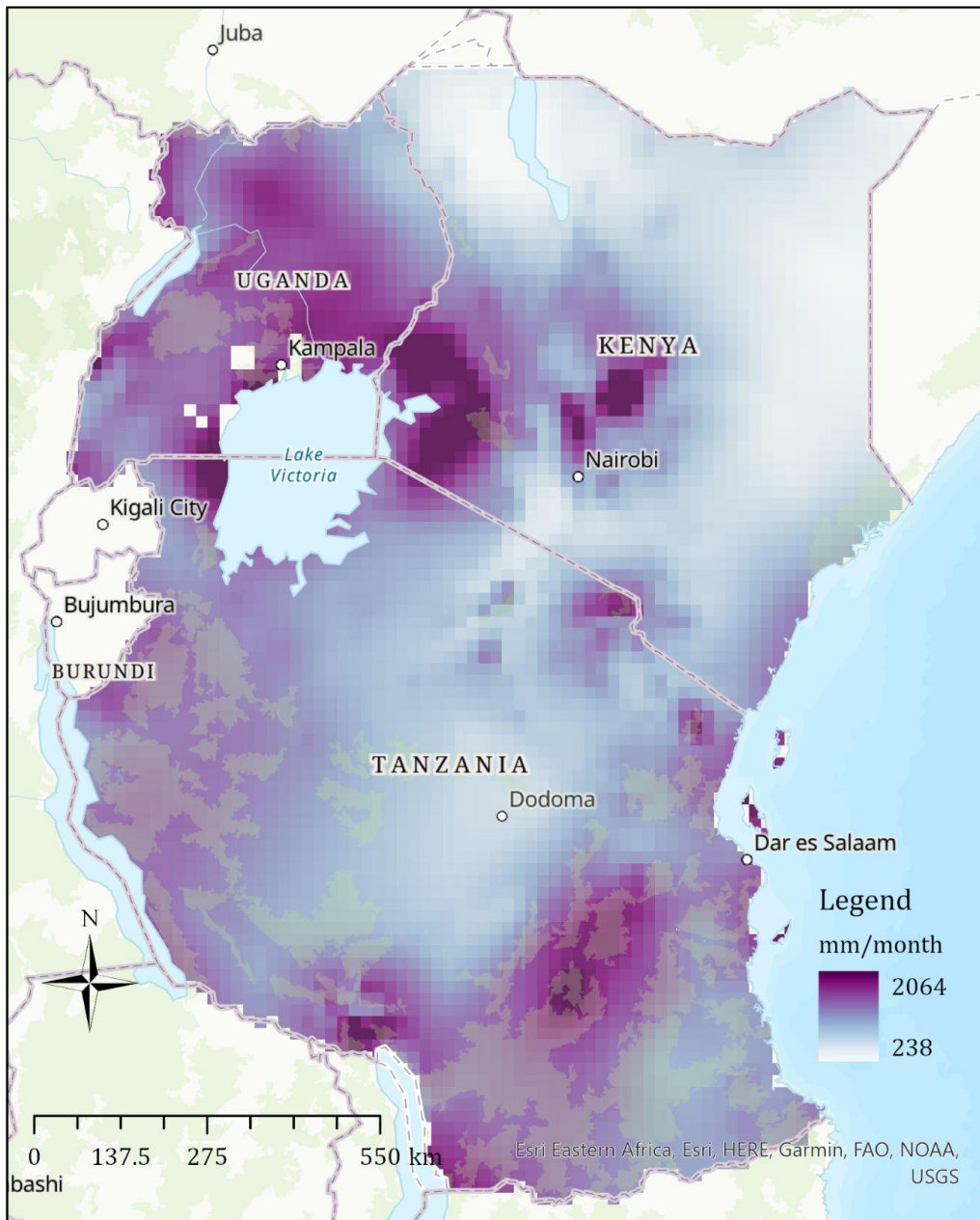


Fig 12. Average monthly precipitation values in Kenya, Uganda, and Tanzania (mm/month). The highest precipitation values are found around Lake Victoria.

Kenya experiences lower average precipitation values than Tanzania and Uganda because while maximum precipitation values are similar among the countries, Kenya has a lower minimum precipitation value than the other two countries (Table 12, Fig. 14).

Table 12. Precipitation (mm/month) statistics in Kenya, Uganda, and Tanzania.

Country	min	max	mean
Kenya	238	1946	724
Tanzania	458	2006	1005
Uganda	582	2006	1188

Precipitation in Kenya, Tanzania, and Uganda

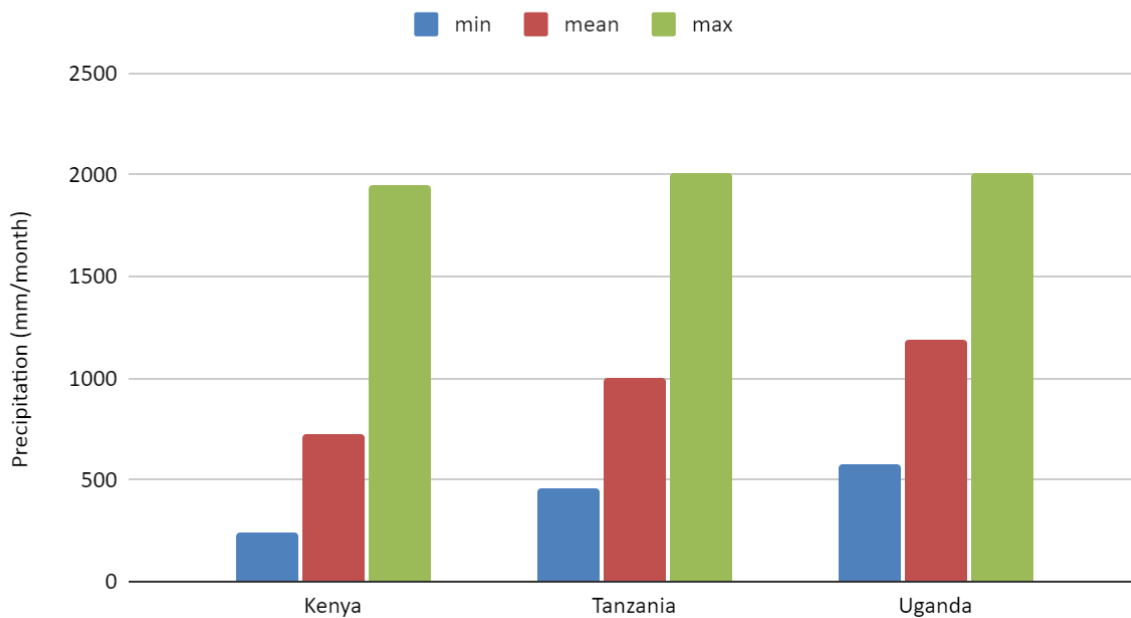


Fig 14. Precipitation (mm/month) statistics in Kenya, Uganda, and Tanzania.

Tanzania contains the highest elevation point in the study area (5,746m) (Table 13), an elevation value that makes up less than 1% of the study area (Fig. 15), although a considerable portion of Kenya also has high elevations. Much of Uganda is a plateau. Kenya and Tanzania have larger elevation variances (Fig. 16) with mountainous areas inland and coastal lowlands (Fig. 17).

