

Aboveground tree carbon stock dynamics in the Central and Upper River Regions of The Gambia

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Abstract

This study assessed modeled aboveground tree carbon in the Central River Region (CRR) and Upper River Region (URR) of The Gambia across forest, grassland, cropland, and settlement classes. Tree inventories from 20 plots per land cover class in each region informed class-specific carbon densities. Land cover maps for 2002, 2013, and 2024 were analyzed with the InVEST carbon model, with a scenario projected to 2034.

In the first set of regional model-output tables, CRR aboveground carbon decreased from 32,531.10 Mg C in 2002 to 30,167.11 Mg C in 2024, whereas URR increased from 15,698.39 to 26,874.60 Mg C. Forest-class carbon declined in both regions, while settlement- and cropland-class totals increased. The projected 2034 totals are 29,283.22 Mg C in CRR and 31,395.42 Mg C in URR. The source also reports incompatible alternative values, which require reconciliation before submission.

These are conditional modeled estimates based on fixed carbon densities for each land cover class. They should not be interpreted as measured carbon fluxes. The results point to a need to conserve remaining forest and to assess how mapped land cover changes affect aboveground carbon.

Keywords:

Carbon stock, forest loss, land use change, InVEST model, cropland expansion, grassland degradation, carbon sequestration, The Gambia, CRR, URR

1.1 Introduction

Tree-based ecosystems play a pivotal role in carbon cycling within terrestrial landscapes, serving as major carbon sinks and regulators of atmospheric carbon dioxide (CO₂) levels. Trees contribute to carbon storage through biomass accumulation, aboveground (stems, branches, leaves) and belowground (roots), and through adding organic matter to soils via litterfall and root turnover. These processes directly affect soil organic carbon (SOC) stocks, which form a critical component of the global carbon pool (Kola-Mustapha *et al.*, 2023).

Trees influence SOC accumulation through several pathways. First, they contribute substantial organic inputs to soils via litterfall (leaf, branch, and fruit drop) and root biomass turnover. These inputs provide substrates for soil microbial communities, promoting the formation of stable SOC compounds. Deep-rooted tree species, common in arid areas also transport carbon into subsoil layers, enhancing the vertical distribution of SOC and increasing its long-term stability.

Second, tree canopies modify the microclimate beneath them, influencing soil temperature and moisture conditions. Shaded soils under tree cover are generally cooler and retain more moisture than exposed soils, which slows organic matter decomposition and enhances carbon retention (Seddon *et al.*, 2020). Furthermore, trees protect soils from erosion by stabilizing soil structure with their roots, thereby preventing SOC loss through surface runoff.

The type, density, and age of tree stands significantly affect the magnitude of these contributions. Natural forests typically exhibit higher SOC stocks than plantations or degraded woodlands, owing to greater

Land use change, particularly deforestation and agricultural expansion, has profound impacts on tree-based carbon stocks. Clearing trees for cropland or settlement drastically reduces aboveground biomass carbon and interrupts the continuous input of organic matter to soils, leading to SOC losses.

In West Africa traditional agricultural practices such as slash-and-burn agriculture, wood harvesting for fuel, and shifting cultivation have historically contributed to tree cover loss. These activities not only diminish aboveground carbon pools but also destabilize SOC by exposing soils to erosion and increasing decomposition rates.

On the other hand, tree-based interventions like afforestation, reforestation, and agroforestry offer opportunities to rebuild carbon stocks. Incorporating trees into agricultural landscapes through agroforestry systems has been shown to significantly increase SOC levels, particularly when deep-rooted, nitrogen-fixing species are used (Haynes and Yongfu, 2014). Managed woodlots and forest restoration efforts can also enhance both aboveground and belowground carbon sequestration. Understanding the spatial extent and dynamics of tree-based land use is therefore critical for predicting SOC patterns and designing effective carbon management strategies in the sub-region.

In the Central River Region (CRR) and Upper River Region (URR) of The Gambia, tree-based LULC systems such as natural woodlands, agroforestry areas, and planted forests have historically supported significant carbon storage. However, pressures from agricultural expansion, shifting land use practices, and climatic variability are altering the structure and function of these ecosystems, which have important implications for carbon dynamics. Understanding how changes in tree-based land cover influence carbon stocks is essential for managing carbon sequestration and enhancing

biomass productivity and continuous organic inputs. (Aabeyir *et al.*, 2020).

Agroforestry systems, which integrate trees with crops or livestock, can also enhance SOC by maintaining perennial vegetation cover and promoting diverse root structures.

Temperature influences both tree metabolism and soil microbial activity. Warmer temperatures can boost tree growth up to a point but also accelerate the decomposition of organic materials, potentially reducing SOC stocks if decomposition rates outpace carbon inputs (Gebeyehu *et al.*, 2020). Conversely, higher rainfall generally increases tree productivity, leading to greater litterfall and root biomass, which in turn enhance SOC accumulation (Hu, Yang and Cai, 2016).

However, climate variability, including increased frequency of droughts or extreme weather events, can stress tree populations, reduce biomass production, and thereby limit organic inputs to the soil. (Villamor *et al.*, 2017), found that climate-induced changes in vegetation cover can have cascading effects on soil carbon dynamics, emphasizing the need to consider climatic factors in carbon stock assessments.

ecosystem resilience to climate change (Dampha 2021)

This study assesses aboveground tree carbon associated with land cover change in the CRR and URR. Field inventory measurements provide class-specific carbon densities, and land cover maps provide the spatial input for the InVEST carbon model. Soil carbon and the effects of climate variables were not estimated in this analysis.

Predictive models enable scenario analyses, allowing us to estimate future carbon stocks under different land use and climate change projections. Such tools are invaluable for guiding reforestation efforts, designing sustainable agroforestry systems, and targeting conservation actions to areas with the highest potential for carbon sequestration (Villamor *et al.*, 2019).

Enhancing tree-based carbon stocks offers a strategic pathway for climate change mitigation, biodiversity conservation, and livelihood improvement in The Gambia. Increasing tree cover through reforestation, agroforestry, and sustainable forest management can simultaneously boost aboveground biomass carbon and enrich SOC pools, creating a win-win for environmental and socio-economic objectives. (Kola-Mustapha *et al.*, 2023) .

Spatial estimates of aboveground carbon can help land managers identify areas where conserving existing tree cover or restoring woody vegetation warrants further study.

Ultimately, a comprehensive understanding of tree-based carbon stock dynamics is essential for designing sustainable land use systems that balance productivity, environmental health, and carbon sequestration. (Kola-Mustapha *et al.*, 2023)

1.2 Materials and Methods

Inventory methods

Four land use classes (forest, grassland, cropland, and settlement) were considered in the carbon dynamics assessment. The carbon loss or gain was estimated as the difference between the carbon stock of the previous LULC and the present one at given location.

From a prepared grid map, 20 sampling points were randomly chosen for each of the four LULC types in each region and the GPS coordinates loaded onto a GPS set indicating the Centre of the plots. In the field, the sampling points were located using GPS based on the identified coordinates on the map. At each sampling point, a circular plot with a radius of 26m was laid, resulting in a plot size of approximately 2124 m². On each plot, the diameter and height of trees ≥10 cm DBH were measured with a tape measure and Suunto clinometer, respectively, and recorded with their names. Data was recorded on field data sheets and then entered manually into spreadsheets.

