Dissertation Thesis

Analysis of sustainability of production processes and proposal of indicators of sustainable development in forest bioeconomy

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DECLARATION

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DEDICATION

I dedicate this study to my all those who have been my source of inspiration and gave me the strength when l thought of giving up. I dedicate these studies to my mother Elizabeth Kankam, my wife Christiana Amoakoaa Addo my son and daughter Kofi Agyei Nyarko and Nana Yaa Nyarko. Finally, to my late father Mr. Charlse Kwaku Fokuo. I hope this achievement will fulfil the dream they envisioned for me.

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ABSTRACT

Sustainable development in a forest bioeconomy is a system geared towards improving people's socioeconomic and environmental health through forestry. Sustainable forest bioeconomy (SFB) as a multidimensional approach for establishing mutual benefits between forest ecosystems, environment, economy, and human is a nature-based solution for promising future.

Thus, a good knowledge about the forest bioeconomic system will enhance people to become custodians of the forest ecosystems instead of being destroyers. For example, Africa including Ghana accounted for the highest forest loss in the global records in the last 3-5 decades which might be attributed to many factors including population growth, poverty, high illiteracy, and political irresponsibility as the major causes. These have adverse effects on the indicators of sustainable forest bioeconomy and development such as GDP, forest area, and forest carbon stocks. This thesis first focused on entire Africa by quantifying the volume of wood charcoal production, its socio-economics, and environmental impacts of the long-term deforestation and forest degradation in the region. After the holistic assessment of the wood charcoal production in Africa, the work became narrowed to only Ghana because of the time scale and data needs and dearth to study entire Africa.

Thus, the second focus of the thesis was on the assessment of the indicators and drivers of a sustainable forest bioeconomy in Ghana for three decades (1990–2020), and the key indicators and drivers examined were areas of forest cover, export quantity, export value, GDP, human population, climate season, average income per citizen, literacy rate, and others. Similarly, the third phase of the thesis comprehensively focused on carbon stocks (Cstocks) which is a major indicator of sustainable

development for forest bioeconomy. Cstocks was chosen because of its high inter/intra-links with other indicators, as well as its dynamics and strong potential in influencing the physical, social, and economic environment. For instance, Cstocks to a large extent controls climate change, nutrients, water, trees, and other biophysical indicators of the forest ecosystems, consequently, regulates the condition of the forests ecosystem services, as well as the people's livelihoods and well-being.

Therefore, both primary and secondary data from the field, national and international databases including historically robust data from the databases of UN-FAO, FAOSTAT, World Bank, International Energy Agency (IEA), United Nations Statistics Division, UN-DESA energy statistics yearbook, and the Forest Resources Assessment (FRA) were used. The data were analyzed using different statistical and geospatial software packages such as IBM SPSS 29.0, CANOCO 5.0, and ArcGIS 10.5. In the study covering entire Africa, it was found that East Africa had the highest average wood charcoal production which was 32,058,244 tonnes representing 43.2% of the production whereas West Africa had 23,831,683 tonnes denoting 32.1%, while other regions accounted for less than 12%. On the studies focusing on Ghana forests' contributions to GDP vary between the forest–vegetation belts and regions and decreased rapidly from 1990 to 2020. The highest drivers of deforestation were population growth, agricultural activities, and commodity-driven deforestation. Cstocks had significant negative correlation with population growth, carbon emissions, forest growing stock, forest loss and use of forest for biofuel.

Findings from the thesis will significantly help to bring lasting solutions to deforestation and enhance the sustainable forest bioeconomy. The study has unveiled remote drivers of forest loss that have been long overlooked by previous studies. A sustainable enlightenment campaign and routine informal education of the rural people

are highly necessary. This is because some of the peoples' reasons for deforestation and preference for forest products compared with modern resources seem convincing and logical.

Key words: Forest bioeconomy, carbon stocks, sustainable development, forest bioeconomy indicators, climate change, deforestation.

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LIST OF ACRONYMS

BE	**Bioeconomy**
FBe	**Forest bioeconomy**
SFB	**Sustainable forest bioeconomy**
FAO	**Food and agricultural organization**
Cstocks	**Carbon stocks**
ES	**Ecosystem services**
EU	**The European union**
GDP	**Gross domestic product**
GHG	**Greenhouse gas**
GVA	**Gross value added**
GWP	**Global warming potential**
IEA	**International energy agency**
SPSS	**Statistical Package for the Social Sciences**
SOC	**Soil organic carbon**
SOM	**Soil organic matter**
AGB	**Above ground biomass**
BGB	**Below ground biomass**
SDGs	**Sustainable development goals**
GSS	**Ghana statistics services**
RE	**Renewable energy**
SIA	**Sustainability impact assessment**
IPCC	**Intergovernmental Panel on Climate Change**
UNFCCC	**UN Framework Convention on Climate Change**
CO2	**Carbon dioxide**
C	**Carbon**
REDD+	**Reducing Emissions from Deforestation and Forest Degradation plus**
BD	**Bulk density (of soil)**
GPS	**Global positioning system**
LUCC	**Land use-land cover change**
PgC yr−1	**Petagram of Carbon per year: 1 Pg = 1015 g = 1 billion metric tonnes.**
ppm	**Parts per million**
Ha or ha	**Hectare**
NPP	**Net primary productivity**
AFOLU	**Agriculture, Forestry, and Other Land Use**

CHAPTER ONE

1 BACKGROUND OF THE STUDY

This chapter discusses the background of the study focusing on forest productions, forest bioeconomy and associated indicators for sustainable development specifically in Ghana, and generally in Africa. The chapter further discusses the study's aim, objectives, and significance of the study.

1.1 Introduction

The concept of the forest bioeconomy has gained reputation in various research over the last decade and is frequently argued to be a key part of the solution to multiple grand challenges in the world now a days. Forests and the forest sector are expected to provide a significant contribution to a bioeconomy sector (EU Commission 2012a). Despite this, there seems to be concerns what forest bioeconomy specially in developing countries such as Ghana.

World Bank report (2001) says that about 1.6 billion rural poor people globally have their livelihood protection from forest. Forest resources play an important role in protecting the environment and in sustainable development (Boon et al. 2009). This work seems to address the analysis of sustainability of the primary forest production processes and propose some indicators to monitor the sustainable development of the forest bioeconomy.

Meanwhile, there is not enough research done or published about forest bioeconomy in Ghana. Others review the role of sustainability in policy documents regarding forest bioeconomy. All in all, they stress the importance of considering sustainability and develop indicators when it comes to forest bioeconomy.

1.2 Overview of the Problem

Bioeconomy can be delineated from the broader concept of a green economy which follows the definition of United Nations Environment Programme (UNEP), namely one “that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities” (UNEP 2010). Consequently, this paper seeks to develop our understanding of what the concept of forest bioeconomy means by exploring the roots, uptake, and contents of the term “forest bioeconomy” and how we can develop various indicators to measure sustainability of this sector.

Ghana’s forests and the forest-based sector plays a central role in a bioeconomy. The sector provides materials like wood and non-wood products, bioenergy and a wealth of other regulating and cultural ecosystem services. Sectors considered in a forest bioeconomy analysis are: agriculture; food (including feed), beverage and tobacco industry; wood products and furniture; bio-based textiles; manufacture of paper and paper products; forestry; bio-based chemicals, pharmaceuticals and plastics; fisheries and aquaculture; biofuels and bio-based electricity (EC JRC 2018). These supplies need to be properly balanced and many targets have to be addressed simultaneously. One will ask how is wood grown and used, what are the economically, environmentally and socially sustainable production processes, products and services means in the field of forest bioeconomy? It furthers goes on to ask how are non-wood goods and ecosystem services managed and valued? These are some of the questions this research work seeks to answer to determining the future of forest bioeconomy in Ghana. Forest bioeconomy has the potential to change the unsustainable conditions created by fossil fuels through its models that minimise the overall consumption of energy and material and maximise the share of renewable resources in the economic system. Forests are Ghana's biggest renewable natural resource in terms of energy and material supply. At the same time, they provide much more than only biomass. They support a rich portfolio of other ecosystem services that range from protective functions (e.g. preventing soil erosion) to cultural services (e.g. recreation) and the provision of goods such as game and mushrooms which are classified as non-timber forest products (NTFP). This situation offers great opportunities for a holistic forest-based bioeconomy through the intelligent use of biomass as well as through developing innovations relating to the entire spectrum of forest ecosystem services. However, of the growing dependence on renewable biological resources needs to be evaluated to monitor its sustainability in Ghana.

The use of domestically available raw materials has a positive impact on securing the supply of energy and goods. Fostering sustainable forest management throughout Ghana will safeguard and avoid the risk of over-exploitation resulting from higher demands on forests. Forest bioeconomy per its role of linking the entire forest value chain, from the point of resource production to its management and use of natural resources to the delivery of products and services when holistically evaluated is key in delivering the Internally determined National Contributions (INDCs) to climate change mitigation and adaptation as signed under the Paris Agreement.

1.3 Aim and Objectives

The goal of this work is to analyze the sustainability of wood production processes and identify indicators of sustainable development for forest bioeconomy. In Ghana as obtainable in most tropical African countries where there is dense human population, the sustainability of wood production is threatened making it difficult to achieve sustainable forest bioeconomy. If good awareness and enlightenment through research are given to the people, they will know the importance of managing the forest ecosystem very well for a successful forest bioeconomy. However, to achieve this success, a good understanding of the indicators of sustainable forest bioeconomy is very crucial. It is on this background that this thesis was conceived. Therefore, to achieve the goal of this work, specific objectives were adopted as follows:

1. To analyze the current level of sustainability of forestry and forest bioeconomy and the main factors that influence sustainability. Subsequently, to propose the sustainability indicators that would correspond to the conditions in the given region.

2. To carry out a qualitative and quantitative analysis of the forest bioeconomy with a closer analysis of charcoal production, which has a significant impact on sustainability in the region, and to evaluate the socio-economic impacts, including environmental impacts, especially the impact of long-term deforestation and forest degradation.

3. To design and assess indicators of a sustainable forest bioeconomy in Ghana and verify their suitability over the past three decades (1990–2020).

1.4 Hypothesis of the Study

H1: Charcoal production has a negative impact on sustainability from the perspective of the forest bioeconomy.

H2: The forest bioeconomy in Ghana contributes significantly to GDP growth and is a promising strategy for economic growth.

H3: It can be expected that the indicator focus on carbon sequestration will grow in the longer term in line with the growing activities of the forest bioeconomy.

H4: The growth of the sustainability of the forest bioeconomy has a positive effect on carbon sequestration.

1.5 Significance, Contributions and/or the Novelty of the PhD Thesis/Study

This work outlined the role of wood charcoal as an essential livelihood support system. To achieve sustainability in wood processing for charcoal, the study recommended the establishment of new policies including commercial wood charcoal production and licensing for revenue and ecological sustainability. Enterprise-based approaches for poverty reduction, smallholders' tree-growing, wood charcoal-energy conserving technologies, improved electricity supply and agricultural productivity were also encouraged (Njenga et al. 2013; Sadiya 2022). The significance of this study can also be explained by the diverse parameters examined in relation to wood charcoal production which no other studies in the region have done.

The findings from the study will really help to bring lasting solutions to deforestation and enhance the sustainable forest bioeconomy. This is because the study has unveiled remote drivers of forest loss that have been long overlooked by previous studies (Teye 2005; Kyere-Boateng and Marek 2021; Fagariba et al. 2018). For example, the sociocultural and political drivers have always been overlooked. Although adoption of some control measures such as the REDD+ and other environmental tax and financial incentives are good policies, as obtainable in some other countries where sustainable forest bioeconomy has been fully adopted and developed (Aguiar et al. 2023; Bastos Lima 2021; Stubenrauch et al. 2022; Korhonen et al. 2021; Page-Dumroese et al. 2022). This work further recommended a sustainable enlightenment campaign and routine informal education of the rural people. This sensitization of the people is crucial because some of the peoples' reasons for preferring forest products (e.g., chewing sticks) to modern resources (e.g., toothpaste and brush) seem convincing and logical (Wu et al. 2001; Agrawal et al. 2010). There should be regular and intensive enlightenment campaigns and workshops as well as house-to-house visits to the people using strong human and environmental health-related evidence and impacts to convince them.

As the first time a conceptual issue as this was studied in Ghana, the work will help to close the gap in knowledge about the indicators of SFB in the country by establishing that a decrease in Cstocks is influenced by increase in population which caused a decrease in forest area, and consequently impacted sustainable forest bioeconomy. Thus, the work might support government in enacting and adjusting forests and land use policies, to refine carbon emission reduction strategies, and to construct and implement better regulations by fully consulting and incorporating the forest-dependent communities.

Finally, as a tropical and coastal country with enough sunlight, wind and sea, the study proposed to the government of Ghana to extract renewable energy from these sustainable energy sources and provide the rural communities with solar-powered cooking stoves (Shahsavari and Akbari 2018, Ramful and Sowaruth 2022; Rezaei et al. 2020; Kasaeian et al. 2020). This if implemented will significantly minimize pressure on the forest ecosystem.

CHAPTER TWO

2 LITERATURE REVIEW AND INDICATORS OF FOREST BIOECONOMY

2.1 Literature Review

2.1.1 Forest Bioeconomy

Wood is the main source of financial revenue from forests, and its demand is rapidly growing (European Commission [EC], 2013). Since forests are large carbon pools, estimating carbon storage in trees and harvested wood products, provides key information to be included when reporting measures aimed at reducing greenhouse gas (GHG) emissions (UNFCCC, 1992). The relevance of including forests and their mitigation capacities emphasized repeatedly in the Second commitment period of the Kyoto Protocol and the Paris Agreement on Climate Change (EC, 2015). Wood serves as a replacement for fossil fuels and therefore, constitutes a key energy source considered in the Renewable Energy Directive (EC, 2009; Bais-Moleman et al., 2018). Furthermore, wood is an increasingly important raw material for emerging bio-based industries, as stated in the updated European Bioeconomy Strategy (EC, 2013, 2018a; Pelli et al., 2018).

The need to increase our understanding of the complex environmental and societal challenges that the forest sector is facing, is recognized by the European Forest Strategy (EC, 2013). The strategy also indicates that relevant variables need to be harmonised at European level. Furthermore, harmonised forest inventory data are vital to the success of efforts to assess forest-based resource availability at a Pan-European scale (Mubareka et al., 2018). The importance of reporting on Forest Available for Wood Supply (FAWS), in relation to the maintenance and enhancement of forest resources, and their contribution to the global carbon cycle reflects in the Sustainable Development Goals (SDGs) of the UN 2030 Agenda for Sustainable Development

(Calicioglu, 2024). It is also exhibited in the agreed criteria and indicators (C&I) for sustainable forest management (SFM) assembled in the latest update of the report on the State of Europe's Forests (SoEF) (Forest Europe, 2015).

Reporting on forest carbon stocks and changes, that has gained particular importance following a legislative proposal by the European Union, which requires that Land Use, Land-Use Change and Forestry (LU-LUCF) activities along with emissions from forests should be accounted for according to a forest reference level (EC, 2018b). The purpose is to inform parties to develop a business-as-usual-projection of the average annual net emissions or wood removals from managed forest land (utilising the same forest management as in the reference period) to establish a baseline within the territory of a member state (Krug, 2018; Vauhkonen and Packalen, 2018). Hence, determining forest available (FAWS) or not available (FNAWS) for wood supply and the biomass stocks of these areas, are critical (EC, 2018b). The method for the estimation of forest area and biomass available for wood supply at national level differs from one country to another. National Forest Inventories (NFIs) provide robust and reliable information on forests. Nevertheless, estimates of forest indicators provided by different countries are not directly comparable due to: different definitions or interpretations of the related concepts (such as FAWS area, or biomass compartments considered); data availability; and different time frames as each NFI refers to a specific time period (Tomppo et al., 2010). To improve the comparability of forest information provided by NFIs at European level, reference definitions ought to be established and specifically indicated.

2.1.2 Ghana’s forest cover and potential for a bioeconomy

Forest environment houses many living organisms, and in most developing countries, provides home and shelter to majority of the people. Ghana’s forest covers about one-third of her total land area, with commercial forestry concentrated in the southern parts of the country. Ghana has a total land area of 23.9 million hectares of which 15.7 million ha lie within the savanna zone (SZ) in the north. The remaining 8.2 million ha lie within the high forest zone (HFZ) in the south of the country. The SZ is characterized by an open canopy of trees and shrubs with woodland covering about 9.4 million ha (60% of the total area). This SZ produces mainly wood fuel and small amount of building poles for local use (Oduro et al. 2014). The HFZ is dominated by farmlands and fallows with about 20 % being occupied by forest reserves (designated forest areas, see Hawthorne and Abu-Juam 1995) that are used to produce wood to meet the country's demand for timber. The forestry sector accounted for 4.2 percent of the GDP in 1990. Since 1983, forestry has benefited from more than US$120 million in investments and undergone substantial changes, resulting in doubled earnings between 1985 and 1990. In 1993, timber and wood products earning totalled US$140 million against a targeted level of US$130 million. Between January and November 1994, exports amounted to 919,000 tons and earned US$212 million. (Boakye 2010). Until the 1980s, forestry production suffered because of the overvalued cedi and deterioration of the transportation infrastructure. Log production and sawed timber declined by 66 percent and 47 percent respectively during 1970 - 1981. The forestry sector was given a large boost in 1986, with a US$24 million timber rehabilitation credit, which financed imports of logging equipment (Oduro et al. 2014). As a consequence, log production rose 65 percent in 1984 - 1987, and export revenues rose 665 percent in 1983 - 1988. Furthermore, the old Ghana Timber Marketing Board was disbanded and replaced by two bodies: The Timber Export Development Board responsible for marketing and pricing, and the Forest Products Inspection Bureau responsible for monitoring contracts, maintaining quality standards, grading products, and acting as a watchdog for illegal transactions. According to the FAO (2015), Ghana has around 9.3 million hectares of forested land, which constitutes to 41.0% of the total land area. Around 9.0 million hectares are primary or otherwise naturally regenerated forest and around 325 thousand hectares are planted forest. The Ghanaian forests broadly fall into two vegetation zones, each with different vegetation and forest types: 34 percent covering the High Forest Zone in South and 66 percent covering Savannah Zone in the North of the land area (Derkyi et al. 2013). Ghana has approximately 2.6 million hectares of forest reserve land, of which 1.6 million hectares falls within the High Forest Zone. 715,000 hectares of reserves have been dedicated for natural timber production, with the remainder under protection and plantation development. However, approximately 500 thousand hectares of unreserved forests as well as a further 2 million hectares of crop land also produce timber (EU, 2012).

In the high forest zone of Ghana, timber is harvested from two distinct land-use types: forest reserves (on-reserve forest areas) and areas outside forest reserves (off-reserve areas). Forest reserves are designated forest areas to be retained as high forest, and are managed for timber production and biodiversity or environmental conservation (protection). Off-reserve areas have little remaining closed canopy forests because most of it have been converted to agriculture land-use, and is partly dominated by perennial crops like cocoa and oil palm.

The drivers of deforestation and forest degradation are complex and interconnected. Geist and Lambin (2002) distinguish between direct or main drivers and indirect or underlying drivers. The main drivers of deforestation and forest degradation in Ghana has been identified to include agricultural expansion, wildfires, logging and fuelwood harvesting, grazing, mining and infrastructural development (Ghana Forest plantation strategy, 2016: Geist and Lambin 2002). The indirect causes in general terms include demographic trends, economic decisions, technological change, and policy and cultural factors (Geist and Lambin, 2002). In Latin America, commercial agriculture, including livestock, is the most important direct driver of deforestation, contributing around two-thirds of total deforestation. In Africa and sub-tropical Asia, commercial agriculture and subsistence agriculture accounted for approximately one-third of deforestation each. Both mining and infrastructure development are important drivers in Africa and Asia, more than in Latin America (Brack and Bailey 2013; Kissinger et al. 2012; Geist and Lambin 2002,). Concerning forest degradation, timber and logging activities accounted for more than 70 per cent in Latin America and Asia, whereas fuelwood collection, charcoal production, forest fires and human settlements are among the main drivers for Africa (Brack and Bailey 2013; Kissinger et al. 2012).

The underlying, or indirect, drivers constitute an interplay between demographic, economic, technological, institutional, cultural and socio-political changes (Geist and Lambin 2002). Forest sector governance and institutions including conflicting policies beyond the forest sector, and increasing the demand for timber and agricultural products in a globalizing economy are among the underlying causes of deforestation and forest degradation. Other causes of forest degradation are illegal activity relating to weak enforcement, poverty and insecure land tenure (Brack and Bailey 2013; Kissinger et al. 2012). For Ghana, the principal drivers of deforestation and forest degradation are agricultural expansion (50%), wood harvesting (35%), population and development pressures (10%), and mining and mineral exploitation (5%) (Kissinger et al. 2012). Thus, the direct causes of deforestation and forest degradation are clearing of forests for food and cash crop farming, logging (both legal and illegal), fuelwood harvesting, infrastructure expansion, and wildfires. The underlying causes are a high international demand for timber, cocoa and minerals, poverty, corruption, the overcapacity of the forest industry, low forest fees, the low enforcement of forestry rules, population growth, urbanization and land and tree tenure issues (Appiah et al. 2009; Obodai et al. 2024; Kumi et al. 2024; Hansen et al. 2009).

Over the years, the government of Ghana has become increasingly concerned about the extent to which deforestation and forest degradation and the future timber production prospects in the country. As a result, various measures are being pursued that are targeted at addressing deforestation and forest degradation and at increasing the forest resource base. Consequently, strategies and policies have been implemented to restore degraded landscapes through the development of commercial forest plantation, small-scale plantations and enrichment planting of degraded forests, to provide support for the incorporation of trees within farming systems. The proposed interventions are expected to provide the basis as a foundation to support the development of a sustainable forest resource, to satisfy future demand for industrial timber and enhance environmental quality (Forestry commission, 2016). These include policy and legislative reforms, capacity building, awareness creation, the establishment of a law enforcement unit to address illegal logging activities, the implementation of a stricter wood procurement policy, consultation with stakeholders in resource management, forest plantation development and the restoration of degraded forest lands (Appiah et al. 2009; Obodai et al. 2024; Kumi et al. 2024; Hansen et al. 2009). The measures being pursued in forest management today will have an impact on forest resources for decades to come therefore insights into the future outlook of the Ghanaian forest resource base is important.

Ghana's forest provides a wide access to more than only biomass, in terms of energy and material supply. It enhances the ecosystem, through its protective functions from by preventing soil erosion, to providing recreational (cultural) services and providing non- timber forest products (NTFP) such as game and mushrooms.

In Ghana, the Wildlife Division of the Forestry Commission is responsible for the protection and management of twenty one (21) wildlife protected areas (WPAs) including five coastal wetlands, totaling 1,347,600 ha (5.6%) of the country's total surface area. The protected area network is a clear representation of the ecological zones of Ghana (Attuaquayefio and Folib 2005).

2.1.3 Sustainability of Forest Bioeconomy

A bioeconomy (BE) is dependent on the sufficient supply of raw material, in this case biomass (wood). While there are, many levels of nuancing concerning that which society 'desire' from the bioeconomy, in practical terms, argues that the principal requirement for a BE is that the products can replace non-renewable, mainly fossil-based chemicals and materials. Other parts enfolding the bioeconomy is seen principally as expressions of efforts to ensure that the shift to renewable resources will not take place "at any cost" – with 'cost' being associated with environmental quality preservation or improvement; climate mitigation; biodiversity preservation or protection, and efficient resource use connected to recycling (Riina et. al., 2017). Bioeconomy also typically contains an element of economic growth and job creation. In fact, a recent study indicates that the broader EU bioeconomy may already generate EUR 2.1 trillion in annual revenue and 18.3 million jobs (Piotrowski et al. 2019).

Biomass resources are at the heart of the debate, involving the global shift from the use of the linear fossil fuel resources to the circular use of biological resources in the manufacture and production of materials such as plastics, textiles and chemicals, that is seen as a way to make our daily lives, "greener" and "more circular" one (FAO/FAOSTAT, 2019).

Electricity generation and supply from biomass projects a promising method in the near future. The global production of biomass estimated at 146 billion metric tons per year, from mostly wild plant growth, accounts for 35% of primary energy consumption in developing countries (Kerolli-Mustafa et al. 2015). This raises the world total to 14% of primary energy consumption. Soon, biomass holds the potential to provide a cost-effective and sustainable supply of energy, and aid countries in meeting their greenhouse gas reduction targets.

The notion of the sustainable bioeconomy has gained importance on national, EU and global levels, and frequently argued as a key part of the solution to multiple grand challenges (Hinderer et al. 2021). Sustainability of the BE, consumption and production is therefore a very important sector that demands monitoring. Three main dimensions classified under the bioeconomy: economy, environment and society (Birner 2018). The sustainable bioeconomy is primarily, attached to its environmental dimension, especially in sustainable production and use of biomass (Bosch et. al., 2015).

Sustainability directly links the Sustainable Development Goals (SDGs). In the 2015 Global Sustainable Development report by the United Nations (2018), the question 'what is to be sustained?' is among other things answered by:

- Goal 12. Ensure sustainable consumption and production patterns.
- Goal 14. Sustainably use of the oceans and marine resources for sustainable development.
- Goal 15. Promote sustainable use of terrestrial ecosystems including Sustainably manage forests.

These goals interlink with bioeconomy, and therefore the study contributes to measuring the progress towards them.

The transition from a fossil-based economy towards a bioeconomy seeks to be supported and adopted by governments and intergovernmental organizations (e.g., European Commission, 2012; Ministry of the Environment, 2014; FAO 2013) (Budzinski et al, 2017). The strategies for achieving the vision of a bioeconomy are associated with several environmental and socio-economic goals such as climate protection, job creation, strengthening the innovation of the economy while preserving biodiversity and food security (Fund et al., 2015). However, assessing the achievement of these targets, a definition of quantifiable indicators cannot be negligible (O'Brien et al., 2017; Bosch et al., 2015). Furthermore, multidisciplinary approaches that integrate social, environmental and technological perspectives are necessary to promote the development of sustainable energy generation and sustainable production (Saez-Martinez et al., 2016). Monitoring tools are crucial as a basis for political interventions, to detect feedstock limitations (Hennig et al., 2016) and to identify undesirable developments and trade-offs (Bezama, 2016). An essential characteristic of a sufficient monitoring approach is the consideration of global impacts due to biomass use. To cope with the complexity and diversity of bio-based value chains within a bioeconomy (Gold and Seuring, 2011), the detailed differentiation between types and utilizations of biomass is needed. However, to this date comprehensive tools mapping the environmental and socio-economic impacts due to biomass use in a detailed as well as in a global manner are not available (Budzinski et al, 2017).

2.1.4 Bioeconomy Initiatives

- Global initiatives on BE include the following (SSTC, 2020): The Global Bioeconomy Summit, a global conference that takes place every two or three years. Since the first summit in Berlin in 2015, the summits have established themselves as a unique format for global exchange on bioeconomy policy, governance and sustainable development. The third Global Bioeconomy Summit (#gbs2020) is to take place in the Berlin Congress Center (bcc) from 19th to 20th November 2020 with the support of the German government (gbs2020.net).

- The Biofuture Platform launched at the United Nations Climate Change Conference in Marrakech in 2016 under Brazil's leadership as a new platform that brings together 20 countries, including 11 developing countries, to advance the low-carbon bioeconomy that is sustainable, innovative and scalable. In particular, the Biofuture Platform aims to support countries with the implementation of their NDCs and the achievement of the SDGs, especially SDG 7 (Affordable and clean energy) and SDG 13 (Climate action), while also contributing to SDG 2 (Zero hunger), SDG 8 (Decent work and economic growth), SDG 9 (Industry, innovation and infrastructure) and SDG 15 (Life on land).
- The FAO-led International Sustainable Bioeconomy Working Group (ISBWG), established in 2016 as a multi-stakeholder expert group, including 30 members from 14 countries, as well as regional governing bodies, non-governmental organizations, private sector entities, research institutions and intergovernmental organizations. The working group, Inter Alia, acts as an advisory body to FAO's project regarding the development of Sustainable Bioeconomy Guidelines.
- BioInnovate Africa, which supports scientists and innovators in Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda to link biological based research ideas and technologies to business and the market. In addition,

BioInnovate Africa is in the process of developing an innovation-led Bioeconomy Strategy for Eastern Africa.

Bioeconomy (BE) as a special program (Winkel, 2017) originated in Europe and is fully adopted in EU and EU's key to address challenges associated with ecology, environment, energy, agriculture, food in(security), forestry, natural resource and general planetary health (European Commission - EC, 2012). The genesis of the BE ideaology in Europe might be attributed to the documentation on Growth, Competitiveness and Employment (EC, 1993), which invited knowledge-based investments and for an enhanced incorporation of biotechnology in innovations (EC, 2000). The growth of BE policy papers by the EU and its member countries could be related to the Organisation for Economic Cooperation and Development's (OECD, 2009). For example, the BE documentations and goals to 2030 (Designing a Policy Agenda), which considers biotechnological implementations to primary production, health, and industrial sectors. The growth and development of BE in these developed countries, especially EU brought a paradigm shift in biotechnological development using the nature-based products. Most other regions and nations of the world are trying to toe same directions as the EU.

2.1.5 (Bio)economic role of Forest in Ghana

Over the years, it has been noticed that the forestry sector of Ghana played a significant role in the country's development. Currently, the forestry sector contributes 2.3 percent (USD 862.9 million) to the country's gross domestic product (GDP) (GSS 2015), with the timber industry being the fourth largest foreign exchange earner after minerals, cocoa and oil exports. In addition to timber, forests provide the main source of domestic energy in the form of fuelwood and charcoal. The average annual per capita wood energy consumption estimates about 1.3 m3 , giving a total estimated wood removal of more than 30 million m3 for fuelwood and charcoal, or about 85% of the total wood removal in Ghana (Foli et al. 2018; MLNR. 2012). Although important as a sector, forestry in Ghana is struggling with a number of challenges, including overexploitation beyond annual allowable cut (AAC), declining stocks and productivity, overcapacity of the timber industry, chainsaw milling and illegal/unauthorised logging.

In an effort to ensure continuous supply of timber from the timber production systems in Ghana, timber harvesting is controlled by the annual allowable cut (AAC), i.e. a maximum volume of timber that is set for annual exploitation. The current AAC is 2.0 million m3: 0.5 million m3 from forest reserves and 1.5 million m3 from the off-reserve areas (Bamfo 2005, Bird et al. 2006). However, current total timber harvest in Ghana is estimated at approximately 3.7 million m3 to 6 million m3, which is almost two to three times the AAC (Birikorang et al. 2001, Hansen et al. 2012). For many years, off-reserve timber harvests accounted for substantial share (70% to 75%) of the total timber harvests in Ghana but the greater proportion of the current harvest rather originates from the forest reserves (FPIB LMC Totals 1980-96, Hansen et al. 2012, Treue 2001). Due to the low compliance with the AAC and the many decades of overexploitation in the timber production systems, the current AAC no longer represents a sustainable level for harvesting (Wong 1998). Moreover, fuelwood extraction which used to take place in the savanna zone is increasingly being shifted to the forest reserves in the high forest zone (HFZ), contributing to forest degradation in the HFZ.