Elevation distribution of study area

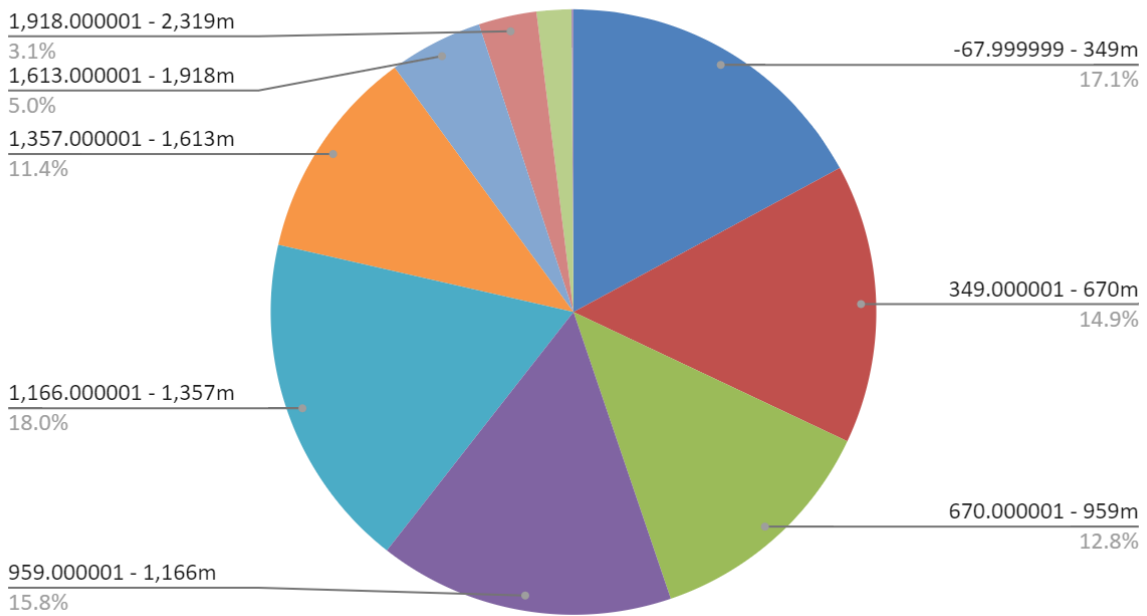


Fig 15. Elevation distribution (m) of study area.

Table 13. Elevation (m) statistics in Kenya, Uganda, and Tanzania.

Country	min	max	mean
Kenya	-68	4748	799
Tanzania	-3	5746	1018
Uganda	190	4625	1156

Elevations of Uganda, Tanzania, and Kenya

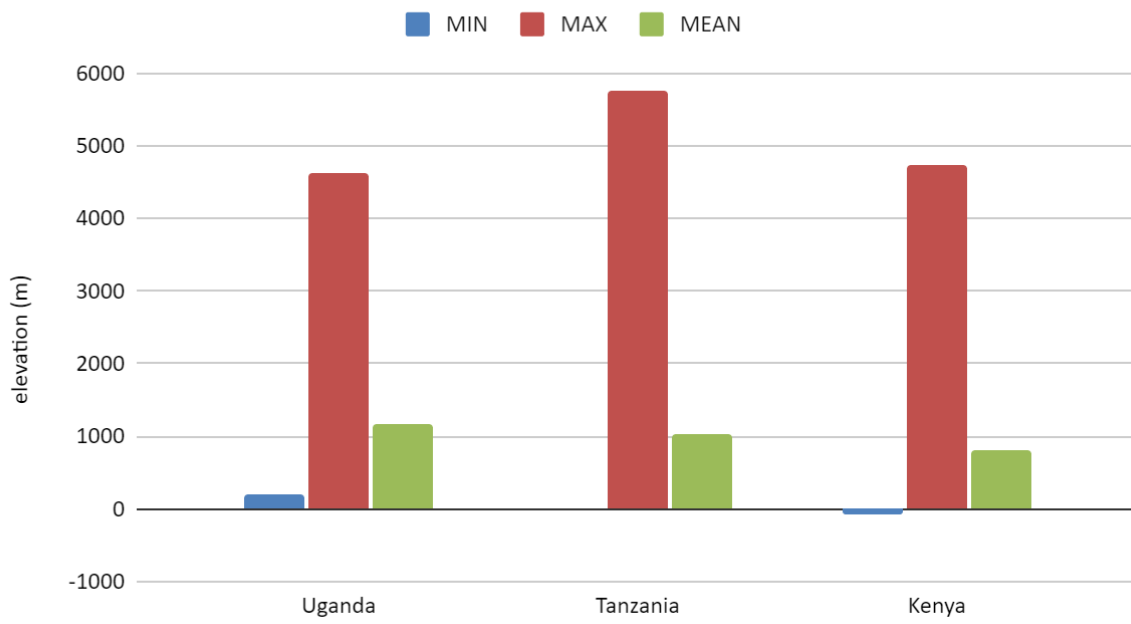


Fig 16. Elevation values (m) of study area.

Elevation (m) in Kenya, Uganda, Tanzania

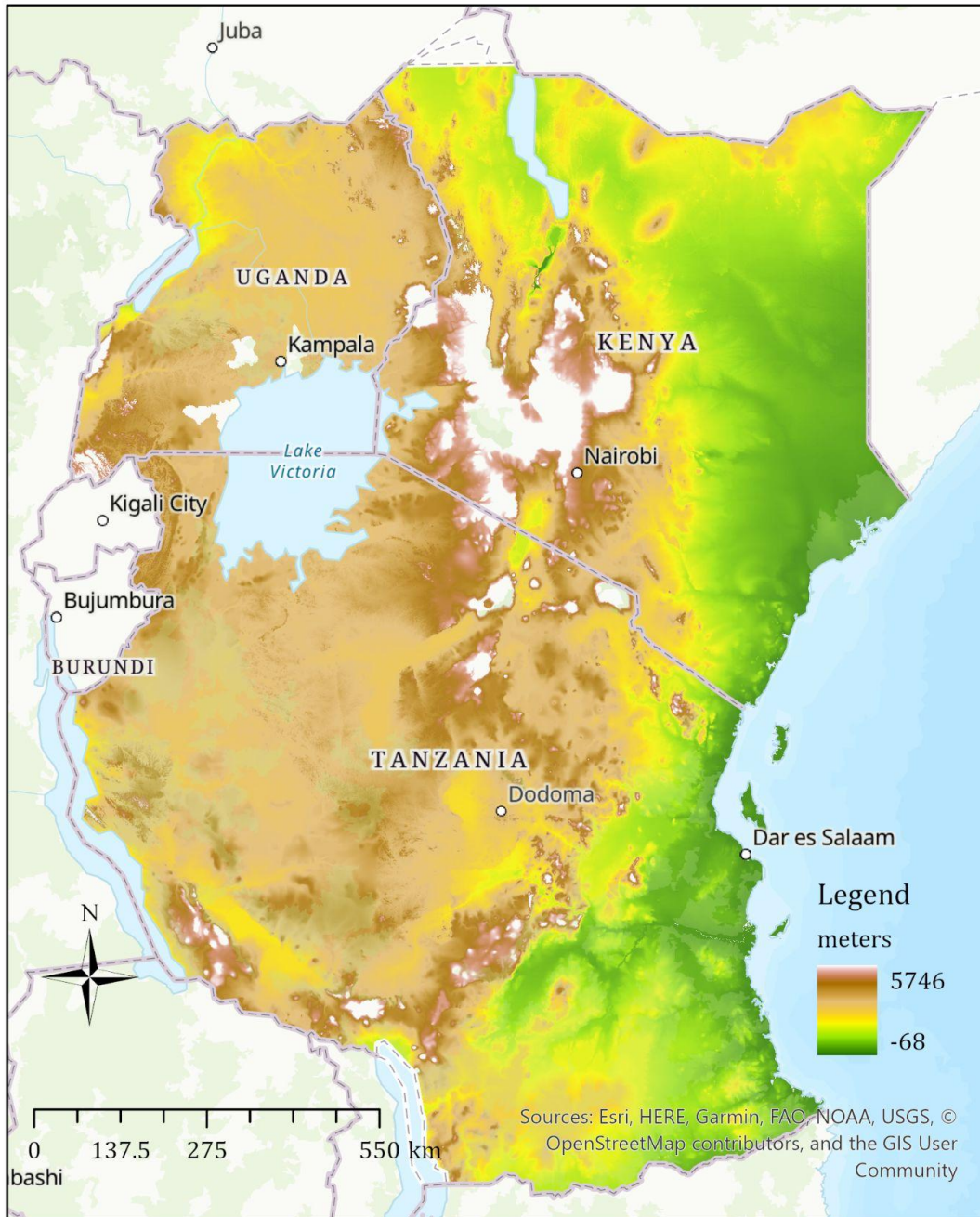


Fig 17. Elevation values (m) of the study area.



Lake Victoria and its surroundings have the highest precipitation values and relatively high elevation values. The high precipitation areas of southeastern Tanzania do not have high elevation values (Fig. 18).

