

## Article

# The Dynamics and Potential of Carbon Stocks as an Indicator of Sustainable Development for Forest Bioeconomy in Ghana

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**Abstract:** Sustainable forest bioeconomy (SFB), as a multidimensional approach for establishing mutual benefits between forest ecosystems, the environment, the economy, and humans, is a nature-based solution for a promising future. The study aims to evaluate the potential of carbon stocks (Cstocks) and variability for SFB. It is hypothesized that the decrease in Cstocks is related to an increase in population and agriculture, which caused a decrease in forest area and growing stock and consequently affected SFB. Primary and secondary data were collected from the field, national, and international databases, and analyzed using some statistical and geospatial software packages including IBM SPSS 29.0, CANOCO 5.0, and ArcGIS 10.5. The results revealed that large forest areas were converted to arable lands between 2000 and 2020. Across the forest zones, the aboveground and belowground Cstocks varied significantly, with the aboveground biomass being higher than the belowground biomass. The main drivers of Cstocks were politics and governance (57%), population growth (50%), soil degradation practices (50%), and socio-cultural beliefs (45%). Cstocks had significant negative correlation with population growth, carbon emissions, forest growing stock, forest loss, and the use of forest for biofuel. Evergreen forest zones (rainforest and moist) had more Cstocks than the moist deciduous and swamp/mangrove forests. The study demonstrated that the variability in Cstocks over the last three decades is attributed to an increase in population and agriculture, but Cstocks variability between the forest-vegetation belts could be better explained by differences in trees abundance than population. The study also revealed that the increase in Cstocks contributed to the realization of many SDGs, especially SDG 1, 2, 3, 6, 7, 11, 12, 13, and 15, which in turn support a sustainable forest bioeconomy. Future study is necessary to evaluate Cstocks in individual tree species, biodiversity, and other forest ecosystem services to promote SFB in the country.

**Keywords:** forest bioeconomy; carbon stocks; sustainable development; carbon emissions; climate change



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## 1. Introduction

Globally, the forest sector is widely known for its vital roles in the global carbon cycle and climate change mitigation [1–5]. Forests have the potential to substantially contribute to the world carbon cycle and climate change mitigation by capturing carbon from the atmosphere and stocking it in the forest ecosystem (such as forest wood-based and non-wood-based products, biomass, and soil) [6,7]. Recent efforts to mitigate global warming have brought the need for atmospheric carbon storage into focus, as many land use practices, such as forestry and integrated agricultural systems, have the potential to absorb (or sequester) carbon dioxide (CO<sub>2</sub>) from the atmosphere. Estimation of global, regional, national, or local carbon stocks and sources is core content of the Intergovernmental Panel

on Climate Change (IPCC) documentations. Countries featuring in the UN Framework Convention on Climate Change (UNFCCC) are involved in presenting national inventories of net GHG emissions, including carbon sources and stocks related with forests, and in reaching their mandates for low emissions under the climate change protocols [8,9].

Carbon stock is the storage of carbon belowground and aboveground in a stable means by the direct and indirect absorbance of atmospheric CO<sub>2</sub> [10,11]. Living plants, through photosynthetic processes, transform CO<sub>2</sub> to biomass by dissipating the carbon in the atmosphere and reserving it in the plant tissues and soils [12,13]. In agricultural or forest ecosystems, the generated biomass is specifically stocked as aboveground biomass (AGB), belowground biomass (BGB), dead wood, litter, and soil organic matter [14–16]. Forest plants and forest ecosystems including soils are key carbon sinks and sources [17–21] and have significant impacts on the realization of many sustainable development goals (SDGs), especially SDG 1, SDG 2, SDG 3, SDG 6, SDG 7, SDG 11, SDG 12, SDG 13, and SDG 15 [22]. Some of the SDGs focus on terrestrial biophysical systems in which soils including SOC play essential roles. For example, zero hunger (SDG 2) relates to the achievement of food security and improved nutrition, and Good Health and Well Being (SDG 3) through sustainable agriculture, and SOC is indispensable for the realization of these goals [23]. An increase in SOC stocks is also vital in climate change mitigation and adaptation (SDG 13), and for the sustenance of life on earth (SDG 17), through carbon-capture approaches such as climate-smart agriculture, integrated forestry–crop–livestock agricultural systems, and others [22,24–27].

Forests contribute significantly to the processes of carbon stocks and sequestration. Thus, forests have attracted much research on the worldwide carbon fluxes, carbon balance, and climate change [20,28]. The role of forest ecosystems as both a carbon source and a carbon stock is pertinent in regulating the carbon fluxes and carbon balance [19–21,29,30]. Studies have revealed that forests are one of the terrestrial ecosystems that accumulate the highest stock of organic carbon, and this value is almost twice that stored in the atmosphere [31–33].

To enhance the processes of carbon stocks in the forest ecosystems, certain natural-based solutions (NBS), such as selective logging, zero deforestation [34–36], afforestation [37], forest restoration [38], and improved forest management [39,40] are essential approaches to achieving climate change mitigation. This potential notwithstanding, the knowledge gaps regarding the combined impact of future socioeconomic factors, management, and policy changes on forest carbon stocks vis-a-vis CO<sub>2</sub> emissions remained unclosed [41,42]. The key gaps include the role of timber demand in carbon fluxes, the influence of climate change policies on forest management and timber production, and the regional variations in carbon and wood product harvest outcomes. To close this gap, the idea of the sustainable forest bioeconomy (SFB) was conceived.

A forest bioeconomy (FB) might be termed as an act that exploits wood and other non-wood products, such as vegetables, snails, fruits, mushrooms, edible insects, and others harnessed from the forests or side streams of forest biomass for domestic, commercial, and industrial purposes for human benefits. In addition, FB commonly encompasses forestry-oriented operations, including mining/logging, transporting, and the production of forest biomass to achieve an effective form of “sustainability” in the environment and forest ecosystem. Sustainability, for instance, in general terms, could be defined as a system approach that interlinks various sectors namely, economic, environmental, and social sectors [43,44], and lately the ideology has been expanded to incorporate spiritualism and culturalism [39]. Therefore, a sustainable forest bioeconomy is the uncompromising stewardship and use of forests and forest ecosystems in a way, and at a rate, that conserves their regeneration, biodiversity, productivity, and naturalness, and their ability to accomplish, both at present and in the future, essential ecological, economic, and socio-cultural services, at local, national, and global levels, without harming other ecosystems [45].

Improved forest management practices and changing environmental conditions (e.g., nitrogen deposition, climate warming and the elevation of atmospheric CO<sub>2</sub> concentrations)

have increased the carbon sequestration and stocks in sustainably managed forests [46–49]. In sum, the increasing stock of C in the European forests has been elevated in recent decades relative to the forest area, with an increase of approx. 17.5 million hectares from 1990 to 2015 [46]. The SFB provides security to forest ecosystems and safety throughout their entire environment; however, in most developing countries especially in the SSA, Ghana in particular, the majority have neither heard about SFB nor understood it perfectly, and are less likely to follow its procedures. In the SSA for example, between 2000 and 2005, Sudan lost an average of 117,807 hectares of forest per annum, whereas Nigeria lost 82,000 hectares of forest per annum [50,51]. Most West African countries including Ghana and Nigeria, lost 55.7% of their primary forests between 2000 and 2005, through logging for energy, timber, and agriculture. This accounted for the highest rate of forest loss globally. In this region, particularly Ghana, many forest management projects, including the Reducing Emissions from Deforestation and Forest Degradation (REDD+), are not viable for several reasons, including the following: (i) their benefits are uncompensated environmental services; (ii) there is a high rate of poverty and illiteracy; (iii) there is rapid population growth and increasing demand on forest resources (food, fodder, fiber, arable land, energy, timber) for peoples' livelihoods; (iv) socio-cultural beliefs; (v) national governments and other local agencies have no strong will to ensure forest management; (vi) there are inadequate finances to undertake conservation activities due to corruption, the diversion of allocated money, or the misappropriation of funds. However, SFB, if well adopted in the region, could support in the development of carbon projects to provide financial aid to government agencies investing in forest conservation. If SFB is embraced, deforestation for any reason will be ameliorated because carbon credits will be established, and both the government and the forest-dependent communities will be adequately compensated. In addition to the economic incentives, zero deforestation will improve the environment. For instance, it is estimated that the total carbon mitigation from avoided deforestation in Africa between 2003 and 2012 could be 615.8 million tCO<sub>2</sub> [45]. With effective harvesting in an SFB, woody biomass is transferred from the ecosystem to the technosphere. Wood is harvested to cater for diverse needs namely, construction, energy, hygiene, and communication. Forests and forest-related products have an enormous influence in both the economic, environment, and social sectors, and can thus promote the United Nations Sustainable Development Goals (UN-SDGs) in many areas.

Ghana is one of the countries in tropical Africa with tangible forest areas that could support, or have been indirectly providing, most of the poor masses with substantial livelihoods, but the impact of carbon stocks on the forest bioeconomy is not familiar to the people. This is because no research or training has been made available on this topical issue. Therefore, this work is unique as it helped to close this gap in knowledge about the carbon stock–bioeconomy nexus by evaluating the potential of carbon stock and variability for SFB. The novelty of this study could further be explained by the fact that, at present, in Ghana, it is rare to find any study that has examined the prospects of carbon stocks for SFB in a larger space (i.e., across the vegetational belts) and over a longer timeframe (three decades). To achieve the aim of this work, specific objectives were developed, including the following: (i) the quantification and mapping forest carbon stocks in the forest-vegetation zones of Ghana; (ii) an estimation of the variability and potential of carbon stocks in SFB; (iii) determination of the key drivers of SFB. The study hypothesized that the decrease in carbon stock is related to an increase in population and agriculture, leading to a decrease in forest area and increase in stock with an increase in carbon emissions, which consequently affected the sustainable forest bioeconomy in Ghana.

## 2. Materials and Method

### 2.1. Study Area

This research was conducted in Ghana. Ghana is in the western part of Africa, between latitudes 4°44' and 11°15' N and longitudes 3°15' W and 1°12' E, with an aerial coverage of 238,539 sq km<sup>2</sup> [52]. Ghana is surrounded by Burkina Fasso, Togo, Ivory Coast, and

the Atlantic Ocean in the south. Currently, the population of Ghana is about 30.8 million persons, with a yearly population growth rate of ca. 2.2% [53]. In 2019, Ghana's regions were increased from ten to sixteen administrative regions (Figure 1). As an African country, Ghana is known for its large hectares of forest areas. There are five dominant forest-vegetation zones, including wet evergreen rainforest, moist evergreen (dry and thick) forest, moist deciduous (NW and SE types) forest, dry semi-deciduous forest and savannah, and swamp forest and mangrove (Figure 2). The wet evergreen rainforest and the moist evergreen (dry and thick) forests are found in the south and south-west, whereas the swamp forest and mangrove vegetation are commonly found in the south-east [54]. On the other hand, the moist deciduous (NW and SE types) forest and the dry semi-deciduous forest and savannah are primarily located in the central and northern regions of the country, respectively (Figure 2). Ghana is one of the African countries facing forest threats due to rapid deforestation. In the year 2020, Ghana's forest loss estimate was above 14,000 hectares [55]. In 1992, only about 1.5 million hectares were estimated as remaining "intact closed forest" in the country. The country had high net CO<sub>2</sub>e emissions between 1990 and 1996, although its sinks rapidly decreased in size [56]. The swift decrease in sinks has been associated with deforestation, particularly a rapid increase in wood energy consumption, timber harvesting, agricultural and settlement expansion, and mining, and low rates of reforestation [54,57–59].