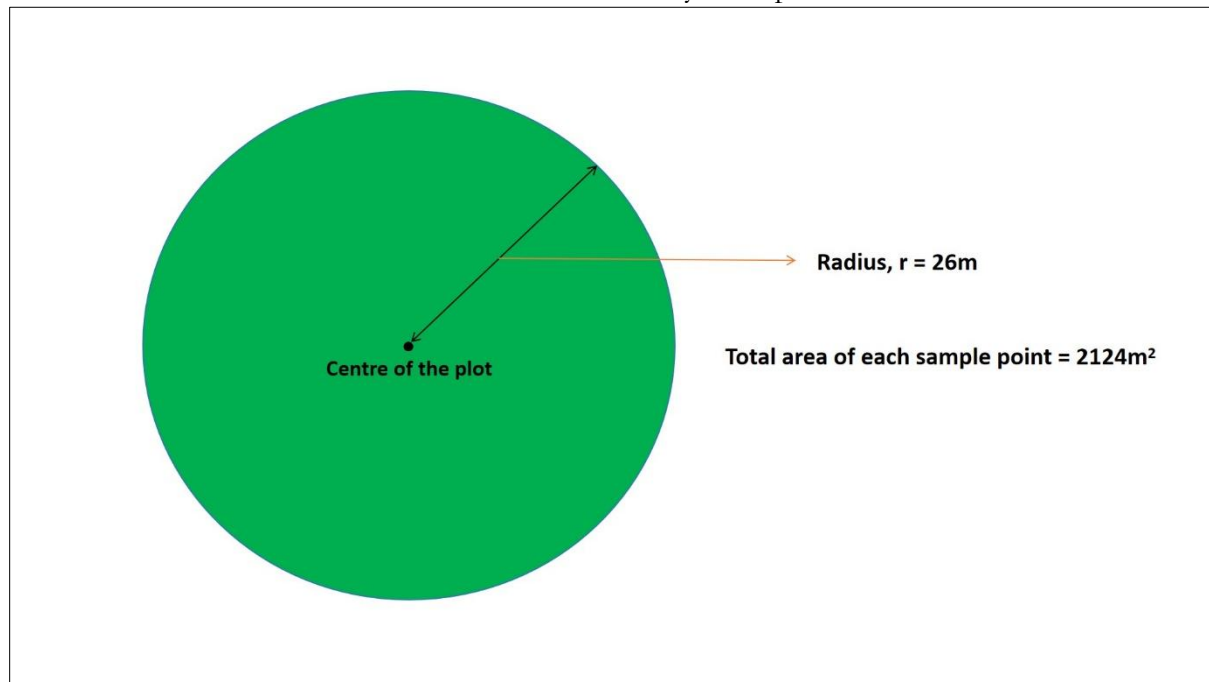


Figure 1. Flow chart of the tree inventory in the field

1.3 Estimation of the Aboveground Carbon from Forest Inventory

Aboveground biomass (AGB) was estimated from tree measurements using an allometric equation attributed to Chave et al. (2014). Wood density values were obtained from a global database. The exact equation and database citation should be checked against the original analysis.

$$AGB = 0.0673 \times (WSG \times DBH^2 \times H)^{0.976} \quad (1)$$

AGB denotes aboveground biomass at the tree scale (kg); wood density is expressed in g cm⁻³, diameter at breast height (DBH) in cm, and height in m. Tree-level values were summed by plot and expressed per hectare. The authors should verify the formula, biomass-to-carbon conversion, plot-level calculations, and assumptions behind any inferential tests.

1.4 Model Parameters in InVEST

The Integrated Valuation and Ecosystem Services and Tradeoffs (InVEST) carbon model was used to estimate carbon stocks in the CRR and URR landscape Imran *et al.*, (2022). InVEST requires categorical land cover maps and carbon values for each land cover class in the study landscape. This

study used the above-ground carbon (AGC) values (MgC/ha) for various LULC classes. The AGC for the classes in the landscape was sourced from the field Inventory Data. Values of 0.38 and 0.32 were used for forest in URR and CRR respectively. Corresponding values for grassland were 0.1 for URR and 0.08 for CRR. For the cropland, 0.07 for URR and 0.06 for CRR were used. Settlement values were 0.37 for URR and 0.09 for CRR. AGC value for the water body was set to zero.

2.1 Results and Discussion

The analysis of vegetation distribution across different land use/land cover (LULC) categories reveals notable differences between the Central River Region (CRR) and Upper River Region (URR). Species presence and abundance vary by region and LULC type, suggesting differences in ecological conditions, land management practices, and levels of anthropogenic disturbance.

In forest plots, 134 trees were recorded in URR and 57 in CRR, corresponding to approximately 32 and 13 trees per hectare, respectively, based on the nominal sampled area per class and region. Settlement plots contained 48 trees in URR and three in CRR. Grassland and cropland counts should be interpreted alongside the complete plot-level inventory (Table 3.1). Reported significance tests must be recalculated from the underlying observations.

Combretum glutinosum was the most abundant species in both regions, with a higher occurrence in URR (53) than in CRR. (19). Additionally, species such as *Cassia sieberiana*, *Guiera senegalensis*, *Azadirachta indica*, and *Adansonia digitata* were found exclusively in URR forests, indicating richer species diversity and potentially better ecological integrity. This could be attributed to more effective forest conservation practices or lesser anthropogenic interference in the URR. Similar findings have been obtained by (Kucuker *et al.*, 2015).

In contrast, CRR forests were dominated by fewer species, such as *Combretum micranthum* (13) and *Terminalia macroptera* (5), which indicates lower diversity and possibly more disturbed forest environments due to human activities like logging or shifting cultivation. Similar results have been reported by (Aabeyir *et al.*, 2020).

Grasslands in CRR were generally richer in woody species than those of URR. Notably, *Combretum micranthum* and *Combretum glutinosum* were frequent in CRR grasslands, suggesting that these areas may be transitioning toward wooded savannas or may represent degraded woodlands recovering naturally. Conversely, URR grasslands recorded minimal woody vegetation, with *Combretum glutinosum* (11) and *Vitex trifolia* (12) being the only species of significance. This could be due to intensive livestock grazing or frequent bushfires that suppress woody species regeneration in URR.

The presence of tree species in croplands with *Combretum micranthum* (24), *Lannea acida* (5), and *Combretum glutinosum* (7) being the most common in CRR for example suggests a tendency towards agroforestry practices or natural regeneration on fallow lands. In URR croplands the minor occurrences of trees point to more intensive agricultural practices and land clearing that reduce woody plants presence. Similar findings have been reported by, (Amoah, Marfo and Ohene, 2015).

The vegetation composition in settlement areas differed markedly between the two regions. URR settlements had a much higher number of trees, particularly *Mangifera indica* (12), *Combretum micranthum* (23), and *Vitex simplicifolia* (11), indicating intentional planting for food, shade, or landscaping. In contrast, CRR settlements had very limited vegetation, with only scattered presence of species like *Combretum micranthum* and *Vitex simplicifolia*. This suggests less tree planting or higher population

pressure in CRR settlements, which may inhibit the presence of woody plants. While not significant at the 0.05 level, the result is close to statistical significance ($p = 0.083$), suggesting that URR may host a higher number of individual trees per species in settlement areas compared to CRR. This aligns with earlier results showing higher above-ground biomass in URR settlements.

The URR has a notably higher number of trees in forest and settlement areas, while CRR leads in cropland and grassland. Similar results have been obtained by (Bessah *et al.*, 2019).

The differences in species richness and distribution between CRR and URR reflect variations in climatic conditions, land use intensity, and human management practices. URR, having slightly more rainfall and perhaps better-preserved forests, supports greater tree diversity, particularly in forested and residential areas. CRR, on the other hand, shows signs of intermediate disturbance, with more woody species in grasslands and croplands, possibly due to traditional agroforestry practices or land abandonment.

Moreover, the high presence of tree species in URR settlements suggests greater integration of trees into urban or peri-urban landscapes, likely due to socio-economic factors such as the use of trees for food, medicine, or cultural practices.