Elevation and average monthly precipitation in Kenya, Uganda, Tanzania

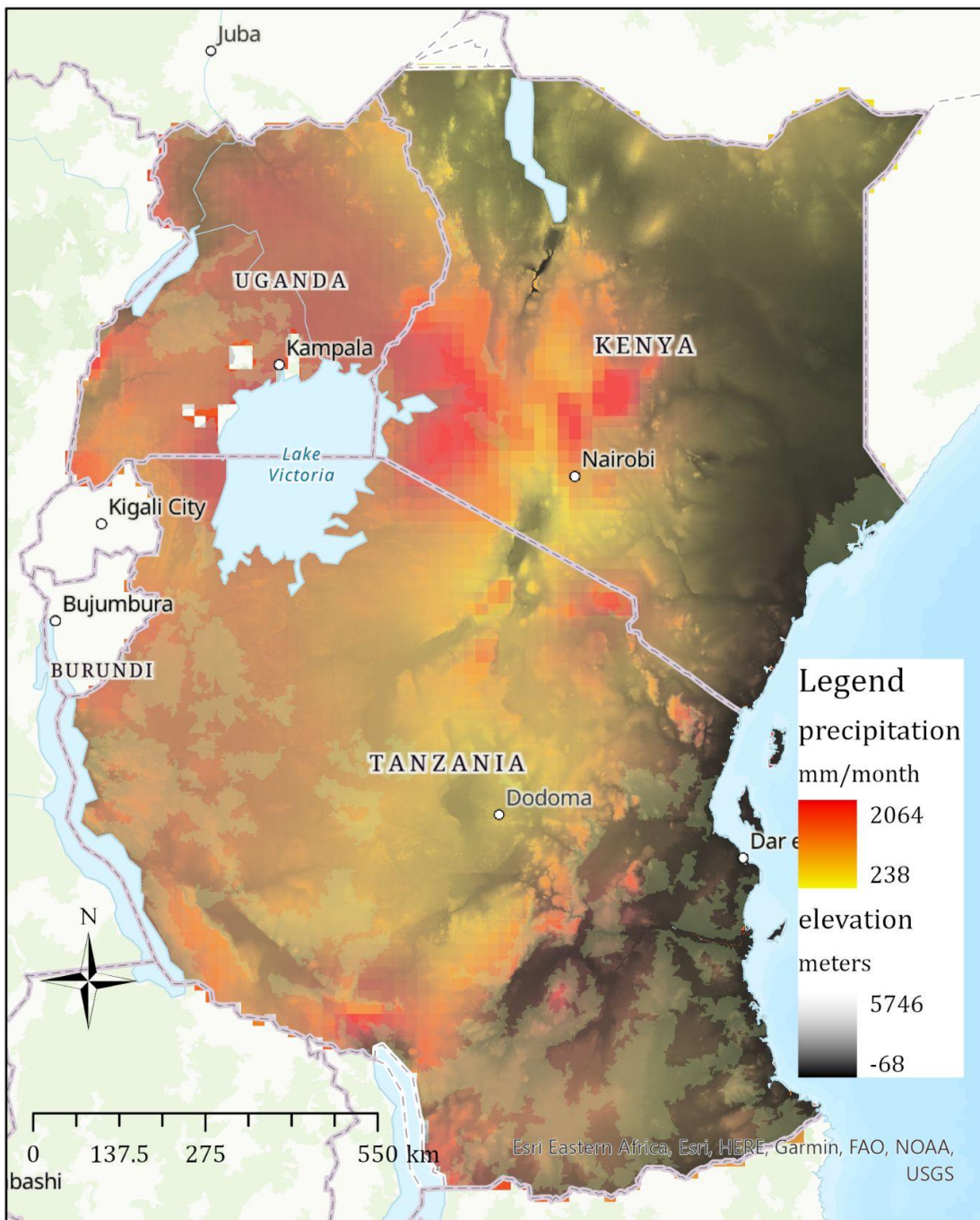


Fig 18. Precipitation and elevation values in the study area.

3.2. Aim 2: Acquire new knowledge by combining geographical datasets.

Tanzania has the highest area of cropland area per capita (5,318 square meters per capita). Furthermore, a large portion (38.5%) of Tanzania is croplands (Table 14). Uganda and Kenya have lower croplands available per capita at 1,646 square meters of croplands per capita and 1,728 square meters of croplands per capita, respectively (Table 14).

Land use classes within the study area inhabit a similar elevation range with area majorities of all classes existing below 1,918m. The majority of croplands and forests are found below 1,613m (Fig. 19). Wetlands are an outlier, existing only in areas higher than 3,000m. Water bodies are not found higher than 3,000m (Fig. 20).

Table 14. Cropland (sq m) per capita in per country in 2020.

Country	cropland per capita (sq m)	cropland % of total country area
Kenya	1728	19.90%
Tanzania	5318	38.50%
Uganda	1646	34.60%

Tanzania contains the largest amount of forest area of the three countries. It is the most highly forested country and has also protected the largest portion of its forest area (Table 15).

Table 15. Relationship between forests and protected areas in study area (sq km).

country	Total forest area	forest area compared to country area	protected forest area	% of country's forest that is protected
Kenya	28,342	4.90%	6,837	24.10%
Uganda	8,869	3.80%	2,367	26.70%
Tanzania	252,670	26.85%	114,280	45.20%

While croplands are found over a wide elevation range (Fig. 19, Fig. 20, Fig. 23), they show a strong preference for an elevation range of 959m-1613m (Fig. 21). The largest area of croplands is found between 1,166 and 1,357m of elevation (Fig. 22).

Elevation distribution of all land classes

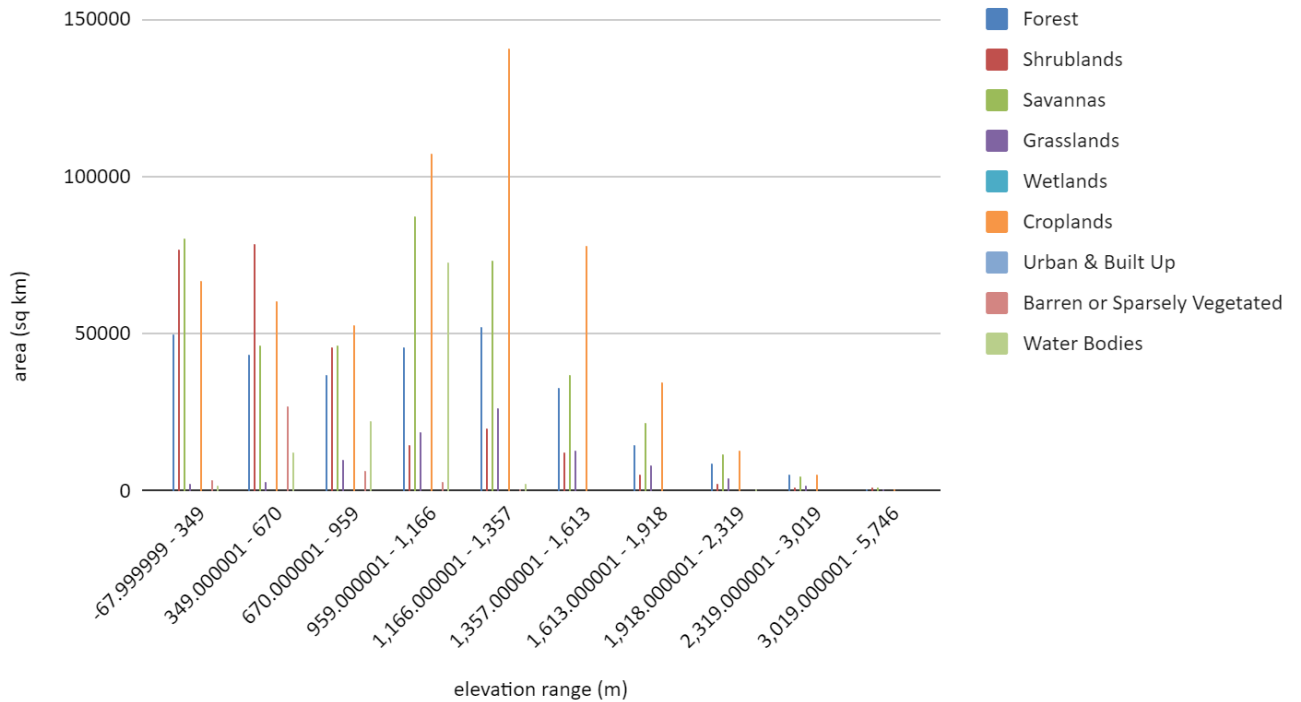


Fig 19. Elevation distribution of all land classes in the study area. Smaller areas are found at elevations above 1,918m for all classes. The majority of croplands and forests are found below 1,613m.