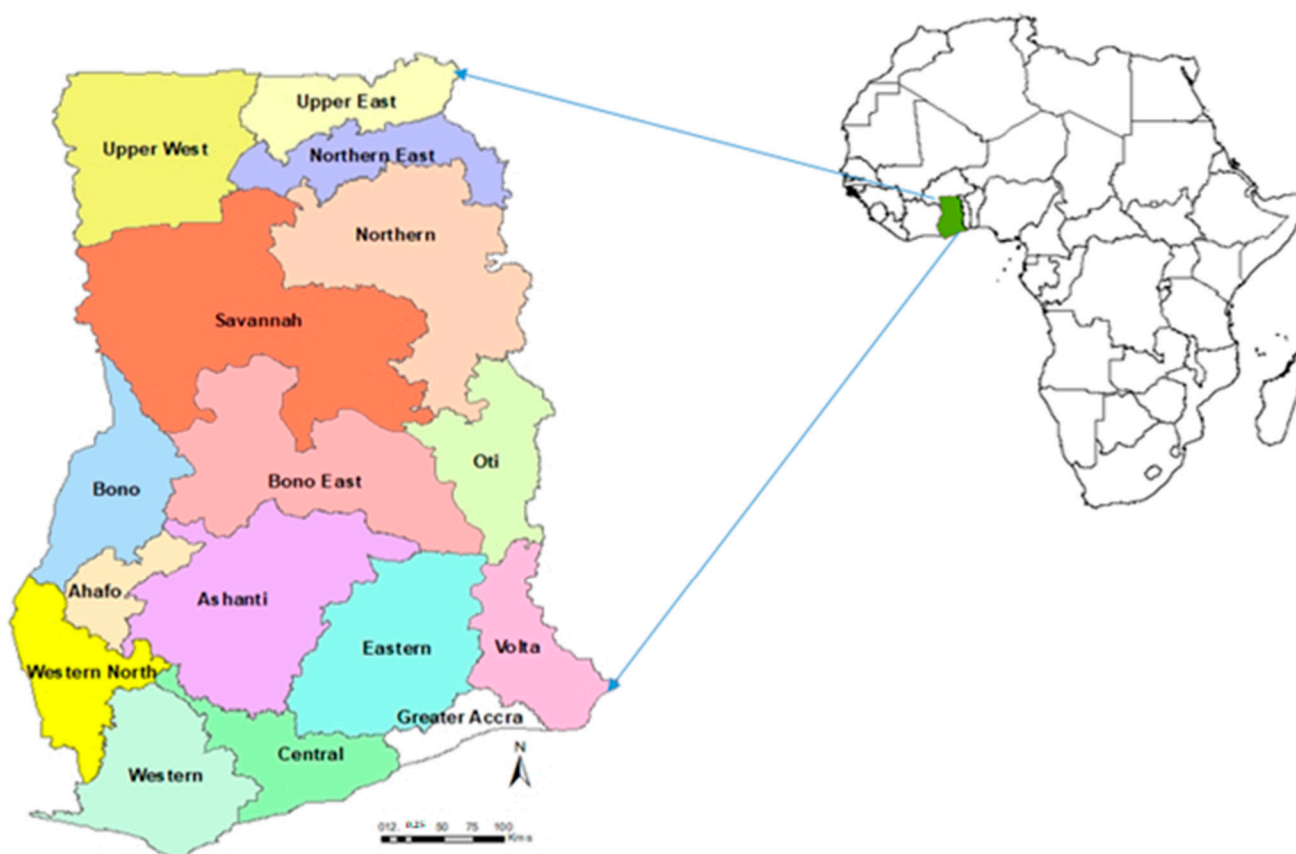
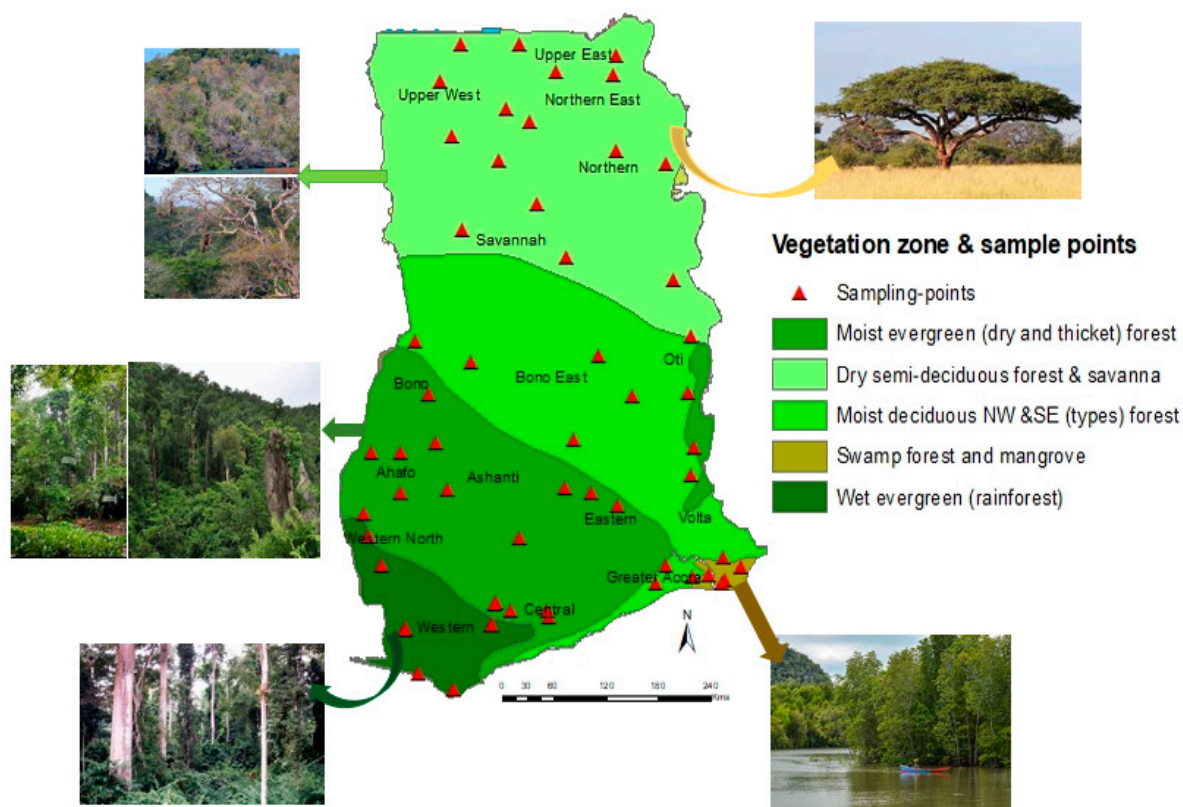


Figure 1. African map showing Ghana (the study area), and the current 16 administrative regions.



**Figure 2.** Forest-vegetation belts, image of the forest's features/layers, regions, and sampling locations.

In terms of climatic conditions, the country is characterized by a tropical climate with different wet and dry seasons [60,61]. Ghana has temporal and spatial temperature variations due to seasonal changes and differences in ecological zone, respectively. The average yearly temperature is generally high and above 24 °C. Average yearly rainfall is about 736.6 mm, and rainfall typically decreases from south to north [56]. Economically, the current GDP growth of Ghana is 3.3%, with an inflation rate of 29.8%, and an unemployment rate of 13.4% [62]. At present, over 3.4 million people in the country are living in acute poverty, with below 1.90 USD per day, with the rural areas accounting for the highest number [63].

## 2.2. Data Collection and Analyses

The primary and secondary sources of data collection were applied to extract relevant data for the study. For the primary data sources, the researchers identified and classified the forest-vegetation belts in Ghana and performed a field sampling by applying a handheld GPS to identify the sampling sites in each forest-vegetation zone (Figure 2, Appendix A Table A1). Data were collected from a total of 55 sampling points, with at least 5 points from each forest-vegetation zone. The larger the coverage of a land use-cover or the vegetation zone, the higher the number of sampling points. This was carried out to achieve a good, uniform spatial distribution of the sampling sites across the entire study area. For example, the dry semi-deciduous forest and savanna zone (16 sampling points) had the highest number of sampling points, while swamp forest and mangrove (5 points) had the lowest number of sampling points. The sample sites were visited thrice between November 2021 and October 2022. Data on carbon stocks (aboveground and belowground) and other related data on a sustainable forest bioeconomy, such as the common tree species, were collected and estimated. Further, as part of the primary data source, the study also used a structured research questionnaire to collect some field data, especially on the drivers of deforestation, socioeconomic and political factors, and the people's perception of carbon stocks' potential to achieve sustainable development. Twenty interviewees were chosen across the five

forest-vegetation zones. The respondents' profiles encompassed researchers in the field, foresters, agronomists, and policy makers and agents from the government and related ministries. All the interviewees were above 30 years old and must have either lived or worked in Ghana for at least 20 years. The secondary data sources included materials from the peer-reviewed literature, and the government and NGOs, established institutions and agencies, including Ghana Statistical Services, Ministry of Food and Agriculture, Commerce, and various industries (Table 1). Other sources of data were United Nations Organizations such as Food and Agricultural Organization (FAO) [64–67], World Bank [68,69], World Income Inequalities Databases [70], Forest Resources Assessment [71], and United Nations Office for the Coordination of Humanitarian Affairs [72]. Further, data were also extracted from the National Aeronautics and Space Administration [73], where some satellite imagery, including land use-cover changes, were retrieved. These secondary data were collated and reconciled with the field data. Where large discrepancies occurred in the data, for instance, between the country-based institutional data and the international institution-based data, the field data were used where available; otherwise, the data were averaged.

**Table 1.** Data sources and variables/measures.

Indicator/Measure	Sources
Administrative regions	<ul style="list-style-type: none"> <li>- OCHA 2022. Global coordinates;</li> <li>- <a href="https://data.humdata.org/dataset/cod-ab-gha">https://data.humdata.org/dataset/cod-ab-gha</a> (accessed on 24 December 2023);</li> <li>- GSS 2020.</li> </ul>
Forest-vegetation zones	<ul style="list-style-type: none"> <li>- White F. 1983</li> </ul>
Sampling points	<ul style="list-style-type: none"> <li>- Field sampling and survey; hand-held GPS.</li> </ul>
Land use-cover and changes	<ul style="list-style-type: none"> <li>- Digital and satellite imageries from <a href="https://eros.usgs.gov/westafrica/land-cover/land-use-and-land-cover-trends-west-africa">https://eros.usgs.gov/westafrica/land-cover/land-use-and-land-cover-trends-west-africa</a> (accessed on 24 December 2023);</li> <li>- <a href="http://www.nasa.gov">www.nasa.gov</a> (accessed on 24 December 2023).</li> </ul>
Forest areas and loss	<ul style="list-style-type: none"> <li>- FAO's Global Forest Resources Assessments Reports.</li> </ul>
Forest tree cover and loss	<ul style="list-style-type: none"> <li>- FAO's Global Forest Resources Assessments Reports.</li> </ul>
Forest growing stocks	<ul style="list-style-type: none"> <li>- FAO's Global Forest Resources Assessments (main and country reports).</li> </ul>
Contributions of forest to GDP	<ul style="list-style-type: none"> <li>- Ghana Statistical Services database;</li> <li>- World Bank websites.</li> </ul>
Country's GDP and poverty rate	<ul style="list-style-type: none"> <li>- Ghana Statistical Services database;</li> <li>- World Bank websites;</li> <li>- Other reports and documents (e.g., Braimoh, 2009; MoFA, 2010).</li> </ul>
Uses of forests: Farming, mining, bioenergy, timber, NWFPs, etc.	<ul style="list-style-type: none"> <li>- Ghana Statistical Services database;</li> <li>- World Bank websites;</li> <li>- Reports of Timber Industry Development Division, Forestry Commission;</li> <li>- Other reports and documents (e.g., Braimoh, 2009; MoFA, 2010).</li> </ul>

Table 1. Cont.