Table 3.1 Species distribution (number of trees/sp.) across various LULC types in the CRR and URR

Data is from 20 plots with an area summing up to approximately 4.24 ha for each LULC in each region

Species	Forest		Grassland		Cropland		Settlement	
	CRR	URR	CRR	URR	CRR	URR	CRR	URR
Acacia								
macrotachys	4	11	3	0	0	0	0	0
Acacia seyal	1	0	0	0	0	0	0	0
Bombax								
costatum	1	0	0	0	0	0	0	0
Combretum								
glutinosum	19	53	13	11	7	2	0	0
Combretum								
micranthum	13	1	11	0	24	17	2	23
Combretum								
nigericin	2	2	1	0	2	0	0	0
Cordyla Africana	1	5	0	0	0	0	0	0
Lannea acida	3	3	3	0	5	4	0	0
Pistigama								
thonningii	1	0	1	0	0	0	0	0
Prosopis Africana	1	0	1	0	0	0	0	0
Strychnus spinosa	1	5	0	0	0	0	0	0
Terminalia								
macroptera	5	0	2	0	0	0	0	0

Vitex simplicifolia	3	8	2	0	2	1	1	11
Ziziphus Mauritania	2	0	0	0	0	0	0	0
Adansonia digitata	0	1	0	0	0	0	0	0
Azadirachta indica	0	2	0	0	0	0	0	2
Cassia sieberiana	0	12	0	0	0	0	0	0
Guiera senegalensis	0	4	0	0	0	0	0	0
Heeria insignis	0	1	0	0	0	0	0	0
Mangifera indica	0	1	0	0	0	0	0	12
Pterocarpus erinaceus	0	1	0	0	0	0	0	0
Sclerocarya birrea	0	1	0	0	0	0	0	0
Terminalia glaucescens	0	1	0	0	0	0	0	0
Vitex trifolia	0	22	0	12	0	2	0	0
Total Number of trees	57	134	37	23	40	26	3	48

Table 3.2 presents a detailed inventory of tree species observed across different land use/land cover (LULC) types, forest, grassland, cropland, and settlements in the Central River Region (CRR) and Upper River Region (URR) of The Gambia. It includes the average diameter at breast height (DBH) and average height for each species, which are critical metrics for estimating above-ground biomass and, by extension, carbon stocks. The species distribution and structural characteristics offer insights into vegetation composition, ecosystem maturity, and land management practices.

Forest areas in both CRR and URR show the greatest structural variation among tree species. Notably, species such as *Bombax costatum* (DBH: 74 cm, CRR), *Prosopis africana* (DBH: 76 cm, CRR), and *Terminalia macroptera* (DBH: 68.2 cm, CRR) indicate mature, carbon-rich forest stands, especially in CRR. Meanwhile, URR forests are characterized by tall species such as *Cordia africana* (Height: 7.3 m), *Adansonia digitata* (Height: 14 m, DBH: 109 cm), and *Pterocarpus erinaceus* (DBH: 126 cm), suggesting old-growth or well-conserved forest patches.

The high average DBH and tree height in URR suggest that forest stands are structurally more developed compared to CRR, potentially explaining higher carbon stock values observed in URR forests (Sohrabi, Bakhtiarvand-Bakhtiari and Ahmadi, 2016). Species such as *Combretum glutinosum* and *Combretum micranthum* are present in both regions, showing consistency in mid-level woody species across ecological zones.

In grassland areas, woody spp. encroachment is evident, especially with species like *Combretum micranthum*, *Combretum glutinosum*, and *Lannea acida* appearing with substantial DBH and height. For example, *Lannea acida* shows a DBH of 49.67 cm in CRR grasslands and 50.8 cm in URR croplands, suggesting shrub-tree transition zones, potentially due to anthropogenic pressure or passive regrowth. Similar findings have been reported by (Sohrabi, Bakhtiarvand-Bakhtiari and Ahmadi, 2016). However, an alternative explanation, and probably a more plausible one is that these large trees are remnants of forest stands that have been degraded into grassland.

Combretum micranthum is common in both CRR and URR grasslands, with taller specimens in URR (5 m average height) indicating a more robust vegetative structure. The presence of species with considerable DBH in grasslands (e.g. *Combretum nigerican* and *Strychnos spinosa*) reflects semi-wooded savanna systems, which are ecologically significant for biodiversity and carbon storage. Similar results have been observed by (Sohrabi, Bakhtiarvand-Bakhtiari and Ahmadi, 2016).

Tree presence in croplands is relatively limited, yet a few species such as *Combretum glutinosum* and *Combretum micranthum* persist, especially in URR. These species, known for their resilience and multiple uses (e.g., fuelwood, medicine), may be intentionally retained during land clearing due to their utility. Similar findings have been observed by (Aabeyir *et al.*, 2016). The DBH values (e.g., *Combretum glutinosum* at 44.5 cm in URR) suggest that agroforestry practices or tree-crop systems might be contributing to above-ground carbon in cultivated landscapes.

Settlements in URR show the presence of *Mangifera indica* (mango) with an exceptionally high average DBH of 95.5 cm and height of 12.1 m. This indicates urban greening or home garden practices, which have been increasingly recognized for their role in urban ecosystem services and carbon storage. Similar Results have been obtained by Dampha,(2021). The absence of trees in CRR settlements implies either limited tree cover or a different urban vegetation profile.

Several species appear exclusively in URR (e.g., *Adansonia digitata*, *Azadirachta indica*, *Guiera senegalensis*), suggesting either regional ecological differences or human-driven planting preferences. Species like *Pterocarpus erinaceus* and *Sclerocarya birrea* are valuable both ecologically and economically and may reflect conservation or sustainable use practices in URR. Table 3.2 Mean tree size (diameter in cm and height in m) for species enumerated in the CRR and URR. Blank spaces in the table indicate spp. absence from plots for the respective region and LULC

Tree diameter and height by land cover and region

Field inventory summary | DBH in cm; height in m

Panel 1 • Forest and Grassland

Species	Forest				Grassland			
	CRR		URR		CRR		URR	
	DBH	Height	DBH	Height	DBH	Height	DBH	Height
<i>Acacia macrotachys</i>	25.75	3.37	20.45	3.93	27.0	3.17	—	—
<i>Acacia seyal</i>	17	4	—	—	—	—	—	—
<i>Bombax costatum</i>	74	5	—	—	—	—	—	—
<i>Combretum glutinosum</i>	33.63	4.16	32.6	4.86	33.31	3.35	24.00	4.61
<i>Combretum micranthum</i>	19.85	3.79	20	5	16.00	2.80	—	—
<i>Combretum nigerican</i>	50	5	33.5	5	45.00	4.00	—	—
<i>Cordyla africana</i>	10	3	123.4	7.3	—	—	—	—
<i>Lannea acida</i>	56	4.33	9	6.67	49.67	3.67	—	—
<i>Pistigama thonningii</i>	23	3	0	0	20.00	2.00	—	—
<i>Prosopis Africana</i>	76	5	0	0	70.00	4.00	—	—
<i>Strychnus spinose</i>	13	4.5	16.80	3.70	—	—	—	—
<i>Terminalia macroptera</i>	68.2	7.4	—	—	65.00	5.50	—	—
<i>Vitex simplicifolia</i>	15.33	3	16.5	3.75	15.00	2.00	—	—
<i>Ziziphus Mauritania</i>	42.5	6	—	—	—	—	—	—
<i>Adansonia digitata</i>	—	—	109.00	14.00	—	—	—	—
<i>Azadirachata indica</i>	—	—	85.00	3.05	—	—	—	—
<i>Cassia sieberiana</i>	—	—	19.08	3.64	—	—	—	—
<i>Guiera senegalensis</i>	—	—	18.00	3.75	—	—	—	—
<i>Heeria insignis</i>	—	—	20.00	4.00	—	—	—	—
<i>Mangifera indica</i>	—	—	101.00	13.00	—	—	—	—
<i>Pterocarpus erinaceous</i>	—	—	126.00	8.00	—	—	—	—
<i>Sclerocarya birrea</i>	—	—	50.00	7.00	—	—	—	—
<i>Terminalia glaucescence</i>	—	—	22.00	3.50	—	—	—	—
<i>Vitex trifolia</i>	—	—	22.73	4.14	22.17	3.75	22.17	3.75
<i>Voacanga africana</i>	—	—	—	—	—	—	30.6	4

— No value supplied. The source mean row was omitted because its columns are misaligned.