Maximum, minimum, and mean elevation

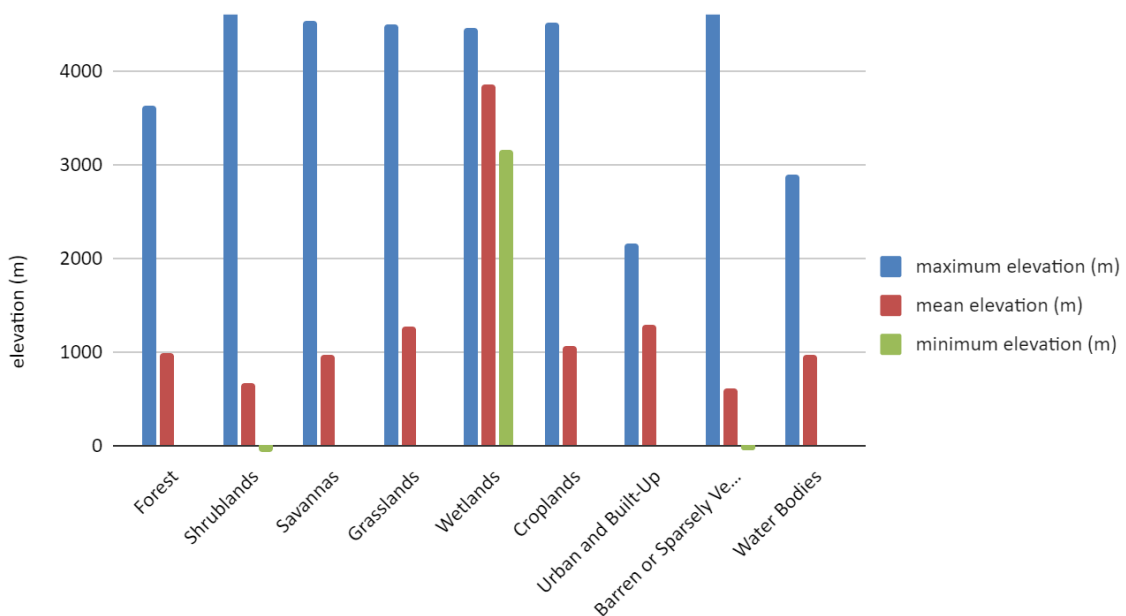


Fig 20. Elevation distribution of all land classes in the study area. Wetlands are an outlier in regards to elevation, only existing within the study area in areas higher than 3,000m. Water bodies are not found in areas above 3,000m.

Elevation makeup of cropland areas

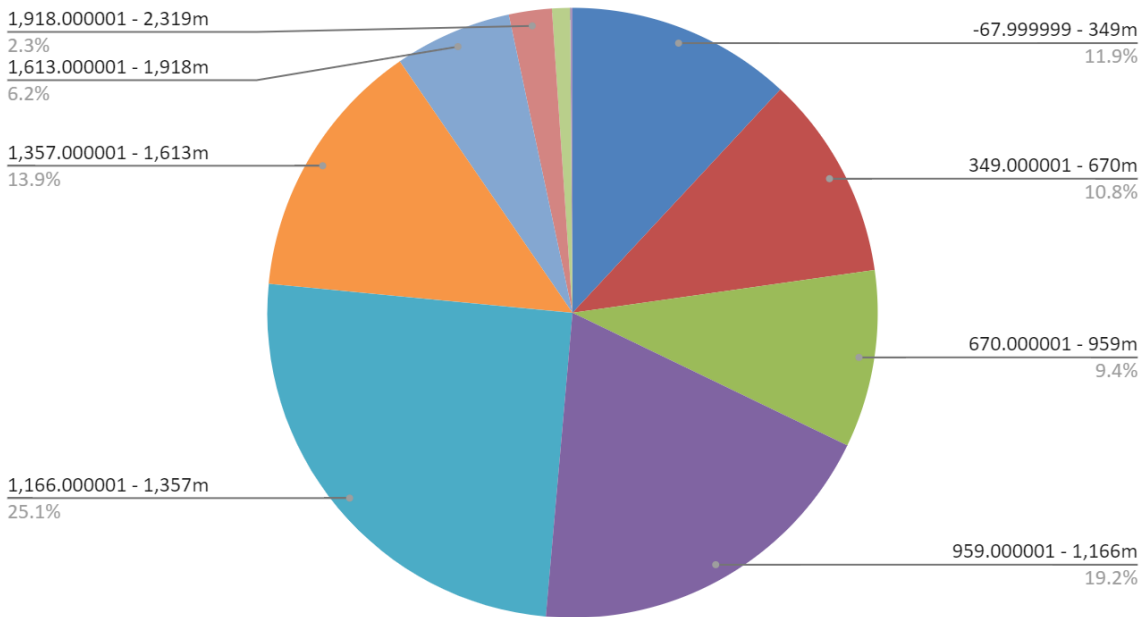


Fig 21. Elevation distribution of croplands in study area. The largest group in area of croplands is found between 1,166 and 1,357m of elevation.

Elevation distribution of cropland areas

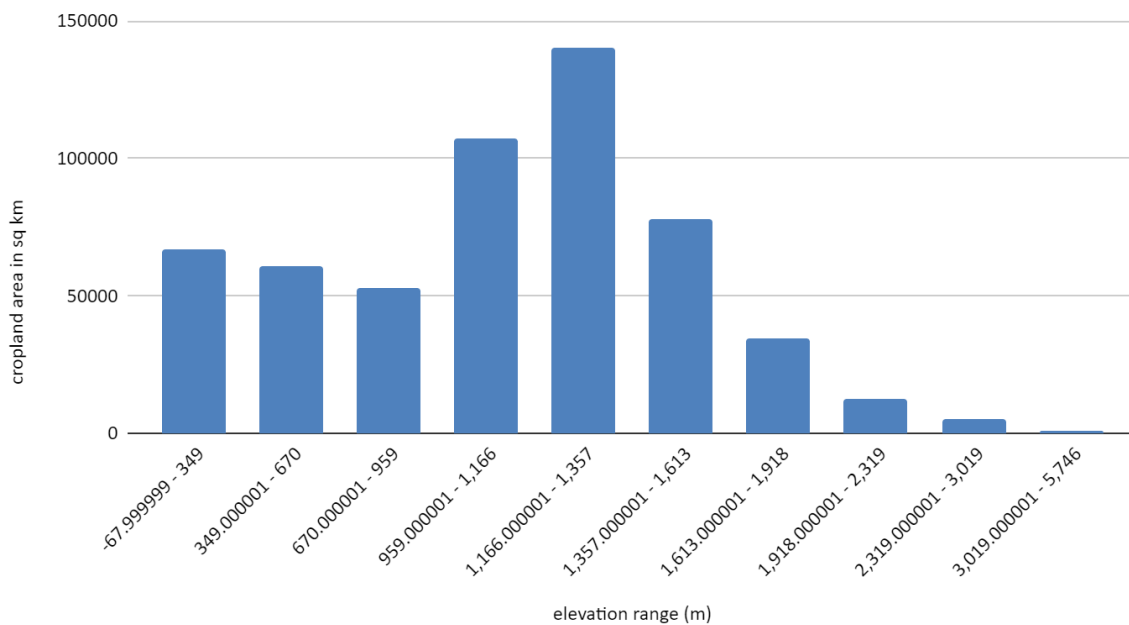


Fig 22. Elevation distribution of croplands in study area.