The current management regime for timber production within production forest reserves is the use of a polycyclic selection felling system using a cutting cycle of 40 years. There are regulations that define the selection of harvestable trees and the setting of the annual allowable cut (AAC).

This is supposed to result in less damage to the residual forest and ensure sufficient regeneration. However, silvicultural treatments after harvest are not applied and the increment of the residual depends entirely on the forest's response to logging, leading to continuous decline of the forest resource base.

Ghana's timber industry is characterized by an over-capacity and inefficient mills. The industry has a processing capacity of about 5.2 million m3, which is far in excess of the AAC (Oduro et al. 2014; Agyeman 2014). The increase in mill capacity is attributed largely to the availability of relatively cheap raw material. Worsening the situation is the fact that the industry is operating at a low recovery rate (20-40 %) due to the inefficiency of the mills. The timber industry is distressed due to unavailability of trees for felling and growing demand for timber. Consequently, a major problem facing the timber industry is the large unutilized installed capacity and low rates of recovery against a rapidly declining timber resource base.

Ghana is among the countries in West Africa having a well-developed sawmilling industry and the export of timber has been a key activity in the country. The Ghanaian timber industry is made up of 130 wood-processing units and about 200 other enterprises focusing on furniture production. There are over 41,000 small-scale carpenters registered with the Association of Small Scale Carpenters. These represent the largest group of end-users and they require about 219,000 m3 of sawn timber annually. This represents about 72 % of the total domestic timber requirement for the entire country (Agyarko 2001). Meanwhile, the sawmill industry in Ghana is export-oriented serving the more attractive export market and does not find it economically feasible to satisfy the low-priced domestic lumber market. The high domestic demand for sawn timber of about 590,000 m3 (Marfo 2010), and the conventional sawmill industry's inability to supply the domestic demand remains one of the principal driving forces, not only of chainsaw milling (CSM) but also of illegality in the timber industry in general. CSM refers to the on-site conversion of logs into lumber for commercial purposes using chainsaws. CSM has been banned in Ghana since 1998 making it illegal, but remains widespread in the country despite measures put in place by government to enforce the ban (Oduro et al. 2014; Marfo 2010). The domestic timber trade is mostly served by chainsaw operators who operate without any legal authority or license, contributing about 84 percent of the domestic lumber supply (Oduro et al. 2014; Marfo 2010) with the remaining 16 percent being supplied by sawmills. The supply of legal timber to the domestic market is a crucial issue in the forestry sector in Ghana. The informal CSM sector is almost equal in size as the formal sector in terms of employment: CSM employs 97,000 people, formal sawmill employs 100,000 people (Adam and Dua-Gyamfi 2009, Marfo 2010). The CSM sector is also the main source of illegal overland export lumber to neighbouring countries with an estimated volume of around 260,000 m3 (Marfo 2010, MLNR 2012).

2.1.6 Sustainable Indicators of Forest Bioeconomy (FBe)

Considering the role of the forest ecosystem (e.g, different plant species, soil, and other fauna and flora components) in promoting FBe through their discharge of ecosystem services, it is essential to identify the indicators of the FBe. The study has identified many sustainable indicators of FBe to include vital variables that cut across the three main dimensions of sustainability such as economic, environment and social sectors which also form the pivot of the nation's development. These encompass Forest coverage areas, Carbon stocks (soil and biomass), Soil organic matter (SOM), and Net Primary Productivity (NPP). Others are Greenhouse gases (GHG), Forest growing stock, Dead wood at it quantity, Water (im) purity, Biodiversity, and Gross domestic production (GDP). It is also important to state that the rate of employment in the forest industry, Human health and well-being derived from the forest, Peoples livelihood and Rural development are among the indices to be categorized as sustainable indicators of FBe. For example, the areas and growing stock of a forest to a large extent determine the quality and quantity of ecosystem services to be provided by such forest. This further influences the amount of carbon stocked as well as the potential of the forest ecosystem to sink substantial quantity of CO2, consequently contributing in climate change mitigation. In addition, both social and economic aspects of development have strong links with the forest size, quality, amount of dead wood and SOM because these have significant control on the forest health, and the volumes of wood and non-wood resources derived from the forest. A healthy forest is a forest with high NPP, rich in biodiversity, and could contribute largely to GDP and economic growth.

Based on the information from the field survey, major international agencies and processes, and the 2030 Development Agenda, a core set of indicators have been summarized in Table 2.1. The indicators have been categorized and given examples of units and connections as well as data sources for each indicator.

Table 2.1. Indicators categorized in dimensions, examples of units, inter-linkages to other aspects and/or indicators of sustainability and possible data sources.

Indicator	**Dimension**	**Indicator unit(s) (in example)**	**Strong indicator interlinkages**	**Other major connections**	**Main data and/or cofactor sources**
Forest coverage areas	Environmental	% per ha	Land use, timber trade	Renewable energy: wood, population.	National statistics, Field survey, FAOSTAT, legacy data base.
Carbon stocks (soil and biomass)	Environmental	Gt C $^{-}$yr, mg OC g-1, Mg C ha^{-1}, %, tons,	AFOLU	IAS, soil health Ecosystem services, Renewable	National statistics, Field survey, FAOSTAT, legacy data base.

				energy, population.	
Soil organic matter (SOM)	Environmental	Gt C - yr, mg OC g-1, Mg C ha-1, %	AFOLU	IAS, soil health Ecosystem services, Renewable energy, population	National statistics, Field survey, FAOSTAT, legacy data base.
Net Primary Productivity (NPP)	Environmental	%, tons,	AFOLU	IAS, soil health Ecosystem services, population	National statistics, Field survey, FAOSTAT,
Greenhouse gases (GHG)	Environmental	tCO2eq, GWP	Fossil fuel use	Biodiversity	National statistics
Forest growing stock	Environmental	%, ha	AFOLU, Wood fuel use	Agriculture, soil health Ecosystem services, population.	National statistics, Field survey, FAOSTAT, legacy data base.
Dead wood	Environmental	Tons	AFOLU wood fuel use	Agriculture, soil health Ecosystem services, population.	National statistics, Field survey, FAOSTAT, legacy data base.
Fossil fuel use	Environmental	tons, % - of all fuels	GHG, trade, national self-reliance	Renewable energy	National statistics, industry
Fine particle emission	Environmental	particle sizes >10, 1–10 and < 1 µm	Fossil fuel use	Health	Industry, literature, derivable from other indicators
Water contamination	Environmental	m3		Ecosystem services, fossil fuel use	Industry
Land use and land use change	Environmental	Ha	Biodiversity	(indirect) GHG	National statistics, Industry (e.g. wood use)
Biodiversity	Environmental	Area protected/area used, species richness,		Harvested forest area	Experts, industry

Gross domestic production (GDP)	Economic	€, %-change in GDP	GVA/LVA		National statistics
Gross and/or local value added (G/LVA)	Economic	€ added to product per m3 wood used	GDP, Trade	Rural developme nt	Industry, (Inter)Nation al statistics
Trade	Economic	Import/expo rt change	GDP, G/LVA, National supply security and self-reliance	National self-reliance	National statistics
National supply security and self-reliance	Social	Import/Tota l energy use	Fossil fuel use, Trade		National statistics, industry
Employmen t	Social	Person years	Accidents, salaries	Capacity and freedom, well-being	National statistics, industry
Human health and well-being	Social	N/A	Fine particle emissions	Accidents and work related diseases, social costs.	Questionnair es, industrial accounting.
Accidents and work related diseases	Social	Person days-off/working days	Employmen t		National statistics, industry, Insurance institutions
Equity	Social	Paid salaries, Gini-index	Employmen t	Reflections to health and Capacity and freedom	National statistics, industry
Capacity and freedom		Disposable income, Free time	Participatio n	Rural developme nt	Questionnair es
Participatio n	Social	Number of participants, Number of hearings	Capacity and freedom	Equity	Public documentatio n

Rural developmen t	Social	Rural/urban jobs	Employmen t	Equity and Capacity and freedom	National statistics, Industry

(Source: Adapted and modified after Karvonen et al. 2017).

The indicators provided in Table 1 are widely applicable within many contexts, including those outside the forestry sector. However, some of these (e.g. biodiversity) may be difficult to assess. It is not anticipated that all the criteria in Table 1 must be applied in every assessment even though many may improve the value of information in the SIA significantly, especially regarding acceptance by the public. It reports for the Rio conventions, accompanied by an agreement between agencies and national correspondents as to how to manipulate collecting and sharing of information. It serves and provides several benefits including the following:

- Better, more understandable, more comprehensive, information for policy makers, in the forest sector, in other sectors, and at the national, regional and global levels;
- A clearer, more understandable, and less contested, "story" about developments in the forest sector, and better understanding of forest related issues by the general public;
- A more holistic approach, as debates are not constrained by data sets limited to one particular aspect.
- A shift in the policy debate away from data problems towards addressing the search for solutions;
- More synergies and better coordination between agencies in planning and implementing action and investment programmes;
- Significantly reduced reporting burden, at the national level: information to be provided only once, and the same information to be held in all international data banks.

- A consistent framework for presenting and analysing information, and for research.

However, there are major obstacles in developing such a comprehensive global set of forest indicators, and these may include: The many improvements in information and analysis over the last two decades have not been tightly coordinated: there has been a major (and worthwhile) investment in systems which are suited to their specific objectives, but are not completely compatible with each other. Reaching agreement on a global set will involve compromise, and the loss of data continuity in some areas. In some cases, there may be problems at a more formal level, for instance when concepts and definitions are "hard-wired" into mandates or other formal commitments, limiting the potential for adjustment to the needs of partners. Different perspectives, perceptions, values and interests on forests by different groups of experts, scientists, stakeholders, civil society and policy makers from a wide range of intellectual backgrounds. Different approaches are inevitable, so sensitivity and open minds will be required to reach agreement. There are real differences on the ground between forests in different regions, as demonstrated by the articulation of indicator sets by regional C&I process. A global core set must identify the common features, of global importance, while providing a common framework within which national and regional data can be gathered and analysed.

To overcome these obstacles, and achieve the benefits of a global core set of indicators, advance planning is essential, as well as transparency as regards objectives, methods and data. Sensitive understanding of the mandate, goals and potential of all "players", as well as flexibility, are also essential. This study aims to bring together what has been done so far in this direction, make preliminary suggestions and propose a roadmap for the future. However, it can only be the first step in a process.

CHAPTER THREE

3 METHODOLOGY

This chapter summarizes research methods, materials, and procedures used in collecting and analyzing data. The chapter is divided into the study area, research approach, population, sampling, instruments and materials, procedures, data analysis, ethical considerations, and limitations.

Africa as a continent is currently having 54 countries with a total area of 30,368,609 km2 (11,725,385 sq mi). Africa measures about 5000 miles (8000 km) from north to south and about 4600 miles (7400 km) from east to west. The landmass of the continent accounts for 20% of the Earth’s land surface. The human population is approximately 1.2 billion and is increasing at a rapid pace which is almost thrice faster when compared with other continents. According to World Bank (2020), Africa’s population will triple or quadruple by the end of this century. In terms of climate, Africa lies mainly within the inter-tropical zone and is therefore a regularly hot continent. The various climate belts are principally influenced by their rainfall trends. The major climatic zones are classified into six major categories namely, Equatorial, Humid Tropical, Tropical, Sahelian, Desert, and Mediterranean climate. The primary soil types in the continent are Oxisols, Ultisols, Alfisols, Etisols, Gelisols, Vertisols and Aridisols.

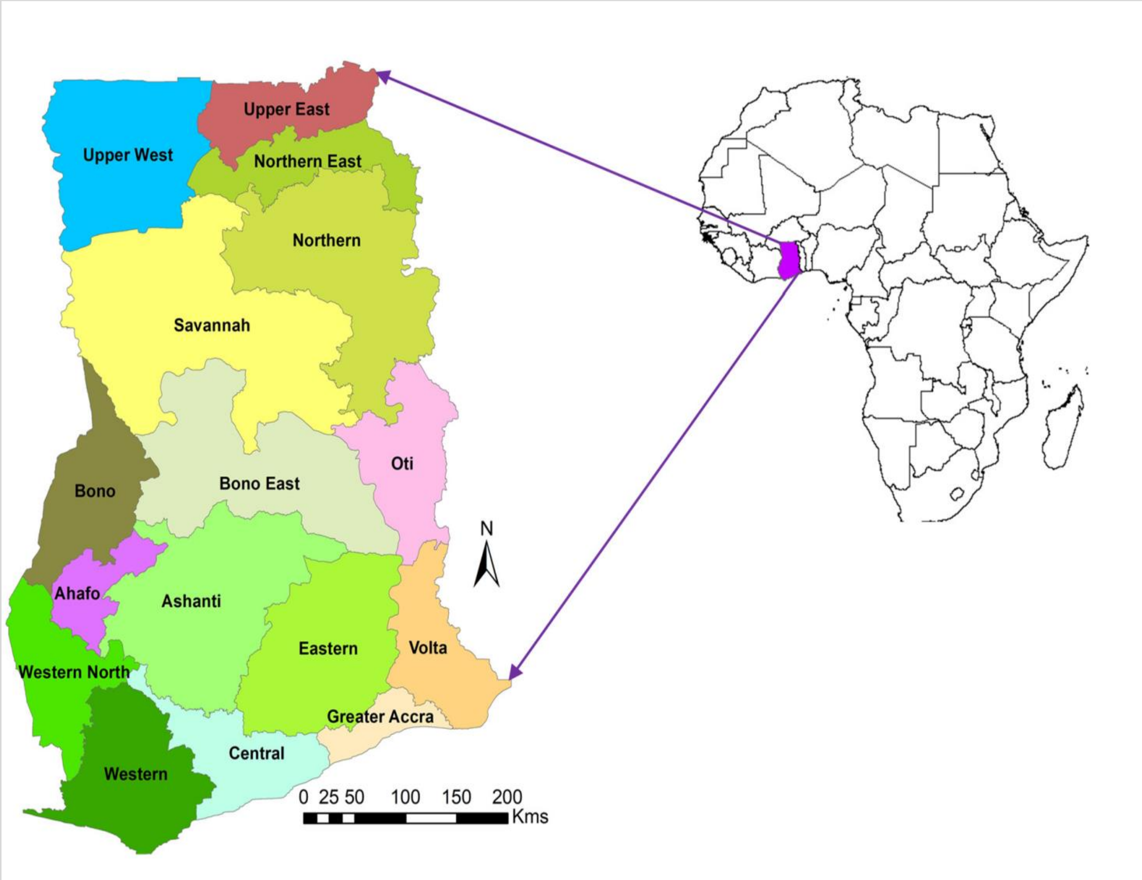

Figure 3.1. African map showing Ghana (the study area) and the current 16 administrative regions.

Geopolitically, Ghana is a country in the west of sub-Saharan Africa that lies between latitudes 4◦441 and 11◦151 N and longitudes 3◦151 W and 1◦121 E, with a land area of 238,539 km2 (Armah et al. 2011). Ghana is bordered northwards by Burkina Faso, eastwards by Togo, westwards by the Ivory Coast, and southwards by the Atlantic Ocean. The current population of the country is estimated at 30.8 million people, with a population growth rate of about 2.2% per annum (GSS 2011). Contemporarily, Ghana has sixteen administrative regions (**Figure 3.1**).

Ghana is one of the countries in sub-Saharan Africa (SSA) that has been known for large hectares of forest areas. There are five dominant forest–vegetation belts, namely, 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 3.2**). The wet evergreen rainforest and the moist evergreen (dry and thick) forests are found in the south and south-west, while the swamp forest and mangrove vegetation are predominantly in the south-east. On the other hand, the moist deciduous (NW and SE types) forest and the dry semi-deciduous forest and savannah are commonly found in the central and northern regions of the country, respectively (**Figure 3.2**). Ghana is among the countries in Africa that used to have rich forest areas but in 1992, only about 1.5 million hectares were estimated as remaining "intact closed forest" in the country. The country is among the SSA countries that have a rapid deforestation rate per year. In 2020 alone, the country recorded more than 14,000 hectares of forest loss (Mongabay 2022). Generally, Ghana is characterized by a tropical climate with distinct wet and dry seasons (Frimpong et al. 2003; Donkor et al. 2006). The country had a high net CO2e emissions between 1990 and 1996 though its sinks rapidly decreased in size (Jackson 2015). The swift decrease in sinks has been associated with deforestation, particularly a rapid increase in woodenergy consumption, timber harvesting, agricultural and settlement expansion, mining, and low rates of reforestation [Andrée et al. 2019; Haripriya 2000a, b). The country experiences temporal and spatial temperature variations depending on seasonal changes and ecological zone. The mean annual temperature is generally high—above 24 ◦C. Mean annual rainfall is about 736.6 mm, and rainfall generally decreases from the south to the north (EPA 2000). Economically, the GDP growth of the country is 3.3%, with an inflation rate of 29.8% and an unemployment rate of 13.4% (Awuah 2022; Sasu 2022). Currently, over 3.4 million people in Ghana are living in extreme poverty on less than USD 1.90 per day, with the majority of them living in rural areas (Sasu 2022).

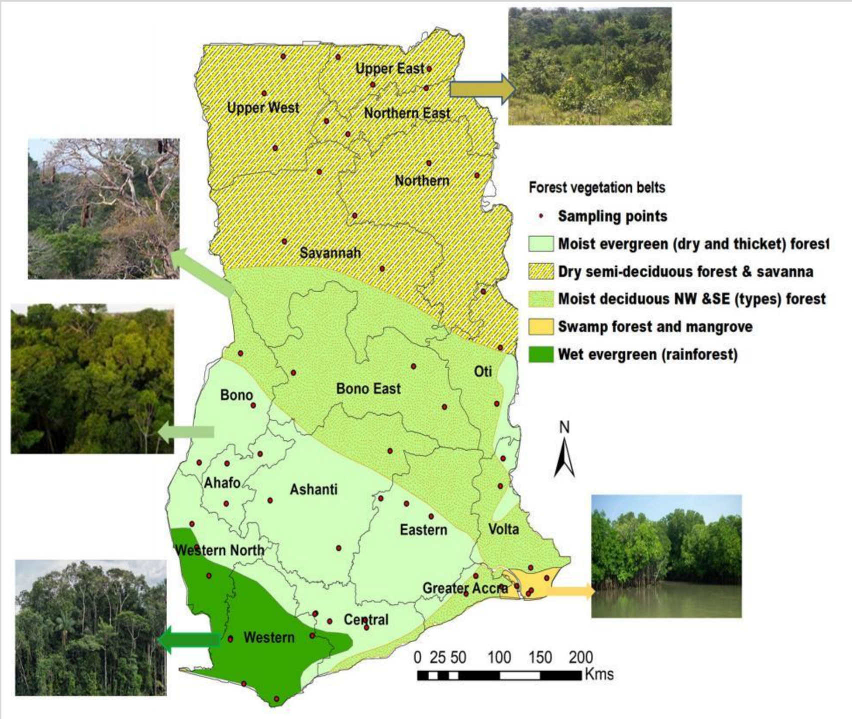

Figure 3.2. The Ghana's dominant forest–vegetation belts, their locations, features, and sampling points for the study.

The research methodology adopted in this thesis was done to achieve the aim and objectives of the work and are summarized in the following paragraphs.

Data for this study was collected using both primary and secondary sources. The primary data were the field data. The secondary sources used include materials from peer-reviewed journals; books; book chapters; NGOs and government-established institutions and agencies such as the Ghana Statistical Services and the Ministry of Food and Agriculture, Commerce and Industries; and important international organizations such as the United Nations' Food and Agricultural Organization (FAO). The information on the field sampled data and sources of the secondary data are shown in **Appendix Table 2.1, and Appendix Table 2.2**. Both field data and historically robust data from the relevant databases of various local and international institutions such as UN-FAO, FAOSTAT, International Energy Agency- IEA, United Nations Statistics Division, UN-DESA energy statistics yearbook 2019, and the Forest Resources

Assessment (FRA) were visited, and relevant data were downloaded. Microsoft Excel was employed to compute the relative WCH. Additional data were acquired from the United Nations Statistics Division (UNdatabase) on WCH. Other sources of data for the study were the official National Bureau of Statistics of various countries covering the relevant study periods, as well as online literature and publications. Data were also collected from interviews. The interview involved the WCH producers, the marketers, transporters and the consumers. Primarily, WCH producers in the sub-region exploit trees and shrubs that are available within their area. The commonly preferred tree species that were identified during the study were the hardwoods such as *Dialium bipindense, Diospyros spp., Pentaclethra macrophlla, Letestua durissima, Lophira alata, Milicia excels, Baphia kirkii, Cleistanthus mildbraedii, Cylicodiscus gabonensis, Desbordesia pierreana, Manilkara cuneifolia, and Parinari glabra.* Others are *Strombosia glaucescens, Swartzia fistuloides, Tessmania Africana, Klainedoxa gabonensis, Afzelia Africana spp.,* and *Piptadeniastrum Africanum.* Furthermore, some softwood species such as *Triplochiton scleraxylon, Gmelina arborea, Juniperus procera, Pinus halepensis, Pinus pinaster, Cedrus atlantica, Hagenia abyssinica, Taxus baccata, Hevea brasiliensis,* and *Celba pentandra* were also commonly used for WCH production by the people. This information was derived from online sources and literature (Mensah et al. 2020). Data on income and literacy rate were collected from World Development Indicators and World Literacy rate of the World Bank (2020), World Bank data on, and World Income Inequalities Database (2019).

By visiting the sites between November 2021 and October 2022, data related to the forest indicators including the common tree species were collected. Past literature (from published articles and government institutional documents), foresters, and plant ecologists were consulted for the identification of the tree species. In addition, the farmers, foresters, and experts in the field were interviewed to obtain valid information about the drivers of deforestation as well as their sociocultural and political perceptions on deforestation (Table 2.3). However, data on most variables investigated were derived from secondary sources yet visits to the people and the forest belts helped to collect more relevant data and reconcile the information acquired from the secondary sources.

The indicators for a sustainable forest bioeconomy were selected based on reviewed scientific literature and documents from different sources including (1) Guidelines from the European Forest Institute (EFI), which is an international organization established by the European states (Wolfslehner et al. 2016); (2) the European Forest Institute on Implementing Criteria and Indicators for Sustainable Forest Management in Europe (EFI 2013); (3) a Report on Pan- European Criteria and Indicators for Sustainable Forest Management—Experiences from Liechtenstein (Requardt et al. 2007); (4) a work on bioeconomy mapping indicators and methodology, a case study of the forest sector in Latvia by Dagnija et al. (2017); and (5) The Contribution of Sustainable Development Goals and Forest-Related Indicators to National Bioeconomy Progress Monitoring (Linser and Lier 2020). From the above literature and with experience from the study country, the following indicators were chosen as the most indicators for sustainable forest bioeconomy in Ghana: forest area, forest growing stock, forest area loss by deforestation drivers, forest tree cover and loss by drivers of deforestation, forest deadwood volume, forest contribution to GDP, employment in a forest-based sector, and forest soil quality and productivity (such as organic matter content and net primary productivity).

To acquire professional knowledge regarding the key drivers for deforestation, top publishers in the topic who have papers based in Ghana were consulted. They were interviewed, and a structured questionnaire that included a list of 38 current and potential or future drivers of deforestation was developed from 25 reviewed studies. The drivers were grouped based on decades (Decade 1: 1990–1999, Decade 2: 2000–2009, and Decade 3: 2010–2020). They were also listed in two main categories (direct and indirect drivers). The direct drivers of deforestation were identified as human and biophysical factors. The human factors were farming, grazing, mining, building/settlements, exploitation for biofuel, timber, and NWFPs, while the biophysical factors were climate change, soil degradation, pests and diseases, and wildfire. On the other hand, the indirect drivers of deforestation were listed as demographic, socio-cultural, economic, and political factors. The clustering of indirect drivers was performed according to Geist and Lambin (2002). The ranking of the drivers followed a Likert scale approach. This scale ranged from 0 to 5, with 0 representing zero influence and 5 representing strong influence. In addition, the interviewees, especially the experts, were provided with detailed definitions of each proposed/potential drivers. Besides recommending the most drivers, they also placed them in accordance with the decades where they had much impact on the forest. The questionnaire was sent to the top known researchers in this field, especially those who are experts in Ghana. In addition, selected individuals who live and work in Ghana as farmers and/or foresters in the 16 regions were also involved. In sum, 15 out of 20 experts, and 30 out of 40 farmers and foresters, that were contacted returned their completed questionnaires. To improve the reliability of the answers given in the questionnaire, the Delphi approach was applied (Okoli and Pawlowski 2004). The questionnaires were returned to the interviewees together with the synthesized information of the group. By review and adoption of results of the first Delphi round, the variance in the driver ranks were reduced, and consensus was reached. The drivers were reduced to 21 out of 38 based on the derived final rating from the experts, literature, and farmers and foresters. A total of 21 drivers out of 38 had a rating of at least 50% from each of the three categorized (selected) evaluations (experts, literature, and farmers and foresters).

Data were analyzed using IBM SPSS (version 29.0, Armonk, NY, USA), CANOCO (version 5.0, Wageningen, The Netherlands) (Ter Braak and Smilauer 2012), and/or ArcGIS (version 10.5, Redlands, CA, USA) (ESRI 2009) software packages. Data were transformed where necessary to meet the requirements and suitable values used for the analyses. From the described sources (Table 1), information on the LUCC, contributions of forest to GDP, and the percentage of the population that exploited forests for different benefits were spatially mapped and presented based on the forest–vegetation belts and regions using the GIS spatial analytical tools in ArcGIS 10.7. The top 21 drivers of deforestation and the identified common tree species were analyzed using the multivariate ordination of Canoco 5.0 to show their distributions across the decades and forest belts. To determine the interrelationships among the indicators of sustainable forest bioeconomy, the pairwise correlation adjusted to Bonferroni significance levels at 0.01 and 0.05 was used in the IBM SPSS 29.0 (SPSS Inc., Armonk, NY, USA) statistical software.

Table 2.3. Summary table of the number of experts, farmers, and foresters who chose the variables as drivers of deforestation in the interviews, with emphasis by the authors in the literature.

Group/Class of Drivers	Current Drivers of Deforestation	Interviews: % (no.) of Experts (*n* = 15) Who Endorsed the Driver	Interviews: % (no.) of Farmers and Foresters (*n* = 30) Who Mentioned the Driver	Literature: % (no.) of Authors (*n* = 25) Who Indicated the Driver
Direct driver: anthropogenic or human	**Population growth (rural and urban)**	100% (15)	100% (30)	100% (25)
	Agricultural intensification (modern and conventional)	100% (15)	90% (27)	84% (21)
	Use of forest for biofuel	80% (12)	73% (22)	80% (20)
	Use of forest for timber	100% (15)	100% (30)	100% (25)
	Use of forest for NWFPs	53% (8)	57% (17)	52% (13)
	Construction and building (settlements, canoes, etc.)	60% (9)	63% (19)	64% (16)
	Mining	87% (13)	90% (27)	92% (23)
	Wildfire	53% (8)	50% (15)	52% (13)
	Overgrazing/livestock	60% (9)	53% (16)	56% (14)
	Wildlife (game and hunting)	53% (8)	50% (15)	52% (13)
	Infrastructural development (road, schools, markets, hospitals, etc.)	**53% (8)**	**57% (17)**	**56% (14)**
Direct driver: biophysical	**Soil quality (e.g., degradation, SOM)**	**67% (10)**	**60% (18)**	**60% (15)**
	Topography	33% (5)	27% (8)	24% (6)
	Rainfall variability	**73% (11)**	**67% (20)**	**68% (17)**
	Temperature variability	**60% (9)**	**53% (16)**	**56% (14)**
	Wind intensity	**47% (7)**	**53% (16)**	**48% (12)**
	Pests and diseases	**53% (8)**	**50% (15)**	**52% (13)**
Indirect driver: socio-cultural and economic	**Civil/communual conflicts**	**53% (8)**	**50% (15)**	**52% (13)**
	Migration	**53% (8)**	**57% (17)**	**56% (14)**
	Religious beliefs and patterns	13% (2)	20% (6)	28% (7)
	Cultural/traditional beliefs	60% (9)	70% (21)	72% (18)
	Illiteracy rate (level of education)	53% (8)	77% (23)	68% (17)
	Land tenure system	20% (3)	23% (7)	16% (4)
	Poverty rate (e.g., Rising living standard)	93% (14)	100% (30)	96% (24)
	Rural farmers lack of capital	27% (4)	17% (5)	12% (3)
	Foreign agricultural medium-scale investments	0% (0)	3% (1)	0% (0)
	International funding/development aid	0% (0)	0% (0)	0% (0)
	Credits by family, bank, government, or NGO	6% (1)	10% (3)	4% (1)
	Labour shortage	13% (2)	6% (2)	8% (2)
Political/governance	**Unsound policies**	**60% (9)**	**77% (23)**	**52% (13)**
	Weak governance	**53% (8)**	**60% (18)**	**72% (18)**
	Lack of law enforcements	**73% (11)**	**73% (22)**	**56% (14)**
	Landlessness	**53% (8)**	**70% (21)**	**52% (13)**
	Unclear allocation of rights	**53% (8)**	**63% (19)**	**56% (14)**

Table 2.3. Cont.

Group/Class of Drivers	Current Drivers	Interviews: % (no.) of Experts (n = 15) the Driver	Interviews: % (no.) of Farmers and Foresters (n = 30) Who Mentioned the Driver	Literature: % (no.) of Authors (n = 25) Who Indicated the Driver
	Impoverishments of the	**87% (13)**	**80% (24)**	**68% (17)**
	Lack of investments and	**67% (10)**	**86% (26)**	**72% (18)**
	National	13% (2)	13% (4)	12% (3)
	Fertilizer subsidies	6% (1)	10% (3)	8% (2)

In **bold** are the drivers and values that had at least 50% ranking in the three respective sources.

The following indicators were chosen as the most indicators for sustainable forest bioeconomy: forest area, forest growing stock, forest area loss by deforestation drivers, forest tree cover and loss by drivers of deforestation, forest deadwood volume, forest contribution to GDP, employment in a forest-based sector, and forest soil quality and productivity (such as organic matter content and net primary productivity).

In terms of measuring the carbon stocks as indicator, data was collected on the soil properties including carbon stocks and bulk density. ISRIC soil property data repository (soilgrids.org) supported in the data. The values of BD (Mg m−3) and CoF (%) were extracted from the SoilGrids layers at the geographically located sampled points. The field soil (BG) carbon stocks were estimated using the Global Soil Information Facilities (GSIF; Hengl et al. 2016) based on a standardized calculation prescribed by Nelson and Sommers (1982) (Eq. (3.1)).

$$\text{BG or soil-Cstock} = (\text{SOCD}/1000) \times (\text{SD}/100) \times \text{BD} \times (100\text{-CoF}/100) \qquad \text{(Equation 3.1)}$$

Where, BG or soil-Cstock is the aboveground carbon stock; SOCD is the soil carbon density (kg m-3), SD is the soil profile depth (30 cm), and CoF is the coarse fragments (%).