Indicator/Measure	Sources
Biophysical: climate, soil and biomass carbon, and carbon emissions	<ul style="list-style-type: none"> <li>- Ministry of Food and Agriculture database;</li> <li>- Forestry Commission;</li> <li>- Energy Commission;</li> <li>- The published literature;</li> <li>- FAOSTATS websites</li> <li>- ISRIC Soil geographic databases: <a href="https://www.isric.org/explore/soil-geographic-databases">https://www.isric.org/explore/soil-geographic-databases</a> (accessed on 24 December 2023).</li> <li>- Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite: <a href="https://neo.gsfc.nasa.gov/">https://neo.gsfc.nasa.gov/</a> (accessed on 24 December 2023).</li> </ul>
Population and settlement	<ul style="list-style-type: none"> <li>- Ghana statistical services database.</li> </ul>
Forest-based employment, migration, civil/communal conflicts	<ul style="list-style-type: none"> <li>- Ghana statistical services database;</li> <li>- Other published literature (e.g., GSS, 2000, 2010, 2021).</li> </ul>
Drivers of deforestation, socio-cultural and political views, and stands on deforestation	<ul style="list-style-type: none"> <li>- Field sampling and survey (online and physical) using the literature, interviews, questionnaires.</li> </ul>
Common forest tree species	<ul style="list-style-type: none"> <li>- Field sampling and survey;</li> <li>- The previous literature (published articles and NGOs/Government institutional documents;</li> <li>- Foresters and plant ecologists.</li> </ul>

The harmonization and standardization of belowground carbon values were performed following the descriptions from a recent study published by authors from the country [74]. For the estimated carbon stocks, the data were processed following the international standards for field survey and laboratory analysis [75]. The SOC content of the soil samples was determined by Walkley–Black titrimetry (dichromate oxidation). Other data included bulk density (BD) and coarse fragments (CoF) data, which followed a depth interval of 0–30 cm for the entire of Ghana, and were downloaded as grids and/or layers from the ISRIC soil property data repository (soilgrids.org). The values of BD ( $\text{Mg m}^{-3}$ ) and CoF (%) were extracted from the SoilGrids layers at the geographical sampled points [76]. After the field sampling was conducted based on the sampling locations identified using the GPS, as shown in Figure 2, the samples were taken to the laboratory and analyzed. Using the results that were harmonized and reconciled with the other sources of soil data from the soilgrids, the soil (BG) carbon stocks were estimated using the Global Soil Information Facilities (GSIF; Hengl et al. [77] based on a standardized calculation prescribed by Nelson and Sommers [78] (Equation (1)).

$$\text{BG or soil-Cstock} = (\text{SOCD}/1000) \times (\text{SD}/100) \times \text{BD} \times (100 - \text{CoF}/100) \quad (1)$$

where BG or soil-C stock is the belowground carbon stock, SOCD is the soil carbon density ( $\text{kg m}^{-3}$ ), SD is the soil profile depth (30 cm), and CoF is the coarse fragments (%).

Biomass/vegetation (Aboveground carbon): The carbon emission intensity of forest zone types refers to the carbon emissions per unit of land area, which can reflect the change in carbon emissions from forest zones and its correlation. Here, this was calculated following the work by Li et al. [79] and Shoumik and Khan [80], as shown in Equation (2):

$$C_e = \sum C_f / \sum S_f \quad (2)$$

where  $C_e$  represents the carbon emission intensity of the forest-vegetation zone,  $C_f$  is the carbon emissions of the forest-vegetation zone, and  $S_f$  is the area of the forest zone.

The remotely sensed vegetation indices were used to estimate forest carbon using regression analysis. The normalized difference vegetation index (NDVI) was first computed by applying the data from high-spatial-resolution satellite imagery downloaded from NASA (Table 1), covering the study period. The normalized difference vegetation index was first applied by Li et al. [79], and Shoumik and Khan [80], as shown in Equation (3):

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) \quad (3)$$

NDVI is the most common vegetation index and has a range of from  $-1$  to  $+1$ . NDVI is computed from the visible and near-infrared light reflected by vegetation. Healthy vegetation absorbs most of the visible light it makes contact with and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light. The NDVI map of Ghana was generated using the Landsat-7 ETM+ satellite imagery and ArcGIS 10.5. In all vegetation indices computations, we used the red spectral band and the near-infrared band (NIR-1), because NIR-1-derived vegetation indices demonstrated stronger relationship with carbon compared with NIR-2. The NDVI was also used because it has been well documented as a good measure of biomass and vegetation vigor [79,80]. The reflectance in the vegetation indices was extracted from the satellite data using a window with an average size of  $15 \times 15$  pixel ( $30 \times 30$  m), centered on the GPS location of each field sampled plot.

The previous literature (from published articles and government institutional documents), as well as foresters and plant ecologists, were consulted for the identification of the tree species and drivers of carbon stocks. Data on most of the investigated socioeconomic variables were derived from secondary sources, yet visits to the people and the forest zones prompted the collection of more relevant data and helped to reconcile the information acquired from the secondary sources.

### 2.3. Additional Methods Used for Carbon Stock Estimations

The carbon storage and sequestration model (CSSM) developed under the InVEST software was used in the estimation of carbon stock. InVEST was developed by the Natural Capital Project of Stanford University and presents a compilation of theoretical models that allows for the evaluation of several ecosystem services, including carbon stocks and economic values. The InVEST model was used to determine the spatial distribution of carbon stocks in the terrestrial land model [81]. The model estimates carbon stocks for the aboveground, belowground, and total carbon stock of any study area, based on the aggregated carbon values assigned for each land use–land cover (LULC), which included the forest types in our case. The carbon socks ( $C_i$ ) for LULC type ‘i’ is equal to the sum of aboveground, belowground, dead carbon, and soil carbon for LULC type ‘i’, represented as follows:

$$C_i(\text{above}) + C_i(\text{below}) + C_i(\text{dead}) + C_i(\text{soil}) \quad (4)$$

The total carbon storage ( $C_{\text{total}}$ ) is equal to the sum of carbon density for LULC type i multiplied by the area ( $A_i$ ) for LULC type i, with n as the number of LULC types, in the study.

$$C_{\text{total}} = \sum (i)^n \times (C_i + A_i) \quad (5)$$

It is important to state here that, in the CSSM of InVEST model, the classified images were set as the LULC raster input.

### 2.4. Forests and Other Land Use Classifications

For the remote-sensing- and geospatial-related data, ArcGIS 10.5 [82] was used to project the data to the same coordinate system (WGS\_1984\_UTM\_Zone\_30N). Secondly, the data were reclassified to support LUCC analyses at the regional scale [83]. The land use-cover was classified based on a classification scheme developed by the Food and Agriculture Organization (FAO). The main classes identified during the investigation period included forests, agricultural areas, savannah, mangrove, settlements, open mining



areas, wetlands, waterbodies, and others. The secondary data were reconciled with the field data. All the data were averaged, georeferenced, and classified based on the appropriate forest zones, and for the entire country.

### 2.5. Geospatial and Statistical Analyses

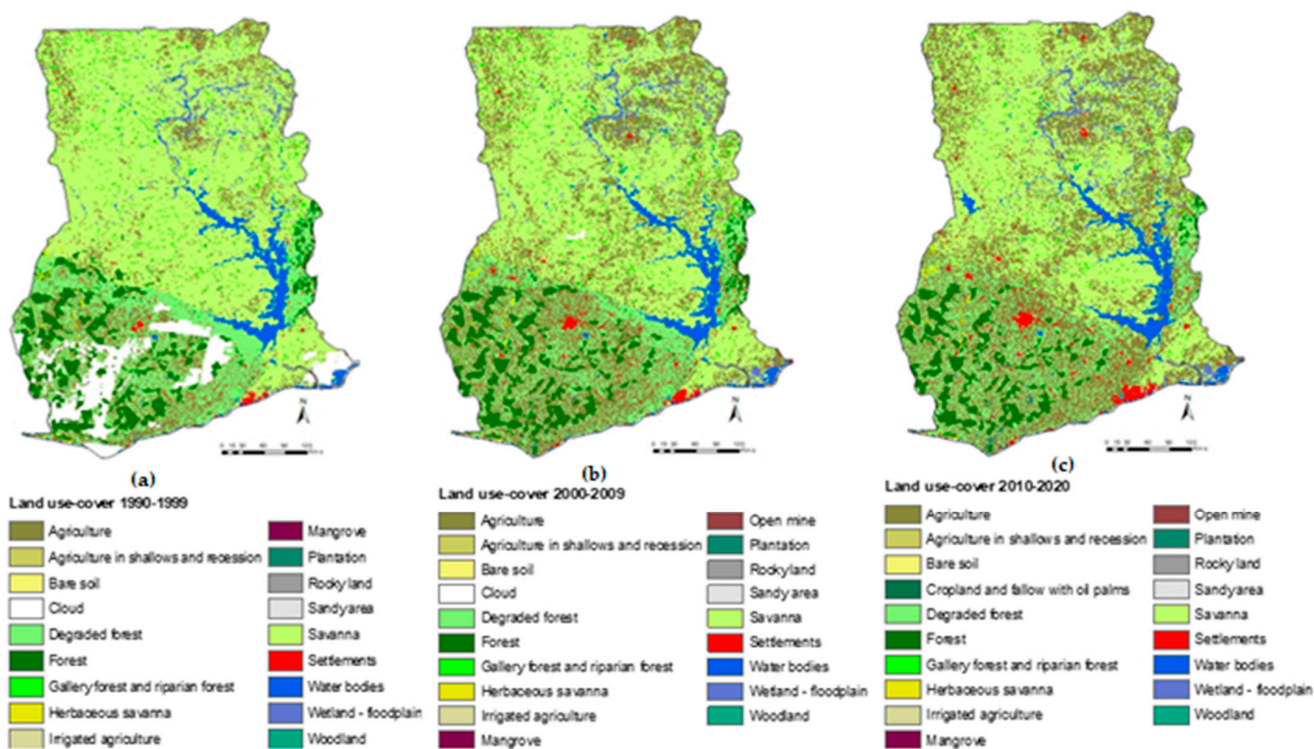
Data were analyzed using IBM SPSS (version 29.0, Armonk, NY, USA), CANOCO (version 5.0, Wageningen, The Netherlands) [84], and ArcGIS (version 10.5, Redlands, CA, USA) [82] software packages. Data were transformed where necessary to meet the requirements and to obtain suitable values for the analyses. For instance, where the units used for soil- or forest-based data varied between data sources, and in years, such data were converted to same units of measurements. The GIS spatial analytical tools were used to model and map the distributions of the forest areas and the carbon stocks in space and time. The multivariate ordination of Canoco 5.0 was used to identify and show the distributional trends of the common forest tree species across the decades and forest belts. To determine the interrelationships among the indicators of sustainable forest bioeconomy and carbon stocks, we used Spearman's correlation analysis because our data (i) tends to show a non-linear relationship, (ii) has outliers that can influence the result, (iii) and has some variables in the ordinal (e.g., GDP and poverty level). The correlation was performed after the ranking, and at significant levels of 0.01 and 0.05, via IBM SPSS 29.0 (SPSS Inc., Armonk, NY, USA) statistical software.