Elevation in croplands of Kenya, Uganda, & Tanzania

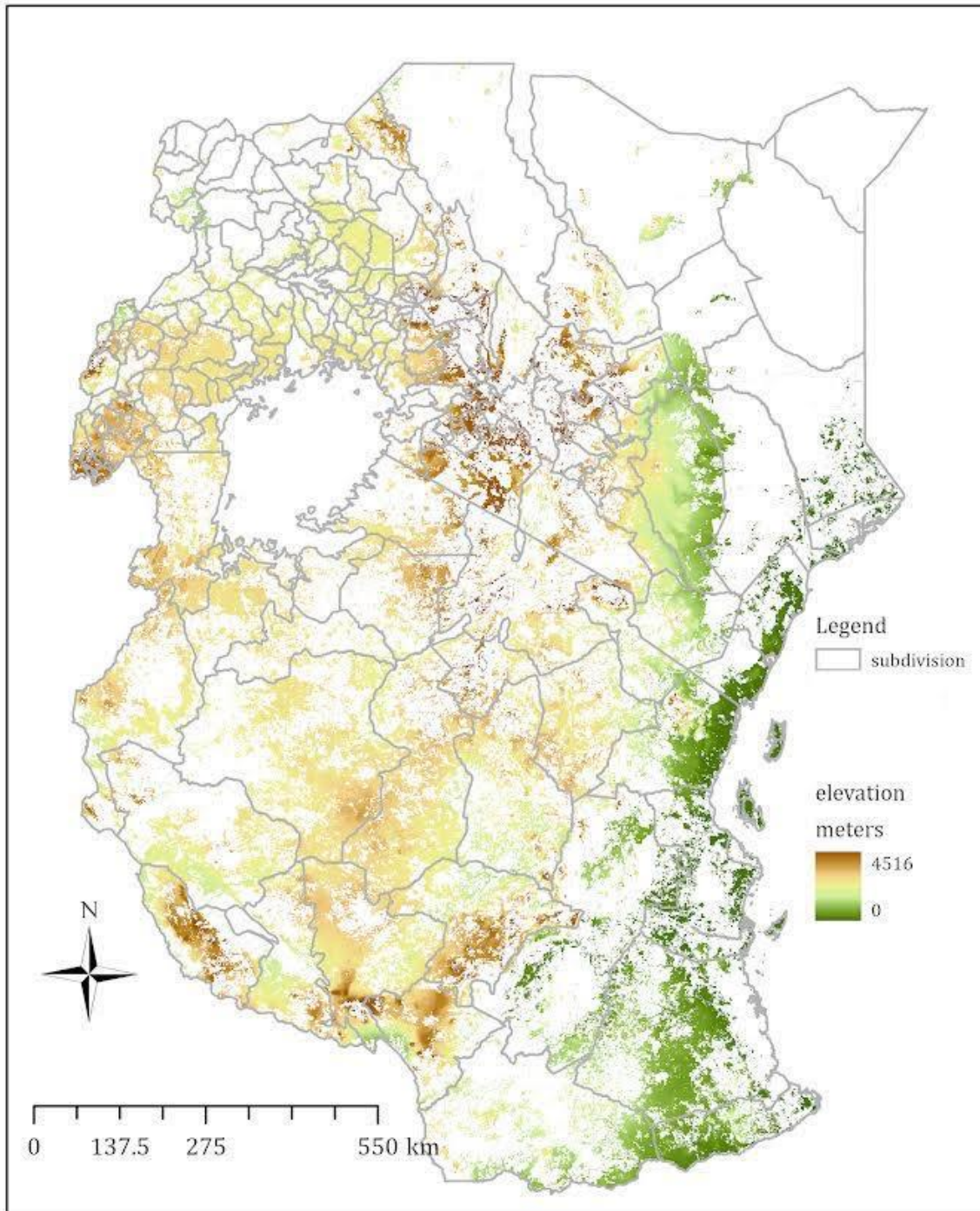


Fig 23. Elevation in croplands of study area. Croplands are found in a wide elevation range but show a strong preference for an elevation range between 959m-1,613m.

Croplands and forests both display preferences for areas below 1,613m of elevation (Fig. 19) that receive 881-1,136 mm/month of precipitation per month (Table 16, Table 17). 38.1% of total cropland areas exist within this precipitation range (Fig. 24). Shrublands are an outlier, showing a strong preference for receiving 238 - 606mm of precipitation per month (Table 16).

Out of all classes except forests, savannas have the second most similar precipitation and elevation preferences to croplands, preferring 881-1,136mm/month of precipitation (Table 16) and -67m - 1,357m in elevation.

The monthly precipitation range of 881-1,136 mm is the most commonly seen range throughout all land use classes. However, shrublands deviate from this, preferring 238-606 mm/month of precipitation.

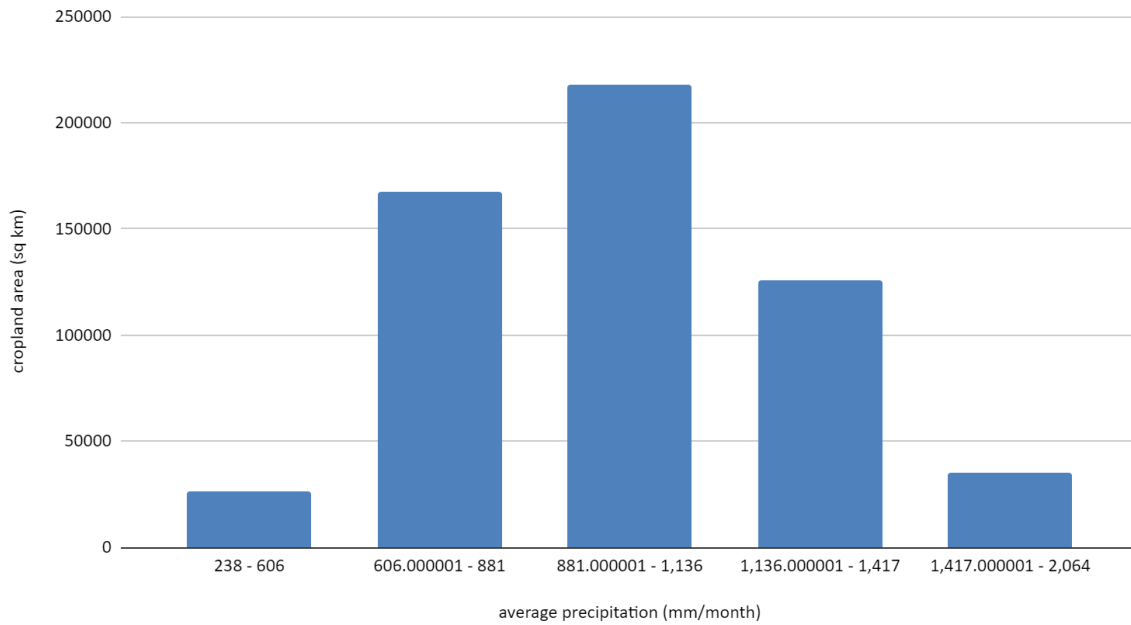
Croplands around Lake Victoria and in southern Tanzania receive the most precipitation (881 mm/month and higher) (Fig. 25). These areas also have moderate elevation levels (959 m or higher).

Table 16. Average precipitation distribution across land use classes.



Table 17. Average precipitation distribution across cropland areas in the study area.

Average precipitation distribution across cropland areas



Division of cropland areas (sq km) by average precipitation levels

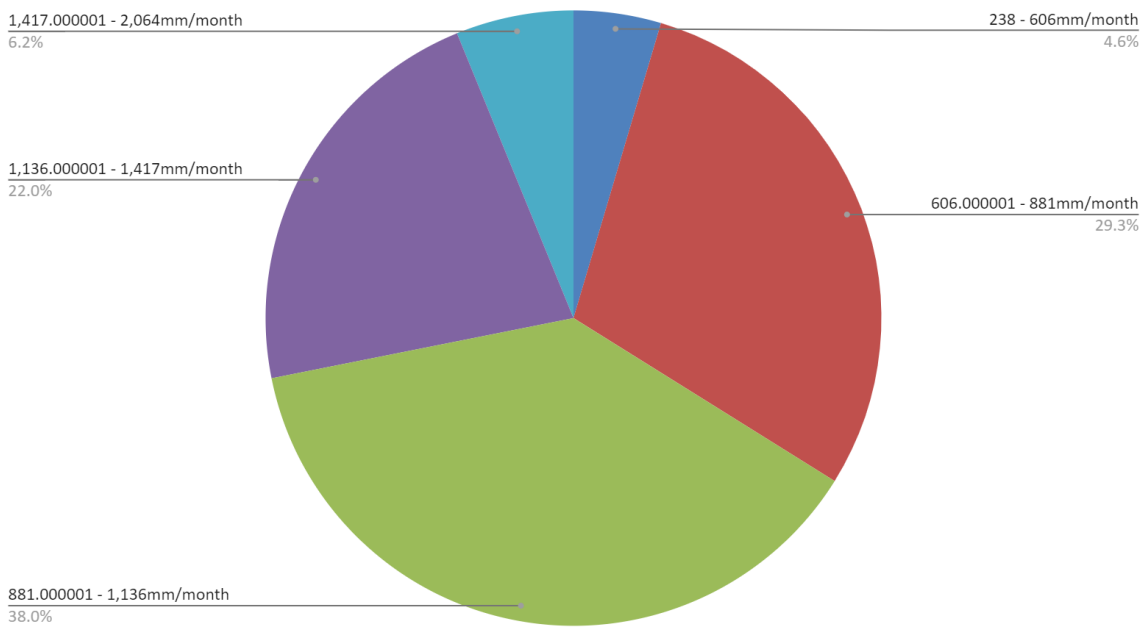


Fig 24. Distribution of precipitation levels in cropland areas in study area.