The carbon emission intensity of forest zone types refers to the carbon emission per unit of land area, which can reflect the change of carbon emissions from forest zones and its correlation. Here, it was calculated following the work by Li et al. (2023) and Shoumik and Khan (2023) as shown in equation (3.2):

$$CE = \sum Cf / \sum Sf \qquad \text{(Equation 3.2)}$$

Where, CE represents the carbon emission intensity of the forest-vegetation zone, Cf is the carbon emission of the forest-vegetation zone, and Sf is the area of forest zone.

The remotely sensed vegetation indices were used to estimate forest car-bon 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. Normalized Difference Vegetation Index was first applied by Li et al. (2023), and Shoumik and Khan (2023) as shown in equation (3.3):

$$NDVI = (NIR - Red) / (NIR + Red) \quad \text{(Equation 3.3)}$$

NDVI is the most common vegetation indices and has a range of -1 to +1. NDVI is computed from the visible and near-infrared light reflected by vegetation. Healthy vegetation absorbs most of the visible light in its contact 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 good measures of biomass and vegetation vigour (Li et al. 2023; Shoumik and Khan 2023).

The drivers of forest degradation/deforestation were grouped based on decades (Decade 1: 1990–1999, Decade 2: 2000–2009, and Decade 3: 2010–2020). And were further listed in two main categories (direct and indirect drivers). The direct drivers of deforestation were identified as human and biophysical factors. The human factors were farming, grazing, mining, building/settlements, exploitation for biofuel, timber, and NWFPs, while the biophysical factors were climate change, soil degradation, pests and diseases, and wildfire. The indirect drivers of deforestation were listed as demographic, socio-cultural, economic, and political factors. The clustering of indirect drivers was performed according to Geist and Lambin (2002). The ranking of the drivers followed a Likert scale approach.

The top 21 drivers of deforestation and the identified common tree species were analyzed using the multivariate ordination of Canoco 5.0 to show their distributions across the decades and forest belts. To determine the interrelationships among the indicators of sustainable forest bioeconomy, the pairwise correlation adjusted to Bonferroni significance levels at 0.01 and 0.05 was used in the IBM SPSS 29.0 (SPSS Inc., Armonk, NY, USA) statistical software. The LUCC, contributions of forest to GDP, and the percentage of the population that exploited forests for different benefits were spatially mapped and presented based on the forest–vegetation belts and regions using the GIS spatial analytical tools.

The multivariate methods used were correlation, principal component analysis (PCA) and redundancy analysis (RDA). For the geospatial data analysis, we employed spatial analytical tools of ArcGIS which were used to map the distributional trend during the years. In this study, the PCA was introduced to reduce the parameters associated with wood charcoal production to the most significant ones (Nguyen and Holmes 2019). The parameters were reduced from 20 to 10 most significant including forest area cover, export quantity, export value, GDP, climatic Season, tree species, population, income, years (in decades), and Literacy rate. The RDA was used to show the study periods (in decades) and the commonly available tree species for the wood charcoal production. Redundancy analysis permits the examination of the relationships between these groups of variables and their directions. All statistical analyses were performed in Canoco 5 (Ter Braak and Smilauer 2012), and Statistica 13 (TIBCO Software Inc. 2017), while the spatial analysis and mapping were done using ArcGIS 10.7.1 (2019).

CHAPTER FOUR

4 RESULTS

All the published papers are attached below in the **Appendix B** section.

Paper 1

Authors: Isaac Nyarko, Chukwudi Nwaogu, Miroslav Hájek and Prince Opoku Peseu

Title: Socio-Economic Analysis of Wood Charcoal Production as a Significant Output of Forest Bioeconomy in Africa

Journal: Forests Volume 12 Issue 5 10.3390/f12050568


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CERTIFICATE OF PUBLICATION

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Socio-Economic Analysis of Wood Charcoal Production as a Significant Output of Forest Bioeconomy in Africa

Authored by:

Isaac Nyarko; Chukwudi Nwaogu; Hájek Miroslav; Prince Opoku Peseu

Published in:

Forests **2021**, Volume 12, Issue 5, 568

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Basel, December 2023

Paper 2

Authors: Isaac Nyarko, Chukwudi Nwaogu, and Miroslav Hájek

Title: Forest Bioeconomy in Ghana: Understanding the Potential Indicators for Its Sustainable Development

Journal: Forests Volume 14 Issue 4 10.3390/f14040804


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Forest Bioeconomy in Ghana: Understanding the Potential Indicators for Its Sustainable Development

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Published in:

Forests **2023**, Volume 14, Issue 4, 804

MDPI Academic Open Access Publishing since 1996

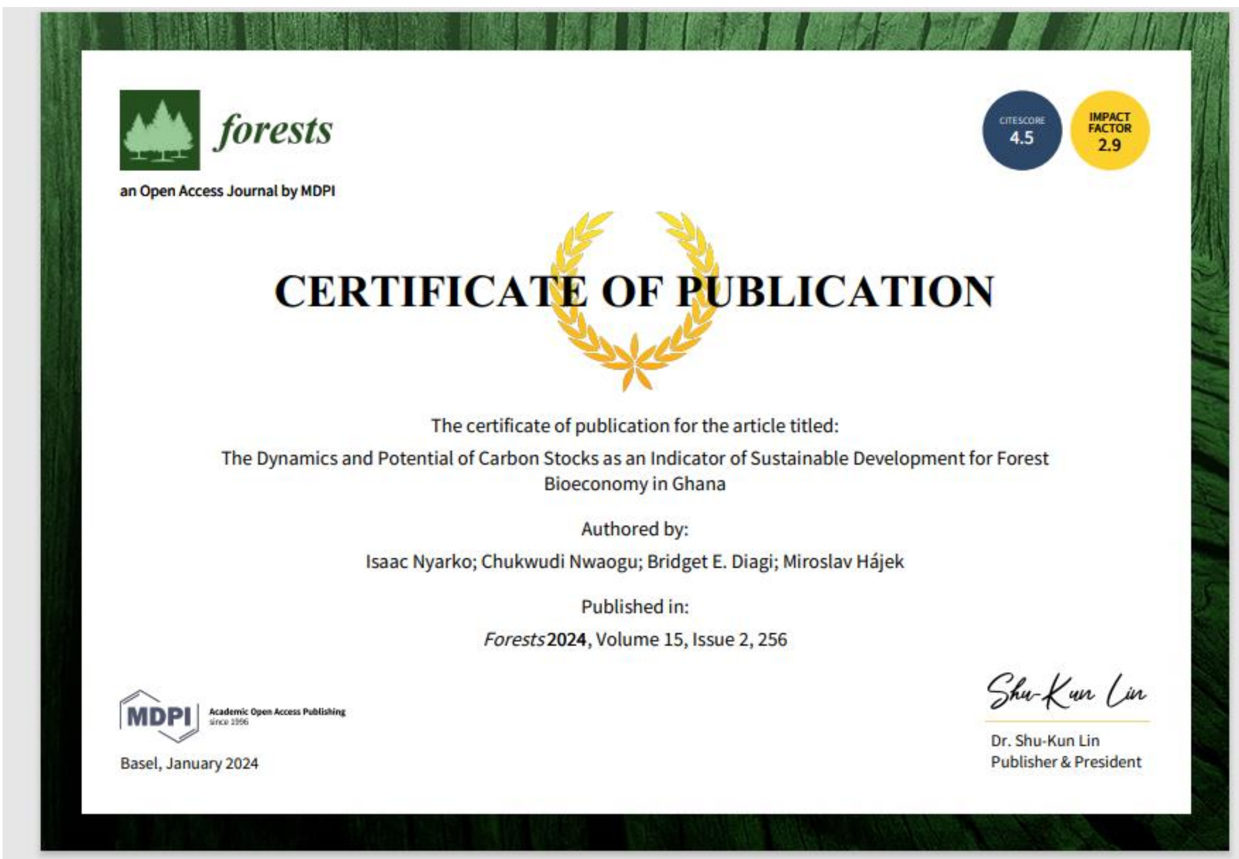
Basel, December 2023

Paper 3

Authors: Isaac Nyarko, Chukwudi Nwaogu, Bridget E. Diagi and Miroslav Hájek

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

Journal: Forests Volume 15 Issue 2 10.3390/f15020256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CHAPTER FIVE

5 DISCUSSIONS OF FINDINGS

This chapter discusses the findings of the study, and it is divided into four sections, namely sustainable forest indicators, the drivers of deforestation and forest degradation, forest products and productions, and the summarized section. The sectional divisions were deemed necessary to promote a clear discussion of the findings based on the goals and hypotheses by clustering findings with similar context. It is important that the discussions compare the results with the relevant literature on the topic. Although, the study focused partly on Africa and mainly in Ghana, some of the findings might be relevant to other regions and countries with similar conditions.

5.1 Forest Contributions to GDP, Biofuel, Employment, and Livelihood as Indicators of Sustainable Development in Forest Bioeconomy

Historically, Ghana is among the countries that have been enriching their GDP through forest products, but lately the contributions of forest to GDP has substantially decreased, a scenario that has affected the sustainable forest bioeconomy in the region. In terms of regions, the west and southern regions (such as Western, Western North, Ahafo, Ashanti, Eastern, Central, and Bono) accounted for the regions with the highest forest contributions to the national GDP. The decline in forest contributions to GDP is probably attributed to the decrease in forest area during the period. Many studies have affirmed the impact of forest loss on its contribution to GDP (Liu et al. 2020; Crespo-Cuaresma et al. 2021; Seidl et al. 2021). Consistent with the findings from this work, other studies have reported a huge decline in the forest area in Ghana (Iiyama et al. 2014), a situation that has negatively impacted forests' quota in terms of the nation's economic growth (Iiyama et al. 2014; Chandrasekaran et al. 2021).

Generally, the findings from this study showed that people, particularly in the rural communities of Ghana depend on the forests to eke out their livings. Consistent with the findings of this work, other studies on the global level also revealed that about 1 billion of the world's poorest people depend on forests for their livelihoods (Arnol et al. 2011; Agrawal et al. 2013). Moreover, in the tropical developing countries such as Ghana, the potential of forest and its associated products in supporting people's livelihoods, especially among the poor rural dwellers, has also been observed by many researchers (Malleson et al. 2014; Markus 2022; Courtney et al. 2022; Getu 2022; Maritza and Kaulard 2022; Jagger 2022). The study concluded that although forests have an important poverty mitigation function, they are not a means alone to move most people out of poverty. Apart from biofuel, forests provide non-wood forest products (NWFPs), which have minimal or zero negative impacts on the forest. These NWFPs sustain the rural people and promote sustainable forest bioeconomy campaign (Malleson et al. 2014).

The thesis work observed that employment rate in forestry and the forest-based sector as an indicator of sustainable forest bioeconomy decreased with time in Ghana. In Cameroon, for instance, a study reported that reductions in deforestation was positive in the reduction of atmospheric CO2, but led to a decrease in employment in the forestry sector and forestry's contribution to GDP (Epule et al. 2014). In truth, a decrease in deforestation will lower carbon emissions, but inevitably the economic consequences are negative because the contribution of forest to GDP and employment will reduce. To ameliorate this unacceptable scenario, the government and stakeholders in Ghana should fully adopt the Reducing Emissions from Deforestation and Degradation (REDD+) initiatives or some other financial rewarding systems such that the economic losses incurred in reducing deforestation and carbon emission could be compensated as in the cases of Brazil, Costa Rica, and Colombia (Tollefson 2009; Barbier et al. 2020).

5.2 Drivers of Forest Loss, Carbon Stocks and Emissions: As Vital Indicators of Forest Bioeconomy

To satisfy the growing needs of humans, creating more land areas for agriculture, houses, and infrastructure that consequently caused deforestation and the creation of substantial impacts on the environment including emissions of carbon are inevitable (Geist and Lambin 2002; Curtis et al. 2018; De Sy et al. 2012; Busch et al. 2017; IPBES 2019). It has been reported that West African countries including Ghana are responsible for a large portion of carbon emissions from deforestation at an average annual emission of 350 Tg/year (Abdulraheem et al. 2022). Several studies have revealed that a reduction in deforestation-induced activities over time could positively bring a tangible reduction to CO2 emissions and could promote sustainable forest bio economy (Epule et al. 2014).

The study established that aboveground biomass carbon (AGB-Cstocks) and belowground carbon (BG-Cstocks) have significant impacts on FBe in Ghana. This finding was consistent with other studies that observed a strong correlation between carbon stocks and FBe (Xu et al. 2018; Raihan et al. 2021; Omar et al. 2015; Matthew et al. 2018). In terms of the variability, the average AGB-Cstocks were higher than the BG-Cstocks across the forest-vegetation zones in Ghana. Similar with the results of this work, Raihan et al. (2021) discovered higher AGB-Cstocks than BG-Cstocks in Malaysia. Further, Omar et al. (2015) and Matthew et al. (2018) found higher contents of aboveground carbon than belowground carbon, with net differences of at least 60%. Contrary to this study, Xu et al. (2018) 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. (2018) 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, and this largely affects FBe in Ghana.

This thesis established that increase in SOC stocks has potential impacts on SDGs vis-à-vis FBe. Several studies have reported an association between SOC stocks, SDGs, and FBe in different parts of the world (Lorenz et al. 2019; Blum 2016; Smithwick 2019; Ahirwal et al. 2022; Xu et al. 2021; Keesstra et al. 2016). 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 which might consequently enhance FBe (Lorenz et al. 2019; Keesstra et al. 2016).

5.3 Wood Charcoal Production, Environment, Socioeconomic and Forest Bioeconomy Nexus

The three decades (1990–2019) established that the production of wood charcoal was relatively high and on increase from 1990 to 2019 in Ghana and other African countries investigated. This was caused by rapid population growth and high demand for natural resources which consequently led to the high rate of deforestation. There are many studies that focused on the high rate of wood charcoal production in Ghana and other African countries Nigeria (Jekayinfa et al. 2020; Mensah et al. 2020; Ngahane et al. 2015; Bede-Ojimadu and Orisakwe 2020; Bamwesigye et al. 2020; Ndegwa et al. 2016; Downward et al. 2018; Anang et al. 2011; Wurster 2010).

Wood charcoal production in Decade 2 showed a significantly positive correlation with Decade 3, while Decade 3 had the highest volume of wood charcoal production followed by

Decade 2. In exemption of the major tree species, the production for the three decades indicated a significant positive correlation with all the measured parameter (such as areas of forest cover, export quantity, export value, GDP, human population, climate season, average income (PPP) per citizen, and literacy rate (Ndegwa et al. 2016; Chitecul et al. 2018). This revealed that an increase in population leads to an increase in demand for charcoal which in turn has a negative effect on the forest (FAO 2003).

The rural populace has a higher number in the use of firewood than charcoal. This could be attributed to many reasons including (i) poor or zero electricity source in the rural areas, and/or (ii) lack of money or low income to process the charcoal among the rural people. This finding was consistent with the report by Anang et al. (2011), that charcoal consumption accounts for 61% of the fuel (as opposed to 13% in rural households) urban households in Ghana. This might be highly associated with the fact that charcoal is in high demand in the cities where the price is high and the local producers prefer selling them to increase their income (Kammen and Lew 2005).

The socioeconomics and environmental impacts of wood charcoal production can never be overemphasized as this has recently drawn the attention of many studies (Udali et al. 2021; Crespo-Cuaresma et al. 2017). Wood charcoal has increased and supported the livelihood, income and revenue of households, individuals, and governments of various countries in Africa and other developing countries. In most rural and urban poor, charcoal is a cheap, reliable, convenient, and accessible source of energy for households and commercial cooking. Though Kerosene, electricity and LPG may be considered the most desired cooking energy sources in urban areas, their affordability and availability of necessary resources to use these forms of energy are outside the reach of many citizens. Therefore, many households resort to using charcoal. In contrast to the benefits of wood charcoal production, the negative effects recently associated with wood charcoal are given great concern to decision-makers (Bede-Ojimadu and Orisakwe 2020).

The analysis adopted in this work was very effective and supportive in achieving the goal of the work. For example, the descriptive statistics were applied to show the rates, quantities, and average, and sum of wood charcoal productions, forest area cover, export quantity and export value over the three decades in the study area. The quantitative statistics such as the multivariate analysis: correlation, principal component analysis (PCA) and redundancy analysis (RDA) were also very supportive. The PCA was introduced to reduce the parameters associated with wood charcoal production to the most significant one including only forest area cover, export quantity, export value, GDP, climatic Season, tree species, population, income, years (in decades), and literacy rate. The RDA was used to show the study periods (in decades) and the commonly available tree species for the wood charcoal production. Redundancy analysis permits the examination of the relationships between these groups of variables and their directions. To determine the interrelationships among the indicators of sustainable forest bioeconomy, the correlation analysis was applied. On the other hand, the geospatial data analysis software is the spatial analytical tools of ArcGIS which was used to map the spatial distributional trends of the wood charcoal production, the forest-vegetation zones, and the Cstocks across the study area during the years of investigation. The InVEST model, a universal model developed to determine carbon stocks was used in this work to determine the contents and spatial distribution of carbon stocks in the study area. 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 (which are the forest-vegetation zones, in the case of this PhD work).

Based on the findings of this work, the following environmental and socioeconomic variables were identified as the most indicators for sustainable forest bioeconomy in Ghana: Environmental were forest area, forest growing stocks, volume of dead wood, forest net primary productivity, tree cover loss, soil organic matter content, and Cstocks. The socioeconomic indicators were forest contributions to GDP, rates of employment in the forest sector, quantity and quality of products (wood and non-wood) derived from the forest. However, these indicators of forest bioeconomy are substantially influenced by many other factors such as human population, literacy rate, poverty rate, forest use as biofuel, forest use for non-biofuel, and climate (especially temperature and rainfall). Others are settlements, logging of timber for commercial purposes, infrastructural development, forest deforestation for other household uses, civil/communal conflicts, wildlife gathering for game and hunting, political and governance policies, weak governance, and lack of law enforcement.

In the light of the findings, it could be deduced that the hypotheses of this work were affirmed and confirmed that:

H1: Charcoal production has a negative impact on sustainability from the perspective of the forest bioeconomy.

H2: The forest bioeconomy in Ghana contributes significantly to GDP growth and is a promising strategy for economic growth.

H3: It can be expected that the indicator focused on carbon sequestration will grow in the longer term in line with the growing activities of the forest bioeconomy.

H4: The growth of the sustainability of the forest bioeconomy has a positive effect on carbon sequestration.

CHAPTER SIX

6 CONCLUSIONS AND RECOMMENDATIONS

The study observed that the common processes of producing wood for biofuel was not sustainable and affected FBe in Ghana during the 3 decades of study. Further, many indicators of sustainable forest bioeconomy including Cstock, contribution of forest to GDP, rates of forest area, loss, forest growing stock, and others were identified. At this point it could be agreed that the title of the thesis: “Analysis of sustainability of production processes and proposal of indicators of sustainable development in forest bioeconomy”, and the objectives have been achieved as outlined and concluded in the following paragraphs:

6.1 Conclusions

The thesis presented the following conclusions based on the findings from the studies: Firstly, it was established that wood charcoal production had significant correlation with the socioeconomic and biophysical parameters (such as areas of forest cover, export quantity, export value, GDP, human population, climate season, average income per citizen, and literacy rate). The common practice of producing much wood for biofuel substantially affected FBe in Ghana during the 3 decades of study. Secondly, the study concluded that Ghana forests’ contributions to GDP and FBe vary between the forest–vegetation belts and regions and decreased rapidly from 1990 to 2020. So many factors including rapid growth in population where found to be responsible for this dynamics between the forest-vegetation zones. Thirdly, it was observed that the highest drivers of deforestation in Ghana were population growth, agricultural activities, and commodity-driven deforestation. Fourthly, the study affirmed that a decrease in Cstock as sustainable indicator of forest bioeconomy is related to increase in population and agriculture which caused significant decrease in forest area and growing stock that in turn affected sustainable forest bioeconomy in

Ghana. The study further observed that an increase in Cstocks supported the achievement of several SDGs, especially SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well Being), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible consumption and production), SDG 13 (Climate Action), and SDG 15 (Life on Land). These in turn largely supported a sustainable forest bioeconomy. Moreso, the relevance of the findings from the thesis can never be overemphasized because they might significantly help to bring lasting solutions to deforestation and enhance the sustainable forest bioeconomy.

It could also be concluded that the hybridization of methods of statistics, geostatistics, and geospatial analysis produced effective results in the identification, modelling, mapping, and assessment of the principal indicators for SFB in Ghana. This could be extended in other parts of Africa and regions. In addition to unveiling the remote drivers of forest loss that have been long overlooked by previous studies, the study concludes that sustainable enlightenment campaign and routine informal education of the rural people are highly necessary. This is because some of the peoples' reasons for deforestation and preference for forest products compared with modern resources seem convincing and logical.

In general, to achieve optimum and sustainable forest bioeconomy all the indicators of SFB must be considered because all are directly or indirectly linked, thus ignoring one over the other might truncate the main objectives. For example, providing the people an alternative source of energy away from wood charcoal might not be sustainable if rapid population growth is also not addressed. In sum, the study revealed that the sustainable forest bioeconomy is indeed a multidimensional approach involving economic, social, and environmental indicators, thus a direct or indirect impact in one will definitely influence the others positively or negatively. For example, deforestation might increase GDP, income, and/or an individual's economic well-being, but there might be a reduction in forest areas that could lead to decline in employment rate, forest stocks, net primary productivity, poor soil, and increased carbon emissions. On the other hand, a reduction in deforestation might bring about a reduction in carbon emissions; however, the economic repercussions could be negative as the contribution of forest to GDP, income, and employment will fall as trade-offs. Thus, a balance is necessary to be applied based on the findings from this this study and other related studies, and policy-makers can reach at a balanced equilibrium. Therefore, at this point it could be agreed that the objectives of this work have been achieved.

6.2 Recommendations

The conducted research results in recommendations for the government and for further research, and these were described below but not in order of preference or significance:

Firstly, the government should enact and adjust forest and land use policies, to refine carbon emission reduction strategies, and to construct and implement better regulations by fully consulting and incorporating the forest-dependent communities. This will make the rural and indigenous people to become partisans and stewards in policies regarding protection of the forest resources in their neighbourhood.

Secondly, in as much as larger population of the people who depend much on forests live in the rural areas, the collaborations of the local people in achieving SFBe should be a crucial agenda in the decision-making by the Government of Ghana. This is because most of the activities of the greater percentage of the populace center in the forest ecosystem.

Thirdly, the government and the stakeholders in forest bioeconomy should support economic diversification, and rural education are also needed to promote the awareness, growth, and benefits of carbon stocks as a component of SFBe in the country.

Additionally, Ghana is a tropical and coastal country with enough sunlight and sea; therefore, the Government should extract renewable energy from these sustainable energy sources (such as solar, wind, hydro-power, and their hybridization) and provide the rural communities with solar-powered cooking stoves. This recommendation, if adhered to will drastically reduce pressure on the forest which occurs due to the use of the forest as the only source of domestic energy for cooking, housewarming, and so on.

Last but not the least, further studies need to be conducted on the impacts of nature and national forest reserves in the achievement of FBe in Ghana because this current work did not specifically focus on the restricted forest areas. Meanwhile, there are many reserve areas in the country, and extending similar study in them will promote awareness about their prospects for sustainable forest bioeconomy in the country.

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APPENDICES

Appendix A

Appendix Table 1. 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	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
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

Table A1. *Cont.*

Forest-Vegetation Belts	Regions	Latitude	Longitude
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	9.146967	−
Dry deciduous forest and savanna	Northern region	9.771445	−1.94689
Dry semi-deciduous forest and savanna	Northern region	9.886262	0.173559
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	−1 .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	0.7391

APPENDICES B

1. **Nyarko, I**., Nwaogu, C., Miroslav, H., & Peseu, P. O. (2021). Socio-economic analysis of wood charcoal production as a significant output of forest bioeconomy in Africa. Forests, 12(5), 568.

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3. **Nyarko, I.,** Nwaogu, C., Diagi, B. E., & Hájek, M. (2024). The Dynamics and Potential of Carbon Stocks as an Indicator of Sustainable Development for Forest Bioeconomy in Ghana. Forests, 15(2), 256.

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Article

Socio-Economic Analysis of Wood Charcoal Production as a Significant Output of Forest Bioeconomy in Africa

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Abstract: Wood charcoal (WCH) is a sustainable biofuel for rural and urban users because of its higher energy density and emission of marginal smoke when compared with firewood. Besides helping the poor majority who cannot afford kerosene, electricity or liquid petroleum gas (LPG), WCH is a key source of income and livelihood. This work aimed at quantifying the volume of WCH production as well as appraising its socio-economics, including environmental impacts, especially the impact of long-term deforestation and forest degradation in Africa. Historically robust data from the databases of UN-FAO, FAOSTAT, International Energy Agency (IEA), United Nations Statistics Division, UN-DESA energy statistics yearbook, and the Forest Resources Assessment (FRA) were used. The data analysis involved descriptive statistics, multivariate analysis, and geospatial techniques. The result revealed that East Africa had the highest average wood charcoal production which was 32,058,244 tonnes representing 43.2% of the production whereas West Africa had 23,831,683 tonnes denoting 32.1%. Others were North Africa (8,650,207 tonnes), Middle Africa (8,520,329 tonnes), and South Africa (1,225,062 tonnes) representing 11.6%, 11.5% and 1.6% respectively. The correlation matrix showed that WCH production for the three decades had a significant positive correlation with all the measured parameters (such as areas of forest cover, export quantity, export value, GDP, human population, climate season, average income per citizen, and literacy rate). Wood charcoal is an essential livelihood support system. New policies including commercial wood charcoal production and licensing for revenue and ecological sustainability are required. Enterprise-based approaches for poverty reduction, smallholders' tree-growing, wood charcoal-energy conserving technologies, improved electricity supply and agricultural productivity are encouraged. The novelty of this study can also be explained by the diverse parameters examined in relation to WCH production which no other studies in the region have done.

Keywords: biofuel; socioeconomics; bio-economy; forest resources; sustainable development; Africa

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1. Introduction

Wood charcoal (WCH) can be defined as the solid residue generated from the process of carbonization, distillation, pyrolysis and/or torrefaction of the trunks and branches of trees, and wood by-products, by continuous or batch systems of earth kilns (pit, mound and brick) or metal kilns [1]. Wood charcoal production has been an essential anthropogenic activity since the prehistoric era [2,3], and charcoal is known as the foremost synthetic matter developed by humans. Wood charcoal production has always sustained the peoples' livelihood since the medieval period. The uniqueness of WCH such as affordability, supply-reliability and availability made it more preferable to other renewable and non-renewable energy sources [4,5]. Wood charcoal is also value-added energy for rural and urban users because of its higher energy density and emission of marginal smoke than firewood. Socioeconomically, the importance of the WCH sector in Africa cannot be overemphasized. For example, the WCH industry has provided direct and indirect employment to millions of people and thousands of groups as manufacturers, transporters and traders and their families [6]. In various countries in the region, the WCH sector has increased the economic value of the people at the local and national level and is reported to rival some other highly valued sectors in most countries. For instance, the WCH sector in Kenya has equivalent worth to the tea sector and employs as many people as the educational sector [7]. In Tanzania, the WCH industry produces greater revenue (worth USD 650 million) which is 5.8 times more than the combination of tea and coffee industries [6]. In Nigeria, it generates more income for the local people when compared with groundnut, cocoa and palm oil in the north, west and eastern part of the country respectively [8]. In Sudan, South Sudan and Uganda, WCH is recently an economic sector that has got almost equivalent rating with the cotton industry [9]. Woodfuels including WCH contributed to about 3.5% of Malawi's GDP, and 160,000 in direct and indirect employment in 2008 [10]. In addition, WCH production shares a high percentage in the Gross Domestic Product (GDP) of many other countries including India, Ethiopia, Ghana, Brazil, Zambia, and Rwanda [11].

The wood charcoal production process involves getting the wood heated in the absence of air or partially combusted with a finite or restricted oxygen supply [12,13]. By applying any of the processes (such as carbonization, distillation, pyrolysis or torrefaction) WCH is produced in Africa, and the region accounted for an estimated 65% of global charcoal production [5]. Nigeria, Ethiopia, Ghana, Senegal, Tanzania and Madagascar are the top producers [5,14,15]. The annual average WCH production in Africa showed a drastic increase since the 1970s ranging from 629,083.33 tonnes in 1970, 2,769,416.66 tonnes in 2017, to more than 3 million tonnes in 2019 [14]. This increase was prompted by the need to satisfy the high demand for cooking and heating energy from urban and sub-urban households [6]. It has been reported that about 40% of the charcoal used in Europe was imported from Africa [16].

In exemption of the afore-mentioned benefits of WCH, its production and consumption in Africa are associated with many ecological and health challenges [4,17,18]. The commonly reported consequences of WCH production were a decline in forest and forest degradation especially in countries such as Nigeria, Ethiopia, Ghana and others which have extremely high demands for charcoal without policies. In such places, completely deforested land is visible because sustainable selectivity of trees for size and species has been supplanted by economic incentives [19].

Most of the studies on WCH production in Africa focused on either one to few countries, or their studies were only related with a singly selected parameter such as biofuel implication [4,5], tree species and wood quality [20,21], political issues and policies [22,23], environmental and health implications [4,8,17,18,24], impacts on food safety [25], and socioeconomic [6–11]. A study with a holistic approach that integrates most of these factors as they relate to WCH production is lacking in Africa. Therefore, the novelty of this work is obvious because it aimed at quantifying the volume of WCH production in Africa as well as appraising its socio-economics, including environmental impacts, especially the impact of long-term deforestation and forest degradation. The inclusion of multiple variables (such as, areas of forest cover, export quantity, export value, GDP, human population, climate season, average income per citizen, and literacy rate) which were simultaneously examined in relation to WCH production was also remarkable. At present, there is no record of any studies that have performed such robust investigation on this topical issue in the region (Africa).

2. Materials and Methods

2.1. Description of Study Area

Africa as a continent is currently having 54 countries with a total area of 30,368,609 km^2 (11,725,385 sq mi). Africa measures about 5000 miles (8000 km) from north to south and about 4600 miles (7400 km) from east to west. The landmass of the continent accounts for 20% of the Earth's land surface. The human population is approximately 1.2 billion, and is increasing at a rapid pace which is almost thrice faster when compared with other continents. According to [26], Africa's population will triple or quadruple by the end of this century. In terms of climate, Africa lies mainly within the inter-tropical zone and is therefore a regularly hot continent. The various climate belts are principally influenced by their rainfall trends. The major climatic zones are classified into six major categories namely, Equatorial, Humid Tropical, Tropical, Sahelian, Desert, and Mediterranean climate. The primary soil types in the continent are Oxisols, Ultisols, Alfisols, Etisols, Gelisols, Vertisols and Aridisols.