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Tree diameter and height by land cover and region

Field inventory summary | DBH in cm; height in m

Panel 2 • Cropland and Settlement

Species	Cropland				Settlement			
	CRR		URR		CRR		URR	
	DBH	Height	DBH	Height	DBH	Height	DBH	Height
<i>Acacia macrotachys</i>	—	—	—	—	—	—	—	—
<i>Acacia seyal</i>	—	—	—	—	—	—	—	—
<i>Bombax costatum</i>	—	—	—	—	—	—	—	—
<i>Combretum glutinosum</i>	39.43	3.51	44.5	4.5	—	—	—	—
<i>Combretum micranthum</i>	15.58	2.79	15.24	2.85	15.5	2.25	15.17	2.35
<i>Combretum nigerican</i>	44.50	4.00	—	—	16	2.5	—	—
<i>Cordyla africana</i>	—	—	—	—	—	—	—	—
<i>Lannea acida</i>	50.80	3.60	55.25	3.75	—	—	—	—
<i>Pistigama thonningii</i>	—	—	—	—	—	—	—	—
<i>Prosopis Africana</i>	—	—	—	—	—	—	—	—
<i>Strychnus spinose</i>	—	—	—	—	—	—	—	—
<i>Terminalia macroptera</i>	—	—	—	—	—	—	—	—
<i>Vitex simplicifolia</i>	12.50	2.50	10	3	11	3	10	3
<i>Ziziphus Mauritania</i>	—	—	—	—	—	—	—	—
<i>Adansonia digitata</i>	—	—	—	—	—	—	—	—
<i>Azadirachata indica</i>	—	—	—	—	—	—	89	3
<i>Cassia sieberiana</i>	—	—	—	—	—	—	—	—
<i>Guiera senegalensis</i>	—	—	—	—	—	—	—	—
<i>Heeria insignis</i>	—	—	—	—	—	—	—	—
<i>Mangifera indica</i>	—	—	—	—	—	—	95.51	12.1
<i>Pterocarpus erinaceous</i>	—	—	—	—	—	—	—	—
<i>Sclerocarya birrea</i>	—	—	—	—	—	—	—	—
<i>Terminalia glaucescence</i>	—	—	—	—	—	—	—	—
<i>Vitex trifolia</i>	—	—	19.5	5.5	—	—	—	—
<i>Voacanga africana</i>	—	—	—	—	—	—	—	—

— No value supplied. The source mean row was omitted because its columns are misaligned.

CRR = Central River Region • URR = Upper River Region • Data transcribed from the supplied table

The data presented in Table 3.3 compares the above-ground biomass (AGB) across four major land use/land cover (LULC) classes: cropland, forest, grassland, and settlement, in two regions of The Gambia: the Central River Region (CRR) and the Upper River Region (URR). The table provides the mean AGB, as well as the minimum, maximum, and standard deviation of AGB values (in megagram per hectare, Mg/ha), reflecting the variation in biomass across each LULC type and region.

Forests display the highest mean AGB among the LULC types, with URR showing a higher mean (0.76 Mg/ha) compared to CRR (0.64 Mg/ha). A statistical t-test was performed for the above-ground biomass Mean values: CRR: 0.13Mg/ha, URR: 0.34Mg/ha. The URR region shows higher average biomass, suggesting potentially more productive or less degraded land cover. However, this difference is not statistically significant ($p = 0.069$).

More importantly, the range of AGB is much broader in forests, with maximum values reaching 11.26 Mg/ha in URR and 9.87 Mg/ha in CRR. The high standard deviations, 2.01 Mg/ha in URR and 1.72 Mg/ha in CRR, make the difference marginally non-significant ($p \approx 0.07$). However, with a larger sample, this difference might reach significance. Typically, the variability within dry forested areas, which is common due to differences in tree density and forest maturity, may necessitate large sample sizes to detect significant differences between different forest locations. Grasslands exhibit moderate biomass values, with URR showing only slightly higher AGB (mean of 0.20 Mg/ha) than CRR (0.16 Mg/ha). The AGB variability is somewhat greater in URR, reflected in a higher maximum value (1.04 Mg/ha) and a larger standard deviation (0.25 Mg/ha) compared to CRR (0.96 Mg/ha maximum, 0.19 Mg/ha standard deviation). No significant difference in carbon stocks in grasslands between the two regions was found. The means are relatively close, and variability is high, with $p = 0.50$. These values indicate limited but slightly more heterogeneous biomass storage in URR grasslands. Similar findings have been reported by (Kucuker *et al.*, 2015).

Table 3.3: Above-ground biomass for CRR and URR based on carbon stocks on 20 individual plots, each measuring 2124 m² for each LULC type

LULC	Region	Mean AGB (Mg/ha)	Min AGB (Mg/ha)	Max AGB(Mg/ha)	Std Dev (Mg/ha)
Cropland	CRR	0.12	0.01	0.43	0.11
	URR	0.14	0.01	0.48	0.14
Forest	CRR	0.64	0.04	9.87	1.72
	URR	0.76	0.06	11.26	2.01
Grassland	CRR	0.16	0.00	0.96	0.19
	URR	0.20	0.01	1.04	0.25
Settlement	CRR	0.18	0.01	2.89	0.77
	URR	0.74	0.02	3.30	0.89

Table 3.4 provides estimates of above-ground carbon stocks (C_{above}) across five land use/land cover (LULC) classes in the Central River Region (CRR) and Upper River Region (URR) of The Gambia. The figures reveal marked spatial variations in carbon storage potential between the two regions, highlighting the importance of LULC types in regional carbon dynamics.

Water bodies are not associated with any above-ground biomass and thus do not contribute to the above-ground carbon pool in either region. This is consistent with methodologies adopted by models such as InVEST and IPCC guidelines, which exclude open water surfaces from above-ground carbon estimates due to the lack of biomass (Touré and Rasmussen 2002).

Grasslands show relatively low carbon stocks, with CRR storing 0.08 Mg/ha, notably less than URR at 0.1 Mg/ha. Statistical test was performed, the results showed that there are no significant differences between these two regions in terms of carbon stock in the grassland, with p values of ($p = 0.545$), respectively.

This difference may reflect denser vegetation or the presence of bigger trees in the grassland ecosystems in CRR. Grasslands generally contribute modestly to carbon storage but play a significant role in maintaining soil carbon and biodiversity similar findings have been reported by (Beyer *et al.*, 2022).

Settlements present an interesting contrast, with URR recording a substantially higher above-ground carbon stock (0.37 Mg/ha) compared to CRR (0.09 Mg/ha). This suggests a higher density of “urban” vegetation in URR. Settlements in URR has strong significance differences from CRR because URR has far more trees in settlements than CRR, marking the most pronounced contrast among all land covers. ($p = 0.000004$).

Croplands exhibit the lowest above-ground carbon values of the vegetated LULC classes, with CRR at 0.06 Mg/ha and URR slightly higher at 0.07 Mg/ha. This finding is consistent with previous research, which indicates that croplands, particularly those dominated by annual crops, contribute minimally to above-ground biomass carbon due to frequent harvests and low plant biomass (Aabeyir *et al.*, 2020). In the Gambia, rice is the dominant crop and to avoid bird pests, rice farmers would not normally retain many trees on their farms.

Forests unsurprisingly have the highest above-ground carbon estimates, with URR Storing 0.37 Mg/ha and 0.09 Mg/ha was observed in CRR. The significant difference lies in URR having more trees in forests than CRR, though the disparity is moderate. ($p = 0.035$). This aligns with numerous studies highlighting the critical role of forests in carbon sequestration due to their dense and perennial biomass (Aabeyir *et al.*, 2020). The disparity may indicate more intact forest cover, better forest management, or higher biomass density in URR, consistent with regional forest assessments (Aabeyir *et al.*, 2017).