## 3. Results and Discussion

### 3.1. Land Use-Cover Change vs. Carbon Stocks and Emissions

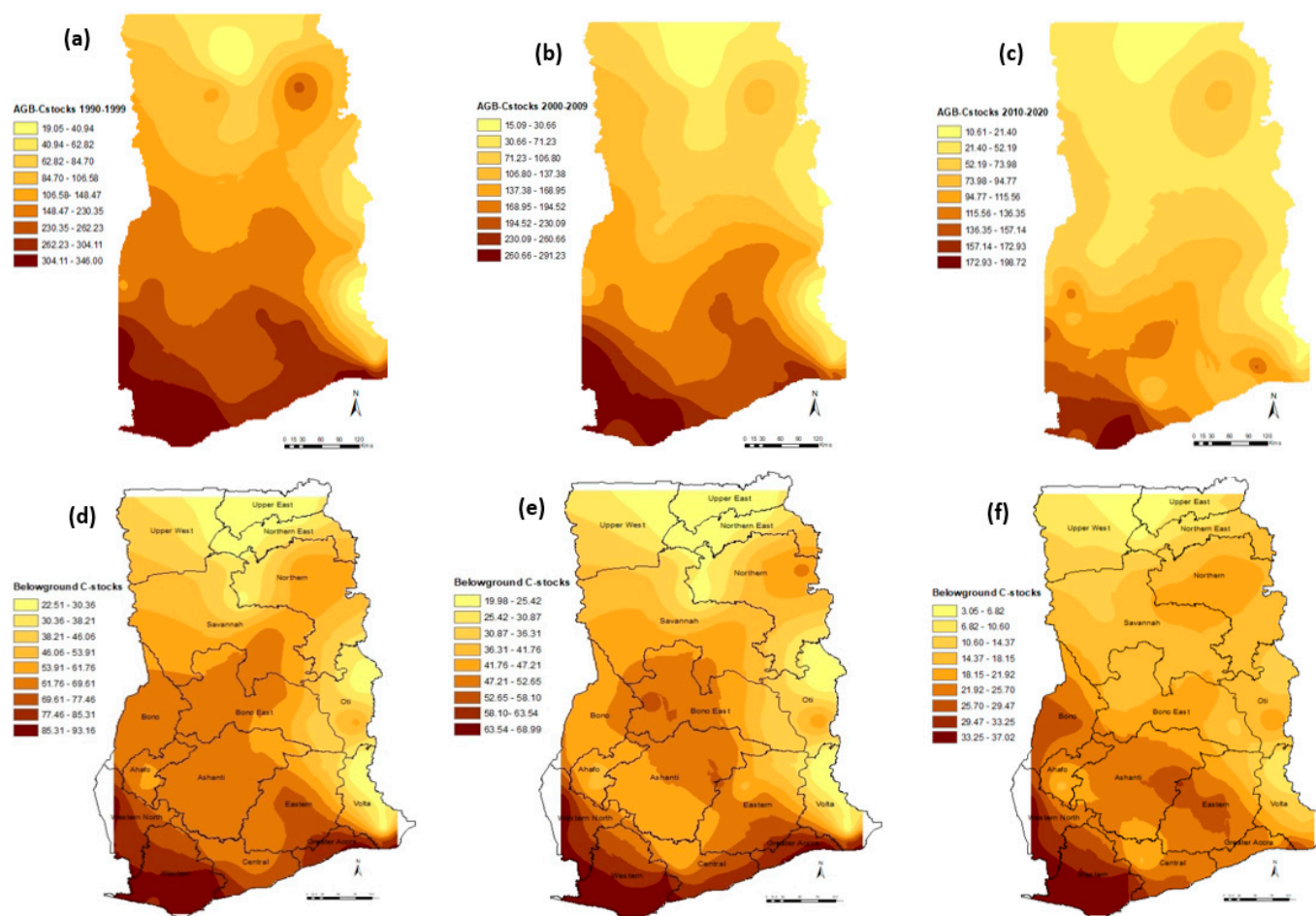
Land use-cover is an essential regulator of C stocks and shifts from one LUC type to another might cause large C fluxes in and out of the terrestrial ecosystem, including forests. Historically, emissions from land have been responsible for a huge percentage of the cumulative human-induced CO<sub>2</sub> emissions. However, land use-cover C emissions are no longer prominent as key forms of human perturbation of the C cycle in most regions, except in tropical developing countries like Ghana. It is in this context that this study investigated the land use-cover changes which have shown tangible transformations between 1990 and 2020 (Figure 3). Larger hectares of forest areas were recorded in 1990–1999, decade 1 (Figure 3a), than were found in either 2000–2009, decade 2 (Figure 3b), or 2010–2020, decade 3 (Figure 3c). In contrast, decade 2 and decade 3 accounted for the largest agricultural and settlement areas, which covered at least 60% of the entire area as compared with decade 1. The results from the c-stocks modeling indicated that both the aboveground biomass carbon stocks (AGB-Cstocks) and the belowground(soil) carbon stocks (BG-Cstocks) varied significantly in space and time (Figure 4). For example, the AGB-Cstocks in decade 1 (1990–1999), decade 2 (2000–2009), and decade 3 (2010–2020) ranged from 19.1–346 Mg C ha<sup>-1</sup>, 15.1–291.2 Mg C ha<sup>-1</sup>, and 10.6–198.7 Mg C ha<sup>-1</sup>, respectively (Figure 4a–c). On the other hand, the belowground carbon stocks ranged from 22.5–93.2 Mg C ha<sup>-1</sup>, 19.9–68.9 Mg C ha<sup>-1</sup>, and 3.1–37.0 Mg C ha<sup>-1</sup> for decade 1, decade 2, and decade 3, respectively (Figure 4d–f). The study further demonstrated that both the AGB-Cstocks and the BG-Cstocks were higher in the moist evergreen and the wet evergreen forest belts relative to the other forest-vegetation belts (Figure 4). Generally, the evergreen forest-vegetation zones had highest carbon stocks; on the other hand, the AGB-Cstocks were higher than the BG-Cstocks, while the values of Cstocks for decade 1 (1990–1999) were higher than those for decade 2 and decade 3. The Cstocks in both the aboveground and belowground decreased every decade. This decrease could be attributed to several reasons, including rapid changes in land use-cover, increases in population, and expansions in agriculture [85–88]. Consistent with this study, other researchers observed a regular change in land use-cover in recent decades relative to past decades, especially in developing nations [57,89–91]. These transitions were attributed to population growth, commercialized agriculture, and unregulated severe deforestation [85,88]. For instance, deforestation was considered the primary cause of land use-cover change in tropical settings, and is typically

a consequence of diverse factors, including population growth, urbanization, agricultural expansion, and logging [85]. Another study in Ghana, which aimed to identify the driving forces of land use-cover changes using a mixed-method approach, observed that rural population growth is the main driver of the changes [88]. Similarly, a study performed in the region to investigate the dynamics of LUCC in Burkina Faso between 1999 and 2011 agrees with our findings that more forest areas were found in previous decades, while the present decades have more agricultural areas due to the growing demand for food as the population increases [86]. In the western region of Ghana, which is covered by evergreen forests, Koranteng et al. [88] discovered significant changes in the landscape from 1990 to 2020. They attributed these changes to deforestation through agriculture.



**Figure 3.** Land use-cover over three decades, 1990–2020, showing average changes between (a) 1990 and 1999, (b) 2000 and 2009, and (c) 2010 and 2020.

The higher Cstocks found in the moist evergreen and the wet evergreen forest belts relative to the other forest-vegetation belts could be attributed to the dense vegetation prevalence in these evergreen forest zones. Studies reported larger Cstocks in dense vegetations due to the higher pools of carbon that were obtained through increased photosynthetic and organic matter mineralization processes, especially in the tropical regions [92–94].



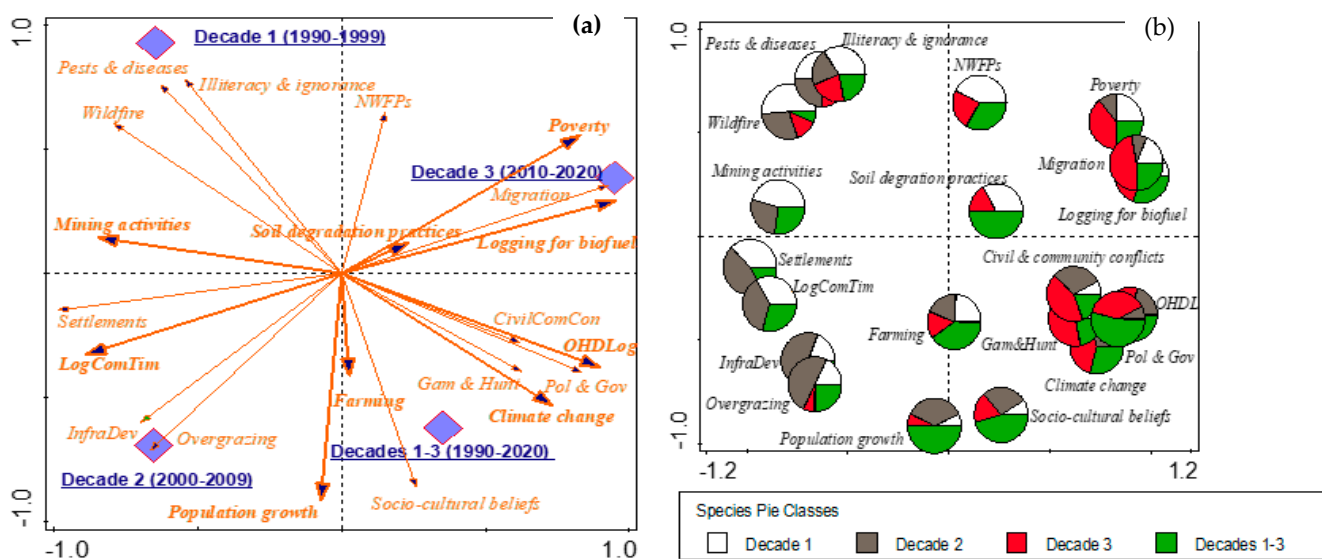
**Figure 4.** Ordinary kriging model showing the spatial distribution and variability of the forests' aboveground carbon stocks for (a) 1990–1999, (b) 2000–2009, and (c) 2010–2020, and in the forests belowground carbon stocks for (d) 1990–1999, (e) 2000–2009, and (f) 2010–2020.