Precipitation in croplands of Kenya, Uganda, & Tanzania

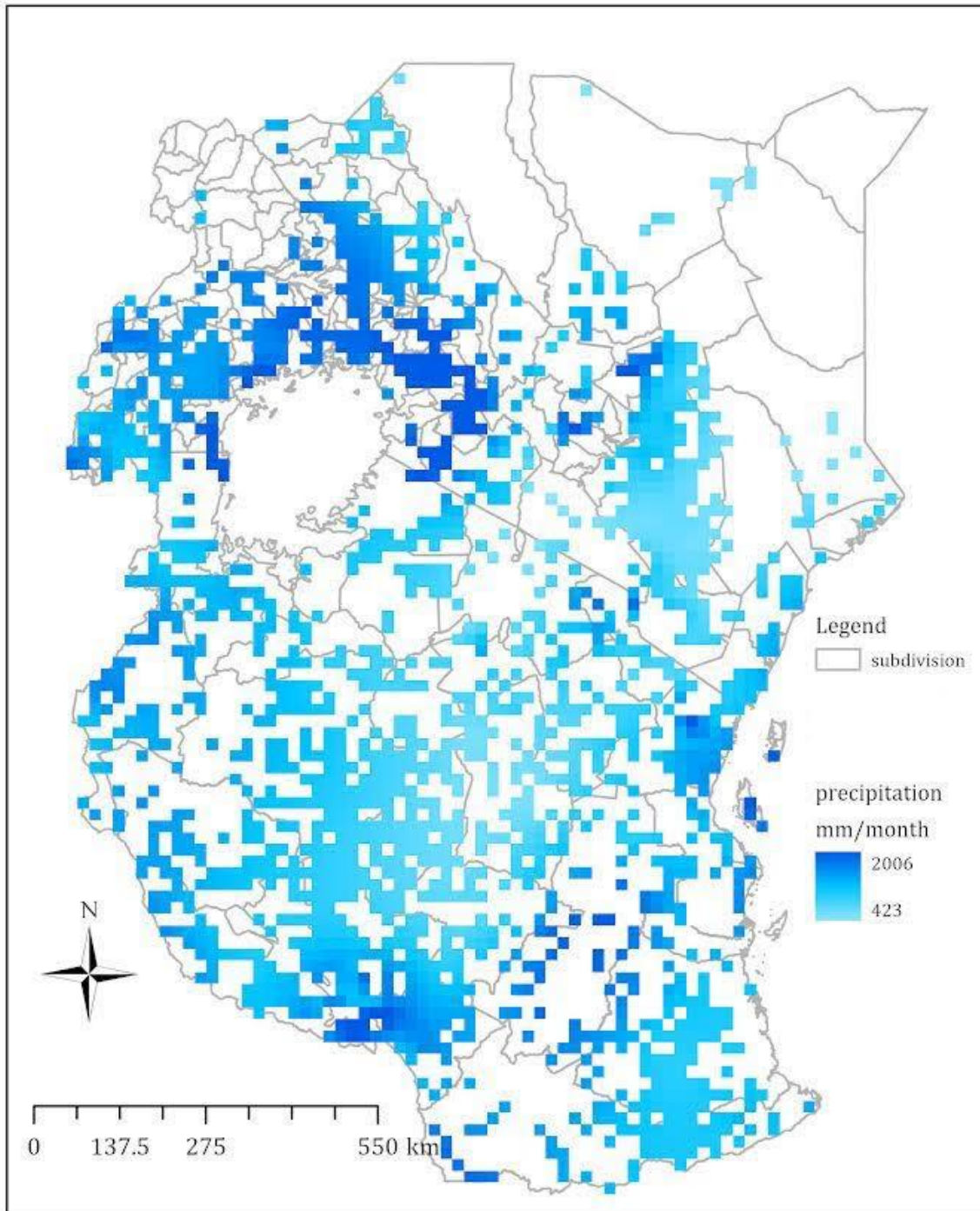


Fig 25. Precipitation in croplands of study area.

3.3. Aim 3: Predict expected future populations.

The following calculations estimate future populations based on the population growth between the years 2000 and 2020:

$$\text{Predicted 2040 population} = (\text{2020 population}) * (1+r)^1$$

$$r = (\text{2020 population} - \text{2000 population}) / \text{2000 population}$$

By 2040, it is predicted that the population of Kenya will be 125,804,423, Uganda will be 90,372,189, and Tanzania will be 117,499,917.

By 2060, it is predicted that the population of Kenya will be 235,323,221, Uganda will be 166,525,385, and Tanzania will be 202,623,178 (Table 18).

Table 18. Population predictions for 2040 and 2060 in Kenya, Uganda, and Tanzania.

Country	2000	2020	r	2040	2060
Tanzania	39,512,493	68,137,469	0.7244537917	117,499,917	202,623,178
Kenya	35,954,906	67,255,380	0.870548075	125804423	235323221
Uganda	26,616,045	49044369.97	0.8426618454	90372189	166525385

Dar es Salaam, Wakiso, and Nairobi City are predicted to have both the highest populations and the largest population increases between 2000-2060 (Fig. 26, Fig. 27, Table 19)

