DOI: https://doi.org/10.32381/PROD.2024.64.04.9

Focus

Assessment of Climate Trends and Carbon Sequestration in a Forest Ecosystem through InVEST

T.V. RAMACHANDRA, TULIKA MONDAL, PARAS NEGI AND BHARATH SETTURU

Focus

Assessment of Climate Trends and Carbon Sequestration in a Forest Ecosystem through InVEST

T.V. RAMACHANDRA, TULIKA MONDAL, PARAS NEGI AND BHARATH SETTURU

Carbon sequestration constitutes a vital ecological function executed by ecosystems to mitigate global warming due to the burgeoning sustained anthropogenic activities which release greenhouse gases (carbon dioxide, methane, carbon monoxide, etc.). The current study evaluates carbon dynamics in forest ecosystems through the InVest model with temporal land use analyses using remote sensing data from 1973 to 2021 in the Chikamagaluru district of Karnataka. Land use dynamics were assessed using temporal remote sensing data through a machine-learning-based supervised Random Forest algorithm, which shows a decline in forest cover of 28.98%, an increase in agricultural area by 5.31%, and horticulture by 42.52% in the last five decades, which has led to the depletion of carbon stock by 30683.81 Gg. Land use changes have a long-term effect on climatic variables, leading to changes in local temperature, annual rainfall, and number of rainy days in the study area.

T.V. Ramachandra, Energy & Wetlands Research Group, Environmental Information System, Center for Ecological Sciences [CES].

Centre for Sustainable Technologies (Astra).

Centre for Infrastructure, Sustainable Transportation and Urban Planning [CiSTUP], Indian Institute of Science, Karnataka, India.

Tulika Mondal, Energy & Wetlands Research Group, Environmental Information System, Center for Ecological Sciences [CES].

Paras Negi, Energy & Wetlands Research Group, Environmental Information System, Center for Ecological Sciences [CES].

Bharath Setturu, Energy & Wetlands Research Group, Environmental Information System, Center for Ecological Sciences [CES], Chanakya University, Bangalore, Karnataka, India.

DOI: https://doi.org/10.32381/PROD.2024.64.04.9

Introduction

Carbon is a foundational element within the Earth system, forming the structural framework of compounds containing energy that sustains bio-geo-chemical processes (Reichle, 2023). Carbon occurs in diverse forms (as elements, compounds etc.) and reservoirs (carbon sink in plants, sediments, etc.), intricately distributed and consistently exchanged among the four major spheres of the earth system (Ramachandra & Bharath, 2020). Biogeochemical mechanisms govern carbon transitions from one reservoir to another, and insights into the process are crucial for mitigating carbon dioxide (CO_2) emissions and climate change (Ussiri & Lal, 2017).

Land degradation due to unregulated developmental activities with sustained human activities leading to deforestation, biomass burning, pollution in aquatic environments, and the burning of fossil fuel in transportation, electricity manufacture, industrial processes, and agricultural practices along with the uncontrolled rapid urban development has been contributing to the global carbon cycle, which alters previously inert carbon reserves (Tyrrell et al., 2012; Ramachandra et al., 2015). Consequently, the concentrations of greenhouse gases in the atmosphere and their influence have progressively increased (Lal, 2008), particularly since the Industrial Revolution in 1850, with rapid growth in the human population. Globally, the greenhouse gas (GHG) footprint has been continuously increasing, with 72% of the resulting carbon dioxide (CO_2) significantly influencing global warming and consequent climate modifications (Yoro & Daramola, 2020). These changes have a distinct impact on the subsistence and livelihood of people due to the degradation of vital ecosystem services such as ecosystem productivity, soil fertility, carbon storage, and water retention capacity (Ramachandra & Bharath, 2021). The leading international forums have engaged in extensive deliberations on global climate change and have reached a unanimous consensus to reduce carbon emissions, aiming to attain global carbon neutrality by the middle of this century while also striving to cap the potential increase in global temperatures at a maximum of 1.5°C (United Nations Climate Action, 2021).

Forest ecosystems sequester significant amounts (45%) of carbon during photosynthesis and contribute about 50% of the net production (Bonan, 2008). These ecosystems play a pivotal role in mitigating the carbon footprint by sequestration of atmospheric carbon and retard global warming and associated climatic changes (Ramachandra & Bharath, 2019). Forests also serve as extensive terrestrial carbon repositories and hold a pivotal position within the carbon cycle (C-cycle). The significance of forests lies in their capacity to sequester atmospheric carbon within components such as above-ground biomass (AGB), below-ground biomass (BGB), and soil organic carbon (SOC; Leuschner et al., 2013; Raha et al., 2020). Sequestration of carbon (C) in ecosystems refers to the assimilation of atmospheric CO_2 and storage in various constituents, which increase its mean residence time (MRT) and minimize sinks of re-emission (Lal et al., 2015). This process is most effective in native, intact forests (Ramachandra & Bharath, 2019).

Alterations in landscape structures along with mismanagement have resulted in soil degradation, contributing to the emission of greenhouse gases, which include carbon species (such as CO_2, CH_4, etc.). The scale and composition of these emissions from land deterioration depend on factors such as vegetation cover, agricultural methodologies, and soil administration. Decline in soil quality demands urgency in adopting sustainable land management techniques for agricultural activities and in pursuing the restoration of degraded and depleted forests to enhance carbon reservoirs (Lal, 2003).

Modifications in land use and land cover (LULC) within forest ecosystems lead to significant changes in the composition and structure of a landscape (van Noordwijk et al., 1997). Long-term alterations have resulted in the fragmentation of forest ecosystems, with the breaking of contiguous forests, which have led to the depletion of biodiversity and modifications in hydrological processes and biogeochemical cycles (Bharath et al., 2014).