Globally, studies have revealed that carbon stocks are substantially influenced by the changes in land use-cover caused by agriculture, mining, urbanization, and other drivers of deforestation [35,95–99]. For example, Bruinsma [95] reported that the increase in cropping intensification had large effects on soil carbon stocks worldwide. Soil carbon stocks are rapidly released into the atmosphere under constant land use changes, and this has with other environmental implications. Anderson-Teixeira et al. [96] observed that the conversion of forest land to biofuel agriculture resulted in significant carbon loss, an effect that was most pronounced when native forest land was converted to sugar cane agriculture. In Ghana, it was discovered that a corn residue harvest (at 25%–100% removal) consistently resulted in carbon losses averaging 3–8 Mg ha<sup>-1</sup> in the top 30 cm of the soil, which is the cropped layer of the soil [99].

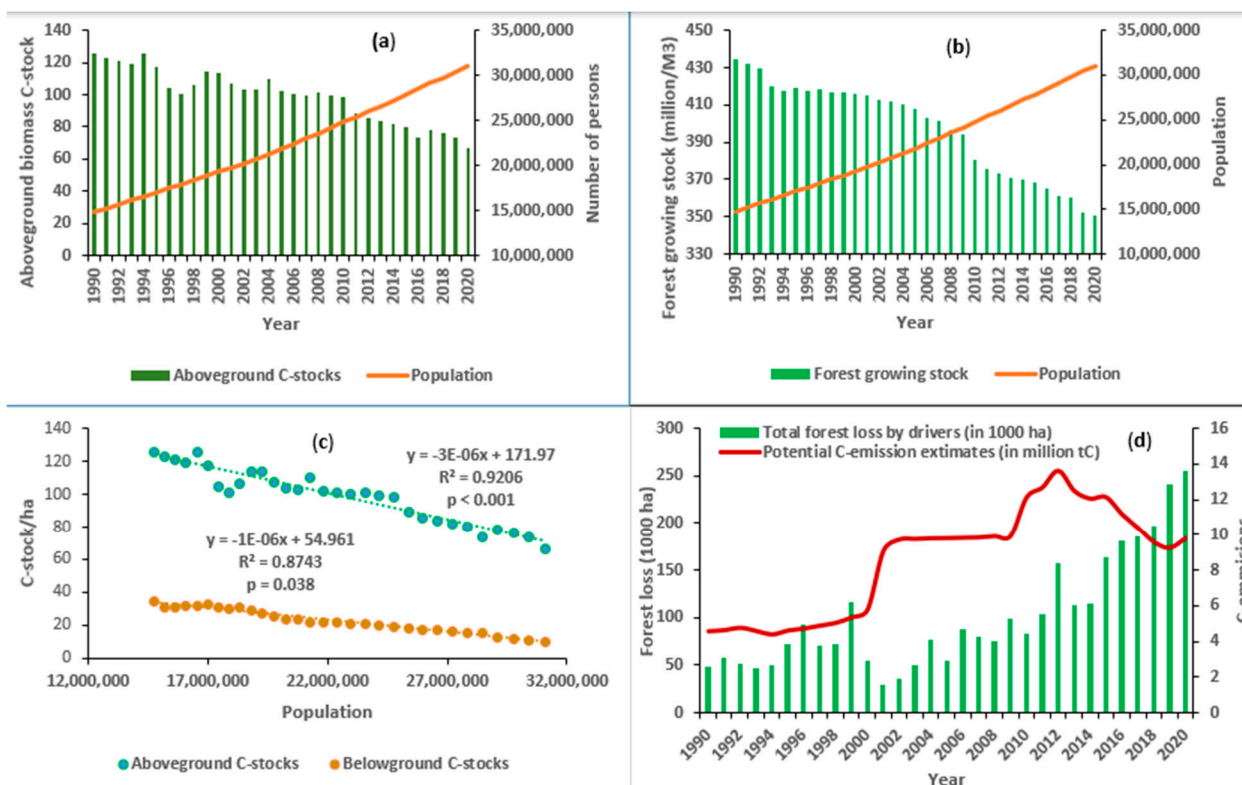
### 3.2. Drivers of Forest Loss and Carbon Fluxes

The study discovered that sustainability in the forest bioeconomy has been negatively impacted in Ghana by many drivers of carbon stocks and deforestation during the three decades of investigation (Figure 5). Although all the drivers had significant effects on carbon fluxes, some of the drivers had a higher impact than others. The study found that population growth, climate change, farming, poverty, logging for biofuel, mining activities, logging for timber, soil degradation practices, and forest logging for other household purposes (Figure 5a) had higher impacts on carbon fluxes and forest loss, which consequently affected SFB. Furthermore, the effects of some of these drivers were significant in

all three decades. For example, politics and governance accounted for 57% of the impacts in 1990–2020 (decades 1–3), while population growth (50%), soil degradation practices (50%), and socio-cultural beliefs (45%) were other long-term drivers of carbon fluxes (Figure 5b). This finding was supported by subsequent results which indicated that, during the study periods, the forest total carbon stock decreased by about 5 t C ha<sup>-1</sup>yr<sup>-1</sup>, forest growing stock decreased by about 2.5 million M<sup>-3</sup> yr<sup>-1</sup>, and the population increased by 2 million persons per year (Figure 6a,b). In addition, significantly strong correlation coefficients were observed between the population and AGB-Cstocks ( $R^2 = 0.921$ ;  $p < 0.001$ ) and BG-Cstocks ( $R^2 = 0.874$ ;  $p = 0.038$ ) (Figure 6c). Furthermore, the study revealed that forest loss caused by these drivers increased with an increase in carbon emissions, especially in the last 10 years (i.e., decade 3) (Figure 6d). An increase in the use of forest as a source of biofuel and non-biofuel between 1990 and 2020 might have been one of the primary drivers for forest loss and the increase in carbon emissions (Figure 7). The result showed that the use of forests for biofuel and non-biofuel increased by more than 50% between 1990–1999 and 2010–2020. This has many causes (increase in population, expanded farming, and a higher demand for food, fodder, and energy) and effects (decline in forest area, growing stock, carbon sinks, and an increase in carbon emissions). Globally, several authors have reported a strong relationship between population growth, forest growing stocks, carbon stocks, and carbon emissions [100–106]. A similar study in Afghanistan reported that the growth in population from 1993 to 2020 caused an increase in the demand for food and fuelwood, which led to an increase in forest loss and carbon emissions but a decrease in carbon stocks [105].



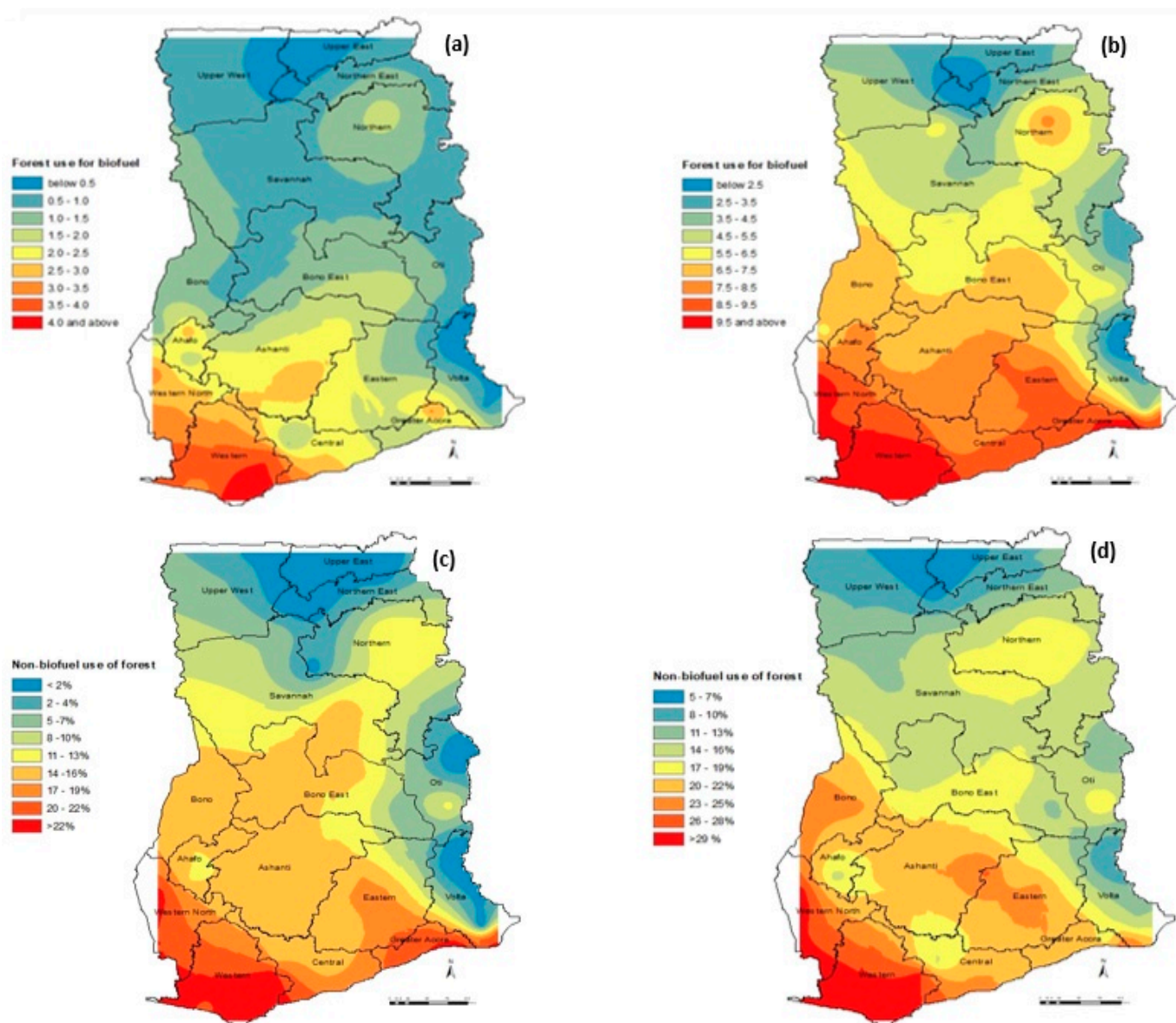
**Figure 5.** Multivariate analysis showing (a) the main drivers of carbon stock as an indicator of sustainable forest bioeconomy and the magnitude of their influence in the various decades, and (b) the sectoral proportion and the distribution of each driver of carbon stocks during the study periods. Diamond symbols in light blue color represent the decades; the arrows’ size and length indicate the extent to which the driver influenced carbon stocks during the study periods. Description of abbreviations: NWFPs = non-wood forest products; LogComTim = logging for commercial purposes such as timber; InfraDev = infrastructural development such as the building of markets, schools, hospitals, roads, etc.; OHDLog = forest deforestation for other household benefits; Civil-ComCon = civil–communal conflicts; Gam & Hunt = wildlife gathering for game and hunting; Pol and Gov = political and governance drivers such as unsound policies, weak governance, lack of law enforcements, landlessness, unclear allocation of rights, impoverishments of the rural people, and lack of investments and financial resources.



**Figure 6.** Relationships between (a) forest total carbon stocks and population, (b) forest growing stocks and population, (c) aboveground and belowground forest carbon stocks, and (d) the total forest loss caused by the drivers and carbon emission estimates covering the period from 1990 to 2020.