2.2. Wood Charcoal Production and Markets in Africa

Wood charcoal is traditionally produced in Africa in earth, brick, metals or steel drum kilns in batches from about 1 to 5 tons. The production methods are detailed in much of the literature [1,27].

There are three markets identifiable for WCH production in Africa. These are domestic, overland and overseas. The domestic charcoal markets in Africa are strongly linked with high population, urban and sub-urban areas. Besides the rapidly growing human population, these areas are denoted by a class of citizens that can afford WCH products [6]. The overland markets involve WCH trading between the countries within the region. As some countries (e.g., those in the Sahel belts) have little or no trees and shrubs due to geographical location and climate, they depend on their neighbors in the south for WCH. For instance, Burkina Faso, Niger Republic, Mali, and Chad rely on Nigeria and Ghana for their WCH [28]. The overseas markets flourish mainly between Nigeria, Ghana, Ethiopia and Tanzania selling to the developed nations, mostly the European countries [14,29]. Africa accounts for about 65% of global charcoal production with 21% of its charcoal output being exported [5].

2.3. Data Collection

The study evaluated and mapped wood charcoal production and the associated parameters in Africa for three decades (1990–2019) focusing on all countries. The study also compared WCH production based on regions and top producing countries. Historically robust data from the databases of UN-FAO, FAOSTAT [14], International Energy Agency-IEA, United Nations Statistics Division, UN-DESA energy statistics yearbook 2019, and the Forest Resources Assessment (FRA) were visited and relevant data were downloaded. Microsoft Excel was employed to compute the relative WCH parameters of countries in Africa. Additional data were acquired from the United Nations Statistics Division (UNdatabase) on WCH for respective countries. Other sources of data for the study were the official National Bureau of Statistics of various countries covering the relevant study periods, as well as online literature and publications. Data were also collected from interviews focusing on the top four producing countries (Nigeria, Ghana, Ethiopia, and Senegal) as case studies. The interview involved the WCH producers, the marketers, transporters and the consumers. Primarily, WCH producers in the sub-region exploit trees and shrubs that are available within their area. The commonly preferred tree species are the hardwoods such as *Dialium bipindense*, *Diospyros spp.*, *Pentaclethra macrophlla*, *Letestua durissima*, *Lophira alata*, *Milicia excels*, *Baphia kirkii*, *Cleistanthus mildbraedii*, *Cylicodiscus gabonensis*, *Desbordesia pierreana*, *Manilkara cuneifolia*, and *Parinari glabra*. Others are *Strombosia glaucescens*, *Swartzia fistuloides*, *Tessmania Africana*, *Klainedoxa gabonensis*, *Afzelia Africana spp.*, and *Piptadeniastrum Africanum*. Furthermore, some softwood species such as *Triplochiton scleraxylon*, *Gmelina arborea*, *Juniperus procera*, *Pinus halepensis*, *Pinus pinaster*, *Cedrus atlantica*, *Hagenia abyssinica*, *Taxus baccata*, *Hevea brasiliensis*, and *Celba pentandra* are also commonly used for WCH production in Africa. This information was derived from online sources and literature [5]. Data on income and literacy rate were collected from World Development Indicators and World Literacy rate of the World Bank [30], World Bank data on, and World Income Inequalities

Database [31]. The income per citizen was in inflation-adjusted dollars. The year 2010 was used as the base year because the inflation rates for more than 80% of countries in the continent became exacerbated from 2010. This does not mean that no inflation before 2010. There was inflation in some countries but the inflation rate became high from 2010. The collected data covered three decades, namely Decade 1 which includes 1990–1999, Decade 2 represents 2000–2009, and Decade 3 stands for 2010–2019. In this work, the decades and their respective year ranges were used interchangeably to mean the same.

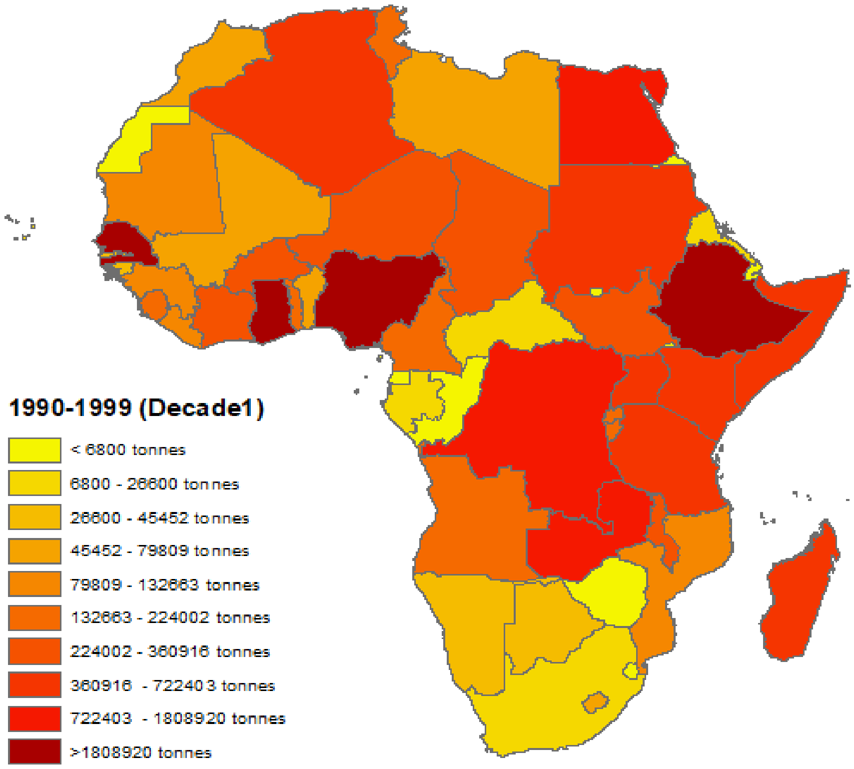
2.4. Data Analysis

The data analysis involved the use of descriptive and multivariate statistics as well as geospatial techniques. The descriptive statistics performed in Microsoft Excel included percentages, sum and average for WCH productions, forest area cover, export quantity and export value. The multivariate methods used were correlation, principal component analysis (PCA) and redundancy analysis (RDA). For the geospatial data analysis, we employed spatial analytical tools of ArcGIS which was used to map the distributional trend during the years. In this study, the PCA was introduced to reduce the parameters associated with wood charcoal production to the most significant ones [32]. The parameters were reduced from 20 to 10 most significant including forest area cover, export quantity, export value, GDP, climatic Season, tree species, population, income, years (in decades), and Literacy rate. The RDA was used to show the study periods (in decades) and the commonly available tree species for the wood charcoal production. Redundancy analysis permits the examination of the relationships between these groups of variables and their directions [33]. All statistical analyses were performed in Canoco 5 [33] and Statistica 13 [34], while the spatial analysis and mapping were done using ArcGIS 10.7.1 [35].

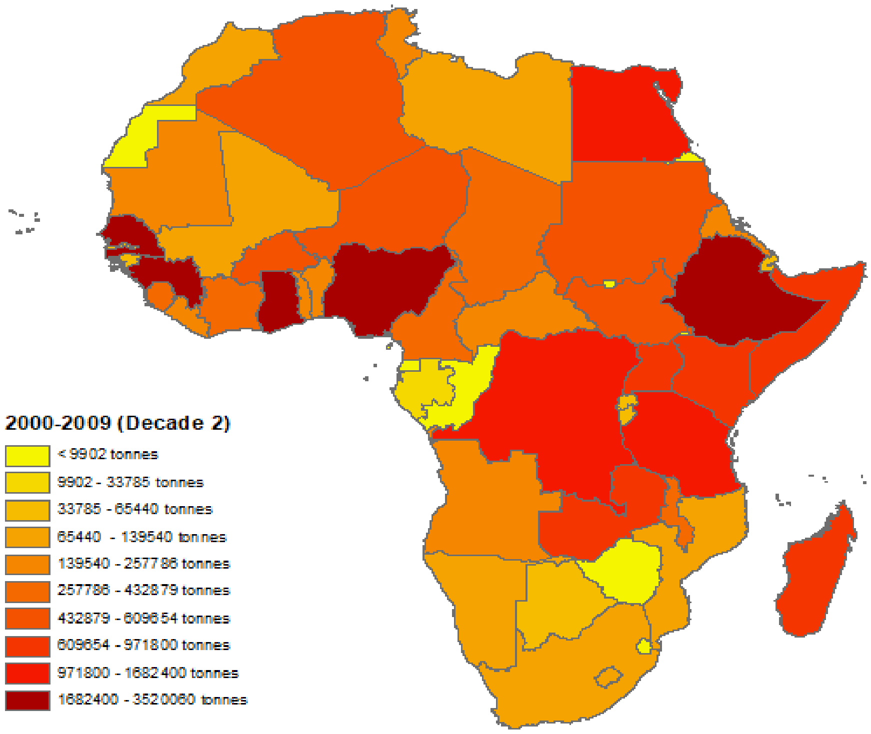
3. Results and Discussion

3.1. Wood Charcoal Production

The results of the average wood charcoal production for the last three decades (1990–2019) among the African countries revealed that the production was not evenly distributed (Figure 1a–c; Table S1). In Decade 1 (1990–1999), the highest wood charcoal producers in descending order were Nigeria (2,783,277 tonnes), Ethiopia (2,623,545 tonnes), Ghana (1,808,920 tonnes), Senegal (1,801,641 tonnes), and Congo DR (1,123,898 tonnes) while the lowest producers were Congo (1592 tonnes), and Mauritius (330 tonnes) (Figure 1a). The countries which had the highest production in Decade 2 (2000–2009) were Nigeria (3,464,538 tonnes), Ethiopia (3,520,064 tonnes), Ghana (1,780,732 tonnes), Congo DR (1,682,395 tonnes), Guinea (1,615,133 tonnes), and Senegal (1,610,208 tonnes) (Figure 1b). The lowest producers were Congo (3336 tonnes), and Mauritius (55 tonnes). In Decade 3 (2010–2019), Nigeria, Ethiopia, Congo DR, Ghana, Tanzania, and Senegal produced the highest wood charcoal of 4,314,708, 3,721,971, 2,362,240, 1,851,235, 1,845,625, and 1,430,607 tonnes respectively (Figure 1c). The lowest producers in Decade 3 were Cabo Verde, and Mauritius which had 921 and 3 tonnes respectively. There are many studies that focused on the high rate of wood charcoal production in Nigeria [4], in Ethiopia [36], Ghana [5,37], Senegal [38], Tanzania [39], Mozambique [40], Uganda [17], Malawi [41], Zambia [42], and other African countries [7].

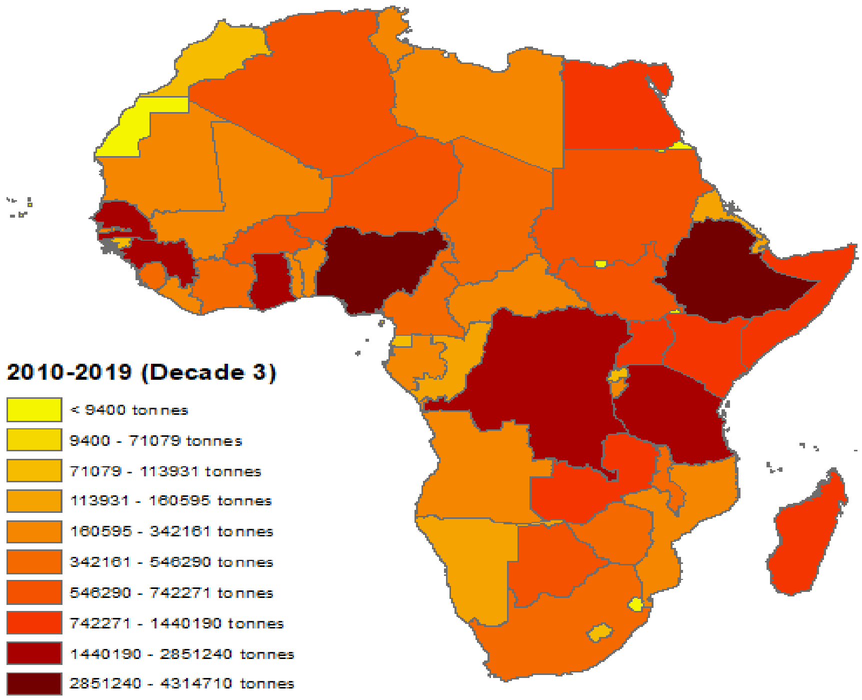


(a)



(b)

Figure 1. *Cont*.



(c)

Figure 1. Average Wood Charcoal Production from 1990–2019, (**a**) Decade 1 (1990–1999), (**b**) Decade 2 (2000–2009), and (**c**) Decade 3 (2010–2019). Sources: Authors' compilation, analysis and mapping from FAOSTAT database.

On the regional basis, East Africa had the highest average wood charcoal production from 1990 to 2019 which was 32,058,244 tonnes representing 43.2% of the production in the region for the three decades (Table 1). West Africa had 23,831,683 denoting 32.1%, while North Africa (8,650,207 tonnes), Middle Africa (8,520,329 tonnes, and South Africa (1,225,062 tonnes) representing 11.6%, 11.5% and 1.6% respectively. Across the region, Decade 3 (31.58 million tonnes) recorded the highest wood charcoal production when compared with Decade 1 and Decade 2. The production in Decade 3 is 43% and 22% higher than the production in Decade 1 and Decade 2 respectively (Figure 2). The increase in wood charcoal production from 1990 to 2019 might be attributed to an increase in demand due to an increase in human population and urbanization in the continent.

Table 1. Wood charcoal production (in tonnes) and percentages (%) by African regions in three decades (1990–2019).

Regions	1990–1999 (Decade 1)	2000–2009 (Decade 2)	2010–2019 (Decade 3)	1990–2019 (Decade 1–3)
	Average (%)	Average (%)	Average (%)	Average (%)
West Africa	5,614,359 (31.0%)	7,862,442 (31.9%)	10,354,880 (32.8%)	23,831,683 (32.1%)
East Africa	7,930,171 (43.8%)	10,610,042 (43.1%)	13,518,030 (42.8%)	32,058,244 (43.2%)
North Africa	2,562,088 (14.2%)	2,880,039 (11.7%)	3,208,079 (10.2%)	8,650,207 (11.6%)
Middle Africa	1,791,318 (9.9%)	2,836,268 (11.5%)	3,892,742 (12.3%)	8,520,329 (11.5%)
South Africa	205,734 (1.1%)	426,917 (1.7%)	592,411 (1.9%)	1,225,062 (1.6%)

Sources: Authors' compilation and analysis.

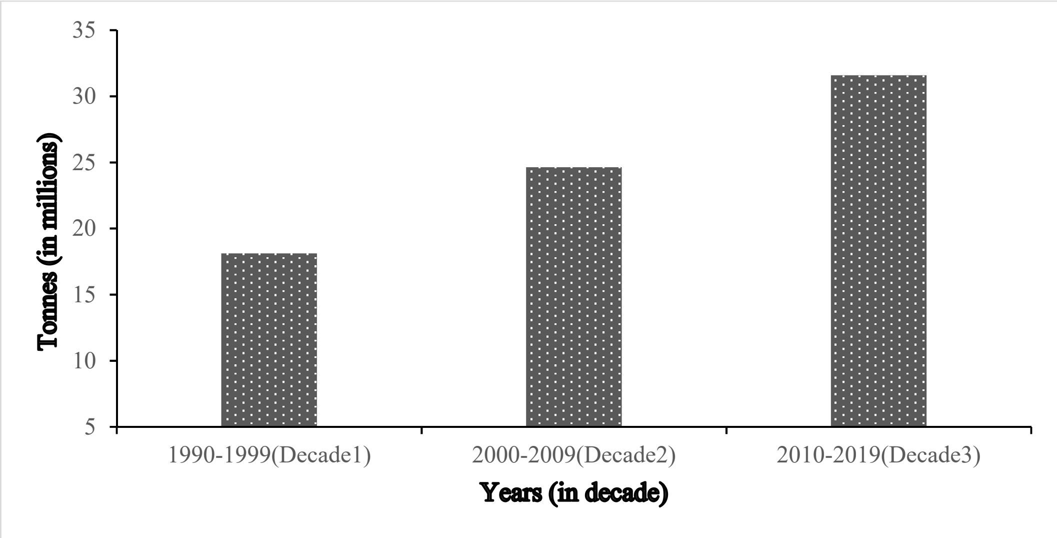


Figure 2. Total wood charcoal production in Africa from 1990 to 2019. Sources: Authors' compilation, analysis and mapping from FAOSTAT database.

3.2. Relationships Between Wood Charcoal Production, Income and Forest Area Change (Deforestation Rate)

The countries in the East African region recorded the largest deforestation (i.e., forest area change) in Africa during the study period (Figure 3). On the other hand, the North African countries accounted for the lowest forest area change during the past three decades. Ethiopia, Congo DR, Tanzania, Nigeria, Egypt and South Africa had the highest deforestation rate while, Western Sahara, Tunisia, Libya, Morocco and had at most 20,000 ha/year as forest area change. The average income per citizen varied greatly among the countries and regions (Figure 4a,b). The Northern Africa (22,057.1 USD/per citizen) and Southern Africa (13,040.6 USD/citizen) countries had the highest income per citizen while, Eastern Africa, Middle Africa and Western Africa accounted for the lowest income rate having 12,342.4 USD, 6496.5 USD and 4209.2 USD respectively per citizen (Figure 4a). On the country bases, Libya, Egypt, Algeria, Tunisia, Gabon, South Africa, Namibia and Botswana recorded the highest average income per citizen while Congo DR, Niger Rep, Somalia, Western Sahara recorded the lowest (Figure 4b). It is important to state that income per citizen was highly associated with wood charcoal production and deforestation. The result revealed that most of the countries which have higher income per citizen tend to have low wood charcoal production and low deforestation during the study period. For example, all the countries that had a higher income per citizen including Morocco, Tunisia, Algeria, Libya, Egypt, Namibia, Angola, Botswana, and Gabon showed relatively low deforestation except South Africa (Figures 3 and 4a). Additionally, refer to Table 2 where charcoal production from 1990–2019 (Decade 1–3) indicated a significant correlation with income ($r = 0.53$), while income was significantly correlated with forest cover ($r = 0.40$). This might probably be attributed to the reason that with higher income, citizens were able to afford other sources of energy than wood charcoal. This consequently, reduced their deforestation rate in comparison with their poor counterparts. Thus, in agreement with this study, [43] concluded that by using charcoal and firewood, the poor majority (72.9%) in Nigeria adapted to the increase in prices of kerosene, cooking gas and electricity. In contrast, other authors revealed that charcoal consumption increased with income [44]. Another study reported that charcoal is not mainly consumed by low-income households rather, it is used across a wide range of income levels with less variation in per capita consumption [17].

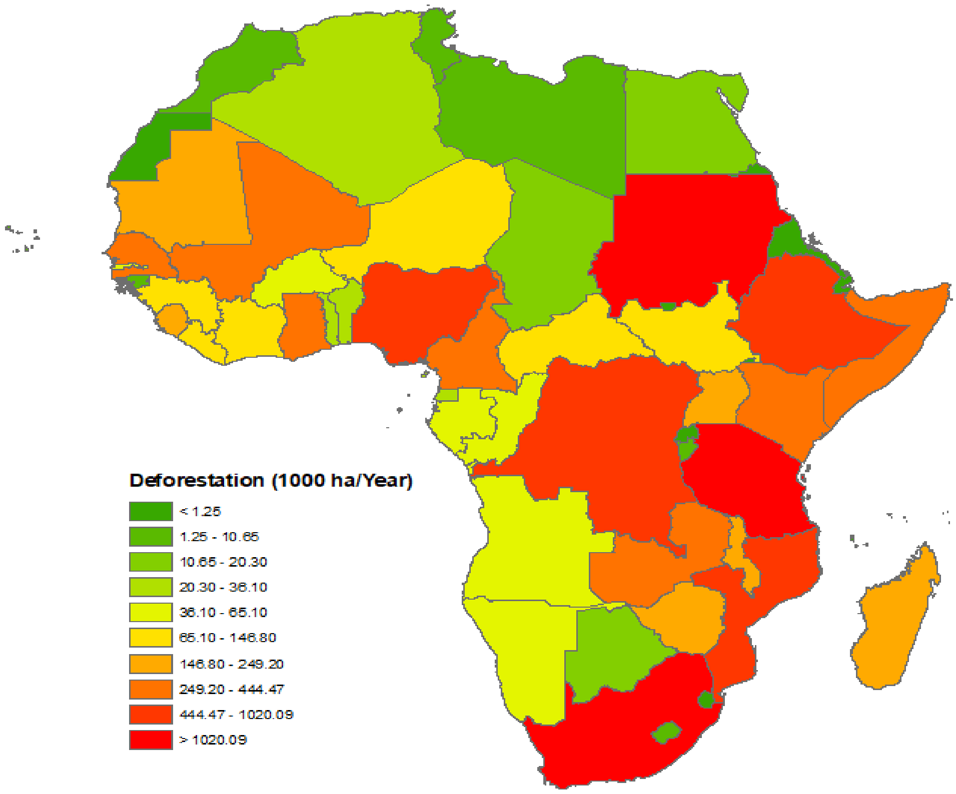
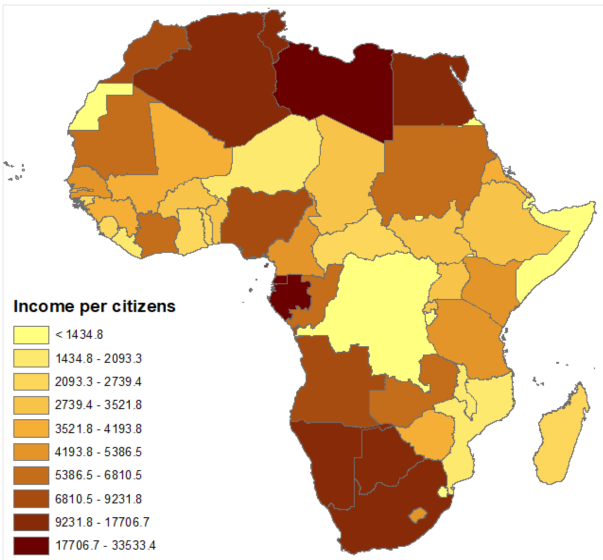
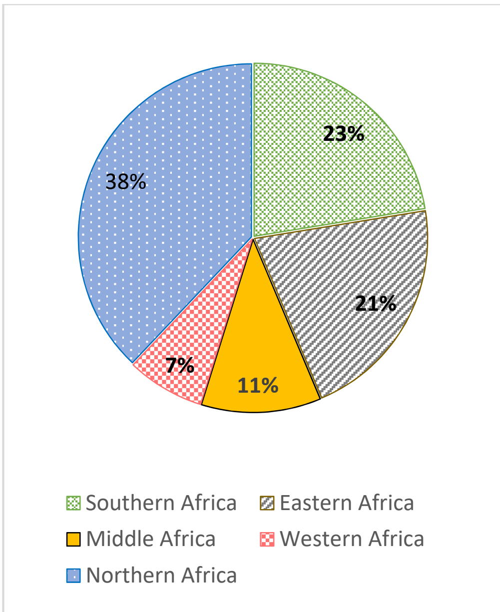


Figure 3. Deforestation (forest area change) in African countries from 1990 to 2020 in 1000 ha/year. Sources: Authors' compilation, analysis and mapping from FAO, FAOSTAT, and FRA databases.



(**a**)



(**b**)

Figure 4. Average income (PPP) per citizens in USD* from 1990–2019 (**a**) for all African countries, (**b**) proportion on regional basis. * The income per citizen was in "inflation-adjusted dollars" based on 2010. The reason for choosing 2010 is explained in the material and method. Sources: Authors' compilation, analysis and mapping from WID, WB, and WDI databases.

Table 2. Summary of Correlation analyses among the studied parameters. Decade 1 (1990–1999), Decade 2 (2000–2009), and Decade 3 (2010–2019), Decade 1-3 (1990–2019).

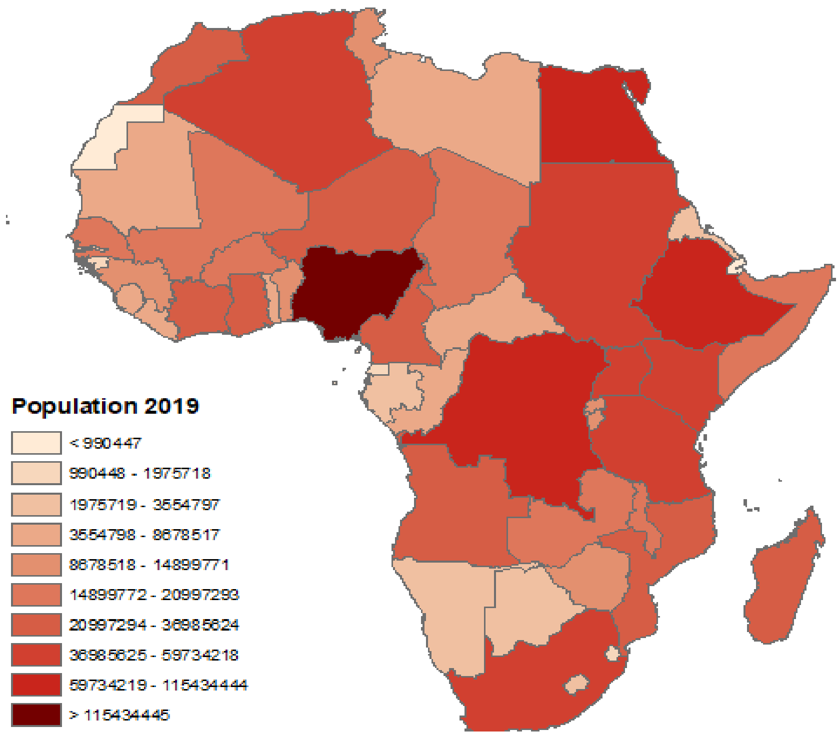
	Decade 1	Decade 2	Decade 3	Decade 1-3	Forest Cov	Export Qtty	Export Val	GDP	Clim Seson	Tree Spp	Pop	Income	Lit Rate
Decade1	1.00												
Decade2	0.55	1.00											
Decade3	0.41	0.59 *	1.00										
Decade1-3	0.63 *	0.68	0.44 *	1.00									
ForestCov	−0.65 **	−0.74 **	−0.81 **	−0.77 **	1.00								
ExportQtty	0.60 *	0.57 *	0.72 **	0.59 *	−0.88 **	1.00							
ExportVal	0.68 *	0.63 *	0.52 *	0.62 *	−0.75 **	0.59 *	1.00						
GDP	0.34	0.50	0.65 *	0.54 *	0.28	0.67 **	0.47	1.00					
ClimSeson	−0.47 *	−0.55 *	−0.71 **	−0.58 *	−0.61 *	−0.09	0.00	−0.16	1.00				
TreeSpp	0.08	0.01	0.09	0.17	0.22	0.00	0.02	0.00	−0.64 **	1.00			
Pop	−0.52 *	−0.64 *	−0.71 *	−0.91 *	−0.83 **	0.01	−0.05	−0.73 *	0.00	0.00	1.00		
Income	0.21	0.19	0.08	0.53 *	0.40 *	0.32	0.28	0.60 *	−0.23	0.07	−0.58 *	1.00	
LitRate	0.04	0.00	0.01	0.45 *	0.27	0.00	0.00	0.51 **	0.00	0.00	−0.79 **	0.53 *	1.00

Sources: Authors' analysis. * Correlation is statistically significant at $p < 0.05$; ** Correlations is statistically significant at $p < 0.01$. Description of Abbreviations: ForestCov = Forest cover; ExportQtty = Export quantity; ExportVal = Export Value; GDP = Gross Domestic Product; ClimSeason = Climatic season; TreeSpp = Tree species; Pop = Population; LitRate = Literacy rate.

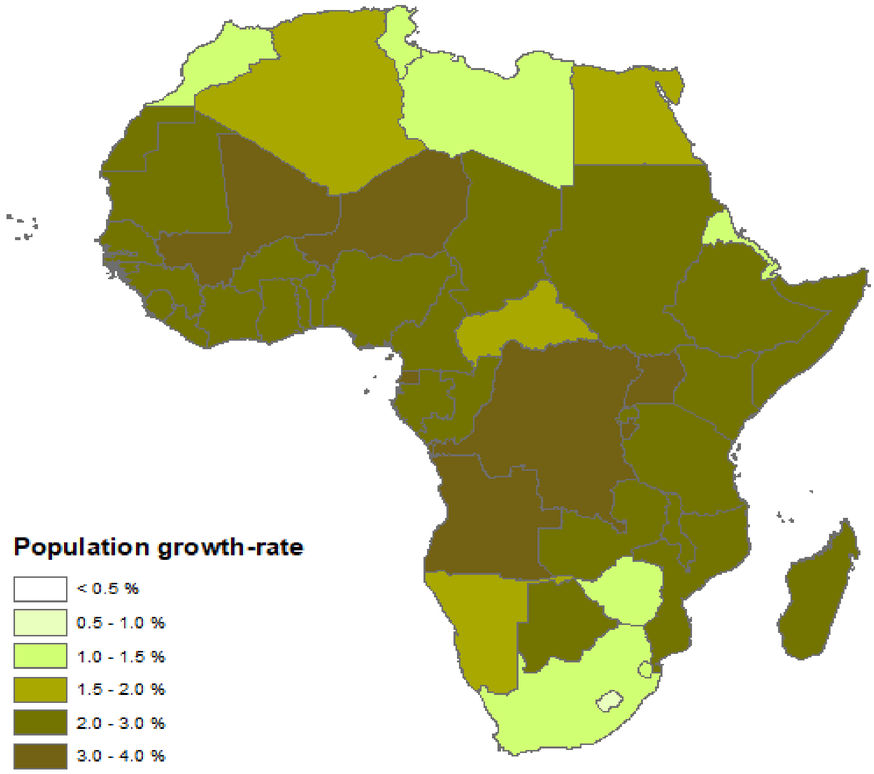
3.3. Population, Export Quantity and Wood Charcoal Production Nexus

The countries with the highest population were Nigeria, Ethiopia, and Congo DR (Figure 5a). In terms of population growth rate, the countries in Western Africa, Eastern Africa and Middle Africa had the highest population growth rate while the Northern African and Sothern African countries had relatively low growth rate (Figure 5b). It could be inferred that the population trend has a clear relationship with wood charcoal production in Africa during the past three decades. The result in Figure 5a,b supports the information in Table 1, which revealed that population and wood charcoal production are strongly correlated. The larger the population, the higher the quantity of wood charcoal produced and consumed by countries [45].