There have been significant carbon emissions of about 43.5 PgC through changes in land use, as is evident from large-scale deforestation in south and southeast Asia. The decline in forest biomass from 76 PgC to 32 PgC from 1850 to 1990 contributed to 58% and 18% decrease in soil carbon, respectively. By 1995, the global carbon emissions of tropical Asia was estimated to be approximately 7.7 PgC (out of 253 PgC), contributing to 3% from the combustion of fossil fuels, and around one-third emissions of 38.6 PgC out of 120 PgC by global land-use change (Houghton & Hackler, 1999). In India, the global carbon flux attributed to Land Use and Land Cover Change (LULCC) was estimated to be approximately 1.14 ± 0.18 Pg of carbon per year (Pg C yr-1) between 1990 and 2012 (Houghton et al., 2012). The net carbon emissions resulting from land use changes vary by region and range from 0 to 50 gCO2/kWh (grams of CO_2 per kilowatt-hour), with levels <12 g/kWh (van de Ven et al., 2021).

Carbon emissions from forest ecosystems have shown consistency during the past two centuries, with estimated emissions increasing from 3Gt CO_2 in 1850 to 6Gt CO_2 in 2021. India holds the seventh position, contributing 3.4% of the cumulative total CO_2 emissions, and more significantly to forest degradation and is ranked slightly ahead of the UK, which accounts for 3.0% of the total emissions (Intergovernmental Panel for Climate Change, 2021).

The industrial revolution and the subsequent globalization during the past century have given impetus to the uncontrolled increase in global atmospheric carbon emissions, aggravating the impacts of climate change on natural resources like land, water, forest, soil, etc., which have made policymakers worldwide focus on the carbon stocks of the Earth (Ramachandra & Bharath, 2021). Deforestation-induced temperature shifts lead to variations in the surface energy budget with changes in albedo, soil moisture, and land-atmosphere turbulent energy exchanges. Tropical deforestation, particularly large-scale clear-cutting, disrupts regional climate, comparable to prolonged global warming in dire emissions scenarios, necessitating appropriate strategic policy interventions for safeguarding community welfare by maintaining ecosystem integrity with sustainable management of fragile ecosystems (Zeppetello et al., 2020). Hence, comprehending land use and land cover (LULC) transformations and associated reduction in biomass and carbon storage is extremely essential for formulating prudent management approaches to mitigate abrupt LULC changes to address the challenges concerning the curtailing of greenhouse gas emissions (Ramachandra & Bharath, 2021).

Earth observation systems have emerged as the primary source for methodically collecting repetitive and reliable spatial datasets for global climate change, earth system modeling, natural resource management, food security, and biodiversity conservation (Roy et al. 2022, p. 1619). The availability of spatial data acquired regularly through remote sensors facilitates the quantification of landscape dynamics, which aids in the assessment of status of forests, deforestation, and carbon stock, and plays a crucial role in decision-making processes at the local, regional and national levels for the sustainable management of forests with systematic alterations in land use (Roy et al., 2022; Ramachandra & Bharath, 2020). InVEST® (the Carbon Storage and Sequestration model at https://naturalcapitalproject.stanford.edu/software/invest) helps in quantifying carbon stock and sequestration potential (Mengist et al., 2023; Babbar et al., 2021) through land use information with field data on four carbon pools (above-ground biomass (AGB), below-ground biomass (BGB), soil, and dead organic matter). Recent developments in geoinformatics and the availability of multi-resolution remote sensing data, coupled with collateral data (compiled through field investigations), have gained prominence for estimating biomass, particularly in tropical forest ecosystems, which play a vital role in future biomass monitoring through AGB, BGB, and soil carbon (Eisfelder et al. 2019, p. 2938) and quantification of changes in carbon footprint due to transitions in land uses.

Objectives

The objectives of this study are (i) assessment of land use dynamics in the Chikamagaluru district of Karnataka during the past five decades, (ii) estimation of changes in forest structure through fragmentation matrices, (iii) evaluation of carbon sequestration in the forest ecosystem using the InVEST model and (iv) appraisal of the impacts of changes in land use on the regional climate.