Predicted population in 2040 of Kenya, Uganda, & Tanzania

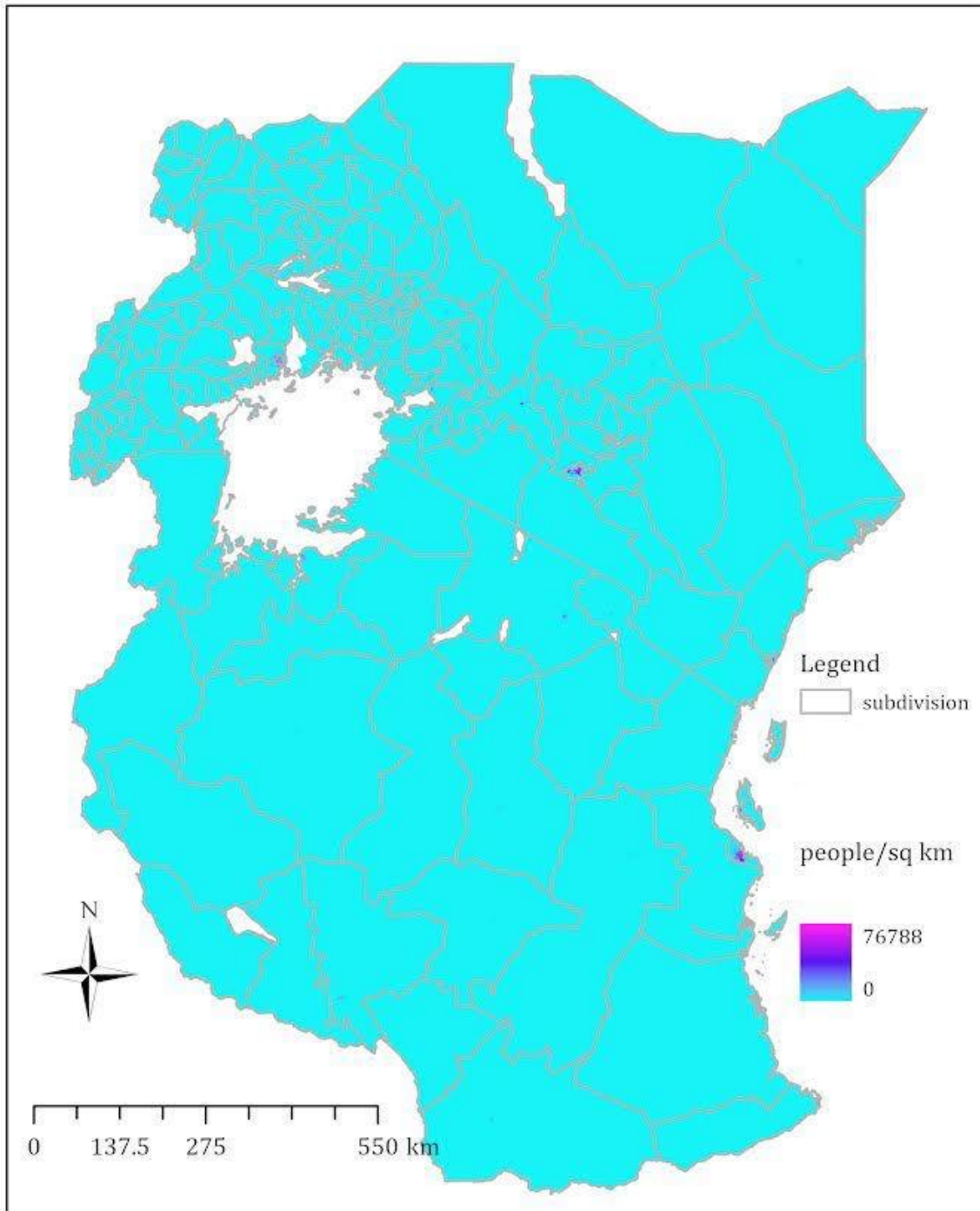


Fig 26. Population prediction for the year 2040 in the study area.

Predicted population in 2060 of Kenya, Uganda, & Tanzania

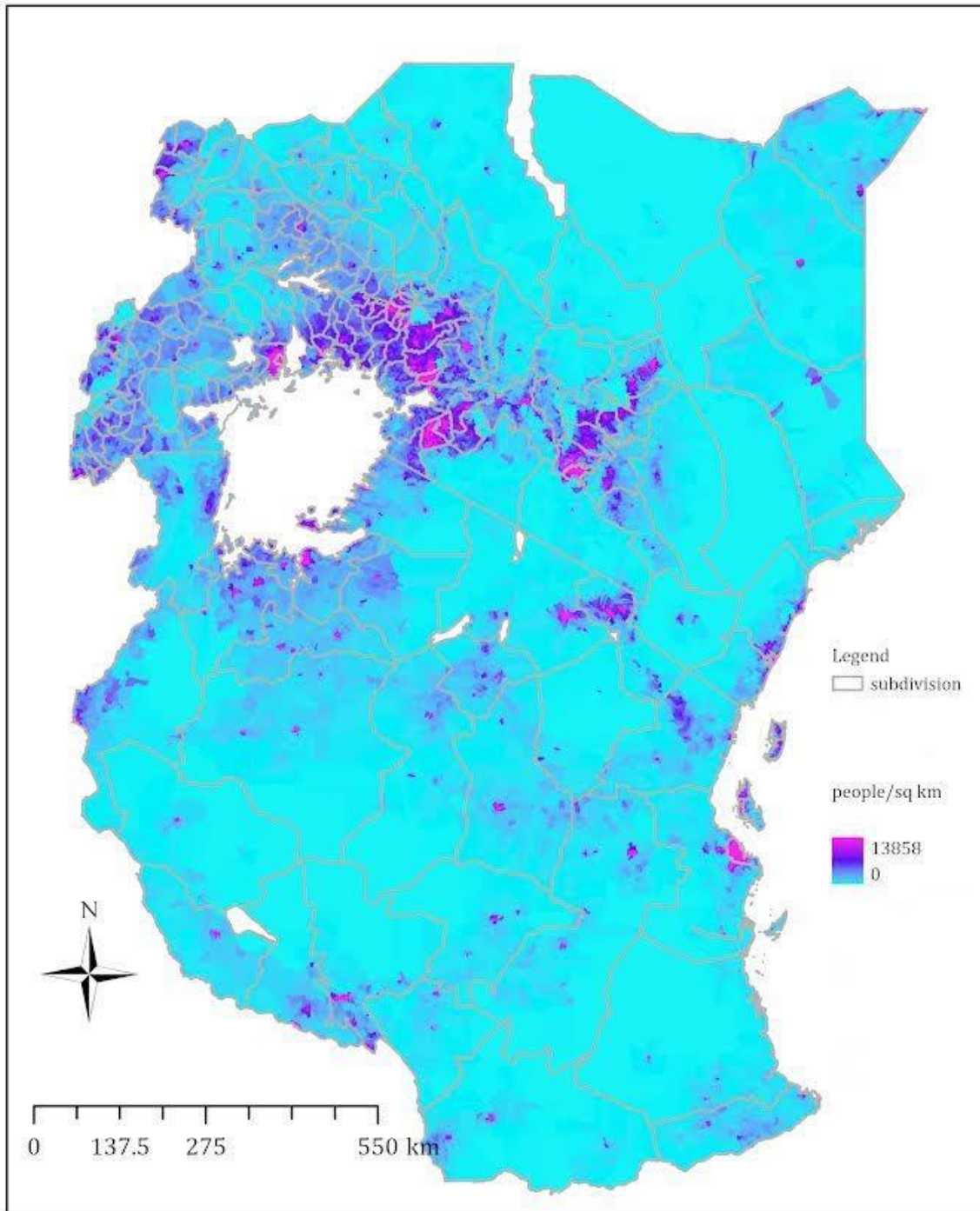


Fig 27. Population prediction for 2060 in the study area. Dar es Salaam, Kampala/Wakiso, and Nairobi City will continue to experience population growth.

Table 19. Subdivisions predicted to have the highest and lowest populations and the largest and smallest population increases between 2000-2060 in the study area.

country	most populated subdivision (2060)	least populated subdivision (2060)	subdivision with greatest population increase (2020-2060)	subdivision with smallest population increase (2020-2060)
Kenya	Nairobi City	Lamu	Nairobi City	Lamu
Uganda	Wakiso	Kalangala	Wakiso	Moyo
Tanzania	Dar es Salaam	Kusini Unguja	Dar es Salaam	Kusini Pemba

Each country within the study area contains both protected and unprotected forest area (Table 20).

Table 20. Forest area per country in 2020 (sq km).

Land use type, 2020	Uganda	Tanzania	Kenya
Total Forest	8,869	252,670	28,342
Protected Forest	2367	114280	6837
Unprotected forest	6502	138390	21505

By 2040, the total cropland needed to maintain current cropland per capita ratios will be 217,397 in Kenya, 624,899 in Tanzania, and 148,738 in Uganda.

By 2060, the total cropland needed to maintain current cropland per capita ratios will be 406,651 in Kenya, 1,077,609 in Tanzania, and 274,074 in Uganda (Table 21).

Table 21. Cropland area needed by 2040 & 2060 to maintain 2020's cropland per capita ratio (sq km).

Country	total cropland need in 2040 to maintain current cropland per capita ratio	cropland needed in 2060 to maintain current cropland per capita ratio
Kenya	217,397	406,651
Tanzania	624,899	1,077,609
Uganda	148,738	274,074

Converting both protected and unprotected forest areas and savannas into croplands in each country would meet the 2040 cropland needs (Table 22).

Table 22. Cropland need by 2040 after converting savannas and all forest areas into cropland (sq km). Negative values indicate that the need is met.

Country	remaining cropland need in 2040 after accounting for existing cropland	remaining cropland need in 2040 after converting unprotected forest area into cropland	remaining cropland need in 2040 after converting all forest area into cropland	remaining cropland needed in 2040 after converting savannas & forests into cropland
Kenya	101,176	79,671	72,834	-78,264
Tanzania	262,524	124,134	9,854	-157,723
Uganda	68,019	61,517	59,150	-31,273

Converting both protected and unprotected forest areas and savannas into croplands in each country would not be sufficient to meet the 2060 cropland needs (Table 23).

Table 23. Cropland need by 2060 after converting savannas and all forest areas into cropland (sq km).