Export quantity is another parameter that showed a significant relationship with wood charcoal production. The result on the export quantity as shown in Table 3 reported that Nigeria, Congo DR, Egypt, Ghana and Tanzania have the highest quantity of wood charcoal export. It could be deduced from the result that most countries that have higher wood charcoal production also had high export quantity. Exceptional cases were Mozambique, Namibia and Somalia which did not record very high wood charcoal production yet were among the countries which had high export quantity. Other exceptional cases were Ethiopia and Senegal which showed high wood charcoal production but had low export quantity. This finding might probably be explained by the quantity of wood charcoal consumed locally. Ethiopia and Senegal were among the countries with a high population, there is the likelihood that because of their large populations, most of their produced wood charcoal is utilized locally for domestic and industrial purposes. Nigeria and Ghana are the only densely populated countries that have high wood charcoal production as well as high export quantity.



(a)



(b)

Figure 5. Africa Population in million (**a**), and Population growth rate (**b**). Sources: Authors' compilation, analysis and mapping from UN-DESA, WB, and WDI databases.

Table 3. Wood charcoal export (in tonnes) by African countries for three decades (1990–2019).

Country	Export Quantity	Country	Export Quantity
Algeria	4200	Madagascar	334,467
Angola	2910	Malawi	1938
Benin	6220	Mali	1597.5
Botswana	1321	Mauritania	540
Burkina Faso	360,000	Mauritius	390
Burundi	159	Morocco	5106
Cameroon	1875	Mozambique	1,025,724
C.A.R	660	Namibia	1,422,746
Chad	60	Niger	2354
Comoros	0	Nigeria	1,544,945
Congo	360	Rwanda	19,314
Côte d'Ivoire	58,344	Sao Tome and Principe	0
DRC Congo	1,592,357	Senegal	95,909
Djibouti	264,046	Seychelles	150
Egypt	1,620,884	Sierra Leone	1443
Equ. Guinea	6060	Somalia	2,015,899
Eswatini	27,131	South Africa	892,399
Ethiopia	1575	Sudan	30,009
Gabon	324	South Sudan	464
Gambia	8982	Togo	1485
Ghana	964,991	Tunisia	4789
Guinea	4393.5	Tanzania	1,174,089
Guinea-Bissau	1573.5	Uganda	3349
Kenya	6322	Western Sahara	0
Liberia	10,224	Zambia	8790
Libya	450	Zimbabwe	53,876

Sources: Authors' research, compilation and analysis based on data from FAO/FRA, and Annual Reports from individual countries.

3.4. Correlation Matrix between Wood Charcoal Production, Environment and Socioeconomic Factors

The study examined the status of some factors and how they correlate with wood charcoal production in Africa (Table 3). Wood charcoal production in Decade 2 showed a significantly positive correlation with Decade 3. In exemption of the major tree species, the production for the three decades indicated a significant positive correlation with all the measured parameter (such as areas of forest cover, export quantity, export value, GDP, human population, climate season, average income (PPP) per citizen, and literacy rate). Significantly strong negative correlations were recorded between forest cover and wood charcoal production [27,46]. The strong negative correlation of population with the decades agreed with the report by [45], showing that an increase in population leads to an increase in demand for charcoal which in turn has a negative effect on the forest. The export quantity and GDP revealed a strong positive correlation (r = 0.67).

3.5. Dynamics in Wood Charcoal Production and Consumption

Climatic seasonality has been reported as a factor that has a significant effect on forest products especially wood charcoal production [47–51]. Results from the four countries (i.e., Nigeria, Ghana, Senegal and Ethiopia) which recorded high wood charcoal production in the three decades revealed that production was higher in the dry season when compared with the wet season (Table 4). This might be because the dry season is easier to cut trees, transport them, gather the wood in logs, and produce charcoal through traditional kiln-building processes. In the wet season, most roads or forest paths are difficult to access. Further, some landscapes and soils become waterlogged and flooded in the rainy season, and heavy rainstorms are common during the wet season especially in West African countries. Thus, the charcoal processing sites are drenched by rainwater. On the contrary, some authors reported that WCH production is highest during the wet season because of higher demand as firewood is less useful when it rains [42].

Table 4. Common tree species used for the production of wood charcoal in Africa (1990–2019).

Scientific Name of Tree Species	Species Abbreviations	Structural Composition	Production Season	
			Wet	Dry
Dialium bipindense	*DialBipi*	Extremely hard	Low	High
Diospyros spp.	*DiospSpp*	Extremely hard	Low	High
Pentaclethra macrophlla	*PentMacro*	Extremely hard	Low	High
Letestua durissima	*LeteDuri*	Extremely hard	Low	High
Lophira alata	*LophAlat*	Extremely hard	Low	High
Milicia excelsa	*MiliExce*	Extremely hard	Low	High
Baphia kirkii	*BaphKirk*	Extremely hard	Low	High
Cleistanthus mildbraedii	*CleiMild*	Very hard	Low	High
Cylicodiscus gabonensis	*CyliGabo*	Hard	Low	High
Desbordesia pierreana	*DesbPier*	Hard	Low	High
Manilkara cuneifolia	*ManiCune*	Hard	Low	High
Parinari glabra	*PariGlab*	Hard	Low	High
Strombosia glaucescens	*StroGlau*	Hard	Low	High
Swartzia fistuloides	*SwarFist*	Hard	Low	High
Tessmania africana	*TessAfri*	Hard	Low	High
Klainedoxa gabonensis	*KlaiGabo*	hard	Low	High
Afzelia africana spp	*AfzeAfri*	Hard	Low	High
Piptadeniastrum africanum	*PiptAfri*	Hard	Low	High
Triplochiton scleraxylon	*TripScle*	Lightly hard	Low	High
Gmelina arborea	*GmelArbo*	Soft	Fairly high	High
Juniperus procera	*JuniProc*	soft	Low	High
Pinus halepensis	*PinuHale*	soft	Low	High
Pinus pinaster	*PinuPina*	soft	Low	High
Cedrus atlantica	*CedrAtla*	soft	Low	High
Hagenia abyssinica	*HageAbys*	soft	Low	High
Taxus baccata	*TaxuBacc*	soft	Low	High
Hevea brasiliensis	*HeveBras*	Very soft	Low	High
Celba pentandra	*CelbPent*	Extremelysoft	Low	High

Sources: Online publications, National statistics of various countries. Interview with the loggers, foresters, wood charcoal producers and other stakeholders.

With respect to location, the rural areas had higher records for wood charcoal production. The reason is probably linked to larger forest land in the rural areas which has the most suitable tree species for wood charcoal than in the urban centres. In terms of the consumption rate, most poor-urban dwellers use charcoal for their daily energy activities. The rural populace has a higher number in the use of firewood than charcoal. This could be attributed to many reasons including (i) poor or zero electricity source in the rural areas, and/or (ii) lack of money or low income to process the charcoal among the rural people. This finding was consistent with the report by [37], that charcoal consumption accounts for 61% of the fuel (as opposed to 13% in rural households) urban households in Ghana. In sum, though wood charcoal is produced in rural areas, yet its consumption is higher in urban areas where it is used to supplement energy from LPG, electricity and/or kerosene. In Africa and many other developing countries, the rural people who produce charcoal are relatively too poor to use charcoal. This might be highly associated with the fact that charcoal is in high demand in the cities where the price is high and the local producers prefer selling them to increase their income [52]. In Nigeria, Ghana, Senegal and Ethiopia reports have also linked higher wood charcoal usage to the urban centres when compared with the rural areas where most productions are performed [4,5,38,53]. A greater percentage of the total population of most African countries live in rural areas.

Studies have shown that at least 60% of the people in Africa reside in the rural areas. For instance, about 64% (of Nigerians), 70% (of Ghanians), 60% (of Ethiopians), 75% (of

Tanzanians), and 78% (of Senegalese) live in rural areas where there is little or no electricity. Therefore, most people depend on wood charcoal and firewood for their domestic cooking and household activities [4,5,37,38]. Besides the rural areas, the majority in urban areas who cannot afford other more expensive energy sources (such as kerosene, Liquefied Petroleum Gas (LPG), and electricity) resort to wood charcoal as an alternative. The difference is that in the urban areas, wood charcoal is the peoples' preference to other sources of biomass energy while the reverse is the case in the rural areas [16,43].

Pentaclethra macrophlla, *Diospyros spp.*, *Letestua durissima*, *Lophira alata*, *Milicia excels*, and *Baphia kirkii* were the commonly used tree species in Decade 1 (Figure 6). These tree species available in Decade 1 became very scarce in Decade 3 because it takes a longer time for their propagation, maturity and usage for charcoal. *Gmelina arborea*, *Juniperus procera*, *Pinus halepensis*, *Pinus pinaster*, *Cedrus atlantica*, *Hagenia abyssinica*, *Taxus baccata*, *Hevea brasiliensis* and *Celba pentandra* were the primary tree species in Decade 3. The possibility of easy planting and shorter growing seasons could be the reason for the flourishing of most soft trees in Decade 3 when compared with the slow-growing hardwood species in Decade 1 [54]. The majority of the wood species in Decade 1 are of hardwood and have high fixed carbon content [55], while many in Decade 3 are categorized as either softwoods or pseudo-hardwoods which are considered to produce lower quality charcoal [12]. Decade 2 had a mixture of both hardwood and softwood because there were still some available stands of the hardwood in Decade 2. As the human population increases with a decrease in income ($r = -0.58$; Table 3), exacerbated use of wood charcoal becomes rampant leading to a decline in hardwood stands. It is also important to mention that in most cases tree species are not as paramount as the tree size [56].

3.6. Implications of the Wood Charcoal Production

The socioeconomics and environmental impacts of wood charcoal production can never be overemphasized as this has recently drawn the attention of many studies [48,50]. Wood charcoal has increased and supported the livelihood, income and revenue of households, individuals and governments of various countries in Africa and other developing countries. In most rural and urban poor, charcoal is a cheap, reliable, convenient and accessible source of energy for households and commercial cooking. Though Kerosene, electricity and LPG may be considered the most desired cooking energy sources in urban areas, their affordability and availability of necessary resources to use these forms of energy are outside the reach of many citizens. Therefore, many households resort to using charcoal.

In contrast to the benefits of wood charcoal production, the negative effects recently associated with wood charcoal are given great concern to decision-makers [8]. In this study, for example, Decade 3 produced higher fumes and CO_2, while Decade 2 showed moderate fume and CO_2 emissions, and Decade 1 discharged low fumes and CO_2 (Figure 6a). The quantities of toxic compound emissions are attributed to the various tree species available in each of the ten-year periods. For example, the common trees used for wood charcoal in Decade 1 were of extremely hardwood type, thus releases low fumes and low CO_2 when compared with the softwood species that were predominant in Decade 3. A greater proportion of wood charcoal in Decade 3 including *Juniperus procera*, *Pinus halepensis*, *Pinus pinaster*, *Cedrus atlantica*, *Hagenia abyssinica*, *Taxus baccata*, and *Hevea brasiliensis* were softwood (Figure 6b). On the other hand, Decade 2 had a mixture of both hardwood and softwood. In 2000, it was reported that overnight carbon monoxide poisoning due to charcoal burning causes thousands of deaths worldwide annually. In Africa, several studies have reported the public health risks associated with smoke and other greenhouse gases (GHGs) released from burning wood charcoal [8,36,57]. In addition to the production of noxious elements, wood charcoal production can contribute to deforestation, global warming, and degradation of forest ecosystem which leads to loss of biodiversity, poor soil quality and consequently low agricultural production [8,17]. Wood charcoal production can also cause the scarcity of some important food sources. Field observations in Africa reported that tree species, such as the *Dacryodes edulis* (Africa plum), *Psidium guajava*

(Guava tree), *Chrysophyllum albidum* (African star apple), *Artocarpus heterophyllus* (Jackfruit tree), *Mangifera indica* (Mango tree), and *Icacina senegalensis* are sources of food, yet their trunks are often used for charcoal production [16].

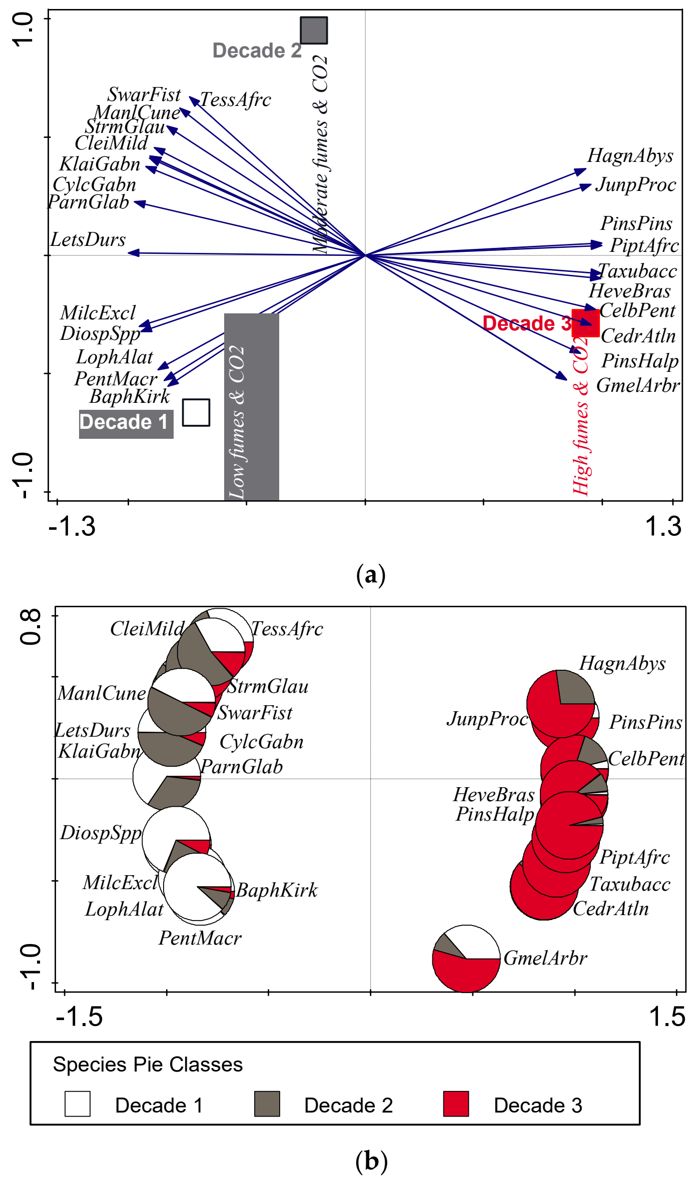


Figure 6. Biplot from the multivariate analysis of ordination showing the study decades and their associated common tree species for the wood charcoal production in the four countries (Nigeria, Ghana, Senegal and Ethiopia). (**a**) Indicated the distribution of species and their pollution emission (fumes and CO_2) status for each decade, (**b**) showed the proportion of species for each decade. Description of the plant species abbreviations is shown in Table 4.

4. Conclusions

During the three decades studied, Nigeria, Ethiopia and Ghana had the highest wood charcoal production in Africa. Most countries that have higher wood charcoal production also had high export quantity. The exceptional cases were Mozambique, Namibia and Somalia which did not record very high wood charcoal production yet were among the countries which had high export quantity. Population and quantity of wood charcoal consumed locally to a large extent affect countries' export quantity.

Most of the wood species in Decade 1 (i.e., between 1990–1999) were hardwood and have high fixed carbon content whereas, the wood species in Decade 2 (2000–2009) were either softwoods or pseudo-hardwoods which produce lower quality charcoal. Decade 2 comprised both hardwood and softwood tree species. As the human population increases with a decrease in income, exacerbated use of wood charcoal becomes rampant leading to a decline in hardwood stands. This was clearly expressed in the result where softwoods formed more than 85% of the wood species which were dominant in Decade 3 (2010–2019). Wood charcoal is a sustainable livelihood support system for people living in rural, urban and sub-urban areas. Sustainable government policies on commercial wood charcoal production and licensing for revenue and ecological sustainability are necessary to ameliorate excessive deforestation and associated consequences. In addition, enterprise-based approaches for poverty reduction, smallholders' tree-growing, wood charcoal-energy conserving technologies, improved electricity supply and agricultural productivity are also recommended.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12050568/s1, Table S1: Average Wood Charcoal Production in tonnes from 1990–2019.

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Article

Forest Bioeconomy in Ghana: Understanding the Potential Indicators for Its Sustainable Development

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Abstract: This study was aimed at assessing the indicators of a sustainable forest bioeconomy in Ghana for three decades (1990–2020). Sustainable development in a forest bioeconomy is a system geared towards improving people's socioeconomic and environmental situation through forestry, yet in Ghana, it is neither heard about nor well understood by many people. A good knowledge about the forest bioeconomic system will enhance people to become custodians of the forest ecosystems instead of being destroyers. Field and secondary data were collected and analyzed using IBM SPSS 29.0, CANOCO 5.0, and ArcGIS 10.5. The study showed that larger areas of forest were found in decade 1 (1990–1999) relative to decade 2 (2000–2009) and decade 3 (2010–2020). Forests' contributions to GDP vary between the forest–vegetation belts and regions, decreasing rapidly from 1990 to 2020. Population growth, agricultural activities, and commodity-driven deforestation ranked highest in the list of the drivers of deforestation. A reduction in deforestation might bring about a reduction in carbon emissions; however, the economic repercussions are negative as the contribution of forest to GDP, income, and employment will fall as trade-offs. Findings from the study will significantly help to bring lasting solutions to deforestation and enhance the sustainable forest bioeconomy. The study has unveiled remote drivers of forest loss that have been long overlooked by previous studies. A sustainable enlightenment campaign and routine informal education of the rural people are highly necessary. This is because some of the peoples' reasons for deforestation and preference for forest products compared with modern resources seem convincing and logical.

Keywords: forest area and stocking; deforestation; population growth; biophysical indicators; Ghana

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1. Introduction

Forests (whether natural or planted) provide a wealth of services and goods to humans, animals, and the environment, such as carbon storage, biodiversity habitat, water filtration, climate mitigation, timber and non-timber products, wild foods and medicines, tourism, and aesthetic values [1,2]. In recent years, there has been a large increase in scientific publications and studies on the bioeconomy [3–5]. Broadly speaking, the bioeconomy is an anchorage for ecosystem services and resource use efficiency [4]. It has also been defined as a diverse component associated with the production of all ecosystem services [5]. Similarly, as a relatively close concept, 'forest bioeconomy' could be defined as an activity that utilizes wood and other non-wood products (e.g., fruits and mushrooms) collected from forests for economic and industrial activities. The forest bioeconomy also consists of forest-associated activities including the harnessing, transporting, and processing of forest biomass. The basic principle of the bioeconomy is sustainability, which needs to be continuously monitored for all activities of the bioeconomy. In general terms, sustainability is a systemic approach that integrates economic, environmental, and social sectors [6]. In forestry, the initial understanding of sustainability was mostly based on sustainable timber yield. However, presently, sustainability in forestry has metamorphosed to a more complex concept with a multidimensional approach, including social, ecological, and economic dimensions that are given simultaneous consideration [7]. Further, some authors have broadened the concept to accommodate spiritual and cultural dimensions [8,9].

This paradigm shift in the concept of sustainability is attributed to the rapid decline of the limited natural resources of the Earth, caused by rising over-utilization, which is consequently posing severe threats to human and environmental safety. According to some authors, human exploitation of natural resources has attained diminishing returns, wherein the biophysical limits of the Earth has already been reached [10]. Therefore, a multidimensional approach, such as the sustainable forest bioeconomy, enhances a holistic assessment and management of the forest system by considering all the related dimensions. For instance, the growth or loss of a forest has diverse causes and effects that cut across economic, socio-cultural, and ecological attributes. These attributes combine to serve as indicators of the sustainable forest bioeconomy. Therefore, the 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. It is also the ability to use forests to accomplish, at the present and in the future, essential ecological, economic, and socio-cultural services at local, national, and global levels, without harming other ecosystems [8]. An illustration of the multidimensional approach in a sustainable forest bioeconomy includes the regulation of the economic, socio-cultural, and ecological indicators. For example, a rise in gross domestic product (GDP) (economic) could impact people's well-being (social) and forest resources (ecological). In other words, deforestation might contribute to GDP, which might improve the economic status of the government and individuals, but this might impact the communities and forest ecosystems, including the forest area, growing stocks, forest net primary productivity (NPP), soil quality, climate, rural people's livelihood, and other indicators.

Forest loss by deforestation is a common act in sub-Saharan Africa (SSA) and other developing countries [11]. It involves the clearing or thinning of forests by humans for various reasons including farming, grazing, building, mining of mineral and forest resources, and other purposes [12]. Deforestation has continuously grown over the years at high rates, especially in the tropical regions of developing countries [11,13–15]. It is one of the largest drivers of greenhouse gas emissions (CO_2, NO_2, and methane), biodiversity loss, and the constrained ecosystem services. Although deforestation is driven by several interconnected processes and factors [16], agricultural land use expansion, including cropland, pastures, and tree crops, has been the main remote cause of tropical deforestation [17–19]. Deforestation is, to a large extent, attributed to the rapid emissions of CO_2, which in turn have influenced the atmospheric condition, leading to global environmental changes including climate change. The increase in energy-related emissions of CO_2 is driven by many factors that are connected to deforestation such as agriculture, GDP per capita, population growth, infrastructural development, and urbanization [20–23]. Growth in population brings with it an increase in the quantity of goods and services that need to be provided, thereby increasing deforestation, as well as the production of GHGs [24].

In the case of Africa and other tropical countries in the developing world, most of the GHG emissions are caused by deforestation [25]. This is because in SSA, more than 75% of the population rely on forests and savannahs for their livelihood, and a projected 20% of the daily income of rural and poor households emanates from the forest ecosystems [26]. For instance, a study of forest areas in Ghana from 2004 to 2008 revealed that in economic terms, timber producers' income ranges from 5000 to 50,000 Ghanaian cedis [27]. Further, the recent increase in population growth and high level of poverty in SSA have caused a high rise in agricultural land extensions. There have been severe encroachments into the forests as well as high dependence on forests and other natural resources for sustenance and income [28]. It has been revealed that about 90% of poor households in SSA obtain energy from firewood, charcoal, and wood fuel, which are products of forests [29]. Furthermore, the high rate of corruption, inequalities in governance, poor policies, and political instabilities are also important indicators for the forest bioeconomy because they contribute intensively to a change in forest areas [30]. However, some individuals are ignorant of the negative impacts of deforestation, and yet even if they know, they have no other means of survival.

In most developed nations, the management of forests have been placed as a high priority in terms of socio-economic and environmental policies, but these are far from being adopted in most developing countries in Africa, such as in Ghana. It is on this background that the idea of this work was conceived.

This study aimed at assessing the indicators of sustainable forest bioeconomy in Ghana between the years 1990 and 2020. The study area, study periods, and topic were of great interest because sustainable development in forest bioeconomy is a system geared towards improving socioeconomic development and the environment through forests, yet in Ghana, it is neither heard of by many nor well understood. Notwithstanding, the country is among the tropical African countries with forest belts that directly or indirectly provide people with livelihoods. It is of interest to clearly identify and thoroughly define the indicators of the sustainable forest bioeconomy, especially among rural people. This will enable them the ability to be re-oriented in terms of the potential of forests for their present and future generations. A good level of knowledge about the forest bioeconomic system will encourage people to become good stewards of the forest ecosystems instead of being destroyers. This study will help people, especially those in the local communities, to realize that if sustainably managed, forests are not just sources of food and wood energy but also serve as carbon sinks for climate change mitigation; as a storehouse for unlimited wealth; as sources of the healthiest nutritional foods; and as the natural purifiers of air, water, and soil. The study will help to close the gap in knowledge about the sustainable forest bioeconomy in Ghana because there has not been any study on this topic in the entire country. The research will help to identify livelihood activities undertaken by the people that should be prioritized to reduce deforestation and, in turn, contribute to the sustainable forest bioeconomy. Findings from this work will serve as a foundation for subsequent studies on this topic. The work will provide support as multipurpose research that will be of benefit to professionals from different fields, including those in forestry and agriculture, environmental economists, planners, ecologists, politicians, technocrats, poor farmers, and many other stakeholders. To achieve the aim of this study, the following research questions were developed: (i) How do the changes in land use/cover influence forest area and growing stock as indicators of a sustainable forest bioeconomy? (ii) What are the main forest species that were important for sustainable forest bioeconomy during the three decades of study? (iii) Does forest contribution to GDP in the five different forest belts and regions of Ghana differ? (iv) What are the key drivers of deforestation, and to what extent do they affect the sustainable forest bioeconomy in Ghana?

2. Materials and Method

2.1. Study Area

Geopolitically, Ghana is a country in the west of sub-Saharan Africa that lies between latitudes 4°44′ and 11°15′ N and longitudes 3°15′ W and 1°12′ E, with a land area of 238,539 km^2 [31]. Ghana is bordered northwards by Burkina Faso, eastwards by Togo, westwards by the Ivory Coast, and southwards by the Atlantic Ocean. The current population of the country is estimated at 30.8 million people, with a population growth rate of about 2.2% per annum [32]. Contemporarily, Ghana has sixteen administrative regions (Figure 1).

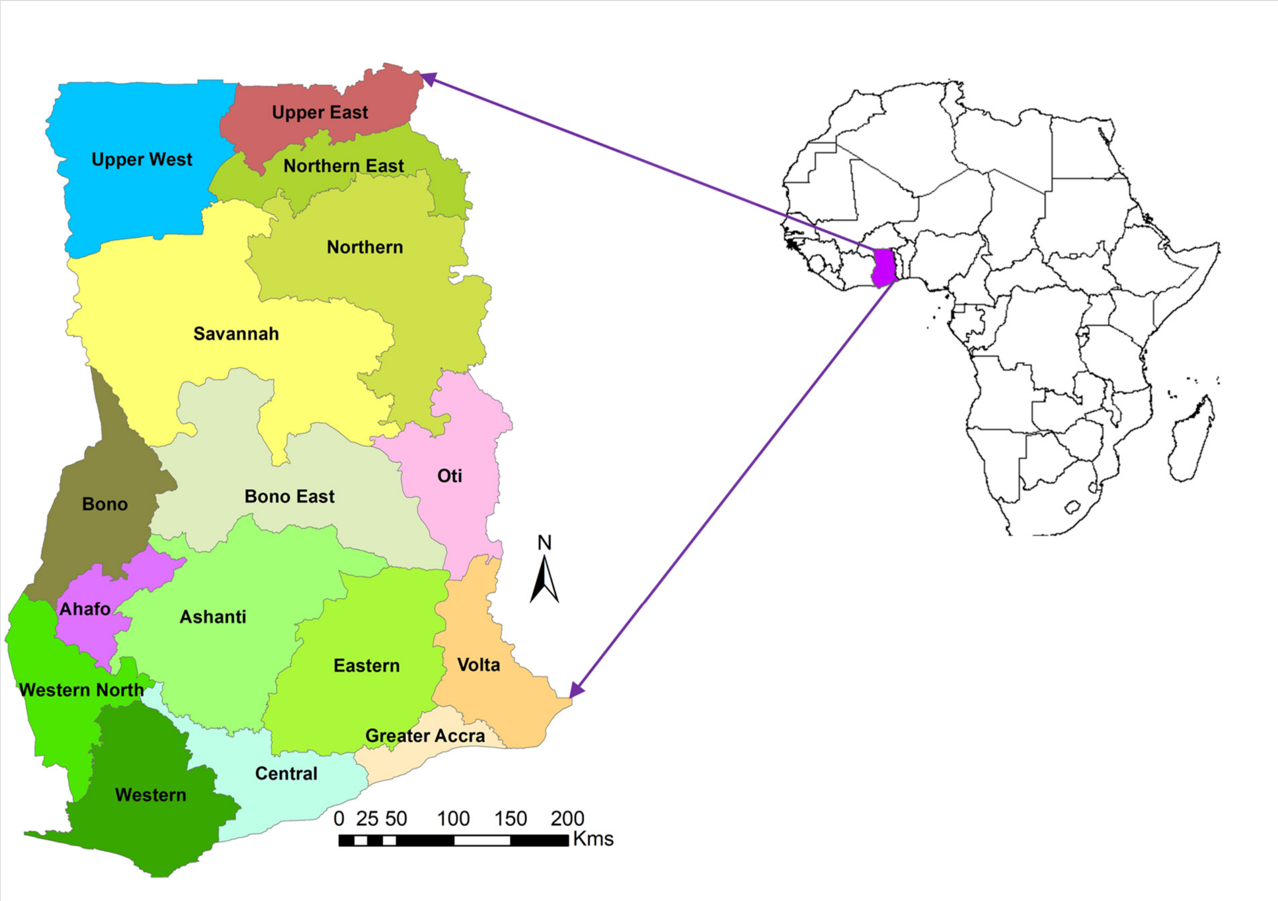


Figure 1. African map showing Ghana (the study area) and the current 16 administrative regions.

Ghana is one of the countries in sub-Saharan Africa (SSA) that has been known for large hectares of forest areas. There are five dominant forest–vegetation belts, namely, 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, while the swamp forest and mangrove vegetation are predominantly in the south-east. On the other hand, the moist deciduous (NW and SE types) forest and the dry semi-deciduous forest and savannah are commonly found in the central and northern regions of the country, respectively (Figure 2). The country is among the SSA countries that have a rapid deforestation rate per year. In 2020 alone, the country recorded more than 14,000 hectares of forest loss [33]. Generally, Ghana is characterized by a tropical climate with distinct wet and dry seasons [34,35]. The country experiences temporal and spatial temperature variations depending on seasonal changes and ecological zone. The mean annual temperature is generally high—above 24 °C. Mean annual rainfall is about 736.6 mm, and rainfall generally decreases from the south to the north [36]. Economically, the GDP growth of the country is 3.3%, with an inflation rate of 29.8% and an unemployment rate of 13.4% [37,38]. Currently, over 3.4 million people in Ghana are living in extreme poverty on less than USD 1.90 per day, with the majority of them living in rural areas [38].