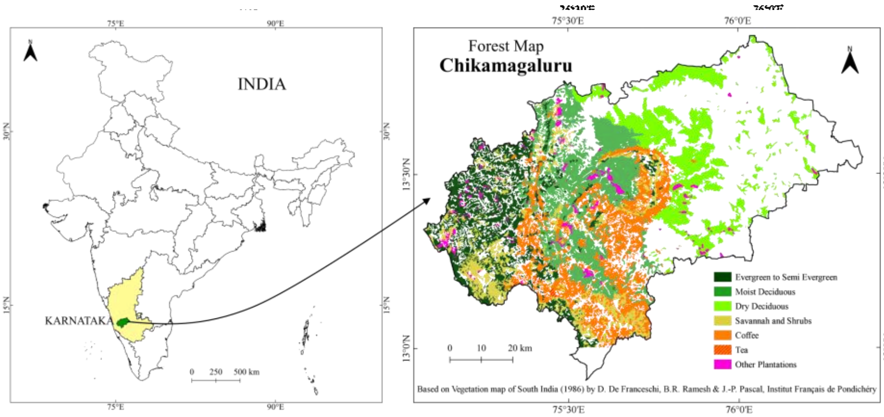
Materials and Methods

Study Area

The Chikamagaluru district (total area 7101 sq. km) is located at 12° 54' 42" N, 75° 04' 46" E and 13° 53' 53" N, 76° 21' 50" E in the south-western part of Karnataka (Figure 1). The district is divided into seven taluks: Chikamagaluru, Kadur, Koppa, Mudigere, Narashimharajapura, Sringeri, and Tarikere. A large part of this district, in the west, is the 'Malnad' area, an undulating forested hilly area. The remaining area, or the eastern part of the district is 'Maidan', which denotes the plain region. The district's highest peak is Mullanagiri, which is 1926 meters above MSL. There are two main rivers in the district named Tunga and Bhadra. Rivers like Hemavati, Netravati, and Vedavathi keep flowing throughout the year. The overall climate is cool because of the extensive hilly area. The mean daily maximum temperature in April (hottest month) is 36°C and the mean daily minimum temperature is 19°C. The average rainfall in the Chikamagaluru district varies from 595 mm to 2379 mm from year to year. There are three agro-climatic zones in the Chikamagaluru district: the hilly zone (Chikamagaluru, Koppa, Mudigere, Narashimharajpura, and Sringeri taluks), the central dry zone (Kadur taluk) and the southern transition zone (Tarikere taluk). Major crops which are produced in this region are ragi (55.5%), paddy (45.6), sunflower (16.1%), jowar (9.8%), Bengal gram (7.0%), groundnut (5.2%) and maize (2.3%). About 5,727 ha of the district has canal-based irrigation facilities. Arecanut, coconut, coffee, black pepper and cardamom agroforestry can be seen in the surrounding hills. Coffee was first grown on the slopes of Baba Budan Giri hills in the Chikamagaluru district in India. In 1966-77, around 67,000 hectares of land was under coffee plantation, producing 40,000 tonnes of coffee. About 85,465 ha of the district is under coffee plantations; the average production is about 55,000 million tonnes. According to the 2011 Census data, the total population is 11,37,867, with a population density of 158 per sq. km. The majority (81%) live in rural areas, while 19% live in urban areas (Directorate of Census Operations, Karnataka, 2011). The district is driven by a thriving agricultural economy, and supplemented by incomes from tourism. The GDP of the district was INR5,222 crore, and the per capita annual income was INR66,366 in 2012-13 (Government of Karnataka, 2020; State Gazetteer Advisory Committee, 1983).

Forests in the Chikamagaluru district are governed through five divisions – Chikamagaluru (25% forest cover), Bhadra Wildlife Sanctuary, Kudremukh National Park, Koppa, and Bhadravathi. The vegetation broadly falls into 4 types - dry deciduous hill, moist deciduous, evergreen, and the Sholas and Grassland. The Bhadra Wildlife Sanctuary (492.46 sq. km) is situated in the Western Ghats in Chikamagaluru district, which has primarily moist deciduous forests in the southern parts and dry deciduous in the north. The Kudremukh National Park is located at the tri-junction of Dakshin Kannada, Udupi, and Chikamagaluru districts, which is one of the largest grassland shola-based ecosystems in the mid-Western Ghats of Karnataka.

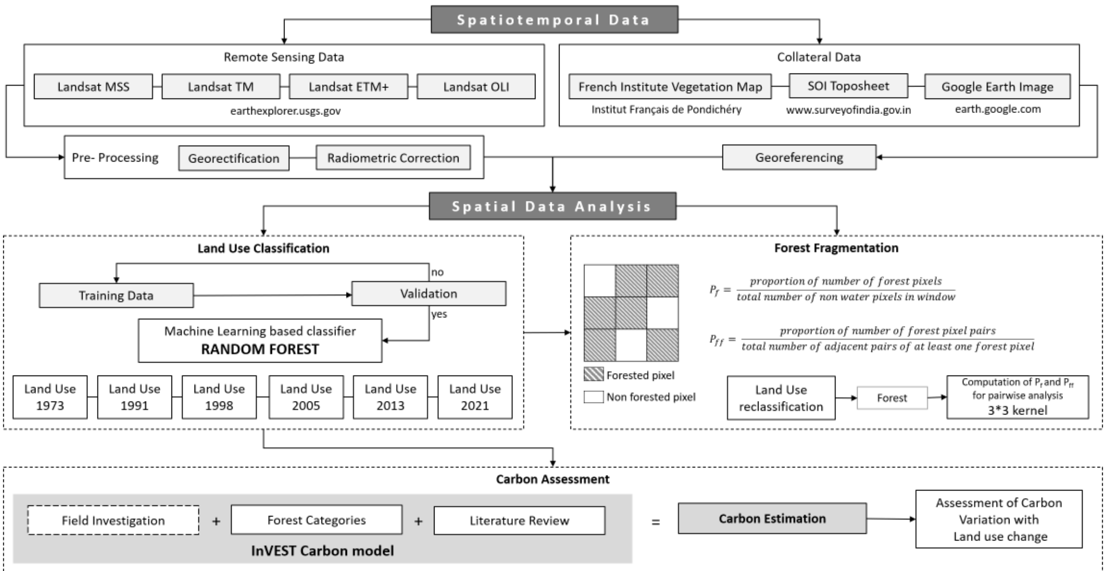
Figure 1: Study Area Chikamagaluru, Karnataka, India



Method

The method adopted for this study, explained in Figure 2, consists of three sections: (a) assessment of land use dynamics, (b) evaluation of fragmentation of forest ecosystem, (c) quantification of carbon, and (d) assessment of climate variability with agents as decline in forest cover with land use changes.

Figure 2: Methods Used for Data Analysis



Landscape Dynamics: Changes in land uses in the Chikamagaluru district have been quantified using remote sensing data from 1973 to 2021 through a Machine Learning (ML) algorithm. Remote sensing data (Landsat MSS, TM, ETM+ OLI) from open data source USGS (https://earthexplorer.usgs.gov/) has been used for the 1973, 1991, 1998, 2005, 2013 and 2021 analyses using Google Earth Engine Platform (https://code.earthengine.google.com/). The remote sensing data was pre-processed with geometric and radiometric rectifications. Red, Green, and NIR bands of the Landsat image were used to create False Colour Composite (FCC), which helped identify diverse landscape features in the district through heterogeneous patches. Evenly distributed training polygons corresponding to heterogeneous patches in FCC, covering 10-15% of the study area were digitized. Attribute data of the training polygons was collected from the field through pre-calibrated GPS (global positioning systems) and supplemented with information from online portals (Google Earth, http://earth.google.com and Bhuwan, http://bhuvan.nrsc.gov.in) with high spatial resolution data. Temporal spatial data was classified through a supervised, non-parametric, machine learning-based Random Forest classifier. Seventy percent of the training data was used for classification, and 30% for validation (Lillesand et al., 2014). Random Forest classifier uses a number of decision trees on subsets of the given dataset and takes the average value to enhance predictive accuracy. It uses bagging or Bootstrap aggregation, which chooses a random sample from the data set, resulting in greater accuracy than other traditional classification methods in a heterogeneous landscape.