Consistent with our findings, Cui et al. [102] found that the drivers of carbon sources increased by almost threefold ( $23,983.7 \times 10^4$  t) in the Beijing–Tianjin–Hebei (BTH) region from 1990 to 2015, whereas carbon sinks have declined rapidly, to one-eighth of the original amount ( $84 \times 10^4$  t), since 1995. Similarly, another study in China observed that the total quantity of carbon stocks decreases by 0.2% with an increase in the annual carbon emissions due to land use changes induced by drivers of forest loss [107]. In Pakistan, the temporal change in forest cover and carbon stock, and trends in corresponding carbon sequestration and emissions, from 1989 to 2018 were estimated. It was found that forest cover and carbon stocks decreased with an increase in carbon emissions from 1989 to 1999, but after 1999, a change in land use policies promoted forest cover and forest carbon stocks, which, in turn, produced low carbon emissions from 2000 to 2018.

Contrary to our study, a study in rural China by Zhang et al. [106] observed that depopulation ( $-14$  million people  $\text{yr}^{-1}$ ) led to extensive AGB-Cstocks of  $0.28 \text{ PgC yr}^{-1}$  between 2002 and 2019. This could be explained by a decrease in the population with good living standards in rural China, while, in Ghana, the rural population grows with the growing rate of poverty, thus leading to deforestation and carbon losses. Similarly, a study in Malaysia concluded that accelerated reforestation and afforestation can enhance carbon stocks and reduce emissions, and, in turn, lead to a sustainable forest bioeconomy [104], but this is difficult to be achieved in Ghana because of the geometrically growing population.

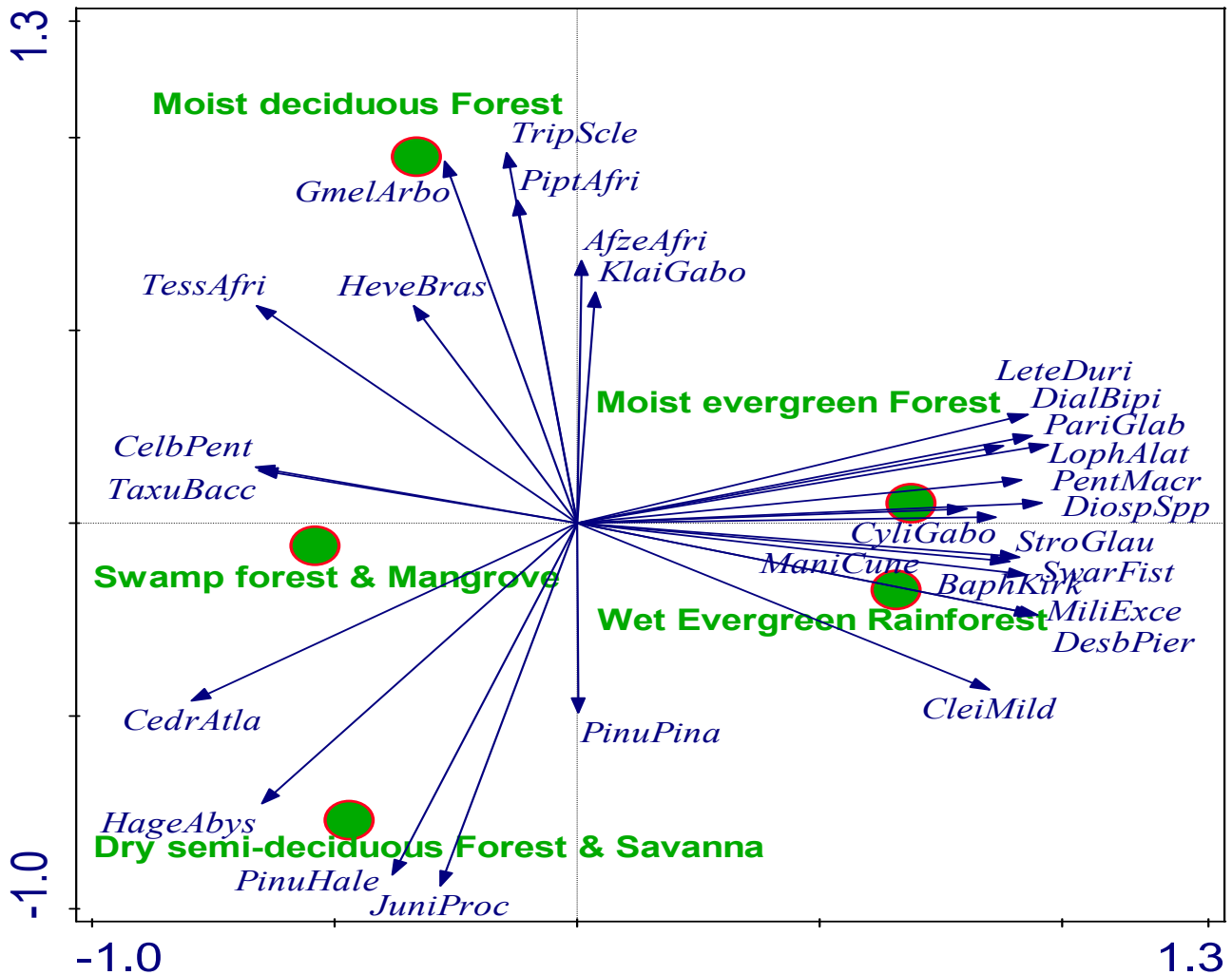


**Figure 7.** Ordinary kriging model showing the spatial distribution and variability (%) in the use of forest and its resources as (a) biofuel from 1990–1999, (b) biofuel from 2010–2020, (c) non-biofuel from 1990–1999, and (d) non-biofuel from 2010–2020.

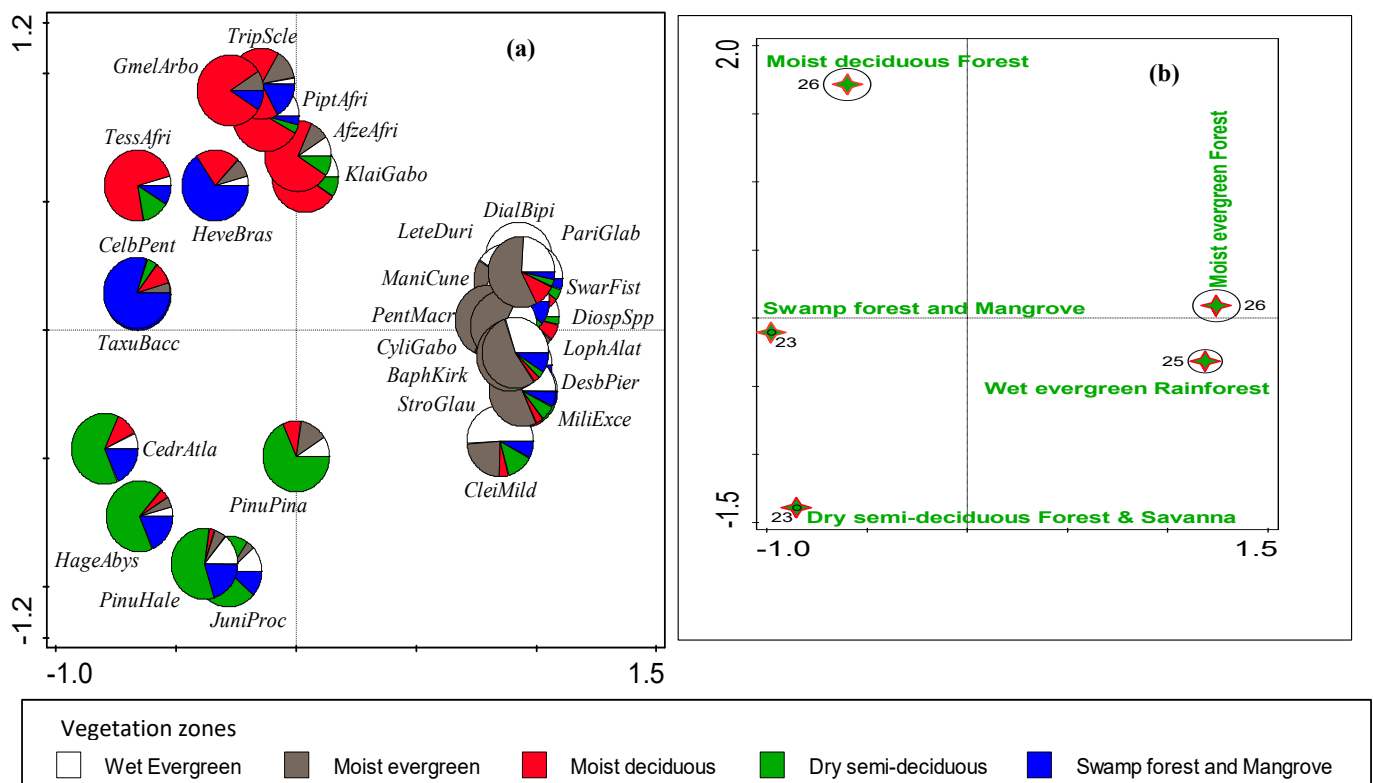
### 3.3. Forest Species and Forest-Vegetation Zones

The influence of forest-vegetation zones and forest tree species on forest growing stocks and carbon fluxes is crucial to understanding the forest bioeconomy [36,108]. Our study indicated that the evergreen forests had more tree species than the other forest-vegetation zones that were investigated (Figures 8 and 9a,b). The presence of *Dialium bipindense*, *Diospyros* spp., *Pentaclethra macropylla*, *Letestua durissima*, *Lophira alata*, *Milicia excels*, *Baphia kirkii*, *Cleistanthus mildbraedii*, *Cylicodiscus gabonensis*, *Desbordesia pierreana*, *Manilkara cuneifolia*, *Parinari glabra*, *Strombosia glaucescens*, *Tessmania africana*, *Klainedoxa gabonensis*, *Azelia Africana* spp., and *Piptadeniastrum africanum* was important. In a recent study, Fleiss et al. [36] identified the relevance of these hardwood species to the forest bioeconomy in Africa because of their potential to increase growing stocks, the provision of reliable biofuel at wet and dry seasons, and their high carbon content [109]. Further, in Cambodia, similar species in the families of *Caesalpinaceae*, *Ebenaceae*, and *Rosaceae* such as *Azelia*, *Diospyros bejaudi* Lecomte, *Diospyros crumenata*, *Diospyros nitida*, *Diospyros helferi*, and

*Parinari annamensis* were observed to be key determinants of the forest bioeconomy due to their high carbon stocks [100]. The presence of evergreen forests (i.e., the moist evergreen and the wet evergreen), which have more tree species than the other forest-vegetation zones enhanced Cstocks in these forest belts as compared to the savannah, as well as the swamp forest and mangrove belts [94].