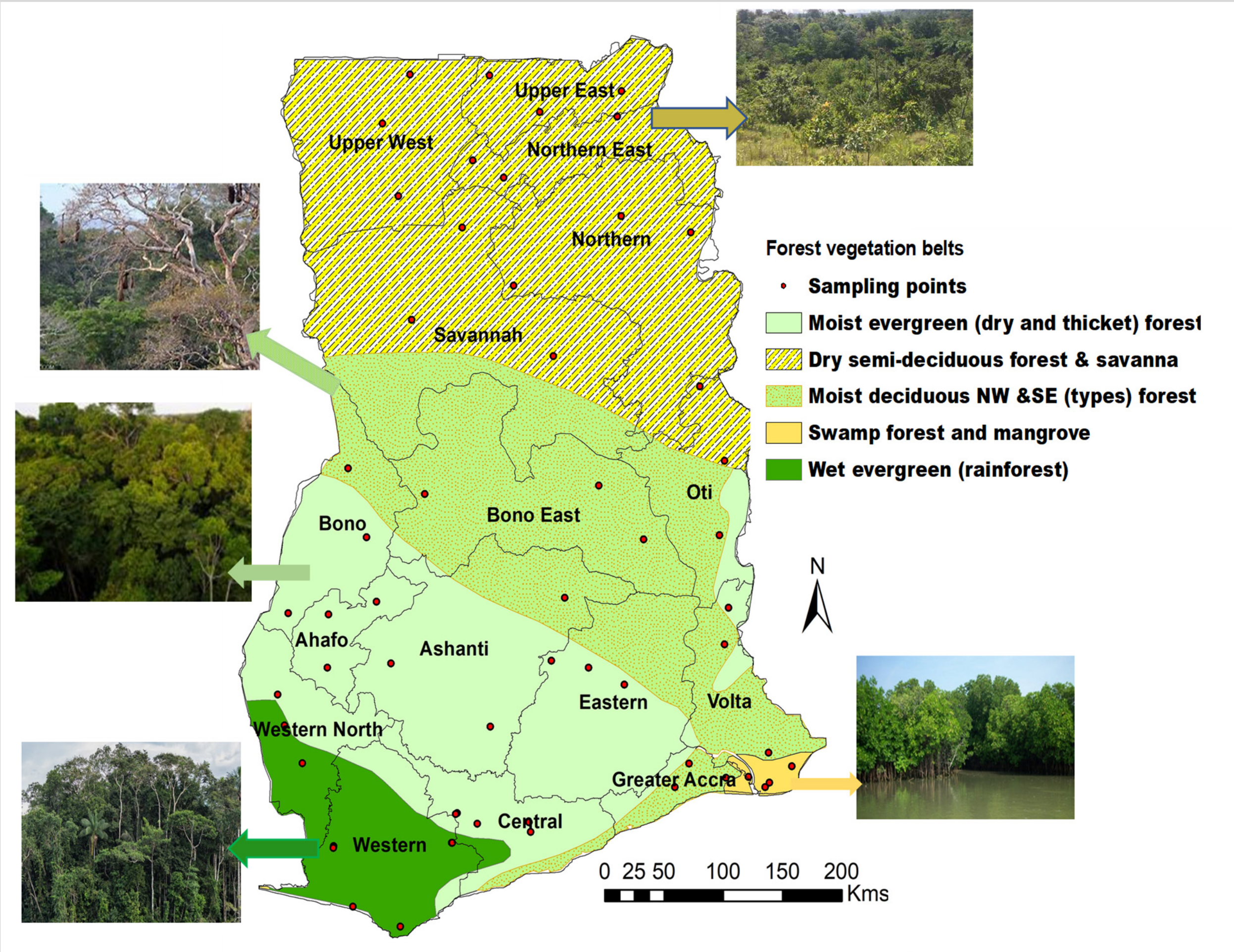


Figure 2. Forest–vegetation belts. Image of the forest features/layers, regions, and sampling locations.

2.2. Data Collection and Analyses

Data for this study were collected using both primary and secondary sources. The secondary sources used include materials from peer-reviewed journals; books; book chapters; NGOs and government-established institutions and agencies such as the Ghana Statistical Services and the Ministry of Food and Agriculture, Commerce and Industries; and important international organizations such as the United Nations' Food and Agricultural Organization (FAO) (Table 1).

Other sources of data for this work were the Forest Resources Assessment (FRA); World Bank; World Income Inequalities Databases (WID); and National Aeronautics and Space Administration (NASA), where some satellite imageries including land use/cover changes were retrieved. In the application of the primary data source, the researchers made use of a field survey by using a hand-held GPS to locate the sampling sites in each forest–vegetation belt (Figure 2; Table A1). By visiting the sites between November 2021 and October 2022, data related to the forest indicators including the common tree species were collected. Past literature (from published articles and government institutional documents), foresters, and plant ecologists were consulted for the identification of the tree species. In addition, the farmers, foresters, and experts in the field were interviewed to obtain valid information about the drivers of deforestation as well as their sociocultural and political perceptions on deforestation (Table 2). However, data on most variables investigated were derived from secondary sources, yet visits to the people and the forest belts helped to collect more relevant data and reconcile the information acquired from the secondary sources.

Table 1. Data sources and variables/measures.

Indicator/Measure	Sources
Administrative regions	Global coordinates https://data.humdata.org/dataset/cod-ab-gha;
Forest–vegetation belts	- www.omap.africanmarineatlas.org (accessed on 7 January 2023)
Sampling points	- Field sampling and survey, hand-held GPS.
Land use-cover and changes, 1990–2020	- Digital and satellite imageries from https://eros.usgs.gov/westafrica/land-cover/land-use-and-land-cover-trends-west-Africa (accessed on 8 January 2023); - www.nasa.gov (accessed on 8 January 2023).
Forest areas and loss, 1990–2020	- FAO's Global Forest Resources Assessments Reports
Forest tree cover and loss, 1990–2020	- FAO's Global Forest Resources Assessments Reports
Forest growing stocks, 1990–2020	- FAO's Global Forest Resources Assessments (main and country reports)
Contributions of forest to GDP, 1990–2020	- Ghana Statistical Services database - World Bank websites
Country's GDP, rates of illiteracy, poverty, and infrastructural development	- Ghana Statistical Services database - World Bank websites - Other reports and documents
Uses of forests: farming, mining, bioenergy, timber, NWFPs, etc.	- Ghana Statistical Services database - World Bank websites - Reports of Timber Industry Development Division - Forestry Commission. - Other reports and documents
Biophysical: climate, wildfire, soil, net primary productivity (NPP), pests and diseases, carbon emissions	- Ministry of Food and Agriculture database - Forestry Commission - Energy Commission - Published literature - FAOSTATS websites - ISRIC Soil geographic databases: https://www.isric.org/explore/soil-geographic-databases (accessed on 15 December 2022) - Moderate resolution imaging Spectroradiometer (MODIS) on NASA's Terra satellite: https://neo.gsfc.nasa.gov/ (accessed on 27 December 2022)
Population and settlement, 1990–2020	- Ghana statistical services database
Forest-based employment, migration, civil/communal conflicts	- Ghana statistical services database - Other published literature
Drivers of deforestation, socio-cultural and political views, and stands on deforestation	- Field sampling and survey (online and physical) using literature, interviews, questionnaires
Common forest tree species	- Field sampling and survey - Past literature (published articles and NGOs/government institutional documents) - Foresters and plant ecologists

For the remote sensing and geospatial related data, ArcGIS 10.5 was used in projecting the data to the same coordinate system (WGS_1984_UTM_Zone_30N). Secondly, the data were reclassified to support land use/cover change (LUCC) analyses at a regional scale [39]. The main LUC classes identified during the periods of the investigation were forests, agricultural areas, savannah, mangrove, settlements, open mining areas, wetlands, waterbodies, and others.

Table 2. Summary table of the number of experts, farmers, and foresters who chose the variables as drivers of deforestation in the interviews, with emphasis by the authors in the literature.

Group/Class of Drivers	Current Drivers of Deforestation	Interviews: % (no.) of Experts (n = 15) Who Endorsed the Driver	Interviews: % (no.) of Farmers and Foresters (n = 30) Who Mentioned the Driver	Literature: % (no.) of Authors (n = 25) Who Indicated the Driver
Direct driver: anthropogenic or human	**Population growth (rural and urban)**	**100% (15)**	**100% (30)**	**100% (25)**
	Agricultural intensification (modern and conventional)	**100% (15)**	**90% (27)**	**84% (21)**
	Use of forest for biofuel	**80% (12)**	**73% (22)**	**80% (20)**
	Use of forest for timber	**100% (15)**	**100% (30)**	**100% (25)**
	Use of forest for NWFPs	**53% (8)**	**57% (17)**	**52% (13)**
	Construction and building (settlements, canoes, etc.)	**60% (9)**	**63% (19)**	**64% (16)**
	Mining	**87% (13)**	**90% (27)**	**92% (23)**
	Wildfire	**53% (8)**	**50% (15)**	**52% (13)**
	Overgrazing/livestock	**60% (9)**	**53% (16)**	**56% (14)**
	Wildlife (game and hunting)	**53% (8)**	**50% (15)**	**52% (13)**
	Infrastructural development (road, schools, markets, hospitals, etc.)	**53% (8)**	**57% (17)**	**56% (14)**
Direct driver: biophysical	**Soil quality (e.g., degradation, SOM)**	**67% (10)**	**60% (18)**	**60% (15)**
	Topography	33% (5)	27% (8)	24% (6)
	Rainfall variability	**73% (11)**	**67% (20)**	**68% (17)**
	Temperature variability	**60% (9)**	**53% (16)**	**56% (14)**
	Wind intensity	**47% (7)**	**53% (16)**	**48% (12)**
	Pests and diseases	**53% (8)**	**50% (15)**	**52% (13)**
Indirect driver: socio-cultural and economic	**Civil/communual conflicts**	**53% (8)**	**50% (15)**	**52% (13)**
	Migration	**53% (8)**	**57% (17)**	**56% (14)**
	Religious beliefs and patterns	13% (2)	20% (6)	28% (7)
	Cultural/traditional beliefs	**60% (9)**	**70% (21)**	**72% (18)**
	Illiteracy rate (level of education)	**53% (8)**	**77% (23)**	**68% (17)**
	Land tenure system	20% (3)	23% (7)	16% (4)
	Poverty rate (e.g., Rising living standard)	**93% (14)**	**100% (30)**	**96% (24)**
	Rural farmers lack of capital	27% (4)	17% (5)	12% (3)
	Foreign agricultural medium-scale investments	0% (0)	3% (1)	0% (0)
	International funding/development aid	0% (0)	0% (0)	0% (0)
	Credits by family, bank, government, or NGO	6% (1)	10% (3)	4% (1)
	Labour shortage	13% (2)	6% (2)	8% (2)
Political/governance	**Unsound policies**	**60% (9)**	**77% (23)**	**52% (13)**
	Weak governance	**53% (8)**	**60% (18)**	**72% (18)**
	Lack of law enforcements	**73% (11)**	**73% (22)**	**56% (14)**
	Landlessness	**53% (8)**	**70% (21)**	**52% (13)**
	Unclear allocation of rights	**53% (8)**	**63% (19)**	**56% (14)**

Table 2. *Cont.*

Group/Class of Drivers	Current Drivers of Deforestation	Interviews: % (no.) of Experts (n = 15) Who Endorsed the Driver	Interviews: % (no.) of Farmers and Foresters (n = 30) Who Mentioned the Driver	Literature: % (no.) of Authors (n = 25) Who Indicated the Driver
	Impoverishments of the rural people	**87% (13)**	**80% (24)**	**68% (17)**
	Lack of investments and financial resources	**67% (10)**	**86% (26)**	**72% (18)**
	National agricultural programmes	13% (2)	13% (4)	12% (3)
	Fertilizer subsidies	6% (1)	10% (3)	8% (2)

In **bold** are the drivers and values that had at least 50% ranking in the three respective sources.

2.3. Selection of Indicators for Sustainable Forest Bioeconomy

The indicators for a sustainable forest bioeconomy were selected on the basis of reviewed scientific literature and documents from different sources including (1) Guidelines from the European Forest Institute (EFI), which is an international organization established by the European states [40]; (2) the European Forest Institute on Implementing Criteria and Indicators for Sustainable Forest Management in Europe [41]; (3) a Report on Pan-European Criteria and Indicators for Sustainable Forest Management—Experiences from Liechtenstein [42]; (4) a work on bioeconomy mapping indicators and methodology, a case study of the forest sector in Latvia by Dagnija et al. [43]; and (5) The Contribution of Sustainable Development Goals and Forest-Related Indicators to National Bioeconomy Progress Monitoring [44]. From the above literature and with experience from the study country, the following indicators were chosen as the most indicators for sustainable forest bioeconomy in Ghana: forest area, forest growing stock, forest area loss by deforestation drivers, forest tree cover and loss by drivers of deforestation, forest deadwood volume, forest contribution to GDP, employment in a forest-based sector, and forest soil quality and productivity (such as organic matter content and net primary productivity).

2.4. Selection of Drivers for Deforestation (Forest Loss) Using the Literature, Interviews, and a Questionnaire

In order to acquire professional knowledge regarding the key drivers for deforestation, top publishers in the topic who have papers based in Ghana were consulted. They were interviewed, and a structured questionnaire that included a list of 38 current and potential or future drivers of deforestation was developed from 25 reviewed studies. The drivers were grouped on the basis of decades (Decade 1: 1990–1999, Decade 2: 2000–2009, and Decade 3: 2010–2020). They were also listed in two main categories (direct and indirect drivers). The direct drivers of deforestation were identified as the human and biophysical factors. The human factors were farming, grazing, mining, building/settlements, exploitation for biofuel, timber, and NWFPs, while the biophysical factors were climate change, soil degradation, pests and diseases, and wildfire. On the other hand, the indirect drivers of deforestation were listed as demographic, socio-cultural, economic, and political factors. The clustering of indirect drivers was performed according to Geist and Lambin [16]. The ranking of the drivers followed a Likert scale approach. This scale ranged from 0 to 5, with 0 representing zero influence and 5 representing strong influence. In addition, the interviewees, especially the experts, were provided with the detailed definitions of each proposed/potential drivers. Besides recommending the most drivers, they also placed them in accordance with the decades where they had much impact on the forest. The questionnaire was sent to the top known researchers in this field, especially those who are experts in Ghana. In addition, selected individuals who live and work in Ghana as farmers and/or foresters in the 16 regions were also involved. In sum, 15 out of 20 experts, and 30 out of 40 farmers and foresters, that were contacted returned their completed questionnaires. To improve the reliability of the answers given in the questionnaire, the Delphi approach was applied [45]. The questionnaires were returned to the interviewees together with the synthesized information of the group. By review and adoption of results of the first Delphi round, the variance in the driver ranks were reduced, and consensus was reached. The drivers were reduced to 21 out of 38 on the basis of the derived final rating from the experts, literature, and farmers and foresters. A total of 21 drivers out of 38 had a rating of at least 50% from each of the three categorized (selected) evaluations (experts, literature, and farmers and foresters).

2.5. Geospatial and Statistical Analyses

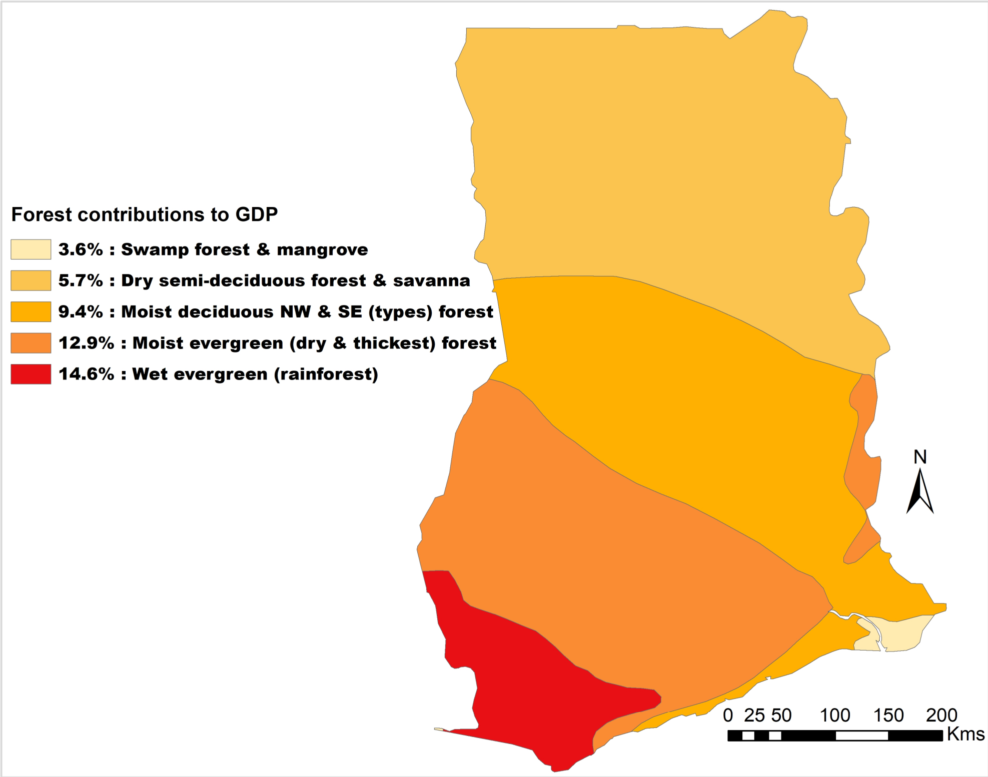
Data were analyzed using IBM SPSS (version 29.0, Armonk, NY, USA), CANOCO (version 5.0, Wageningen, The Netherlands) [46], and/or ArcGIS (version 10.5, Redlands, CA, USA) [47] software packages. Data were transformed where necessary to meet the requirements and suitable values used for the analyses. From the described sources (Table 1), information on the LUCC, contributions of forest to GDP, and the percentage of the population that exploited forests for different benefits were spatially mapped and presented on the basis of the forest–vegetation belts and regions using the GIS spatial analytical tools. The top 21 drivers of deforestation and the identified common tree species were analyzed using the multivariate ordination of Canoco 5.0 to show their distributions across the decades and forest belts. To determine the interrelationships among the indicators of sustainable forest bioeconomy, the pairwise correlation adjusted to Bonferroni significance levels at 0.01 and 0.05 was used in the IBM SPSS 29.0 (SPSS Inc., Armonk, NY, USA) statistical software.

3. Results and Discussion

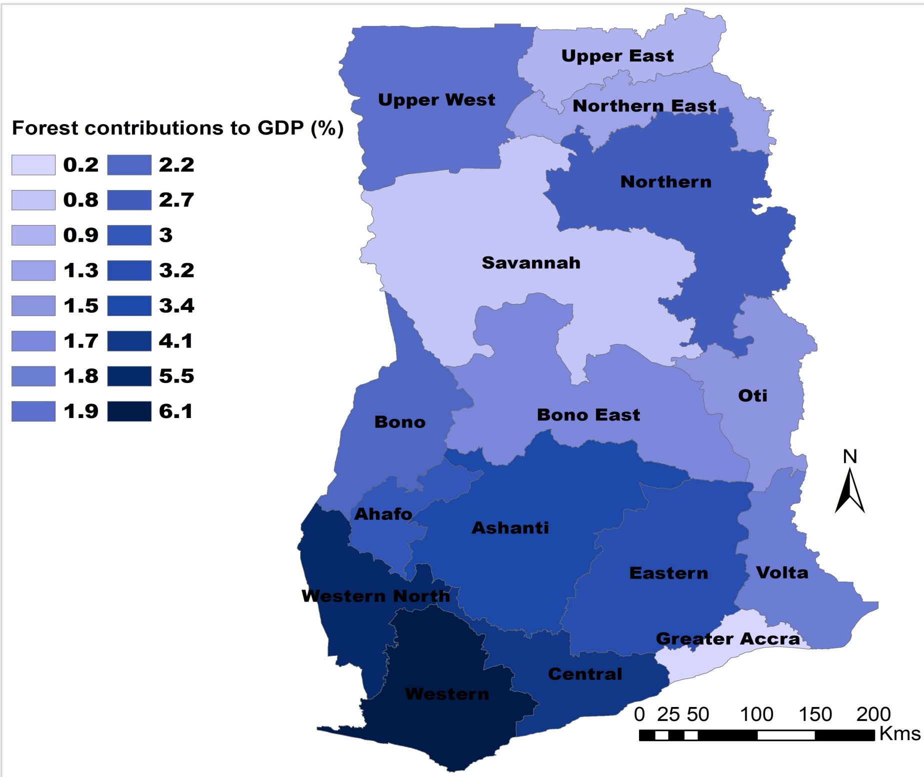
3.1. Forest Contributions to GDP as an Indicator of Sustainable Development in Forest Bioeconomy

Historically, Ghana is among the countries that have been enriching their GDP through forest products, but lately the contributions of forest to GDP has substantially decreased (Figure 3), a scenario that has affected the sustainable forest bioeconomy in the region.

The results showed that during the study periods, forest contributions to GDP vary between the forest–vegetation belts and regions. For example, wet evergreen (rainforest) (14.6%) and moist evergreen (12.9%) forests had the highest contributions to GDP, while dry semi-deciduous forest and savanna (5.7%) and swamp forest and mangrove (3.6%) recorded the lowest contributions to GDP (Figure 3a). In terms of regions, the west and southern regions (such as Western, Western North, Ahafo, Ashanti, Eastern, Central, and Bono) accounted for the regions with the highest forest contributions to the national GDP (Figure 3b). In 1990, forest contribution to GDP was USD 72.35 million, which was higher than the total contributions from 2010 to 2020 summed together (Figure 3c). However, there has been fluctuations in the country's GDP growth, yet the lowest percentages were recorded in the immediate past decades. In addition to serving as a direct source of export-timbers that enriches Ghana's economy, the evergreen forests provide shade to livestock, food, and cash crops, thus influencing farmers' adoption of cocoa agroforestry and integrated crop–livestock–forest systems [48]. The decline in forest contributions to GDP is probably attributed to the decrease in forest area during the period. Many studies have affirmed the impact of forest loss on its contribution to GDP [49–51]. In Cameroon, for instance, a study reported that reduction in deforestation was successful in minimizing CO_2, but the trade-off effect was a relatively low forestry's contribution to GDP [49]. In India, some studies have demonstrated that frequent vegetation loss by fires and grazing claimed about 16% of the total forest area, which has influenced species diversity and economic development [52,53]. Consistent with the findings from this work, other studies have reported a huge decline in the forest area in Ghana [54], a situation that has negatively impacted forests' quota in terms of the nation's economic growth [54,55]. A study in Japan by Wen et al. [56] analyzed seven bioeconomy sectors with the aim of establishing the leading contributing sectors to GDP. They found that forestry and forest-related products have significant contributions to the country's GDP.

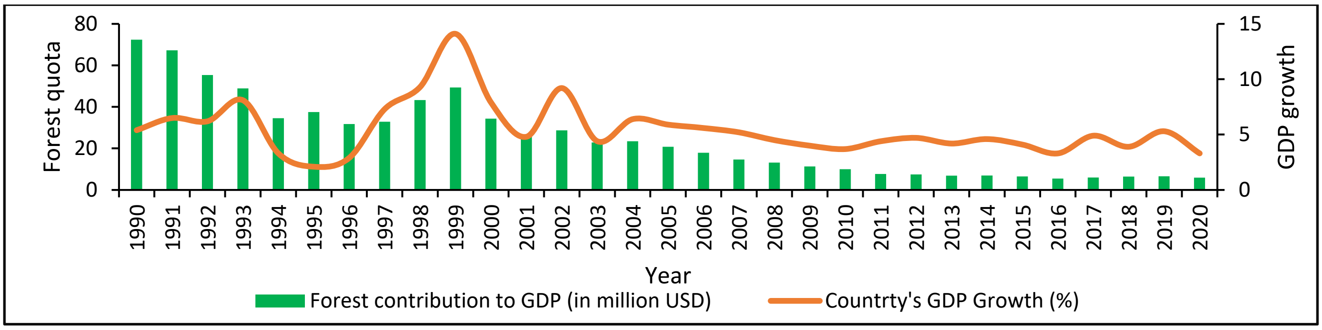


(**a**)



(**b**)

Figure 3. *Cont.*

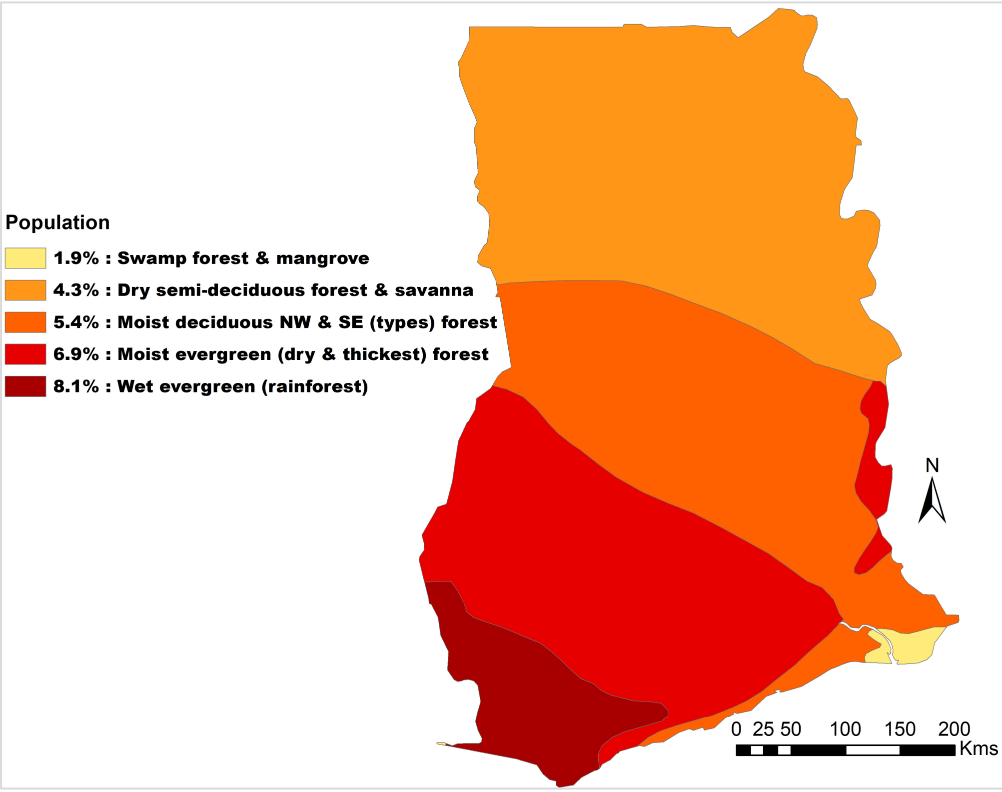


(**c**)

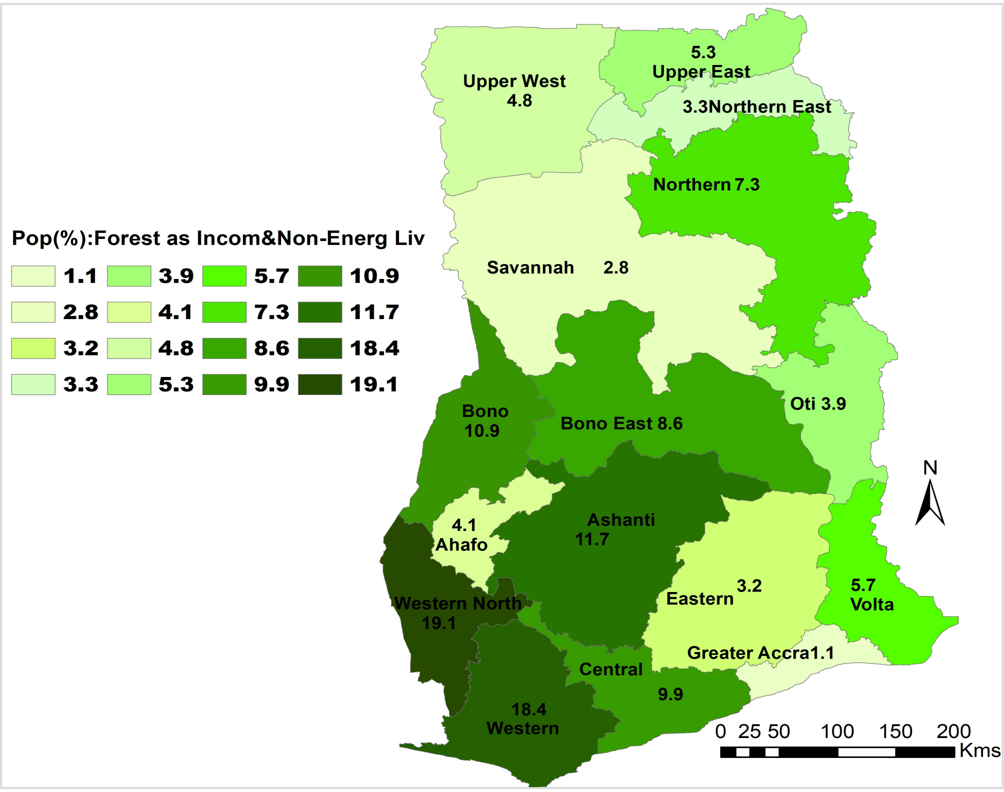
Figure 3. Forest contributions to the nation's GDP from 1990 to 2020 (**a**) on the basis of forest–vegetation belts, (**b**) on the basis of the regions, and (**c**) on the basis of years.

3.2. Use of Forests for Biofuel and Livelihood: An Indicator of Sustainable Forest Bioeconomy

The study further observed that 8.1% of the population use the rainforest and its resources as sources of income and livelihood, whereas the swamp forest and mangrove had only 1.9% of the population depending on it (Figure 4a). With respect to regions, a higher percentage of the population depends on forests for income, livelihood, and bioenergy in the south as compared to either the east or northern regions of the country (Figure 4b,c). Generally, the findings from this study showed that people, particularly in the rural communities, rely on the forests to eke out their livings. Consistent with these findings, other studies on the global level also revealed that about 1 billion of the world's poorest people depend on forests for their livelihoods [57,58]. Moreover, in the tropical developing countries, the potential of forest and its associated products in supporting people's livelihoods, especially among the poor rural dwellers, has also been observed by many researchers [59–64]. In Zambia, for instance, forest provided 70% of the country's energy needs [65]. The study also observed that forest supplies rural people with varieties of wild foods including nutritious vegetables, mushrooms, and edible insects. They revealed that at the national level, forests provide revenue for the government from taxes, fees, royalties, and other charges levied on forest-based activities. The study concluded that although forests have an important poverty mitigation function, they are not a means alone to move most people out of poverty. Apart from biofuel, forests provide non-wood forest products (NWFPs), which have minimal or zero negative impacts on the forest. These NWFPs sustain the rural people and promote sustainable forest bioeconomy campaign [59]. The roles of forests in supporting, maintaining, and satisfying rural consumption; diversifying their incomes; and meeting their basic needs are extremely important, especially for those experiencing transient poverty [64]. However, local people, out of poverty and being left with no other options, engage in the cutting of trees for energy, a practice which in most cases goes against their wishes, considering the other numerous benefits they derive from forests [66]. Meanwhile, in some cases, the local people collect deadwood and/or tree branches only. Studies have shown that in most developing countries, the governments and the richer citizens are culprits for large areas of deforestation [60–63]. In Cambodia, for example, deforestation for timber has been reported as a primary driver of 'shadow state' activities that operate through illicit, corrupt, and patrimonial networks of state authorities [60].