Table 3.4 Carbon stock estimates for CRR and URR. Carbon stock was estimated from AGB by multiplying AGB by a factor of 0.5

Code	LULC Class	CRR	URR
		C_above (Mg/ha)	C_above (Mg/ha)
1	Water bodies	-	-
2	Grassland	0.08	0.1
3	Settlements	0.09	0.37
4	Cropland	0.06	0.07
5	Forest	0.32	0.38

Table 3.5 presents the predicted carbon stock, in Mg, across various land use/land cover (LULC) classes in the Central River Region (CRR) from 2002 to 2034, as modeled by the InVEST Carbon Storage and Sequestration tool. The table reveals a significant shift in carbon storage patterns over time, driven by land use change dynamics such as deforestation, urban expansion, and agricultural development.

Grassland, which held the largest share of carbon stock in 2002 (29,684.39 Mg), shows a consistent and substantial decline over the decades, dropping to 14,443.51 Mg by 2034, a reduction of over 50%. This decline suggests widespread conversion of grasslands to other land uses, particularly cropland and settlements. The trend reflects increasing pressure on natural ecosystems in CRR, likely due to population growth, agricultural expansion, and development. Similar findings have been reported by (Wade *et al.*, 2019).

Carbon stock within settlements increased dramatically from 23.44 Mg in 2002 to 4,210.41 Mg in 2034. This more than 179-fold increase is indicative of urbanization and infrastructural growth, possibly including the establishment of urban trees or home gardens, which would slightly contribute to carbon stock despite generally low values associated with built-up areas. The dramatic rise, however, more likely reflects the spatial expansion of settlements and the associated reclassification of LULC types, absorbing former vegetated areas. Similar results have been reported by Bessah *et al.*, (2019). Cropland's carbon stock rises significantly from 1,763.55 Mg in 2002 to 10,605.80 Mg by 2034. This sixfold increase highlights the agricultural transformation of CRR, as former grassland and forest areas are converted into farmland. While cropland generally has lower per-hectare carbon density compared to forests, the large-scale conversion of land contributes to its rising total stock. The gradual adoption of agroforestry or tree-integrated farming systems might also help retain some biomass and soil carbon. Similar findings have been reported by (Liu *et al.*, (2021).

Forest carbon stock plummets from 1,059.72 Mg in 2002 to just 23.49 Mg by 2034, reflecting near-total deforestation. This 97.8% decrease is highly concerning, given the role of forests in long-term carbon storage, biodiversity, and climate regulation. The degradation and clearing of forests likely feed the growth in cropland and settlement areas. Such a dramatic reduction underscores the need for urgent forest protection and reforestation policies in CRR Villamor *et al.*, (2017).

The total carbon stock in CRR falls from 32,531.10 Mg in 2002 to 29,283.22 Mg in 2034, a modest but steady 10% decline over the 32 years. Similar findings have been reported by Villamor *et al.*, (2017). While the overall loss may seem moderate, it conceals more severe ecosystem shifts, particularly the loss of high-carbon ecosystems like forests and grasslands, which are replaced by lower-carbon systems such as croplands and settlements. Dampha, (2021b).

Table 3.5 Carbon stock for CRR (INVEST)

LULC Class	2002	2013	2024	2034
Water bodies	-	-	-	-
Grassland	29684.39	24216.74	18623.73	14443.51

Settlements	23.44	305.88	3267.38	4210.41
Cropland	1763.55	5747.24	8225.17	10605.80
Forest	1059.72	97.74	50.83	23.49
Total	32531.10	30367.60	30167.11	29283.22

Table 6.1 presents the estimated carbon stock, in Mg, across different land use/land cover (LULC) classes in the Upper River Region (URR) of The Gambia from 2002 to 2034, based on the InVEST Carbon Storage and Sequestration model. The figures reveal profound transformations in land use, resulting in significant changes in carbon dynamics over time.

In 2002, grasslands accounted for 14,162.60 Mg of carbon, making them the primary carbon reservoir in URR. However, this value steadily declines to 6,983.52 Mg by 2034, representing a 50.7% reduction over 32 years. The decline indicates a progressive conversion of grassland to other land uses, notably croplands and settlements, similar to patterns observed in CRR. This ongoing degradation of natural grasslands undermines long-term ecosystem carbon storage (Wade *et al.*, 2019).

Carbon stored in settlements grows exponentially from 322.54 Mg in 2002 to 15,323.92 Mg by 2034, a more than 47-fold increase. This surge reflects rapid urbanization and expansion of built-up areas, absorbing formerly vegetated lands, particularly grasslands and forests. The increase in settlement-related carbon stock is likely due to the spatial spread of urban greenery or misclassified areas where some vegetation remains. Dampha, (2021b). This trend also signals intense anthropogenic pressure on rural landscapes in the URR

Cropland carbon stock rises sharply from 834.36 Mg in 2002 to 9,075.67 Mg in 2034, representing a nearly 11-fold increase. This aligns with land conversion patterns, where grasslands and forests are cleared to expand farmland, possibly in response to population growth and food security needs. Although croplands store less carbon per hectare compared to forests, widespread expansion results in increased total carbon. Similar Results have been obtained by (Bessah *et al.*, 2019). This growth also hints at possible agroforestry practices contributing to carbon retention.

Forests in URR show a dramatic decline in carbon stock, from 378.89 Mg in 2002 to a mere 12.32 Mg by 2034, marking a reduction of over 96%. This highlights an alarming rate of deforestation and forest degradation, with grave implications for carbon sequestration, biodiversity, and ecological stability. Forests are likely being cleared for settlement expansion and agriculture, suggesting an urgent need for reforestation and conservation efforts. Similar findings have been obtained by (Bessah *et al.*, 2019).

Table 3.6 Carbon stock for URR (INVEST)

LULC Class	2002	2013	2024	2034
Water bodies	-	-	-	-
Grassland	14162.60	12009.91	8418.672	6983.52
Settlements	322.54	1389.80	10715.71	15323.92

Croplands	834.36	3816.15	7683.43	9075.67
Forest	378.89	156.04	56.78	12.32
Total	15698.39	17371.89	26874.60	31395.42

The mapped carbon estimates vary over time because the area assigned to each land cover class changes under fixed class-specific carbon densities. The maps should be interpreted together with their legends, classification accuracy, and the assumptions used to produce the 2034 projection.

The transition from red (high-carbon areas) to green (low-carbon areas) highlights the loss of vegetation cover and carbon sequestration capacity over time. Deforestation and land-use changes significantly reduce carbon storage in natural ecosystems. Grassland and forest areas are shrinking, while agricultural and settlement areas are expanding, increasing carbon emissions. Projected trends for 2034 indicate a further decrease in carbon stock, which may contribute to climate instability and biodiversity loss. Without reforestation and conservation efforts, the region will experience reduced carbon sequestration potential, worsening the impacts of climate change.