Assessment of Fragmentation of Forests: The forest fragmentation index is calculated with the help of a fixed area window (3x3) surrounding a forest pixel. The binary map of forest and non-forest categories was generated, excluding waterbody as a non-fragmented land cover. Fragmentation of forests is calculated through metrics P_f and P_{ff} (Riitters et al., 2000). P_f determines the proportion of forest pixels in the window (Equation 1) and P_{ff} determines the proportion of all cardinal pixel pairs with at least one forest pixel, for which both pixels are forested (Equation 2). Different levels of forest fragmentation are computed through P_f and P_{ff} as shown in Table 1.

$$P_f = \frac{\text{proportion of number of forest pixels}}{\text{total number of non water pixels in window}} \quad \ldots(1)$$

$$P_{ff} = \frac{\text{proportion of number of forest pixel pairs}}{\text{total number of adjacent pairs of at least one forest pixel)}} \quad \ldots(2)$$

Table 1: Details of Fragmentation Matrices Calculated through P_f and P_{ff} Using Pair-Wise Analysis

Fragmentation classes	Description	
Interior	Integration of forest pixels and presence of no non-forest pixels.	$P_f = 1$
Perforated	Boundary area between interior forest and patch forest with small perforations.	$P_f > 0.6$ and $(P_f - P_{ff}) < 0$
Edge	Boundary of interior forest.	$P_f > 0.6$ and $(P_f - P_{ff}) > 0$
Transitional	Transition area between forested and non-forested pixels.	$0.4 < P_f < 0.6$
Patch	Small forest pixel patches surrounded by non-forest pixels.	$P_f < 0.4$
Non-forest	Non-forest pixels containing anthropogenic land use areas.	-
Waterbody	Areas covered with water are considered non-fragmented land use feature.	-

Source: Authors' own

Carbon Assessment: Carbon in the forest ecosystems of Chikamagaluru was quantified on the basis of field data (AGB, BGB, and soil carbon) and information from published literature. Different forest categories computed through remote sensing data were validated with the vegetation map developed by the French Institute, Pondicherry (Pascal et al., 1986)

Carbon stored in vegetation and soil was estimated through transect-based quadrats. The number of quadrats per transect in the sampled locality ranged between three to five depending on the saturation of the occurrence of species (species-area curve). Soil organic carbon (SOC) is estimated by collecting soil samples (top 30 cm) across different forest types (Ramachandra & Bharath, 2020; Swamy, 1992) and supplemented with the average soil carbon values reported in published literature (Ramachandra & Bharath, 2020; Ravindranath et al., 1997; Ravindranath & Ostwald, 2008).

Climate Variability Assessment: Daily temperature and precipitation data (of 0.5 degree resolution) from 1901 to 2018 was collected from the Indian Meteorological Department (IMD, n. d.), National Center for Atmospheric Research (NCAR) climate data guide (n. d.), a dataset from Princeton University (2006), and supplemented with the local climate data (Karnataka State Natural Resource Disaster Monitoring Centre [KSNDMC], n. d.). The data from NCAR and Princeton at latitude levels was validated through surface measurements of IMD and local climate (KSNDMC) data. The mean and variance were computed for variability and trend, comparable (with deviation ± 4.3%) to surface measurements (Ramachandra & Bharath, 2019).

Results

Land Use Dynamics and Forest Fragmentation Analyses

Temporal Landsat data was analyzed to understand the changes in land use from 1973 to 2021 in the Chikamagaluru district of Karnataka (Figure 3 and Table 2), which shows a decrease in forest cover of 28.98%, with a rise in agricultural areas (crop area by 5.31%, and horticulture by 42.52%) in last five decades.

Figure 3: Land Use and Forest Fragmentation Dynamics of Chikamagaluru District from 1973 to 2021