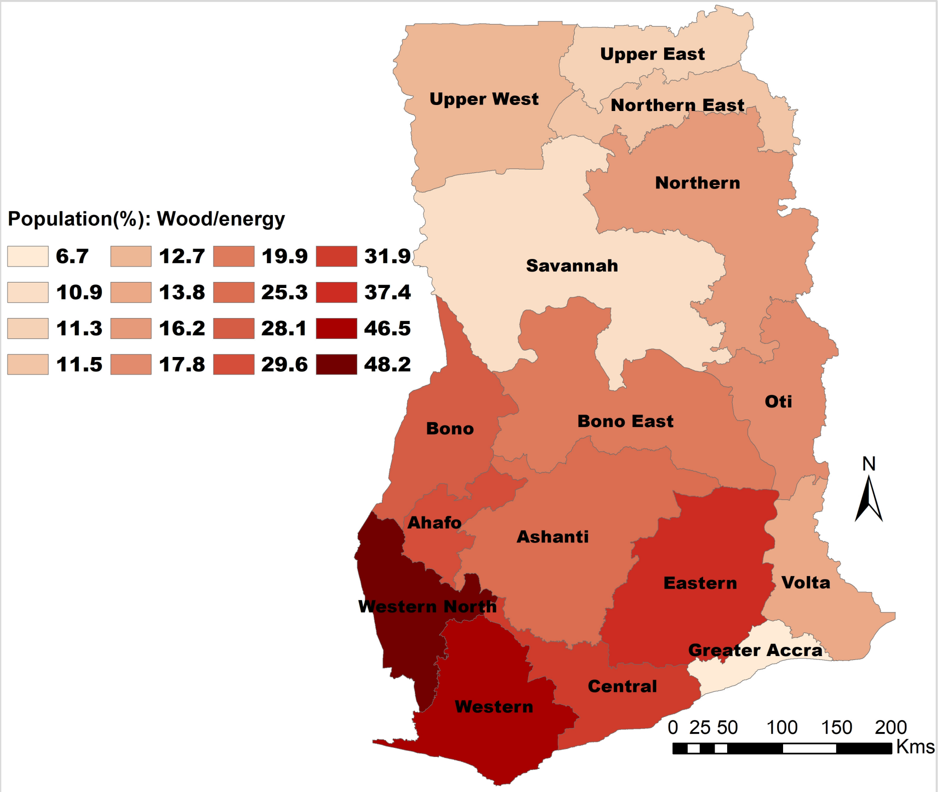


(a)



(b)

Figure 4. *Cont.*



(**c**)

Figure 4. Percentage of the population that use forests and their resources as sources of income and liveliwood in terms of (**a**) the forest–vegetation belts, (**b**) the regions, and (**c**) the regional distribution of people who depend on forests for wood/bioenergy.

3.3. Land Use/Cover Changes

Land use/cover change (LUCC) is an emerging threat to the resilience of socioeconomic and ecological systems because it is often related to land degradation, including forest loss [67]. It has been acknowledged that the drivers of LUCC are often complex and interrelated between anthropogenic (social, political, economic, demographic, technological, cultural) and biophysical factors with direct or indirect impacts on the people, economy, and environment [68]. It is on this background that this study investigated the land use/cover transitions that have shown drastic transformations between 1990 and 2020 (Figure 5). Larger areas of forest were found in decade 1 (1990–1999) (Figure 5a) relative to decade 2 (2000–2009) (Figure 5b) and decade 3 (2010–2020) (Figure 5c). On the other hand, decade 2 and decade 3 had the largest areas for agriculture and settlement as compared with decade 1. In line with this study, many studies in developing countries have reported consistent rapid changes in land use/cover in recent years when compared with many decades ago [68–73]. These changes have been associated with population explosion, industrialized agriculture, and uncontrollably acute deforestation [16,68]. 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 [16]. Another study in Ghana that aimed at identifying the driving forces of land use/cover change by a mixed-methods approach observed that rural population growth was the main driver of the changes [68]. Similarly, a study performed to investigate the dynamics of LUCC in Burkina Faso between 1999 and 2011 agrees with our findings that more forest areas were found in the past decades, while the present decades have more arable areas due to the growing demand for food as the population increases [70]. In the Western Region of Ghana, which is covered by evergreen forests, Koranteng et al. [74] discovered significant changes in the landscape from 1990 to 2020. They attributed the changes to deforestation through agriculture.

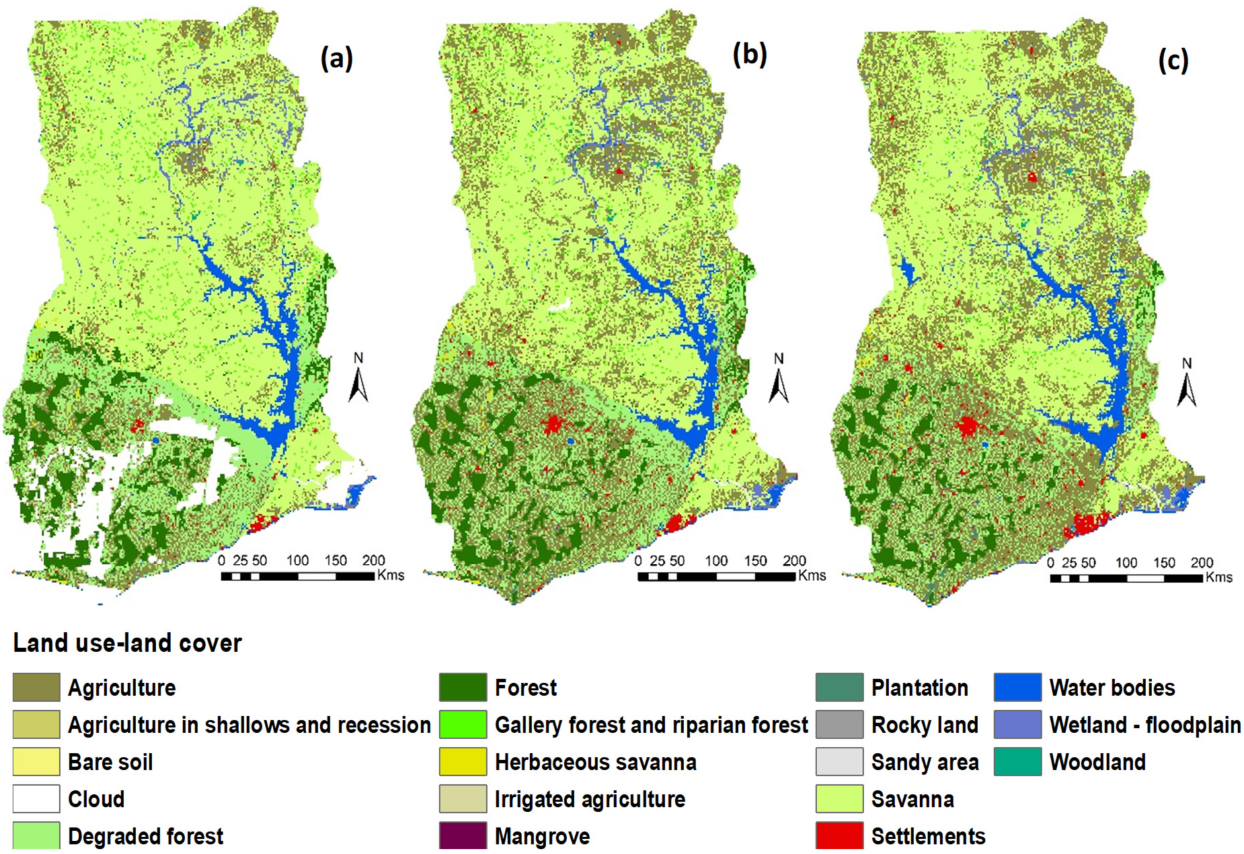


Figure 5. Land use/cover in the three decades 1990–2020, showing average change between (**a**) 1990 and 1999, (**b**) 2000 and 2009, and (**c**) 2010 and 2020.

3.4. Drivers of Forest Loss and Carbon Emissions: As Vital Indicators

The study observed that sustainable development in the forest bioeconomy has been adversely affected in the country by several drivers (Figure 6). Agricultural activities and commodity-driven deforestation ranked highest in the list of the drivers, and their trend increased severely over time (Figure 6a). For instance, in 1990, forest loss through commodity-driven deforestation was 28,798 hectares, while 2020 had 132,308 hectares, which was more than a 350% increase. Similarly, agriculture as a top driver of forest loss increased by more than 700% between 1990 (13,239 ha) and 2020 (118,675 ha). It was also discovered that the increase in deforestation rate was relatively associated with potential carbon emissions, which became higher from 2010 (Figure 6b). In addition to the top drivers, other drivers of deforestation and their influences in the different decades varied (Figure 7). Farming activities, population growth, and climate change were long-term drivers because they cut across the three decades, while wildfire, illiteracy rate, and pests and diseases were mostly associated with decade 1. It is convincing that the rapid growth in human population will have a profound impact on forests. This is because a rise in population means a rise in human demand for food, shelter, and other basic needs and comfort [24].

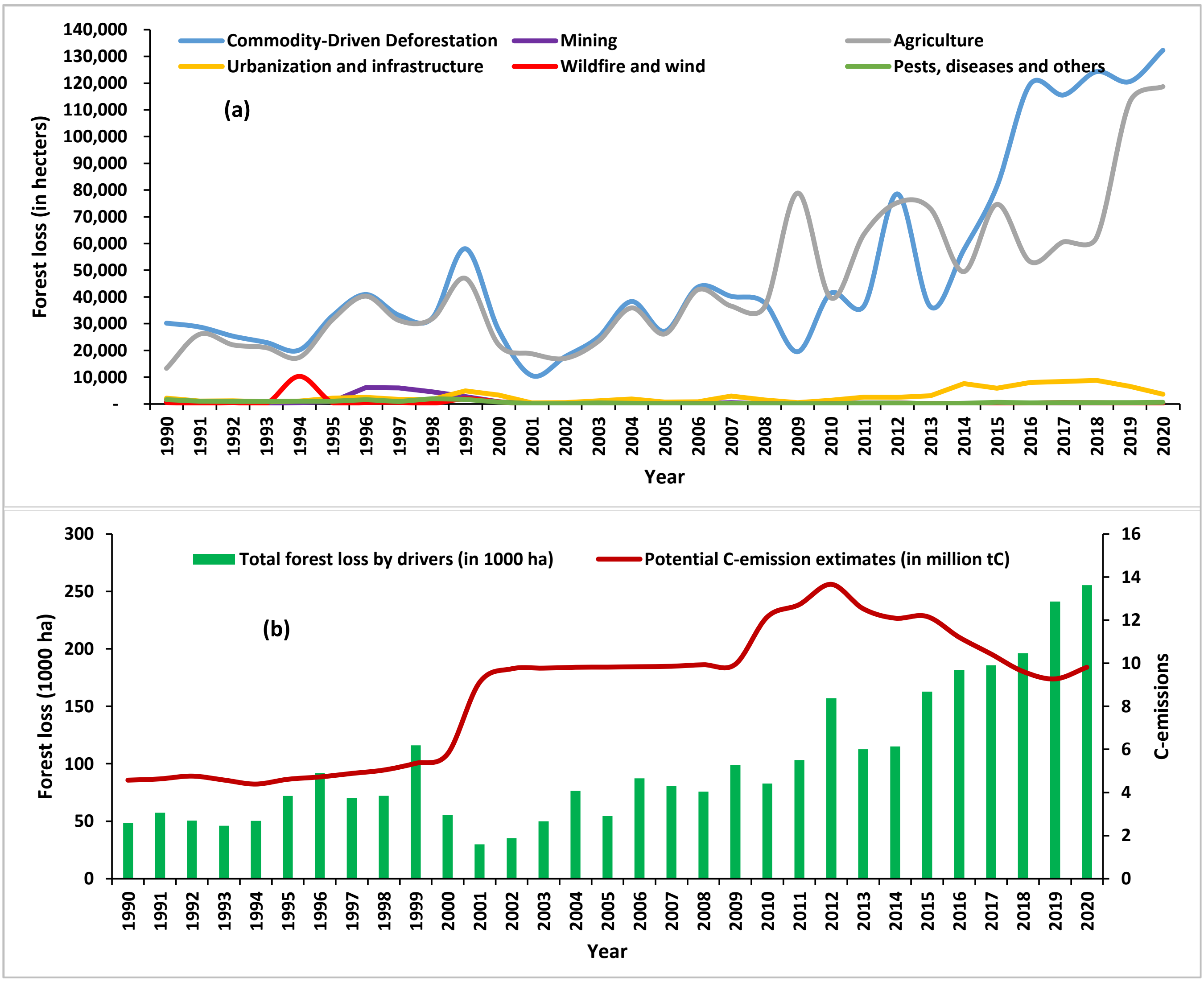


Figure 6. Forest loss (in hectres) from 1990 to 2020 by (**a**) individual drivers and (**b**) combination of all the drivers and carbon emission estimate.

Thus, satisfying these growing needs of humans required creating more land areas for agriculture, houses, and infrastructure that consequently caused deforestation and the creation of substantial impacts on the environment including emissions of carbon [16–19,75]. It has been reported that West Africa is responsible for a large portion of carbon emissions from deforestation at an average annual emission of 350 Tg/year. The regional net global warming potential (GWP) between 1990 and 2019 was estimated to be 11.44 Pg, and Nigeria (18.7%), Mali (15%) and Ghana (13.2%) had the highest GWP from deforestation activities [76]. The recent growth in the population of these countries might be held responsible. The strong links between population growth, deforestation, carbon emissions, and GDP have been studied globally [20–23,77–80]. Several studies have revealed that reductions in deforestation-induced activities over time could positively bring a tangible reduction the CO_2 emissions [49,81].

In contrast to this study, a study in Indonesia emphasized that migration played a highly significant role in the deforestation activities in the region [82]. However, migration could contribute to the loss of forest, but in the case of this study, the impacts of migration was insignificant. This is because most activities of deforestation take place in the rural areas of Ghana, and rural–urban drift is a common type of migration in the country.

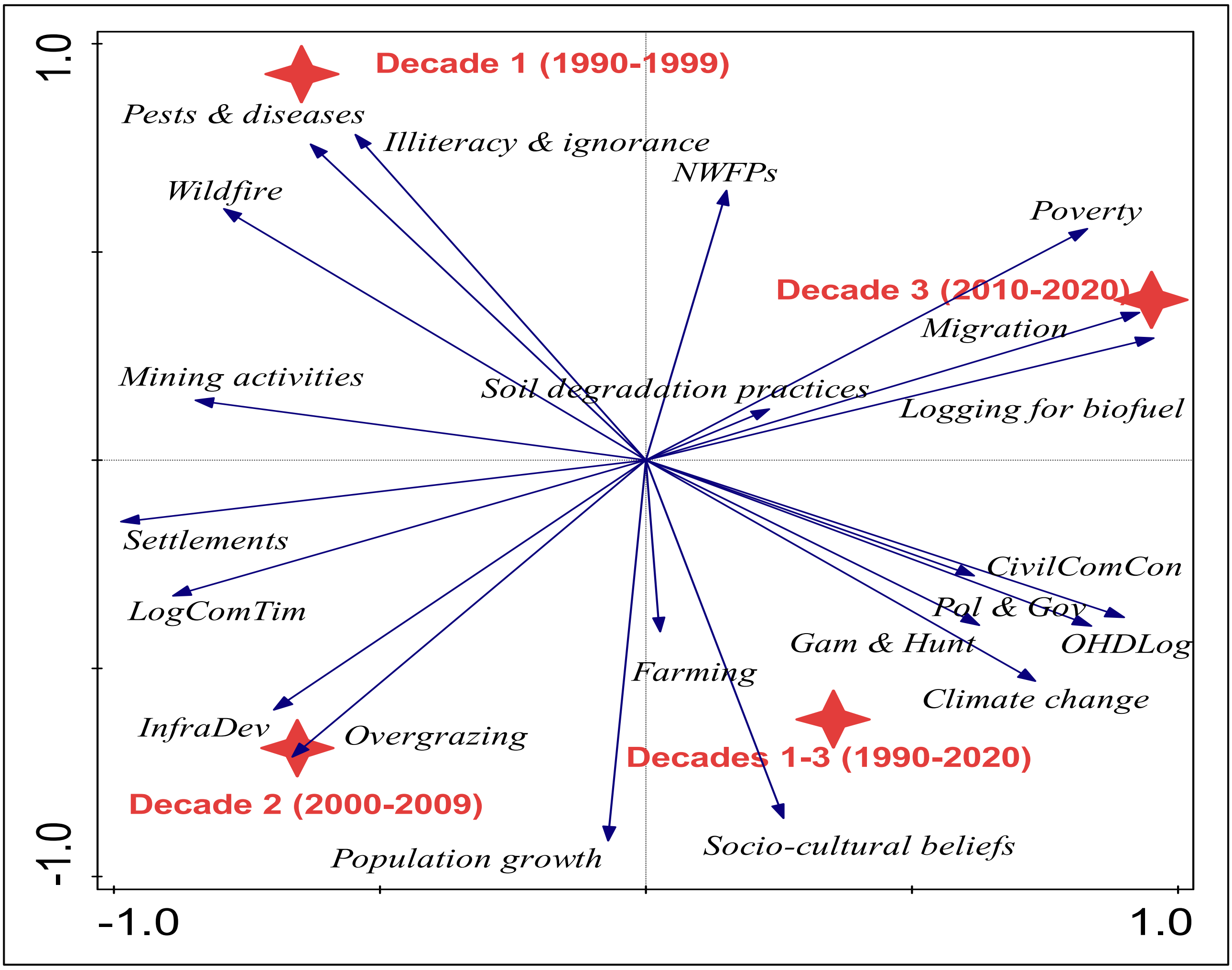


Figure 7. Drivers of deforestation (forest loss) in the study decades: Decade 1 (1990–1999), Decade 2 (2000–2009), Decade 3 (2010–2020), and Decade 1–3 (1990–2020), and the extent of their influences in the different decades investigated. Description of abbreviation: NWFPs = non-wood forest products; LogComTim = logging for commercial purposes such as timber; InfraDev = infrastructural development such as building of markets, schools, hospitals, roads, etc.; OHDLog = forest deforestation for other household benefits; CivilComCon = Civil/communual conflicts; Gam & Hunt = wildlife gathering for game and hunting; Pol & Gov = political and governance drivers such as unsound policies, weak governance, lack of law enforcement, landlessness, unclear allocation of rights, impoverishment of the rural people, and lack of investments and financial resources.

Sociocultural and political factors are drivers of deforestation that have been often overlooked in many studies. This study discovered that these drivers, including population and agriculture, need to be remotely addressed so as to achieve sustainable development in the forest bioeconomy in Ghana. Socio-culturally, some of the rural populace affirmed that they prefer thatch and mud houses to modern buildings, while others prefer food cooked with firewood as opposed to either gas or electricity [83]. During the course of this study, it was found that besides farming and infrastructural development, some of the local people have ‘strong preferences’ towards certain traditions and beliefs, making them become attached to the forests. For example, the preference of chewing-sticks from the forest trees instead of modern toothpastes and brushes, with a belief that the chewing-sticks are healthier for teeth and gums, improve the strength and whiteness of their teeth, and provide them with the finest breath. According to them, the modern style of cleaning teeth destroys human health, teeth, and gums; leads to removal of ones’ teeth at younger age; and propagates health issues because of the chemicals associated with the toothpastes. Some of the people prefer heating their rooms with wood energy to modern heating systems. Similarly, some prefer the smoking and drying of food (fish, meat, and agricultural products) with bioenergy as opposed to the modern smoking/drying facilities. Politically, the findings from the study revealed unsound policies, weak governance, lack of law enforcement, landlessness, unclear allocation of rights, impoverishment of the rural people, and lack of investments and financial resources as factors characterized by the government. In sum, these are drivers that are remotely piloting the forest degradation movements. According to Tan et al. [84], these are contentious issues that require careful management.

3.5. Common Forest Tree Species

An investigation of the common forest tree species and their spatial distributions across the forest–vegetation belts became necessary as to ascertain their contributions to a sustainable forest bioeconomy (Figure 8). *Diospyros* spp., *Pentaclethra macrophlla, Letestua durissima, Lophira alata, Milicia excels, Baphia kirkii, Cleistanthus mildbraedii,* and *Swrtzia* fistuloides were dominant in the wet and moist evergreen forests, while *Piptadeniastrum africanum, Triplochiton scleraxylon,* and *Gmelina arborea* were common in the moist deciduous forest (Figure 8a). On the other hand, the dry semi-deciduous forest and savannah, as well as the swamp forest and mangrove, had *Juniperus procera, Pinus halepensis, Pinus pinaster, Cedrus atlantica, Hagenia abyssinica,* and *Taxus baccata.* Thirty-five major tree species were identified across the forest–vegetation belts, with the moist evergreen and moist deciduous forests recording the highest of 32 species each (Figure 8b). Some species were found in almost all the forest–vegetation belts. These were *Tectona grandis, Cedrela odorata, Terminalia superba, Klainedoxa gabonensis, Hevea brasiliensis, Cylicodiscus gabonensis, Pinus halepensis, Hagenia abyssinica, Desbordesia pierreana, Parinari glabra,* and *Swrtzia fistuloides* (Figure 9).

These particular trees are mostly natives of the region and are essential promoters of sustainable forest bioeconomy. This is because they have the potential to survive (different threats such as climate change, wildfires, and pests) in all the forest belts and are exploited by the people for livelihoods. Further, these classes of tree species improve soil organic carbon and organic matter, which in turn enhances forest area, growing stocks, and NPP, thus increasing the sustainability of forest bioeconomy [85–89].

3.6. Employment in Forestry and Forest-Based Sector(s)

The study indicated that employment rate in forestry and the forest-based sector as an indicator of sustainable forest bioeconomy decreased with time. In the evergreen forest, 5.5% (3.1% male, 2.1% female) of the population were employed in decade 1, and 4.1% for decades 2 and 3 (Figure 10). In all the forest belts, decade 1 recorded the highest percentages of persons employed in forestry and the forest-based sector when compared with decade 2 and decade 3. In Cameroon, for instance, a study reported that reductions in deforestation was positive in the reduction of atmospheric CO_2, but led to a decrease in employment in the forestry sector and forestry's contribution to GDP [49]. In truth, a decrease in deforestation will lower carbon emissions, but inevitably the economic consequences are negative because the contribution of forest to GDP and employment will reduce. To ameliorate this unacceptable scenario, the government and stakeholders in Ghana should fully adopt the Reducing Emissions from Deforestation and Degradation (REDD+) initiatives or some other financial rewarding systems such that the economic losses incurred in reducing deforestation and carbon emission could be compensated as in the cases of Brazil, Costa Rica, and Colombia [90,91].

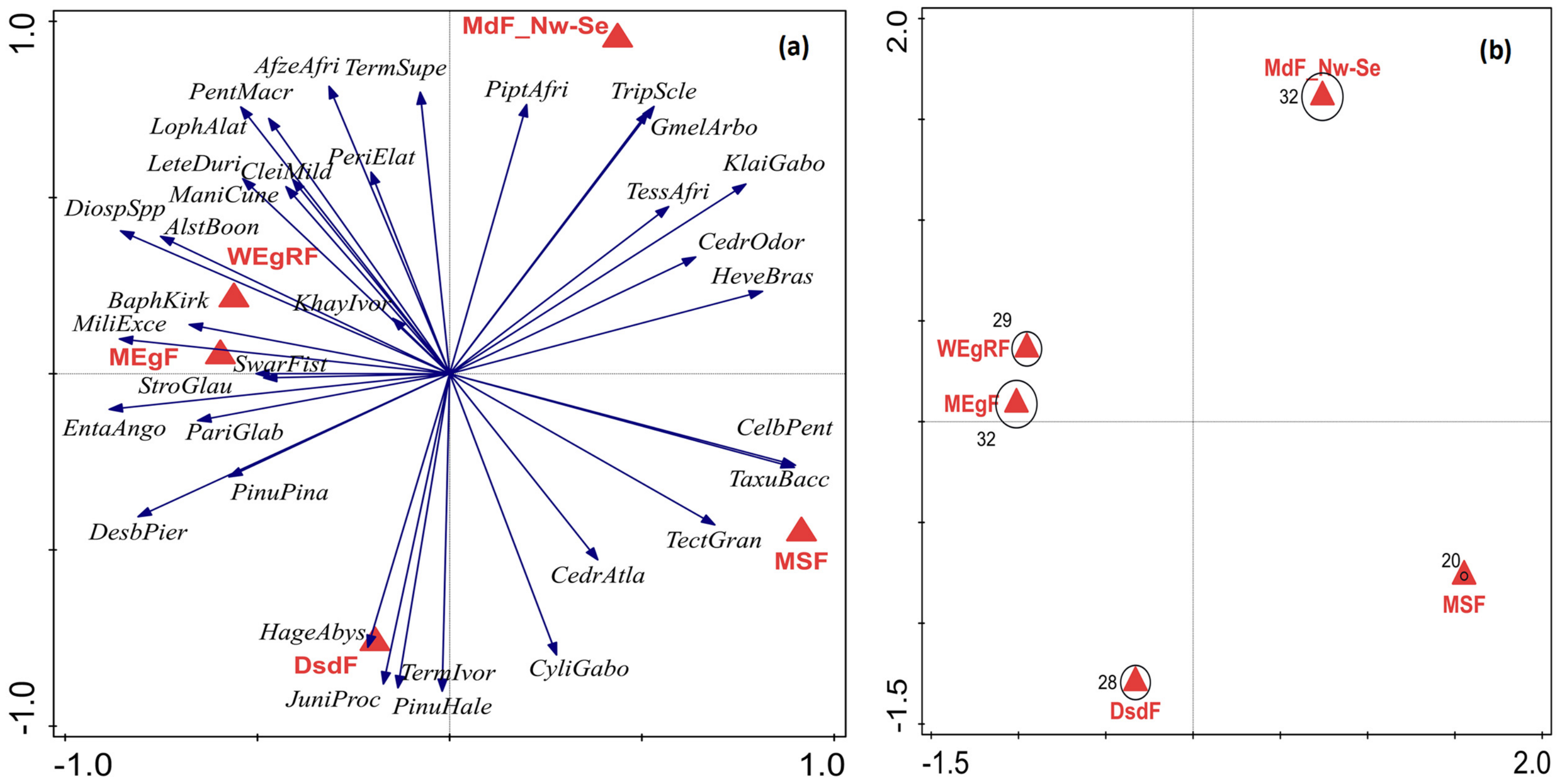


Figure 8. Biplot from the multivariate analysis of ordination showing the forest–vegetation belts with (**a**) their associated common tree species that promote sustainable forest bioeconomy and (**b**) the total number and distribution of tree species for each forest–vegetation belt. Description of the abbreviations are as follows: for the species: *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*, *Swrtzia fistuloides* = *SwarFist*, *Tessmania Africana* = *TessAfri*, *Klainedoxa gabonensis* = *KlaiGabo*, *Afzelia 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*, *Alstonia boonei* = *AlstBoon*, *Khaya ivorensis* = *KhayIvor*, *Pericopsis elata* = *PeriElat*, *Terminalia superba* = *TermSupe*, *Terminalia ivorensis* = *TermIvor*, *Entandrophragma angolense* = *EntaAngo*, *Cedrela odorata* = *CedrOdor*, *Tectona grandis* = *TectGran*. For the vegetation zones: wet evergreen rainforest = WEgRF; moist evergreen (dry and thick) forest = MEgF; moist deciduous (NW and SE types) forest = MDF_Nw-Se; dry semi-deciduous forest and savannah = DsdF; and swamp forest and mangrove = MSF.

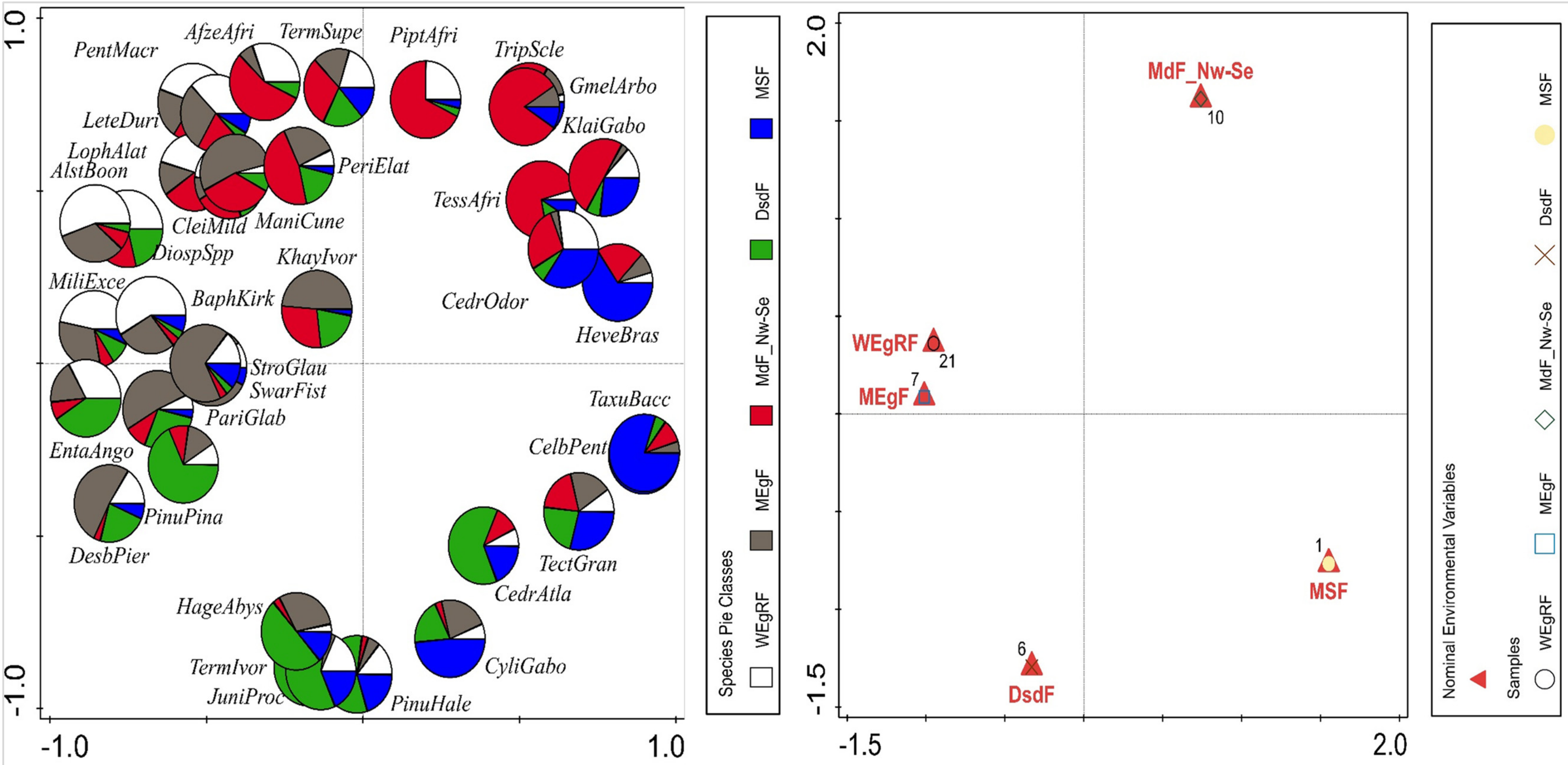


Figure 9. Biplot from the multivariate analysis of ordination showing the proportion of each key tree species that enhanced sustainable forest bioeconomy in each forest–vegetation belt. Description of the abbreviations are shown in Figure 8.