**Figure 8.** Multivariate ordination plot showing the vegetation zones and their associated common tree species, which promoted carbon fluxes vis-à-vis sustainable forest bioeconomy for each vegetation zone during the study period. Description of the abbreviations are as follows for each species: *Dialium bipindense* = DialBipi; *Diospyros* spp. = DiospSpp; *Pentaclethra macrophlla* = PentMacro; *Letestua durissima* = LeteDuri; *Lophira alata* = LophAlat; *Milicia excels* = MiliExce; *Baphia kirkii* = BaphKirk; *Cleistanthus mildbraedii* = CleiMild; *Cylicodiscus gabonensis* = CyliGabo; *Desbordesia pierreana* = DesbPier; *Manilkara cuneifolia* = ManiCune; *Parinari glabra* = PariGlab; *Strombosia glaucescens* = StroGlau; *Swartzia fistuloides* = SwarFist; *Tessmania Africana* = TessAfri; *Klainedoxa gabonensis* = KlaiGabo; *Azelia africana* spp = AfzeAfri; *Piptadeniastrum africanum* = PiptAfri; *Triplochiton scleraxylon* = TripScle; *Gmelina arborea* = GmelArbo; *Juniperus procera* = JuniProc; *Pinus halepensis* = PinuHale; *Pinus pinaster* = PinuPina; *Cedrus atlantica* = CedrAtla; *Hagenia abyssinica* = HageAbys; *Taxus baccata* = TaxuBacc; *Hevea brasiliensis* = HeveBras; *Celba pentandra* = CelbPent.



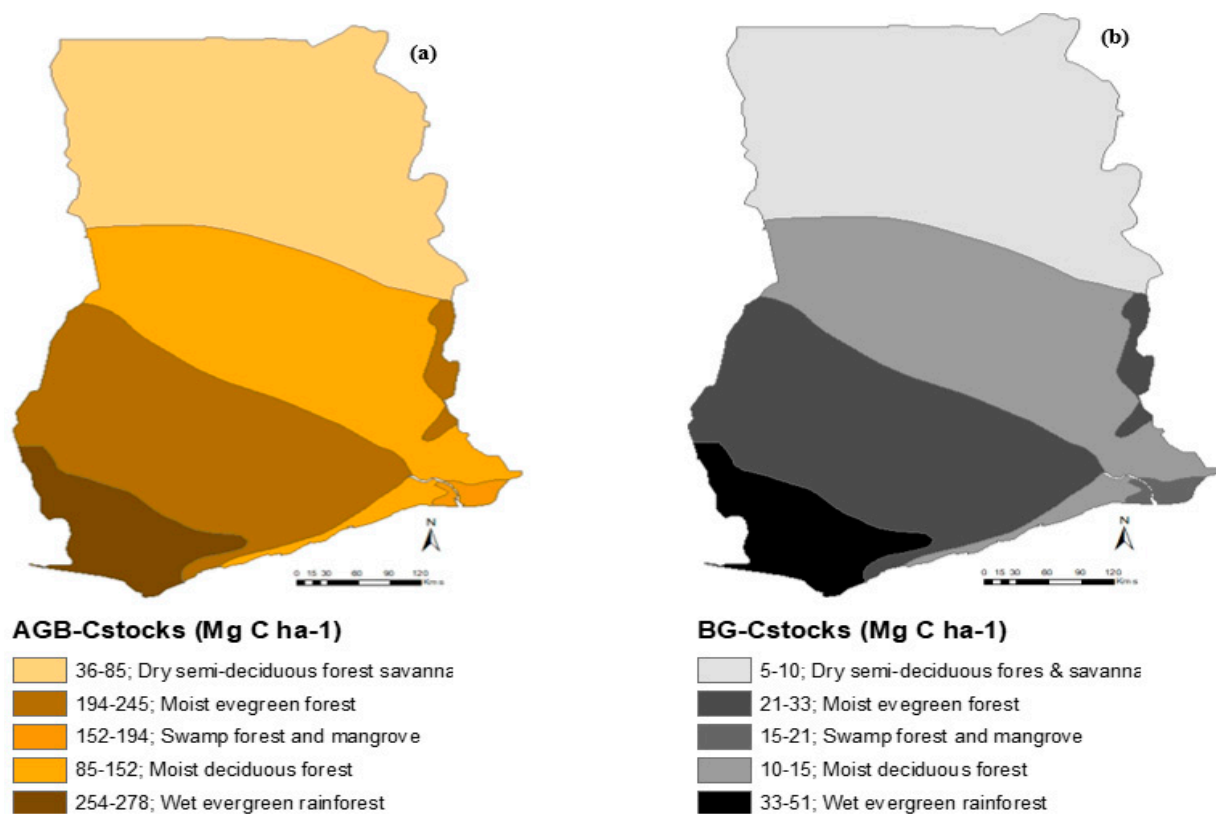
**Figure 9.** Multivariate ordination plot showing (a) the proportion of the major forest tree species that contribute substantially to peoples' livelihood and the forest bioeconomy, and (b) an ordination plot showing the vegetation zones and the associated common tree species that promote carbon fluxes vis-à-vis sustainable forest bioeconomy for each vegetation zone during the study period. A description of the abbreviations is provided in Figure 8.

A study in Zambia by Pelletier et al. [101] affirmed that the biomass gains and carbon sink were concentrated in several dominant species, including the *Fabaceae*, which is a subfamily of *Caesalpinioideae*, although some dominant species showed threats of over-exploitation. In Brazil, Maximo et al. [110] reiterated the importance of the tropical forest species in the production of bioenergy, wood-based textile fiber, lignin-based products, pulp, and paper, which are of great benefit to the SFB of the country.

### 3.4. Carbon Stocks and Other Variables Associated with Forest Bioeconomy

The result revealed that the average AGB-Cstocks were higher than the BG-Cstocks across the forest-vegetation zones (Figure 10a,b). It was also found that, generally, the carbon stocks decreased from the south and southwest to the north, which is probably attributed to a decrease in rainfall in the southern compared to the northern part of Ghana. This agreed with the findings of a previous work in the country [74]. Our study also showed that a significant positive relationship ( $R = 0.87$ ;  $p < 0.001$ ) was recorded between AGB-Cstocks and BG-Cstocks during the study (Table 2). Further, significantly strong negative correlations were recorded between population growth and AGB-Cstocks ( $R = -0.96$ ) and BG-Cstocks ( $R = -0.81$ ). The use of forest for biofuel had significant correlations with all the investigated variables of forest bioeconomy. Previous studies have investigated the variability between aboveground biomass carbon and belowground carbon contents in different forms of land use-cover [111,112]. In Malaysia, Raihan et al. [112] reported higher AGB-Cstocks than BG-Cstocks. In support of the findings of this study, Omar et al. [113] and Matthew et al. [114] found higher contents of aboveground carbon than belowground carbon, with net differences of at least 60%.





**Figure 10.** Average carbon stocks in (a) aboveground biomass and (b) belowground (soil) in the forest-vegetation zones from 1990 to 2020.

In contrast to the findings of this study, Xu et al. [111] reported higher carbon stocks belowground when compared with the aboveground content. Many factors, such as vegetation species, altitude, and climatic and land use management, could be the reasons for the discrepancy between the results. In our study, dead woods are often used for domestic energy, instead of being allowed to decompose and enrich the soil with SOM and carbon. Additionally, the non-biofuel use of forests (such as hunts for mushrooms, dye, herbal leaves, saps, barks, and roots) in Ghana limits the accumulation of carbons in the soil. Furthermore, Xu et al. [111] found higher BG-Cstocks than AGB-Cstocks in the Qinghai–Tibet plateau’s temperate semi-arid regions, which were colder and higher in altitude than our study in Ghana. Furthermore, the vegetation species in our study is characterized by evergreen potential, as such litter falls were substantially reduced.

In line with our findings, various studies in different regions have reported correlations between population growth, poverty, forest area, forest growing stocks, the use of forest as biofuel, carbon stocks, and carbon emissions [99–106]. An increase in population, in most cases, leads to poverty, which consequently poses threats to the forest resources and at the long-term influences on the forest ecosystem services and forest bioeconomy.

**Table 2.** Summary of the correlation analysis for the variables that are linked to carbon stocks and forest bioeconomy in Ghana (2010–2020).

	Pop Ulation	AGB Cstocks	BG C-Stocks	For CoGDP	C- Emission	For GroStok	For Area	For Loss	Tre CovLoss	Pov Rate	Rainfall	Temp	For Biofuel	ForNon Biofuel
Population	1													
AGB C-stocks	−0.96 *	1												
BG C-stocks	−0.81 *	0.87 *	1											
ForCoGDP	−0.76 *	0.69 *	0.17	1										
C-emission	0.63 *	−0.86 **	−0.61	−0.73 *	1									
ForGroStok	−0.81 *	0.95 *	0.95 *	0.75 *	−0.41	1								
ForArea	−0.94 **	0.89	0.87	0.61 *	−0.84 **	0.91 *	1							
ForLoss	0.78 **	−0.80 *	−0.76 *	−0.53 *	0.96 *	−0.77 *	−0.60 *	1						
TreCovLos	0.89 **	−0.91	−0.84	−0.66 *	0.75	−0.94	−0.84	0.83 *	1					
PovRate	0.63 *	−0.54	−0.47	−0.33	0.83 *	−0.62	−0.70 *	0.67 *	−0.55	1				
Rainfall	0	0.52	0.28	0.14	0	0.78	0.67	−0.02	0	0	1			
Temp	0	0.45	0.32	0.02	0.01	0.4	0.51	0.16	−0.03	0	0.43	1		
ForBiofuel	0.89 **	−0.82 *	−0.87 *	−0.71 *	0.92 **	−0.86 *	−0.78 *	0.95 **	0.79 *	0.65 *	−0.07 *	−0.15 *	1	
ForNonBiofuel	0.68 *	−0.19	−0.89	−0.65	−0.08	−0.75 *	0.59	0.06	−0.49	0.58	−0.31	−0.24	0.57	1

\* = Correlation was significant at the 0.01 *p*-value; \*\* = correlation was significant at the 0.05 *p*-value. Description of the abbreviations: AGB Cstocks = carbon from the trees' aboveground biomass; BG C-stocks = belowground carbon, which represents soil carbon; ForCoGDP = forest contribution to GDP; C-emission = carbon emissions, mainly from deforestation; ForGroStok = forest growing stocks; ForArea = forest area; ForLoss = forest loss; TreCovLos = tree cover loss; PovRate = poverty rate; Temp = temperature rate; ForBiofuel = forest use as biofuel; ForNonBiofuel = forest use for non-biofuel.

### 3.5. Soil Organic Carbon Stocks, Soil Characteristics, and SDGs

In nine of the SDGs that are most related to SOC, the results revealed a significant impact of increased SOC stocks (Table 3). All the respondents reported that an increase in soil organic carbon stocks had significant effects on SDG 2 (Zero Hunger), SDG 3 (Good Health and Well Being), SDG 13 (Climate Action), and SDG 15 (Life on Land). Similarly, at least 60% of the sampled population affirmed that increased soil organic carbon stocks had significant effects on SDG 1 (No Poverty), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible consumption and production). It was also indicated that SOC stock significantly impacted soil health and soil biota. Many studies have observed a relationships between SOC stocks and SDGs in different parts of the world [22–27]. Though there is no direct link with SOC for most of the SDGs, soils or SOC can promote the attainment of many of the SDGs, especially those related to climate, food, health, land management, and water [22,27], as demonstrated in this current study.