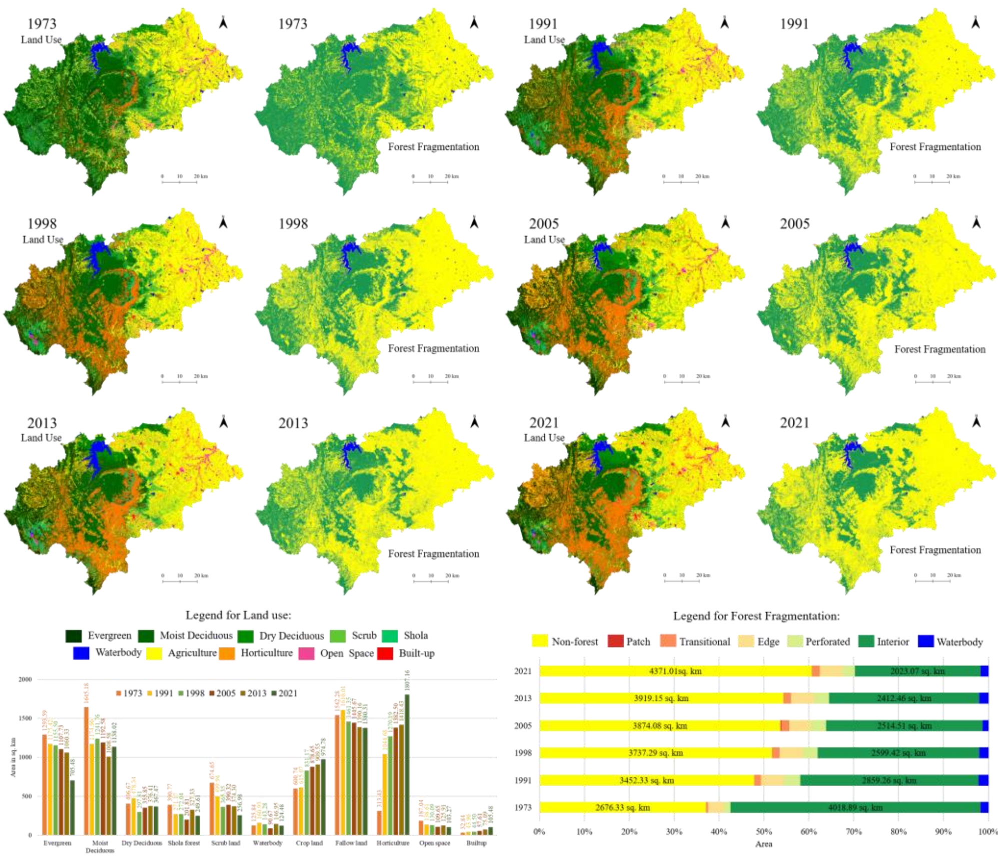


Table 2. Land use changes from 1973 to 2021 in Chikamagaluru District

Land Use		1973	1991	1998	2005	2013	2021
Evergreen	sq. km	1293.59	1175.42	1155.50	1107.73	1060.33	705.48
	%	17.93	16.30	16.02	15.36	14.70	9.78
Moist Deciduous	sq. km	1645.18	1174.90	1241.76	1192.58	1008.58	1138.02
	%	22.81	16.29	17.22	16.53	13.98	15.78
Dry Deciduous	sq. km	406.67	478.34	297.81	355.85	376.41	367.47
	%	5.64	6.63	4.13	4.93	5.22	5.09
Shola forest	sq. km	390.77	271.17	272.04	201.81	327.33	249.61
	%	5.42	3.76	3.77	2.80	4.54	3.46
Scrub land	sq. km	674.65	499.94	365.35	390.32	374.30	256.98
	%	9.35	6.93	5.07	5.41	5.19	3.56
Waterbody	sq. km	125.84	160.93	143.28	90.67	146.95	124.48
	%	1.74	2.23	1.99	1.26	2.04	1.73
Crop land	sq. km	600.74	615.07	831.17	878.65	909.55	974.78
	%	8.33	8.53	11.52	12.18	12.61	13.51
Fallow land	sq. km	1542.28	1610.01	1461.35	1445.67	1390.16	1380.31
	%	21.38	22.32	20.26	20.04	19.27	19.14

Land Use		1973	1991	1998	2005	2013	2021
Horticulture	sq. km	313.43	1044.68	1270.19	1382.50	1418.43	1807.16
	%	4.35	14.48	17.61	19.17	19.66	25.05
Open space	sq. km	187.04	138.61	130.09	109.65	125.91	103.27
	%	2.59	1.92	1.80	1.52	1.75	1.43
Built-up	sq. km	32.84	43.96	44.50	57.61	75.09	105.48
	%	0.46	0.61	0.62	0.80	1.04	1.46

Source: Author's own

The total forest cover declined from 44.60% (1973) to 30.69% (2021). The evergreen forests decreased from 800.14 sq. km in 1973 to 706.38 sq. km in 2021; the moist deciduous forests decreased from 1960.01 sq. km in 1973 to 1139.64 sq. km in 2021. Degradation in dry deciduous forests was seen from 457.41 sq. km (1973) to 368.03 sq. km (2021). The shola forest between the evergreen hills also decreased from 426.96 sq. km (1973) to 249.82 sq. km (2021). The scrub cover area decreased from 707.86 sq. km (1973) to 256.97 sq. km (2021). The conversion of forested areas into agricultural and horticultural land is the prime reason for extensive degradation and deforestation in the study area. The Bhadra Wildlife Sanctuary and Kudremukh National Park, marked as a reserved forest, which has the densest forest region in the district also saw forest degradation at the edge of the national park area.

The area devoted to agricultural activity was around 2174.46 sq. km in 1973, which increased to 2358.52 sq. km in 2021. There has been a constant increase in agricultural land use due to increased water availability from the Bhadra dam in the district, which marks an increase of 5.31% from 1973 to 2021. The area under horticulture increased from 4.64 % (1973) to 25.05% (2021), showing a rise of 42.52%. Many parts of forest and agricultural lands have been converted into horticultural land devoted to growing coffee, pepper, and silver oak in the last five decades.

Changes were also observed in open spaces in agricultural fields and built-up areas. The built-up area increased by 1.97% (from 31.66 sq. km in 1973 to 99.77 sq. km in 2021). Unregulated anthropogenic activities leading to escalation in agricultural and horticultural activities were the prime reasons for land degradation, leading to deforestation and severe decline in ecosystem goods and services.

An assessment of the condition of forest ecosystems through the structure of the forests (Figure 3; Table 3) shows that the interior forest declined from 55.72% in 1973 to 28.05% in 2021, with an increase in patch forest (0.79 sq. km), transitional forest (129.76 sq. km), edge forest (368.33 sq. km), and perforated forest (2023.07 sq. km).

Table 3. Forest Fragmentation analysis from 1973 to 2021 in Chikamagaluru District

		1973	1991	1998	2005	2013	2021
Exterior	sq. km	2676.33	3452.33	3737.29	3874.08	3919.15	4371.01
	%	37.10	47.86	51.81	53.71	54.33	60.60
Patch	sq. km	0.17	0.53	0.57	8.73	0.84	0.79
	%	0.00	0.01	0.01	0.12	0.01	0.01
Transitional	sq. km	32.38	107.78	119.72	129.22	122.61	129.77
	%	0.45	1.49	1.66	1.79	1.70	1.80
Edge	sq. km	260.05	364.75	375.05	343.65	374.05	368.34
	%	3.61	5.06	5.20	4.76	5.19	5.11
Perforated	sq. km	99.37	267.44	237.72	252.18	236.99	195.59
	%	1.38	3.71	3.30	3.50	3.29	2.71
Interior	sq. km	4018.89	2859.26	2599.42	2514.51	2412.46	2023.07
	%	55.72	39.64	36.04	34.86	33.45	28.05
Waterbody	sq. km	125.84	160.93	143.28	90.67	146.95	124.48
	%	1.74	2.23	1.99	1.26	2.04	1.73

Carbon Assessment

Carbon content in the forest ecosystems of Chikamagaluru district was quantified by using field data and literature review. The study shows that the forest ecosystems of Chikamagaluru have an irreplaceable stock of carbon, which aids in the mitigation of global warming. The above-ground biomass in 1973 was 55,706.29 Gg, which decreased to 38,781.6 Gg in 2021 due to extensive land cover changes. A similar trend can be seen in below-ground biomass (decrease of 3,426.41 Gg) and soil and dead biomass (decrease of 1033.71 Gg). The total carbon decreased by 30,683.81 Gg from 1973 to 2021 (Figure 4, Table 4).