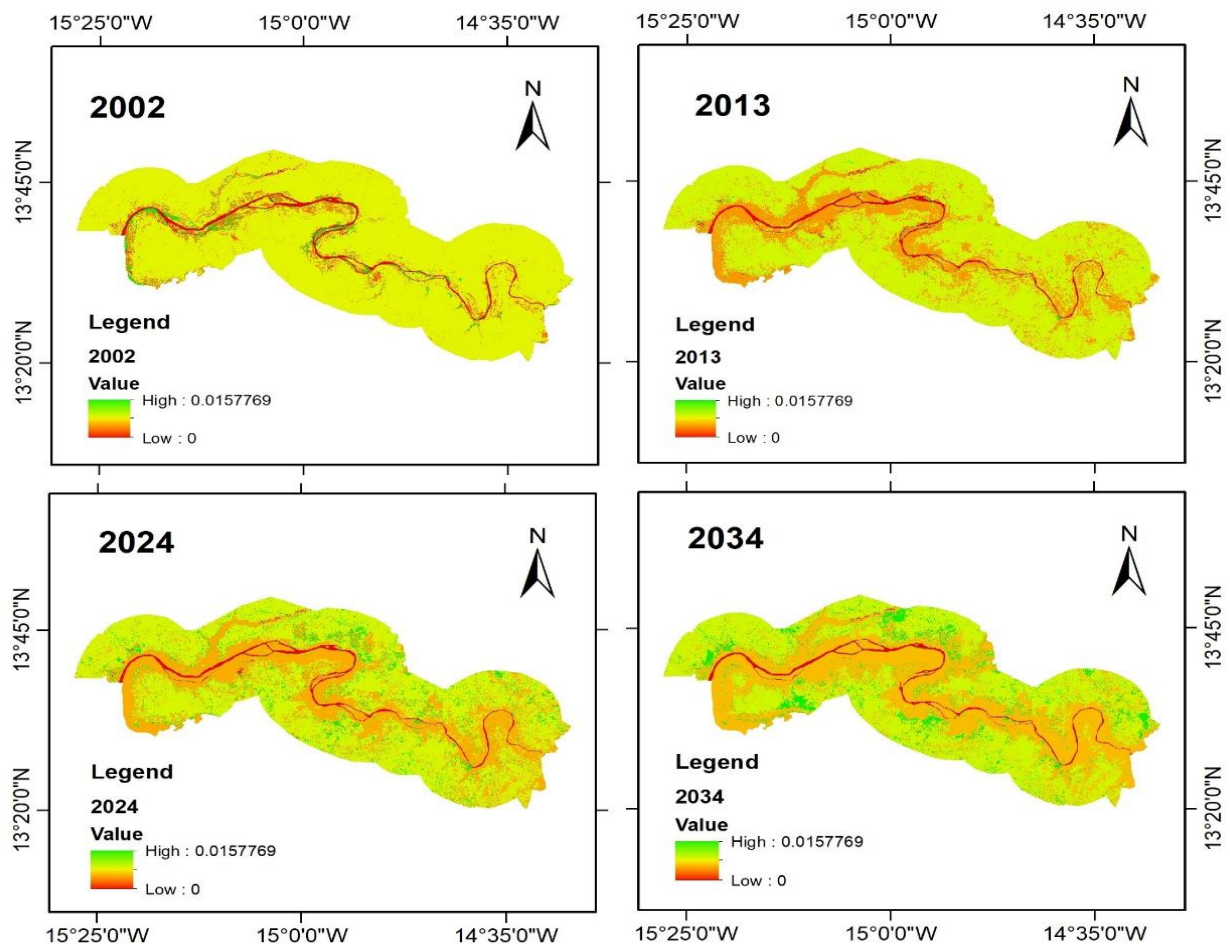


Figure 2. Carbon maps of the Central River Region (CRR)

These maps illustrate carbon stock variations from 2002 to 2034, revealing a declining trend in high-carbon areas green and a growing dominance of low-carbon regions orange-red. This pattern suggests land degradation, deforestation, and land-use changes, reducing carbon sequestration capacity. In 2002, most regions had moderate to high carbon stock, indicated by yellow-orange shades. By 2013, the carbon density slightly decreased, showing early signs of deforestation and land-use transition.

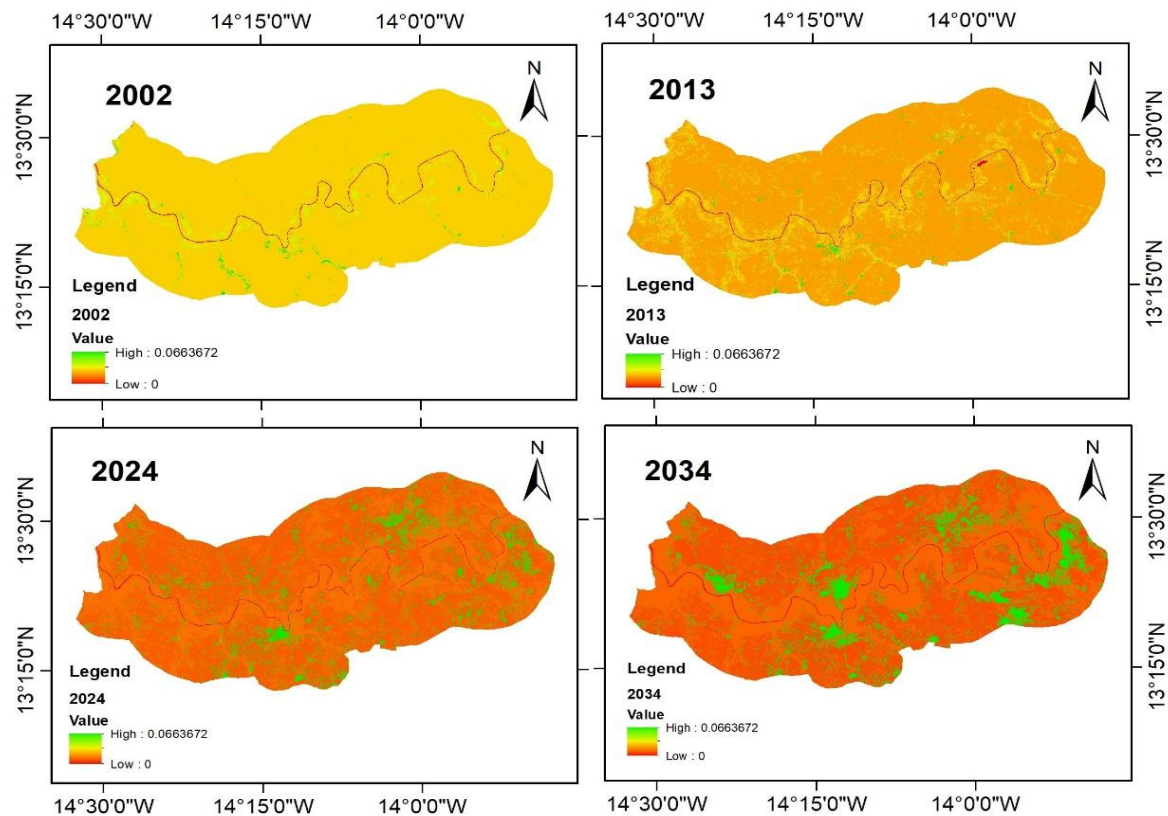


Figure 3. Carbon maps of the Upper River Region (URR)

Conclusions

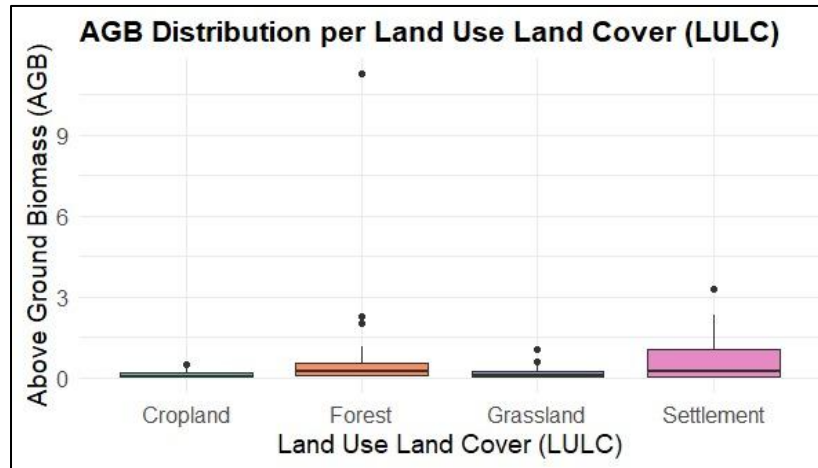
The first set of regional InVEST tables indicates that modeled aboveground carbon declined in CRR between 2002 and 2024 and increased in URR, while forest-class carbon fell in both regions. These changes reflect class areas and the assigned carbon density rather than directly measured carbon sequestration or emissions.

The 2034 values are projections contingent on the land cover scenario. The manuscript contains conflicting total estimates and alternate carbon-density tables. Reconciliation of source rasters, units, class definitions, and calculations is necessary before these results can support a journal submission.

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NON-PARAMETRIC TEST: Significant difference between classes (**CRR**) using Python
The **Kruskal-Wallis test** results:

- Statistic = 3.37
- p-value = 0.338

Since the p-value is greater than 0.05, there is no significant difference between the land cover types.