Country	remaining cropland need in 2060 after accounting for cropland	remaining cropland need by 2060 after converting all forests into cropland	remaining cropland need by 2060 after converting savanna & forests into cropland (sq km)
Kenya	290,430	262,088	110,990
Tanzania	715,234	462,564	294,987
Uganda	193,355	184,486	94,063

Savannas and both protected and unprotected forest areas are suitable for conversion to cropland to fulfill 2040 cropland needs (Fig. 28).

Areas to consider converting to meet 2040 cropland needs in Kenya, Uganda, & Tanzania

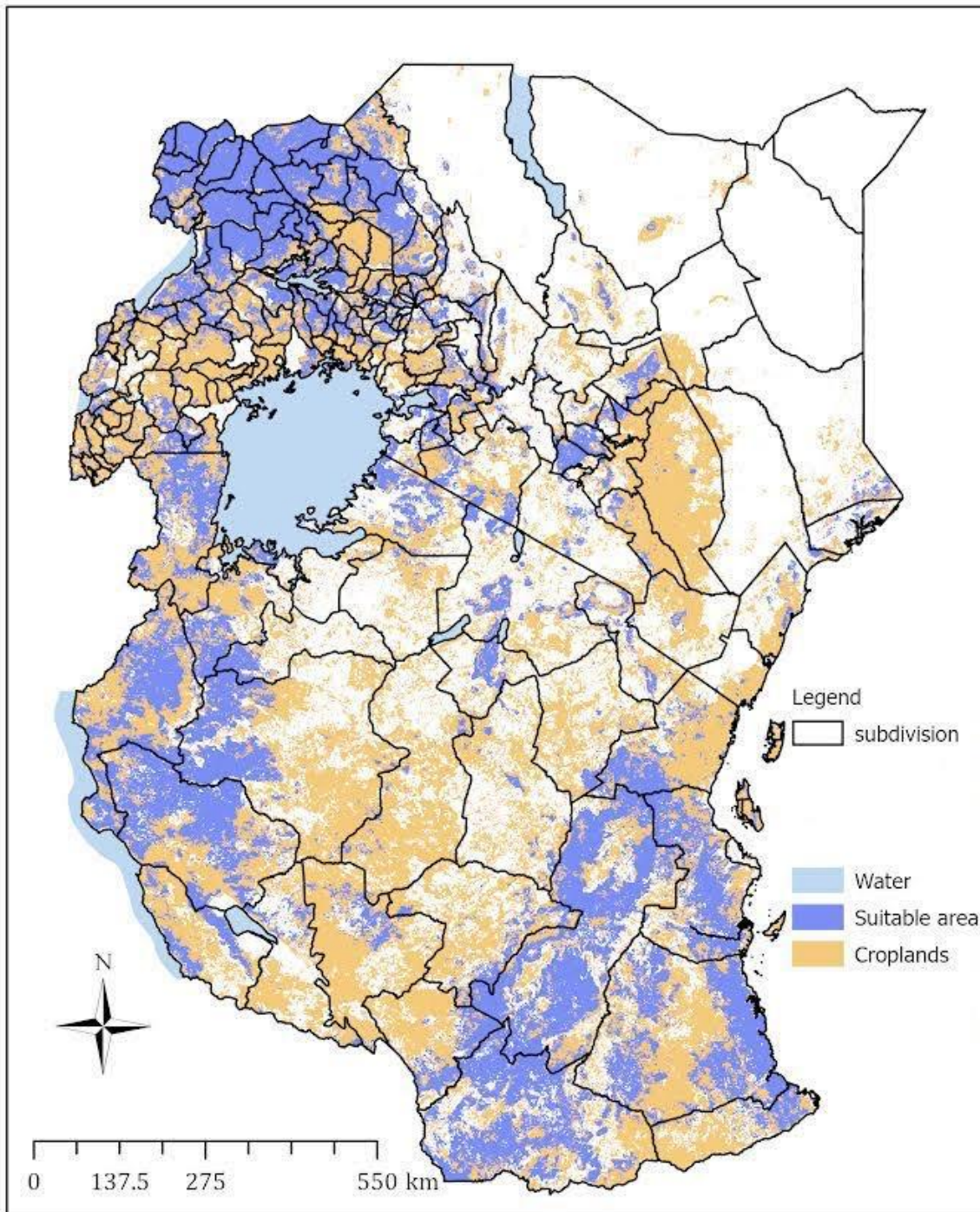


Fig 28. Suitable areas for conversion to croplands in Kenya, Uganda, and Tanzania.

4. Discussion

To meet the cropland needs by 2040, all three countries will need to convert areas into croplands.

Because forests and croplands have similar elevation and precipitation preferences, forests are an ideal class to substitute for croplands. Secondly, savannas have the most similar precipitation and elevation preferences to croplands. Thus, savannas are another suitable land use class to convert to croplands. Forests' preferences are more similar to those of croplands than savannas are. Therefore, forests should be converted first, then savannas. When possible, unprotected areas should be converted before protected areas.

To meet cropland needs in 2040, Kenya will need to convert 72,834 square kilometers of savannas, Tanzania will need to convert 9,854 square kilometers of savannas, and Uganda will need to convert 59,150 square kilometers of savannas (Table 22) in addition to all forest areas.

However, these measures will not fulfill the cropland needs of 2060. After these measures, a 2060 population will require an additional 110,990 square kilometers in Kenya, 294,987 square kilometers in Tanzania, and 94,063 square kilometers in Uganda. However, no land class has highly similar elevation and preference needs to those of croplands, thus none are highly suitable for conversion to croplands.

Considering these limitations in meeting expanding nutrition needs, intensification of agricultural practices within existing croplands should be prioritized. Additionally, there may be negative ecological consequences to eliminating all forest areas. Furthermore, populations may continue to grow, and suitable land is a limited resource. Therefore, sustainable agricultural development should be pursued in the study area rather than continual expansion of croplands.

4.1 Analysis accuracy and soundness

The accuracy of the outcome of this analysis is dependent on the accuracy of the datasets it uses. There are differences between official published data and the results of this analysis, which may be due to differences in how land classes were defined, user error, or inaccurate measurements in the datasets.

The total area of each country found through this analysis varies slightly from those listed by Wikipedia (Kenya, 2023; Tanzania, 2023; Uganda, 2023). The Lambert projection used for this analysis was based on the Lambert Azimuthal Equal Area system, so gives an accurate area calculation. Thus, other potential reasons for the mismatch are errors during analysis or inaccurate reflection of reality in the administrative boundaries file (for example, the file may not have taken terrain into account during measurements).

Each country's populations from this analysis are between 3 million - 16 million higher than those listed under Worldometer (Kenya Population, 2023; Tanzania Population, 2023; Uganda Population, 2023). Population densities align with published data for Tanzania and Uganda, though Kenya's population density was calculated as 118 through this analysis and 97 under Worldometer (Kenya Population, 2023). These differences between these results may be due to errors in analysis.

The cropland areas from this analysis varies slightly from FAO data on agricultural lands (Kenya, 2023; Tanzania, 2023; Uganda, 2023), both overestimating and underestimating in comparison. This discrepancy may be due to differences the FAO's definition of "agricultural lands" and that of croplands in the IGBP land cover layer.

Predictions of future cropland needs were analyzed under the assumption that population growth in the study area will continue at a consistent rate. However, this assumption may be disproven if populations of Uganda, Kenya, and Tanzania reach a cap and begin to decline. The analysis also does not take climate change into account. Changes in temperature and precipitation may invalidate the assumption that current land use classes remain as such. Furthermore, future changes in temperatures

may allow agricultural species to grow at different elevations, which would invalidate this analysis. Genetic modification of crop species may expand or change the areas in which agriculture can be carried out. Lastly, increasing temperature may cause some areas to be uninhabitable, causing mass migration away from the area and shifting population growth rates. A more accurate analysis that reflects rapid climate changes of the future would use datasets that reflect wider climate trends such as temperature and precipitation.

5. Conclusion

To meet 2040 cropland needs for a growing population in Kenya, Tanzania, and Uganda, all forests and some savannas may need to be converted into cropland. However, as population growth will continue to increase pressure on natural resources, agricultural intensification should be a priority. Furthermore, as there may be negative ecological impacts of losing large tracts of forest and savannas, sustainable development plans for the area should focus on the intensification of agricultural yields within existing croplands.

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