Figure 4. Change in Total Carbon in Forest Ecosystem of Chikamagaluru District from 1973 to 2021

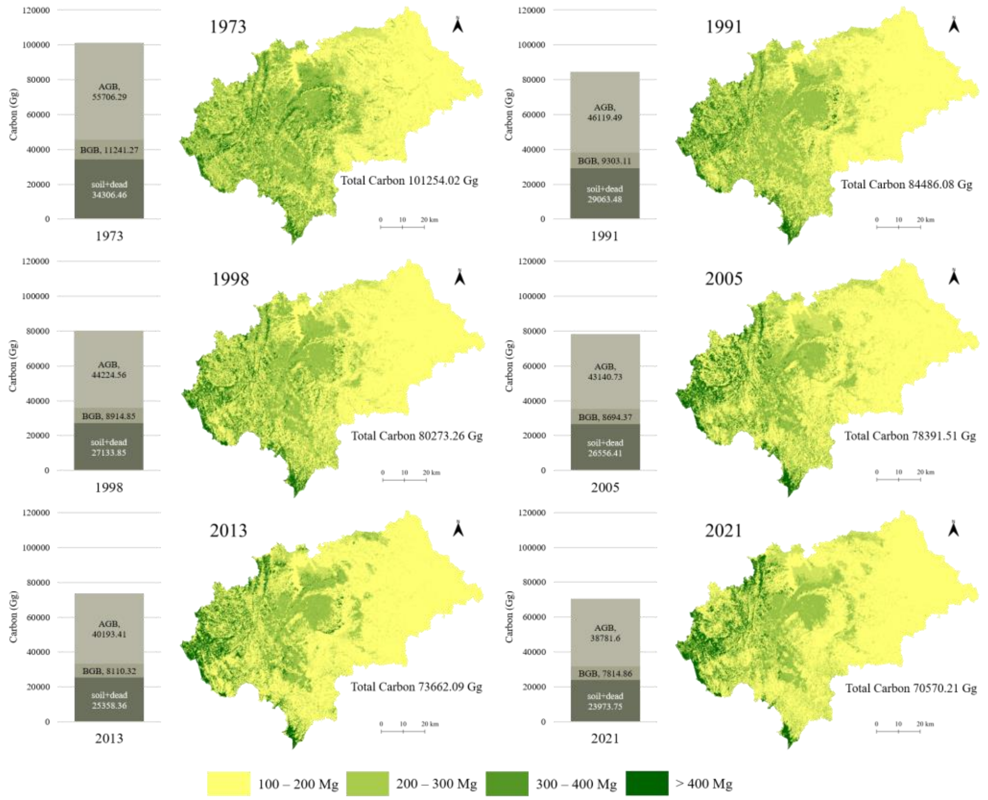


Table 4. Carbon Assessment of Chikamagaluru District from 1973 to 2021

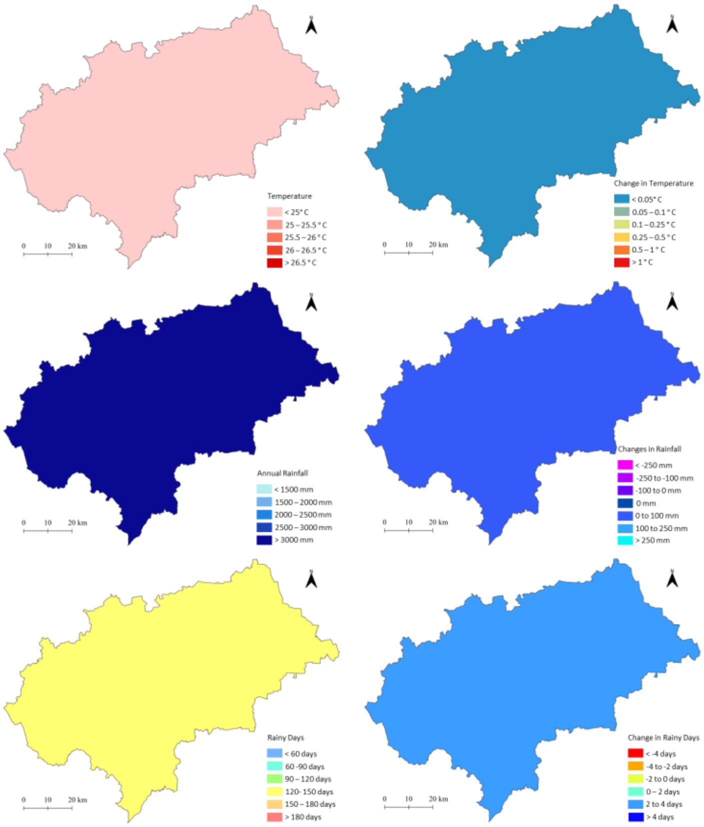
Carbon Assessment	AGB (Gg)	BGB (Gg)	Soil + dead (Gg)	AGB+BGB+S+D (Gg)
1973	55706.29	11241.27	34306.46	101254.02
1991	46119.49	9303.11	29063.48	84486.08
1998	44224.56	8914.85	27133.85	80273.26
2005	43140.73	8694.37	26556.41	78391.51
2013	40193.41	8110.32	25358.36	73662.09
2021	38781.6	7814.86	23973.75	70570.21

Source: Author's own

Appraisal of Climate Variability

Figure 5 depicts the current temperature (°C), number of rainy days and annual rainfall (mm), in the Chikamagaluru district (13° to 14° N latitude), which shows that Chikamagaluru has an average temperature of less than 25°C, 120 to 150 rainy days in a year and annual rainfall of >3000 mm. The analysis of climatic trends through long-term climatic data, presented in Figure 5 highlight that the study area will experience an increase in temperature of < 0.5°C, 0 to 100 mm increase in rainfall, and 2 to 4 days of rainy days, which are comparable to the climatic trends in the Western Ghats (Ramachandra & Bharath, 2019).