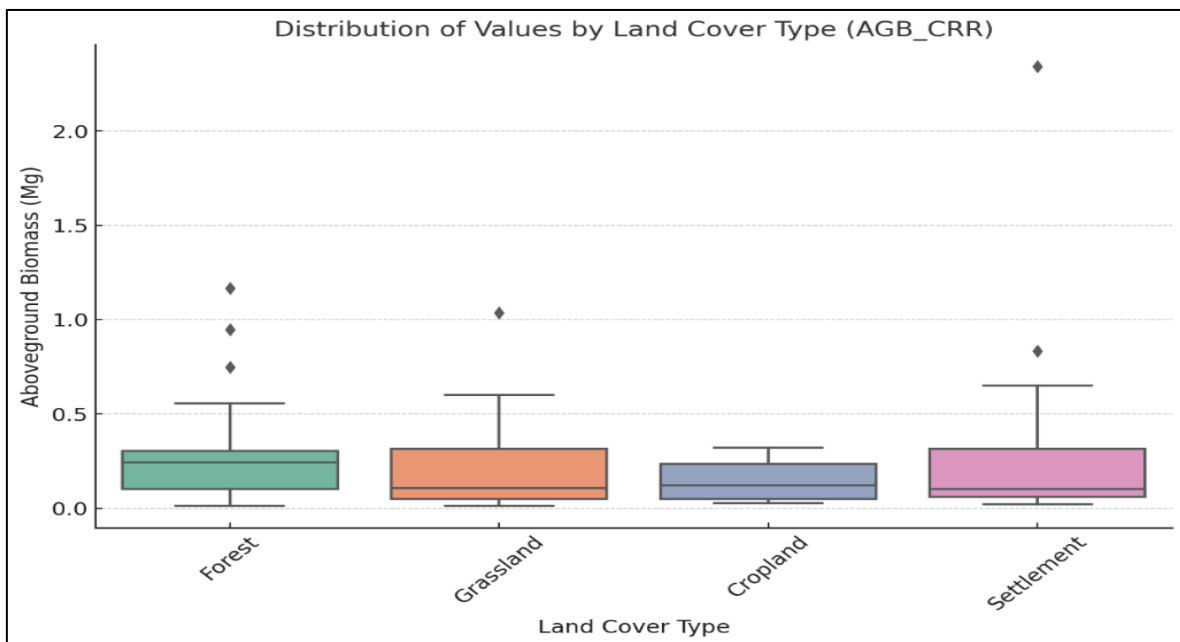


FIGURE 1. ABOVEGROUND DISTRIBUTION PER LAND USE LAND COVER (CRR)

The **Kruskal-Wallis test** results for **URR** are:

- Statistic = 16.10
- p-value = 0.00108

Since the **p-value is less than 0.05**, we conclude that there is a **statistically significant difference** between land cover types.

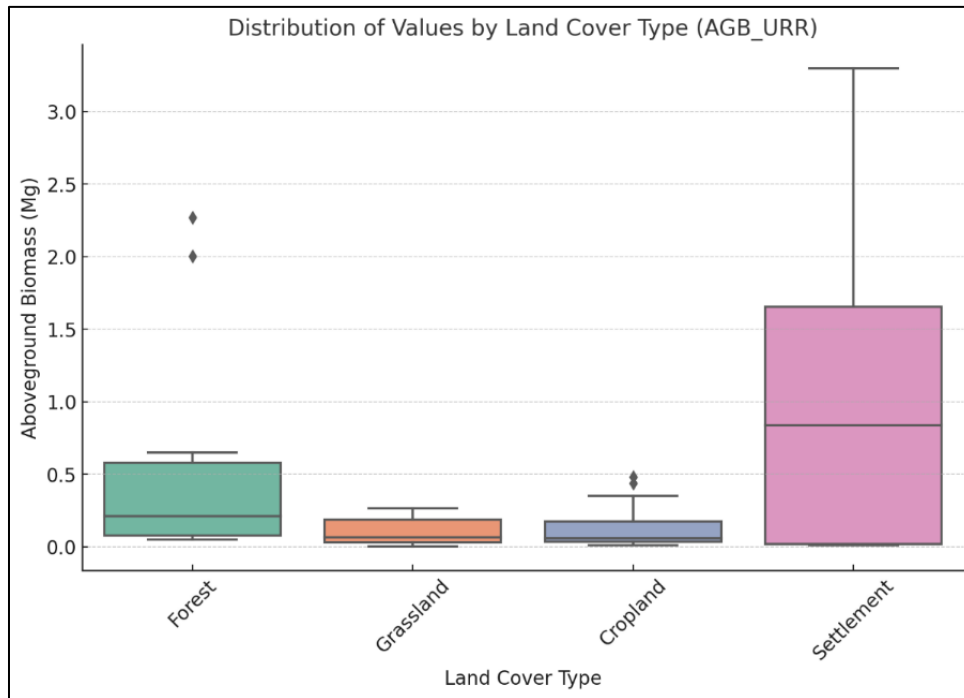


FIGURE 2. ABOVEGROUND DISTRIBUTION PER LAND USE LAND COVER (URR)

Here are the **pairwise post hoc test results** (Mann-Whitney U test) for **AGB_URR** after removing missing values:

Pairwise comparisons of aboveground biomass in URR

Mann-Whitney U tests by land cover class

Class 1	Class 2	p-value	p < 0.05
Forest	Grassland	0.0129	Yes
Forest	Cropland	0.0054	Yes
Forest	Settlement	0.4936	No
Grassland	Cropland	0.8538	No
Grassland	Settlement	0.1093	No
Cropland	Settlement	0.1093	No

Note: p-values reproduced as supplied; adjustment for six comparisons was not specified.

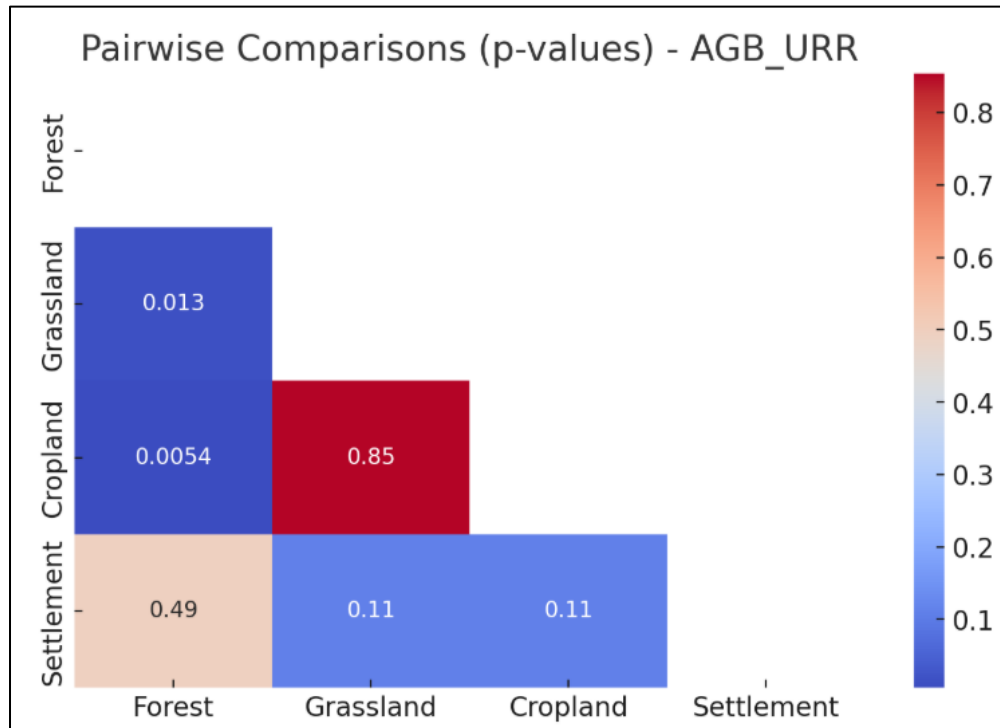


FIGURE 3. THE HEAT MAP OF P-VALUES FROM THE PAIRWISE POST HOC COMPARISONS FOR AGB_URR.