**Table 3.** Increased soil organic carbon stocks and their effects on soil characteristics and SDGs.

Indicators	Very Significant	Significant	No Idea	Insignificant	Very Insignificant
Soil characteristic					
Soil health	11 (55%)	8 (40%)	1 (5%)	0	0
Soil biota	9 (45%)	9 (45%)	2 (10%)	0	0
Erosion risk	0	1 (5%)	4 (20%)	7 (35%)	8 (40%)
Storage, filtering and transformation	10 (50%)	7 (35%)	3 (15%)	0	0
CO <sub>2</sub> sequestration	6 (30%)	5 (25%)	6 (30%)	2 (10%)	1 (5%)
Water holding capacity	8 (40%)	6 (30%)	4 (20%)	1 (5%)	1 (5%)
SDGs					
SDG 1 (No Poverty)	9 (45%)	5 (25%)	4 (20%)	1 (5%)	1 (5%)
SDG 2 (Zero Hunger)	12 (60%)	8 (40%)	0	0	0
SDG 3 (Good Health and Well Being)	11 (55%)	8 (40%)	1 (5%)	0	0
SDG 4 (Quality Education)	0	0	0	0	20 (100%)
SDG 5 (Gender Equality)	0	0	5 (25%)	7 (35%)	8 (40%)
SDG 6 (Clean Water and Sanitation)	6 (30%)	7 (35%)	5 (25%)	2 (10%)	0
SDG 7 (Affordable and Clean Energy)	5 (25%)	9 (45%)	3 (15%)	2 (10%)	1 (5%)
SDG 8 (Decent Work and Economic Growth)	4 (20%)	5 (25%)	7 (35%)	3 (15%)	1 (5%)
SDG 9 (Industry Innovation and Infrastructure)	5 (25%)	5 (25%)	6 (30%)	2 (10%)	2 (10%)
SDG 10 (Reduced inequality)	0	0	0	0	20 (100%)
SDG 11 (Sustainable Cities and Communities)	5 (25%)	7 (35%)	5 (25%)	2 (10%)	1 (5%)
SDG 12 (Responsible consumption and production)	6 (30%)	11 (55%)	2 (10%)	1 (5%)	0
SDG 13 (Climate Action)	12 (60%)	8 (40%)	0	0	0
SDG 14 (Life Below Water)	0	0	5 (25%)	6	9
SDG 15 (Life on Land)	17 (85%)	3 (15%)	0	0	0
SDG 16 (Peace, justice and strong institutions)	0	0	0	0	20 (100%)
SDG 17 (Partnerships for the goals)	0	0	0	0	20 (100%)

### 3.6. Limitations of the Study

Notwithstanding that the study achieved its objectives, it is not devoid of some limitations. One of the major limitations of the study was the total number of participants whose opinions were sought. The choice of only 20 interviewees across the five forest-vegetation zones seems to not be a large enough sample size but, because of the financial constraints involved, only 20 persons were interviewed. Further, the sampling locations did not reveal a perfectly even distribution across the study area and within the forest zones. This limitation was primarily caused by the poor geographical terrains of some locations,

which made easy mobility and access more difficult. In addition, this study involved biophysical, economic, and social factors, which made it a multidisciplinary issue with many variables that had to be included. Only a few of the variables were included in the study because not all the indicators can be investigated at the same time. An unconsidered variable might, in reality, have a more significant influence on Cstocks, SDGs, and FBe than some of the chosen variables.

#### 4. Conclusions

Due to the increasing population in Ghana, forests are being lost as they are either directly used as sources of energy or income or were converted to other land uses to meet the higher demands for food, settlement, urbanization, and other infrastructures. The variability in AGB-C and BG-Cstocks was also estimated for three decades. Forest loss showed an increase over time, with decade 1 (1990–1999) having larger forest areas than the subsequent decades. Carbon stocks were higher in the south, with a substantial decrease towards the north, which can be attributed to dense forest vegetation due to the more favorable climate, such as the higher rainfall in the moist evergreen and the wet evergreen forest zones relative to the northern part of the country. In addition to the increased population and increase in farming, politics and socio-cultural beliefs were among the long-term drivers of carbon fluxes, which serve as strong determinants of a sustainable forest bioeconomy in the country. This is because, in addition to some peoples' preference for forest-based resources and the unsustainable exploitation, the government showed a lackadaisical attitude to addressing the situation with stringent actions and policies.

The study demonstrated that the decrease in Cstocks between 1990 and 2020 is related to an increase in population and agriculture, leading to a decrease in forest area, and growing stock, with an increase in carbon emissions, which consequently affects sustainable forest bioeconomy in Ghana.

Although, based on time, population was a key driver of Cstocks, the variability in the quantity of Cstocks between the forest-vegetation zones could be best explained by the richness and density of the plants, rather than either the population or socioeconomic status of the people. The evergreen forest belts had more trees leading to more Cstocks; however, if the moist deciduous forest, the dry semi-deciduous forest and savannah, and the swamp forest and mangrove belts are sustainably managed, their Cstocks will increase over time.

The study also revealed that the increase in Cstocks contributed to the realization of many SDGs, especially SDGs 1, 2, 3, 6, 7, 11, 12, 13, and 15, which, in turn, support a sustainable forest bioeconomy.

Conclusively, this study observed that, during the three decades, the decrease in Cstocks was influenced by the increase in population, which caused a decrease in forest area, and consequently impacted the sustainable forest bioeconomy of the country. The objective of the study was to evaluate the potential of carbon stocks (Cstocks) and variability for SFB, and was satisfactorily achieved. The dynamics of Cstocks were observed across the forest-vegetation zones, as the carbon quantities also demonstrated a temporal variability. The forest zones that have higher Cstocks were found to provide more SDGs, consequently promoting SFB. The work might support the government in enacting and adjusting forests and land use policies, to refine their carbon emission reduction strategies, and to construct and implement better regulations by fully consulting and incorporating the forest-dependent communities. As a large population of people who greatly depend on forests live in rural areas, collaborations (locally, nationally, and multisectoral-based) are necessary. Additionally, economic diversification, and rural education are also needed to promote the awareness, growth, and benefits of carbon stocks as a component of SFB in the country. Furthermore, future research should focus on the comprehensive valuation of individual tree species, carbon stocks, biodiversity, and other forest ecosystem services to improve the competitiveness of preserving forests, thereby promoting SFB in the country.

The potential of the most common tree species to achieve the SDGs vis-à-vis SFB will be studied in subsequent research.

**Author Contributions:** Conceptualization, I.N. and M.H.; methodology, C.N.; software, C.N. and B.E.D.; validation, all authors; formal analysis, C.N.; investigation, I.N. and C.N.; resources, I.N. and C.N.; data curation, C.N. and B.E.D.; writing—original draft preparation, C.N. and I.N.; writing—review and editing, all authors; visualization, all authors; supervision, M.H.; project administration, I.N. and M.H.; funding acquisition, I.N. and M.H. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the processing of data relative to different sources—some of them were retrieved throughout extensive interview campaigns and others through institutional databases, while some were from the published literature.

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## Appendix A

**Table A1.** Forest-vegetation belts, regions and the geographical coordinates for the sampling points.

Forest-Vegetation Belts	Regions	Latitude	Longitude
Wet evergreen rainforest	Western region	5.39599	−2.53939
Wet evergreen rainforest	Western region	4.820614	−2.0327
Wet evergreen rainforest	Western region	5.419696	−1.64301
Wet evergreen rainforest	Western region	5.418745	−1.63782
Wet evergreen rainforest	Western region	4.96286	−2.39281
Wet evergreen rainforest	Western region	5.38217	−2.54018
Wet evergreen rainforest	Western north region	5.986077	−2.7766
Wet evergreen rainforest	Western north region	6.474528	−2.96298
Wet evergreen rainforest	Western north region	6.255623	−2.91215
Moist evergreen (dry and thick) forest	Central region	5.55462	−1.44816
Moist evergreen (dry and thick) forest	Central region	5.495595	−1.04152
Moist evergreen (dry and thick) forest	Central region	5.630502	−1.60065
Moist evergreen (dry and thick) forest	Eastern region	6.546458	−0.33025
Moist evergreen (dry and thick) forest	Eastern region	6.666549	−0.60226
Moist evergreen (dry and thick) forest	Eastern region	6.716578	−0.88435
Moist evergreen (dry and thick) forest	Ahafo region	6.666549	−2.58694
Moist evergreen (dry and thick) forest	Ahafo region	7.046641	−2.57687
Moist evergreen (dry and thick) forest	Ahafo region	7.136618	−2.21418
Moist evergreen (dry and thick) forest	Ashanti region	6.246104	−1.34778
Moist evergreen (dry and thick) forest	Ashanti region	6.696567	−2.10336
Moist evergreen (dry and thick) forest	Ashanti region	7.166607	−0.7836
Moist evergreen (dry and thick) forest	Bono region	7.056041	−2.88434
Moist evergreen (dry and thick) forest	Bono region	8.089444	−2.42917
Moist evergreen (dry and thick) forest	Bono region	7.596912	−2.28934
Moist deciduous (NW and SE types) forest	Bono east region	7.966366	−0.52589
Moist deciduous (NW and SE types) forest	Bono east region	7.581511	−0.18408
Moist deciduous (NW and SE types) forest	Bono east region	7.904813	−1.84654
Moist deciduous (NW and SE types) forest	Oti region	7.612312	0.390794

Table A1. Cont.

Forest-Vegetation Belts	Regions	Latitude	Longitude
Moist deciduous (NW and SE types) forest	Oti region	8.143279	0.429637
Moist deciduous (NW and SE types) forest	Oti region	8.673542	0.243193
Moist deciduous (NW and SE types) forest	Volta region	6.061995	0.763683
Moist deciduous (NW and SE types) forest	Volta region	7.094401	0.461256
Moist deciduous (NW and SE types) forest	Volta region	6.833926	0.429637
Dry semi-deciduous forest and savanna	Savannah region	8.888897	−0.86903
Dry semi-deciduous forest and savanna	Savannah region	9.804188	−1.56147
Dry semi-deciduous forest and savanna	Savannah region	9.146967	−1.94689
Dry semi-deciduous forest and savanna	Northern region	9.771445	0.173559
Dry semi-deciduous forest and savanna	Northern region	9.886262	−0.3547
Dry semi-deciduous forest and savanna	Northern region	9.390705	−1.17107
Dry semi-deciduous forest and savanna	Northern east region	10.1599	−1.24719
Dry semi-deciduous forest and savanna	Northern east region	10.59689	−0.38406
Dry semi-deciduous forest and savanna	Northern east region	10.28482	−1.48202
Dry semi-deciduous forest and savanna	Upper west region	10.89618	−1.95801
Dry semi-deciduous forest and savanna	Upper west region	10.54698	−2.16744
Dry semi-deciduous forest and savanna	Upper west region	10.02869	−2.04686
Dry semi-deciduous forest and savanna	Upper east region	10.62808	−0.97429
Dry semi-deciduous forest and savanna	Upper east region	10.88995	−1.35509
Dry semi-deciduous forest and savanna	Upper east region	10.77775	−0.35233
Swamp forest and mangrove	Great Accra region	5.883369	0.441012
Swamp forest and mangrove	Great Accra region	5.984483	0.161449
Swamp forest and mangrove	Great Accra region	5.815299	0.052582
Swamp forest and mangrove	Great Accra region	5.847517	0.771192
Swamp forest and mangrove	Great Accra region	5.964303	0.941969
Swamp forest and mangrove	Great Accra region	5.889987	0.611088
Swamp forest and mangrove	Great Accra region	5.815662	0.739171

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