Figure 5. Effect on Climatic Variables Due to Inappropriate Land use Changes



Source: Appraisal of Climate Variability

Discussion

Land use transitions in Chikamagaluru district are due to escalating agricultural and horticultural activities in the forest ecosystem during the past five decades (Nagaraja et al., 2014). Continued land degradation along with a lack of timely ecosystem restoration has been posing a serious threat to food security. The erosion of hydrological and ecological services has been impacting the livelihood of the local people. Declining carbon stock and potential for sequestration necessitate immediate eco-restoration and implementation of stringent policies and norms for the protection of ecologically fragile regions.

The study highlights that land-use alterations have significantly impacted a district's micro-climate. Forests, often referred to as "water towers," play a pivotal role in capturing atmospheric moisture through rainfall and aiding in condensation (Bonan, 2008). The decline in natural forest cover has reduced surface roughness, a change in the hydrological regime, and altered aerodynamics. Consequently, rain-bearing clouds now follow prevailing winds, resulting in rainfall primarily in windward areas. Climate change is evident from the alterations in the spatial patterns of rainfall accompanied by an increase in rainy days and rainfall in the Northern Western Ghats, and a decrease in rainy days and rainfall in the Southern Western Ghats, which will result in recurring instances of flash floods and drought-like conditions (Ramachandra & Bharath, 2019).

Conclusion

Land use dynamics (from 1973 to 2021) and climate variability were studied, and quantification of carbon done to understand likely climatic trends in the Chikamagaluru district. Land use analyses showed a decline in forest cover of 28.98%, an increase in agricultural area by 5.31%, and horticulture by 42.52%. Assessment of forest structure through fragmentation metrics reveals a decrease in intact forests from 55.72% (1973) to 28.05% (2021). Globalization and liberalization in the 1990s provided an impetus to rapid land use changes with the conversion of forest lands into agricultural, horticultural, and built-up areas to meet the needs of the expanding human population. This has caused an imbalance in the ecological structure of the region. Carbon assessment from 1973 to 2021 also shows declining carbon stock (soil, dead biomass, above ground, and below ground biomass), which has led to a decrease in carbon by 30,683.81 Gg from 1973 to 2021. The analyses reveal that continued land degradation and loss of associated native forests would impact the carbon sequestration capability of ecosystems to mitigate changes in the climate with the global warming. Analyses of long-term climatic trend show that the study region will experience an increase in temperature (< 0.5°C), an increase in rainfall (up to 100 mm), and rainy days (2 to 4 days). The analyses of landscape cover dynamics with climatic variability demonstrate that land cover in the Western Ghats landscape has played a critical role in moderating microclimatic conditions and continuance of land degradation with deforestation would have serious implications on the climate with higher temperatures, alterations in rainfall and rainy days, which will eventually have serious implications on the livelihood of people in the form of increase in vector-borne diseases because of increase in temperature and recurring instances of landslides and mudslides due to flooding because of changes in the rainfall pattern.

This study emphasizes the necessity for sustainable development measures and forest restoration policies to protect the ecologically fragile ecosystem in the study region to maintain the carbon sinks. This would also aid in the sustainment of hydrological and other ecological cycles. Proper policy measurements will help the local community to reach the sustainable goal of zero poverty and equal livelihood opportunities.

Acknowledgement

We are grateful to the EIACP (ENVIS) Division, the Ministry of Environment, Forests and Climate Change, Government of India (grant: SP/DEOO-22-001).

Author Contributions: Conceptualization, development of methods, soft computing, field investigation, validation, writing, formatting, and reviewing were carried out by all authors. All authors have read and agreed to the published version of the manuscript.

Funding: Field research was funded by the EIACP (ENVIS) division, the Ministry of Environment, Forests and Climate Change, Government of India, and infrastructure support was provided by the Indian Institute of Science.

Data Availability Statement: Data are archived at our data portal https://wgbis.ces.iisc.ac.in.

Conflicts of Interest: The authors declare no conflicts of interest.

References

Babbar, D., Areendran, G., Sahana, M., Sarma, K., Raj, K., & Sivadas, A. (2021). Assessment and prediction of carbon sequestration using Markov chain and InVEST model in Sariska Tiger Reserve, India. *Journal of Cleaner Production*, Volume 278, 123333.

Bharath, S., Rajan, K. S., & Ramachandra, T. V. (2014). Status and future transition of rapid urbanizing landscape in central Western Ghats — CA-based approach. ISPRS Annals of Photogrammetry, *Remote Sensing & Spatial Information Sciences*, 2(8), 69–75.

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, 320(5882), 1444-1449.

Department of Civil and Environmental Engineering, Princeton University. (2006). Global Meteorological Forcing Dataset for Land Surface Modeling. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/JV89-AH11

Directorate of Census Operations, Karnataka. (2011). District census handbook Chikmagalur. https://cdn.s3waas.gov.in/s367d96d458abdef21792e6d8e590244e7/uploads/2018/08/2018080999.pdf

Eisfelder, C., Kuenzer, C., & Dech, S. (2012). Derivation of biomass information for semi-arid areas using remote-sensing data. International Journal of Remote Sensing, 33(9), 2937-2984.

Government of Karnataka. (2020). District disaster management plan (DDMP) for Chikkamagaluru District 2019-20. https://ksdma.karnataka.gov.in/storage/pdf-files/Chikkamagaluru%20DDMP%202019-20.pdf. Accessed in September 2023.

Houghton, R. A., & Hackler, J. L. (1999). Emissions of carbon from forestry and land-use change in tropical Asia. *Global Change Biology*, 5(4), 481-492.

Houghton, R. A., House, J. I., Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Que´re´, C., & Ramankutty, N. (2012). Carbon emissions from land use and land-cover change. Biogeosciences, 9(12), 5125–5142.

India Meteorological Department. (n. d.). Customized Rainfall Information System (CRIS). https://hydro.imd.gov.in/hydrometweb/(S(mzu2h5vtfc3tq0beczrxb155))/landing.aspx. Accessed in September 2023.

Intergovernmental Panel for Climate Change. (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896.

Karnataka State Natural Disaster Monitoring Centre. (n.d.). Reports. https://www.ksndmc.org / Report HomePage.aspx/Reports. Accessed in September 2023.