- Darker blue areas (low p-values) indicate significant differences (for example, Forest vs Cropland and Forest vs Grassland).
- Red or neutral areas (high p-values) indicate no significant differences (for example, Grassland vs Cropland and Forest vs Settlement).

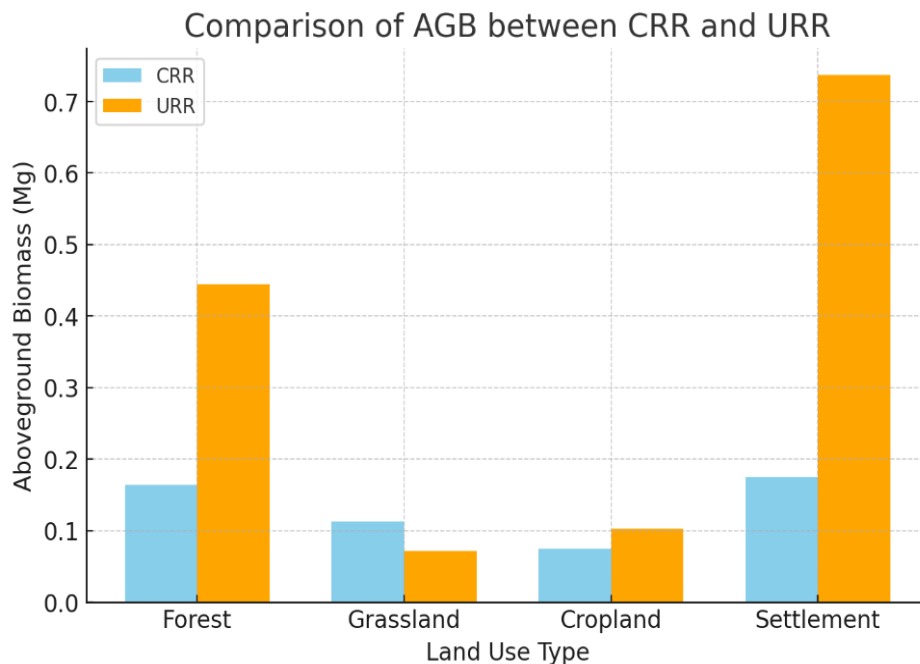


FIGURE 4. THE BAR CHART COMPARES ABOVEGROUND BIOMASS (AGB) BETWEEN CRR AND URR ACROSS DIFFERENT LAND USE TYPES:

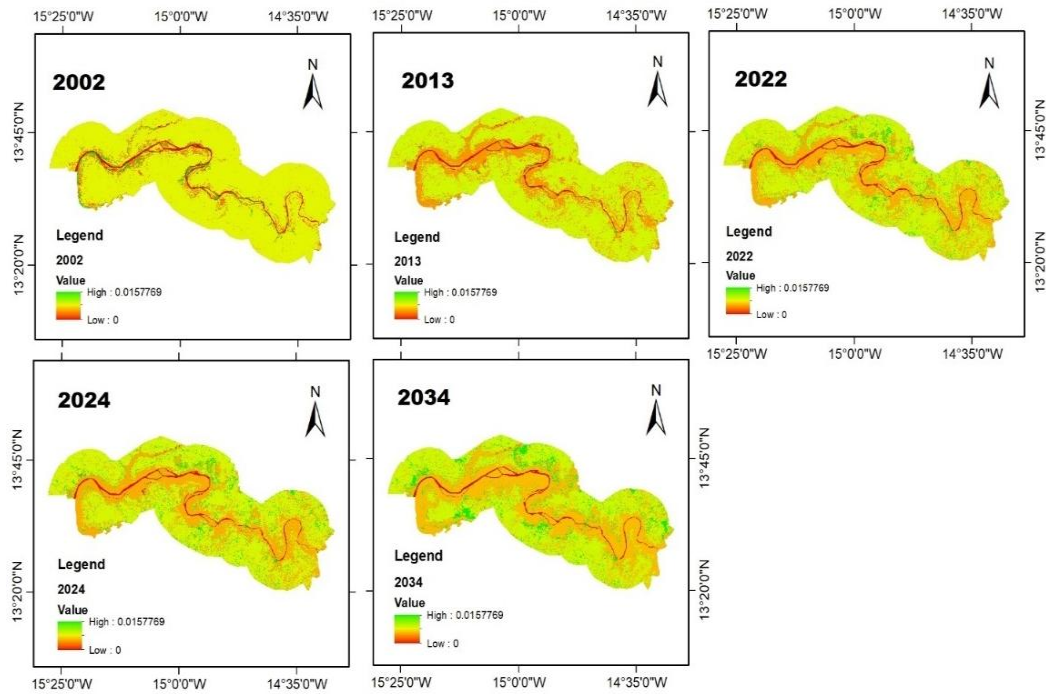


FIGURE 5 . CARBON MAPS OF THE CENTRAL RIVER REGION (CRR)

These maps illustrate carbon stock variations from 2002 to 2034, revealing a declining trend in high-carbon areas (green) and a growing dominance of low-carbon regions (orange-red). This pattern suggests land degradation, deforestation, and land-use changes, reducing carbon sequestration capacity. In 2002, most regions had moderate to high carbon stock, indicated by yellow-orange shades. By 2013, the carbon density slightly decreased, showing early signs of revegetation and land-use transition.

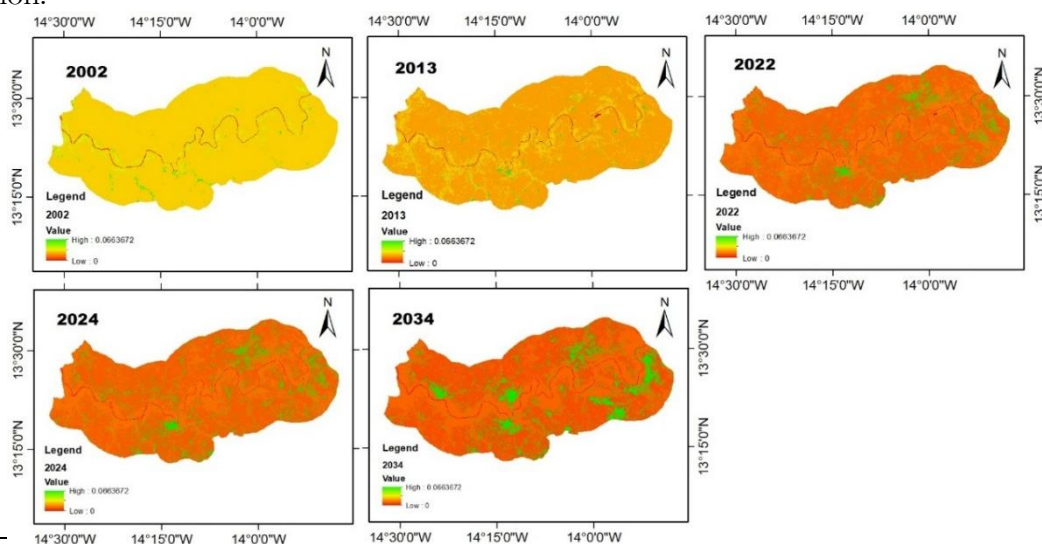


FIGURE 6. CARBON MAPS OF THE UPPER RIVER REGION (URR)

Conclusion

This study combines tree inventories and land cover maps to examine modeled aboveground carbon in CRR and URR. The inventory and carbon model provide useful regional comparisons, subject to verification of the units, class densities, and source data.

The consistent regional tables show substantial forest-class declines in both regions, an overall decline in CRR, and an overall increase in URR. Expanded cropland and settlement areas contribute to the latter pattern under fixed class-specific carbon densities. Future analysis should report land cover classification accuracy, uncertainty, and the 2034 projection method.

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