Lal, R. (2003). Global potential of soil carbon sequestration to mitigate the greenhouse effect. *Critical Reviews in Plant Sciences*, 22(2), 151-184.

Lal, R. (2008). Carbon sequestration. Philosophical Transactions of the Royal Society. *Series B, Biological Sciences*, 363(1492), 815-830. https://doi.org/10.1098/rstb.2007.2185.

Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, 15, 79-86.

Leuschner, C., Moser, G., Hertel, D., Erasmi, S., Leitner, D., Culmsee, H., ... & Schwendenmann, L. (2013). Conversion of tropical moist forest into cacao agroforest: Consequences for carbon pools and annual C sequestration. *Agroforestry Systems*, 87, 1173-1187.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2014). Remote sensing and image interpretation. New York: Wiley.

Mengist, W., Soromessa, T., & Feyisa, G. L. (2023). Responses of carbon sequestration service for landscape dynamics in the Kaffa biosphere reserve, Southwest Ethiopia. Environmental Impact Assessment Review, 98, 106960.

Nagaraja, B. C., Hemanjali, A. M., Somashekar, R. K. & Pramod, K. (2014). Assessment of forest encroachment in Chikamagaluru District of Western Ghats using RS and GIS. *International Journal of Remote Sensing & Geoscience*, Volume 3, Issue 6.

National Center for Atmospheric Research. (2019). Climate data guide. https://climatedataguide.uca r.edu/data-type/gridded-obs. Accessed in September 2023.

Pascal, J. P. (1986). Explanatory booklet on the Forest Map of South India (Sheets: Belgaum-Dharwar-Panaji, Shimoga, Mercara-Mysore). Karnataka Forest Department and French Institute of Pondicherry. Inst. fr. Pondichéry, trav. sec. sci. tech. Hors série 18.

Raha, D., Dar, J. A., Pandey, P. K., Lone, P. A., Verma, S., Khare, P. K., & Khan, M. L. (2020). Variation in tree biomass and carbon stocks in three tropical dry deciduous forest types of Madhya Pradesh, India. *Carbon Management*, 11(2), 109-120.

Ramachandra, T. V., & Bharath, S. (2019). Global warming mitigation through carbon sequestrations in the Central Western Ghats. *Remote Sensing in Earth Systems Sciences*, 2, 39-63.

Ramachandra, T. V., & Bharath, S. (2020). Carbon sequestration potential of the forest ecosystems in the Western Ghats, a global biodiversity hotspot. *Natural Resources Research*, 29(4), 2753-2771.

Ramachandra, T. V., & Bharath, S. (2021). Carbon footprint of Karnataka: Accounting of sources and sinks. Carbon Footprint Case Studies: Municipal Solid Waste Management, Sustainable Road Transport and Carbon Sequestration, 53-92.

Ramachandra, T. V., Aithal, B. H., & Sreejith, K. (2015). GHG footprint of major cities in India. *Renewable and Sustainable Energy Reviews*, 44, 473-495.

Ravindranath, N. H., & Ostwald, M. (2007). Carbon inventory methods: Handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects (Vol. 29). *Springer Science & Business Media.*

Ravindranath, N. H., Somashekhar, B. S., & Gadgil, M. (1997). Carbon flow in Indian forests. *Climatic Change*, 35, 297-320.

Reichle, D. E. (2023). The global carbon cycle and climate change: scaling ecological energetics from organism to the biosphere. Elsevier.

Riitters, K., Wickham, J., O'Neill, R., Jones, B., & Smith, E. (2000). Global-scale patterns of forest fragmentation. *Conservation Ecology*, 4(2).

Roy, P. S., Ramachandran, R. M., Paul, O., Thakur, P. K., Ravan, S., Behera, M. D., ... & Kanawade, V. P. (2022). Anthropogenic land use and land cover changes—A review on its environmental consequences and climate change. *Journal of the Indian Society of Remote Sensing*, 50(8), 1615-1640.

Swamy, H. R. (1992). Organic productivity, nutrient cycling and small watershed hydrology of natural forests and monoculture plantations in Chikmagalur district. Karnataka (No. CONF-9102202-). John Wiley and Sons, Inc., New York, NY (United States).

The State Gazetteer Advisory Committee. (1983). Karnataka state gazetteer, Part II. Government of Karnataka.

Tyrrell, M. L., Ross, J., & Kelty, M. (2012). Carbon dynamics in the temperate forest. In M. Ashton, M. Tyrrell, D. Spalding, & B. Gentry (Eds.). Managing forest carbon in a changing climate, pp. 77-107. Springer Dordrecht. https://doi.org/10.1007/978-94-007-2232-3_5

United Nations Climate Action. (2021). COP26: Together for our planet. https://www.un.org/en/climatechange/cop26. Accessed in September 2023.

Ussiri, D. A., & Lal, R. (2017). Carbon sequestration for climate change mitigation and adaptation. Cham: Springer International Publishing.

van de Ven, D. J., Capellan-Pere´z, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., & Gonzalez-Eguino, M. (2021). The potential land requirements and related land use change emissions of solar energy. Scientific Reports, 11, 2907. https://doi.org/10.1038/ s41598-021-82042-5

van Noordwijk, M., Cerri, C., Woomer, P. L., Nugroho, K., & Bernoux, M. (1997). Soil carbon dynamics in the humid tropical forest zone. *Geoderma*, 79(1-4), 187-225.

Yoro, K. O., & Daramola, M. O. (2020). CO_2 emission sources, greenhouse gases, and the global warming effect. Advances in Carbon Capture, 3-28. https://doi.org/10.1016/B978-0-12-819657-1.00001-3

Zeppetello, L. R. V., Parsons, L. A., Spector, J. T., Naylor, R. L., Battisti, D. S., Masuda, Y. J., & Wolff, N. H. (2020). Large scale tropical deforestation drives extreme warming. *Environmental Research Letters*, 15(8), 084012.

"Preservation of the environment, promotion of sustainable development and particular attention to climate change are matters of grave concern for the entire human family."
—Pope Benedict