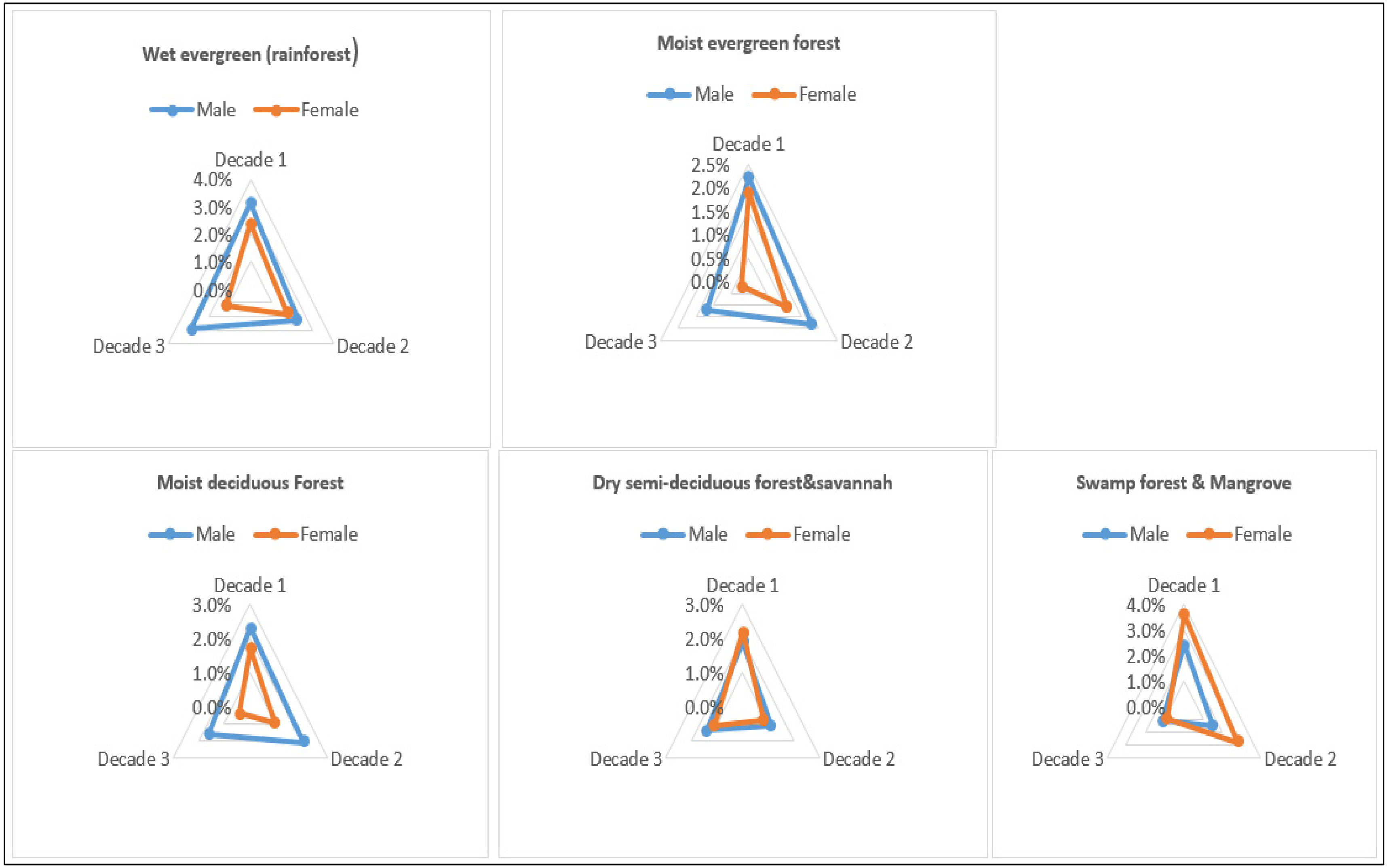


Figure 10. Percentage of total population employed in forestry and forest-based or related sectors in the forest belts during the three decades.

3.7. Correlation among Variables Relating to Forest Bioeconomy

To further test the hypothesis regarding the variability or interactions among the indicators of sustainable forest bioeconomy, the pairwise correlation adjusted to Bonferroni significance levels at 0.01 and 0.05 was used. This correlation test is deemed important because it helped to ascertain the correlation between or among the variables, thus providing more insight or understanding on how the variables inter-relate, or interfere and influence, one another. The population growth and forest area showed significantly high positive and negative correlations with all the indicators of the sustainable forest bioeconomy investigated (Table 3). This is because a rapid growth in human population always has a critical influence on several factors such as forest contribution to GDP, gross domestic growth rate, forest growing stocks, forest soil quality, and forest net primary productivity [68,70,71,74]. On the other hand, a severe change in forest area through deforestation will strongly affect other indicators of the forest bioeconomy [92,93]. The volume of deadwood as an indicator of sustainable forest bioeconomy showed a significant positive relationship with forest protected area, population, forest growing stocks, forest soil organic matter, and net primary productivity. Additionally, it revealed a significant negative interrelationship with forest loss, tree cover loss, poverty rate, and forest use for biofuel. Similarly, forest use for biofuel and forest growing stocks had significant associations with 90% of all the indicators of sustainable forest bioeconomy. For example, a recent study in Nigeria observed that due to growth in population, available resources become insufficient, thereby creating more impoverished people [80]. The authors further stated that the poor people, especially those in the rural area, depend totally on the forests for food and bioenergy, which has not only caused reduction in forest areas and forest stocking but has increased CO_2 emissions and poor soil including low SOM [80]. In Malaysia, a study demonstrated that forests have a large influence on carbon emissions, and thus forest loss through deforestation increases the emissions of the GHGs and global climate change as an effect [93]. The benefits and relationships between deadwood and other indicators of sustainable forest bioeconomy have been investigated in different regions [94]. According to Bujoczek et al. [95], in order to conserve the biodiversity and maintain forest richness, it is pertinent to retain deadwood at different stages of decay, considering environmental, economic, and social benefits. Furthermore, in the tropical rainforests of Malaysian Borneo, Saner et al. [96] observed a strong connection among deadwood, soil carbon, soil organic matter, and net primary productivity. Although the potential of deadwood in the biodiversity of forest trees and soil can never be underestimated, deadwood volume was found in more fertile and moist areas of the forest [95]. This is in support of the fact that deadwood volume has a significant and positive correlation with forest stocks, NPP, and soil nutrient enrichment (that is, SOM).

Table 3. Summary of correlation analysis for the investigated variables that are associated with the forest bioeconomy in Ghana (1990–2020).

	Dead Wood	**For Prot Area**	**Pop**	**For CoGDP**	**GDP Gro**	**For GroStok**	**For Area**	**For Loss**	**Tree CovLoss**	**Pov Rate**	**For Biofuel**	**For NonBiofuel**	**Rain Fall**	**Temp**	**SOM**	**NPP**
Dead Wood	1.00															
ForProtArea	0.86 *	1.00														
Pop	−0.97 **	−0.93 *	1.00													
ForCoGDP	0.73	0.70	−0.76 *	1.00												
GDPGro	0.39	0.28	−0.37 *	0.45	1.00											
ForGroStok	0.99 *	0.86	−0.98 *	0.75 *	0.41	1.00										
ForArea	0.92 *	0.90 *	−0.91 *	0.66 *	0.34	0.91 *	1.00									
ForLoss	−0.77 *	−0.61	0.78 *	−0.55 *	−0.32	−0.77 *	−0.60 *	1.00								
TreeCovLoss	−0.95 *	−0.78	0.92 *	−0.66	−0.34	−0.94 *	−0.84 *	0.83	1.00							
PovRate	0.6 1 **	0.71 **	−0.63 **	0.33	−0.51 *	0.62 *	0.62 *	−0.47 *	−0.55	1.00						
ForBiofuel	−0.86 *	−0.90 *	0.89 **	−0.71 *	−0.32	−0.86 *	−0.88 *	0.55 *	0.62 *	−0.58 *	1.00					
ForNonBiofuel	−0.86	−0.84	0.88 **	−0.65	−0.28	−0.83 *	−0.79 *	0.66	0.79	−0.60 *	0.77	1.00				
Rainfall	0.61 *	0.07	0.00	0.18	0.00	0.55 *	0.51 *	0.23	0.00	0.00	−0.03	0.00	1.00			
Temp	0.57 *	0.00	0.00	0.01	0.00	0.48 *	0.36 *	0.00	0.00	0.00	0.09	0.00	0.51	1.00		
SOM	0.95 *	0.87 *	−0.96 *	0.69 *	0.36	0.95 **	0.89 *	−0.80 *	−0.91	0.64	−0.82 *	−0.89	0.44	−0.32	1.00	
NPP	0.96 *	0.70	−0.98 *	0.73 *	0.34	0.86 **	0.91 *	−0.71 *	−0.90	0.64	−0.91	−0.87 *	0.50	0.57 *	0.94 *	1.00

* = correlation was significant at the 0.01 *p*-value; ** = correlation was significant at the 0.05 *p*-value. Description of the abbreviations: ForProtArea = forest protected area; Pop = population; ForCoGDP = forest contribution to GDP; GDPGro = gross domestic growth rate; ForGroStok = forest growing stocks; ForArea = forest area; ForLoss = forest loss; TreCovLos = tree cover loss; PovRate = poverty rate; ForBiofuel = forest use as biofuel; ForNonBiofuel = forest use for non-biofuel; Temp = temperature rate; SOM = soil organic matter-an indicator of soil quality; NPP = forest net primary productivity.

4. Conclusions and Recommendations

In the three decades of investigation, the study showed that larger areas of forest were found in decade 1 (1990–1999) relative to decade 2 (2000–2009) and decade 3 (2010–2020). Forests' contributions to GDP varied between the forest–vegetation belts and regions, decreasing rapidly from 1990 to 2020. The highest forest contributions to GDP were found in the wet evergreen (rainforest) and moist evergreen forests in comparison with the other forest belts. The study also observed that a higher percentage of the people depend on forests for income, livelihood, and bioenergy in the south than the other regions of the country. This was probably because of the areas of forests, population size, and economic status of the people in the southern part. Agricultural activities and commodity-driven deforestation (such as infrastructural development, logging for biofuel and timber) ranked highest in the list of the drivers, and their trend increased severely over time. On the other hand, population growth and climate change were long-term drivers of deforestation because they cut across the three decades of study. *Tectona grandis*, *Cedrela odorata*, *Terminalia superba*, *Klainedoxa gabonensis*, *Hevea brasiliensis*, *Cylicodiscus gabonensis*, *Pinus halepensis*, *Hagenia abyssinica*, *Desbordesia pierreana*, *Parinari glabra*, and *Swrtzia fistuloides* were identified as the common species important for forest bioeconomy in the study. The employment rate in forestry and forest-based sector as an indicator of sustainable forest bioeconomy decreased with time. The population growth and forest area showed significantly high positive and negative correlations with all the indicators of sustainable forest bioeconomy investigated. Further, the study discovered that the volume of deadwood as an indicator of sustainable forest bioeconomy showed a significant positive relationship with forest protected area, population, forest growing stocks, forest soil organic matter, and net primary productivity, but a negative correlation with poverty rate and forest use for biofuel.

The study signifies that the sustainable forest bioeconomy is indeed a multidimensional approach involving economic, social, and environmental indicators, and thus a direct or indirect impact in one will definitely influence the others positively or negatively. For example, deforestation might increase GDP, income, and/or an individual's well-being, but there might be a reduction in forest areas that could lead to decline in employment rate, forest stocks, net primary productivity, poor soil, and increased carbon emissions. On the other hand, a reduction in deforestation might bring about a reduction in carbon emissions; however, the economic repercussions are negative as the contribution of forest to GDP, income, and employment will fall as trade-offs.

Findings from the study will really help to bring lasting solutions to deforestation and enhance the sustainable forest bioeconomy. This is because the study has unveiled remote drivers of forest loss that have been long overlooked by previous studies. For example, the sociocultural and political drivers have always been overlooked. Although adoption of some control measures such as the REDD+ and other environmental tax and financial incentives are good policies, as obtainable in some countries such as Brazil, Indonesia, Costa Rica, Colombia and others, more might be achieved from these policies by addressing sociocultural and political factors. A sustainable enlightenment campaign and routine informal education of the rural people are highly necessary. This is because some of the peoples' reasons for preferring forest products to modern resources seem convincing and logical. There should be regular and intensive enlightenment campaigns and workshops as well as house-to-house visits to the people using strong health-related evidence to convince them. They should be convinced as to why they should embrace modern toothpastes and brushes instead of chewing-sticks from the forest trees, for example. However, there are eco-forest guards in some regions, and the government should recruit more personnel to safeguard most forests from illegal and unsustainable logging. Annually or bi-annually, monetary compensations should be given to communities whose forest(s) are more protected and denser. Ghana is a tropical and coastal country with enough sunlight and sea; thus, the government should extract renewable energy from these sustainable energy sources and provide the rural communities with solar-powered cooking stoves. This will drastically reduce pressure on the forest.

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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
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

Table A1. *Cont.*

Forest-Vegetation Belts	Regions	Latitude	Longitude
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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forests

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_2) 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_2 [10,11]. Living plants, through photosynthetic processes, transform CO_2 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_2 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_2 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_2 [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^2 [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_2e 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].

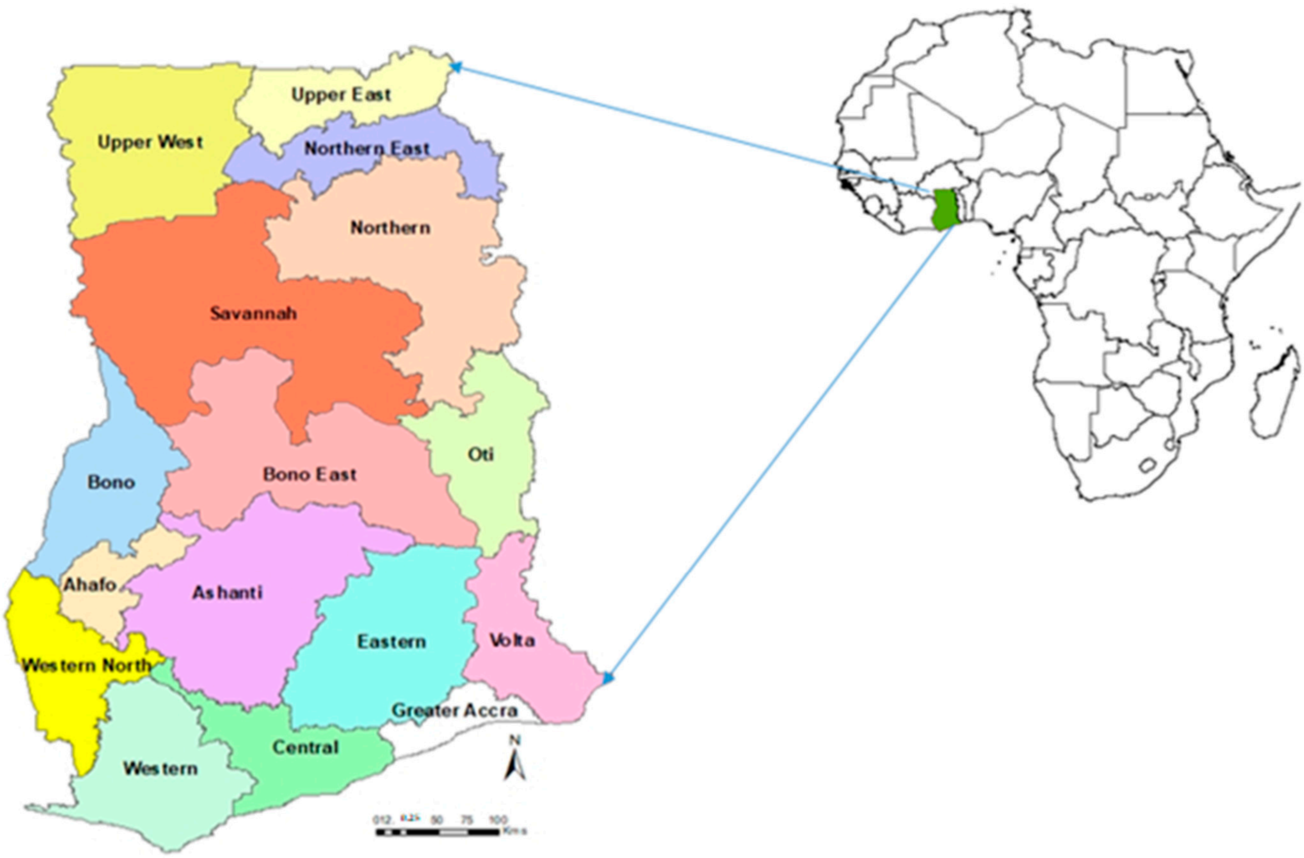

Figure 1. African map showing Ghana (the study area), and the current 16 administrative regions.

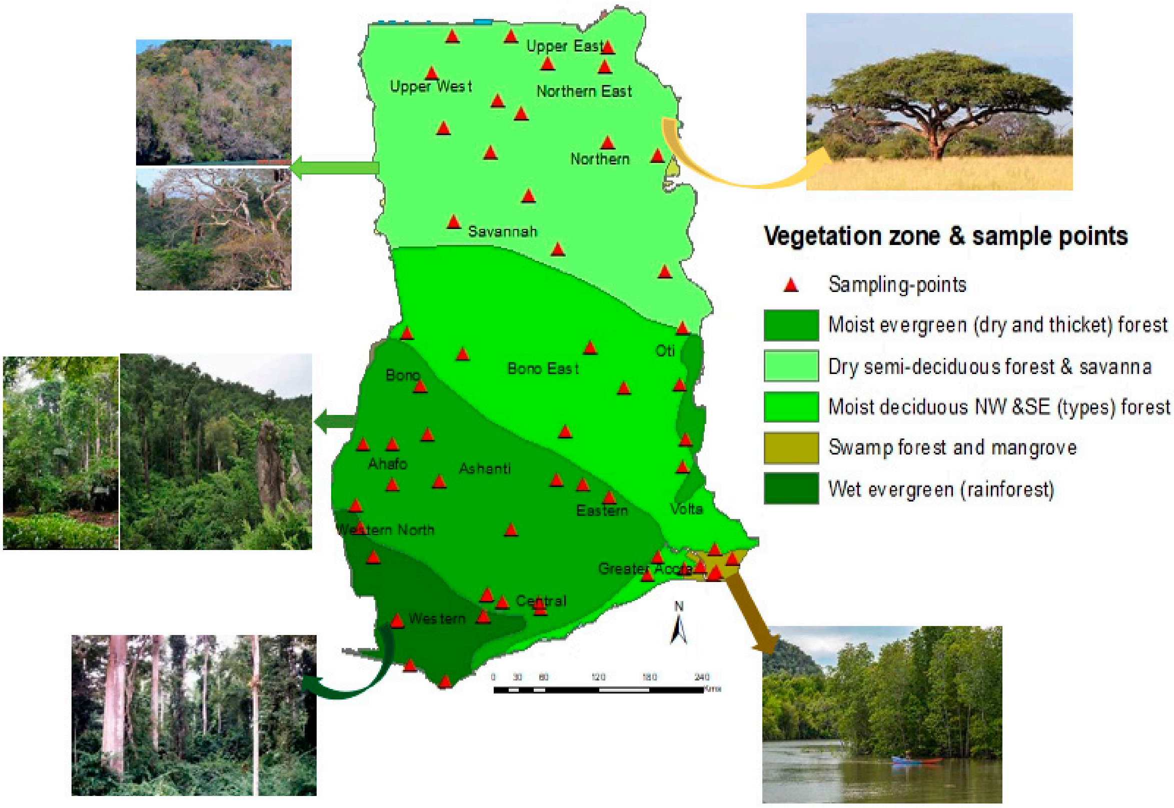

Figure 2. Forest-vegetation belts, image of the forest's features/layers, regions, and sampling locations.

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 savannah 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	- OCHA 2022. Global coordinates; - https://data.humdata.org/dataset/cod-ab-gha (accessed on 24 December 2023); - GSS 2020.
Forest-vegetation zones	- White F. 1983
Sampling points	- Field sampling and survey; hand-held GPS.
Land use-cover and changes	- Digital and satellite imageries from https://eros.usgs.gov/westafrica/land-cover/land-use-and-land-cover-trends-west-africa (accessed on 24 December 2023); - www.nasa.gov (accessed on 24 December 2023).
Forest areas and loss	- FAO's Global Forest Resources Assessments Reports.
Forest tree cover and loss	- FAO's Global Forest Resources Assessments Reports.
Forest growing stocks	- FAO's Global Forest Resources Assessments (main and country reports).
Contributions of forest to GDP	- Ghana Statistical Services database; - World Bank websites.
Country's GDP and poverty rate	- Ghana Statistical Services database; - World Bank websites; - Other reports and documents (e.g., Braimoh, 2009; MoFA, 2010).
Uses of forests: Farming, mining, bioenergy, timber, NWFPs, etc.	- Ghana Statistical Services database; - World Bank websites; - Reports of Timber Industry Development Division, - Forestry Commission; - Other reports and documents (e.g., Braimoh, 2009; MoFA, 2010).

Table 1. *Cont.*

Indicator/Measure	Sources
Biophysical: climate, soil and biomass carbon, and carbon emissions	- Ministry of Food and Agriculture database; - Forestry Commission; - Energy Commission; - The published literature; - FAOSTATS websites - ISRIC Soil geographic databases: https://www.isric.org/explore/soil-geographic-databases (accessed on 24 December 2023). - Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite: https://neo.gsfc.nasa.gov/ (accessed on 24 December 2023).
Population and settlement	- Ghana statistical services database.
Forest-based employment, migration, civil/communal conflicts	- Ghana statistical services database; - Other published literature (e.g., GSS, 2000, 2010, 2021).
Drivers of deforestation, socio-cultural and political views, and stands on deforestation	- Field sampling and survey (online and physical) using the literature, interviews, questionnaires.
Common forest tree species	- Field sampling and survey; - The previous literature (published articles and NGOs/Government institutional documents; - Foresters and plant ecologists.

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 (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 (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 × 15 pixel (30 × 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 (Ci) for LULC type 'i' is equal to the sum of aboveground, belowground, dead carbon, and soil carbon for LULC type 'i', represented as follows:

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

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

$$C_{total} = \sum (i)^{\wedge n} \times (Ci + Ai) \quad (5)$$

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_2 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^{-1}, 15.1–291.2 Mg C ha^{-1}, and 10.6–198.7 Mg C ha^{-1}, respectively (Figure 4a–c). On the other hand, the belowground carbon stocks ranged from 22.5–93.2 Mg C ha^{-1}, 19.9–68.9 Mg C ha^{-1}, and 3.1–37.0 Mg C ha^{-1} 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.

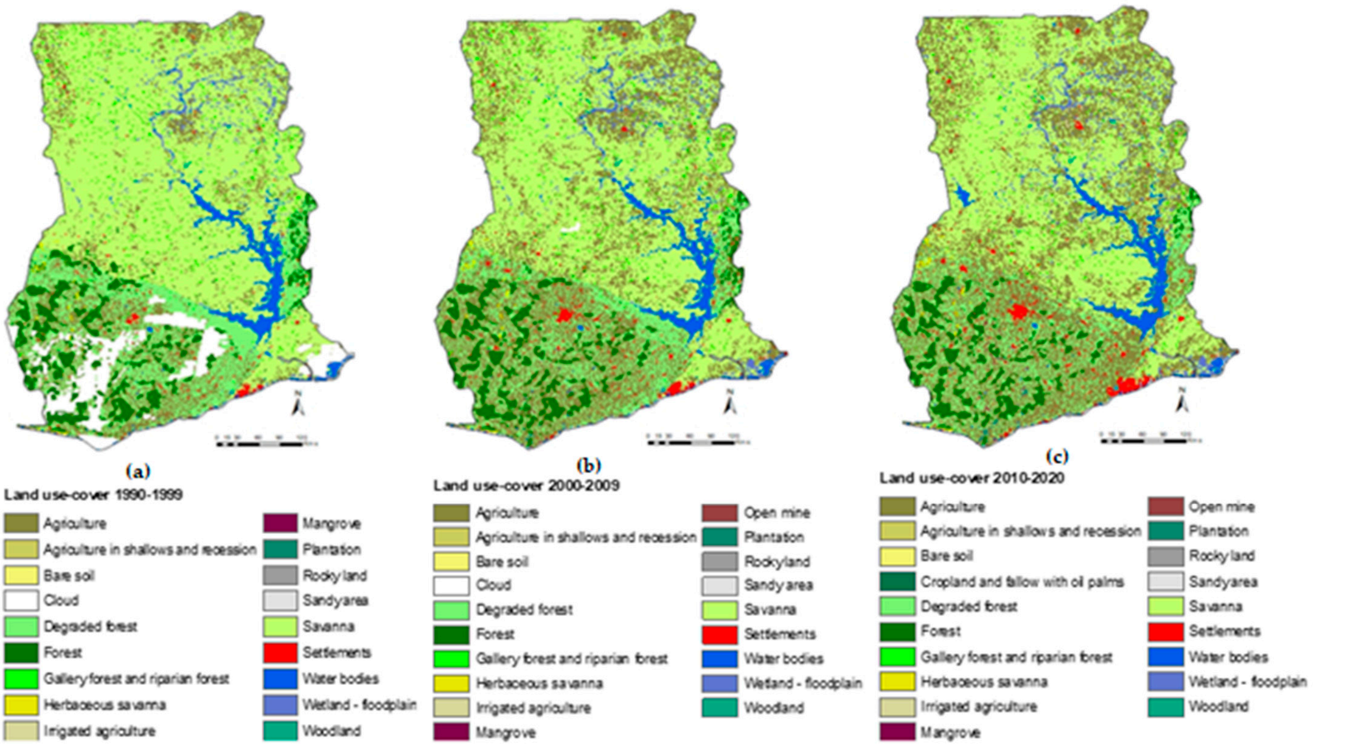

Figure 3. Land use-cover over three decades, 1990–2020, showing average changes between (**a**) 1990 and 1999, (**b**) 2000 and 2009, and (**c**) 2010 and 2020.

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].

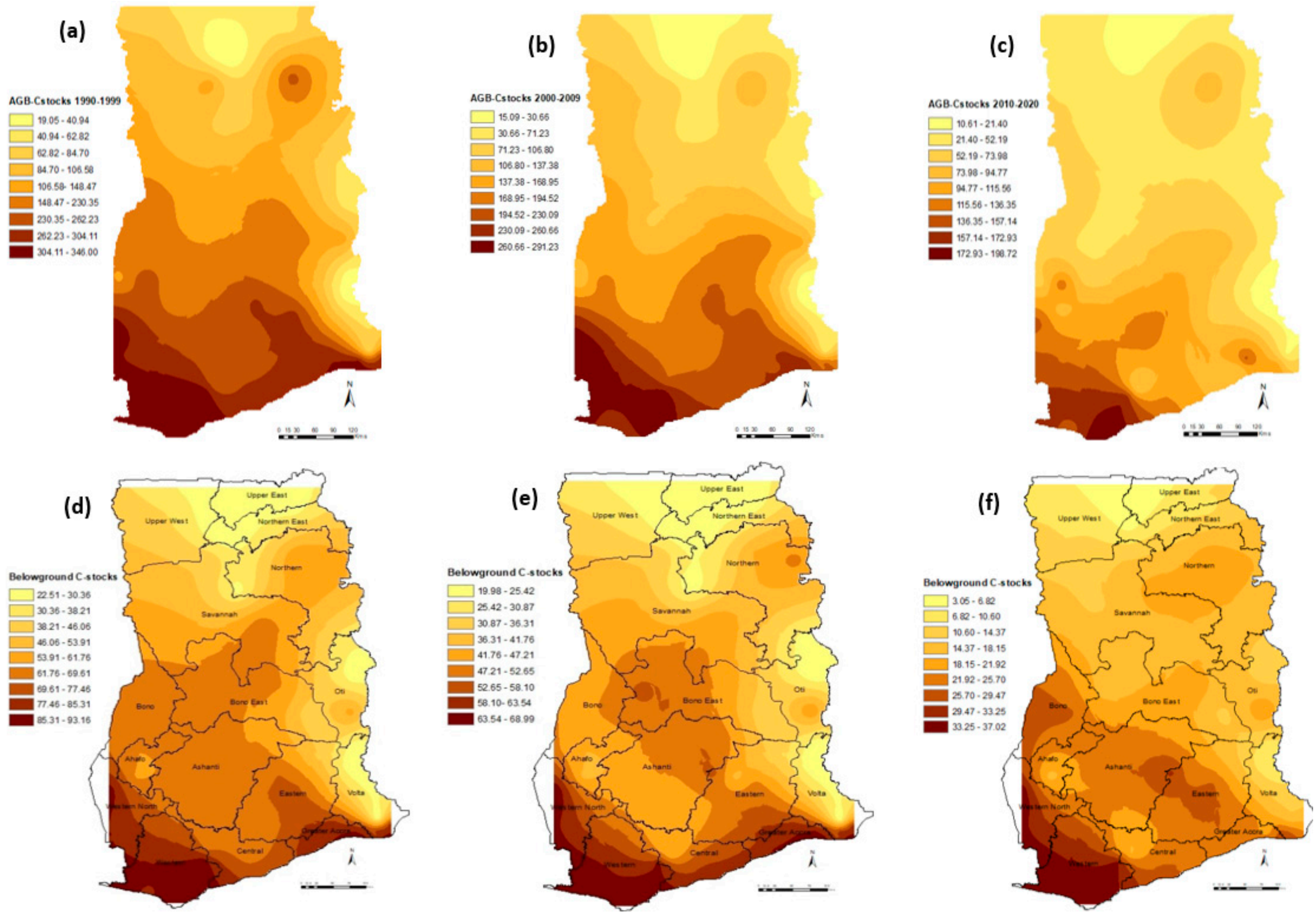

Figure 4. Ordinary kriging model showing the spatial distribution and variability of the forests' aboveground carbon stocks for (**a**) 1990–1999, (**b**) 2000–2009, and (**c**) 2010–2020, and in the forests belowground carbon stocks for (**d**) 1990–1999, (**e**) 2000–2009, and (**f**) 2010–2020.

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^{-1} 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 $ha^{-1}yr^{-1}$, forest growing stock decreased by about 2.5 million M^{-3} yr^{-1}, 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].

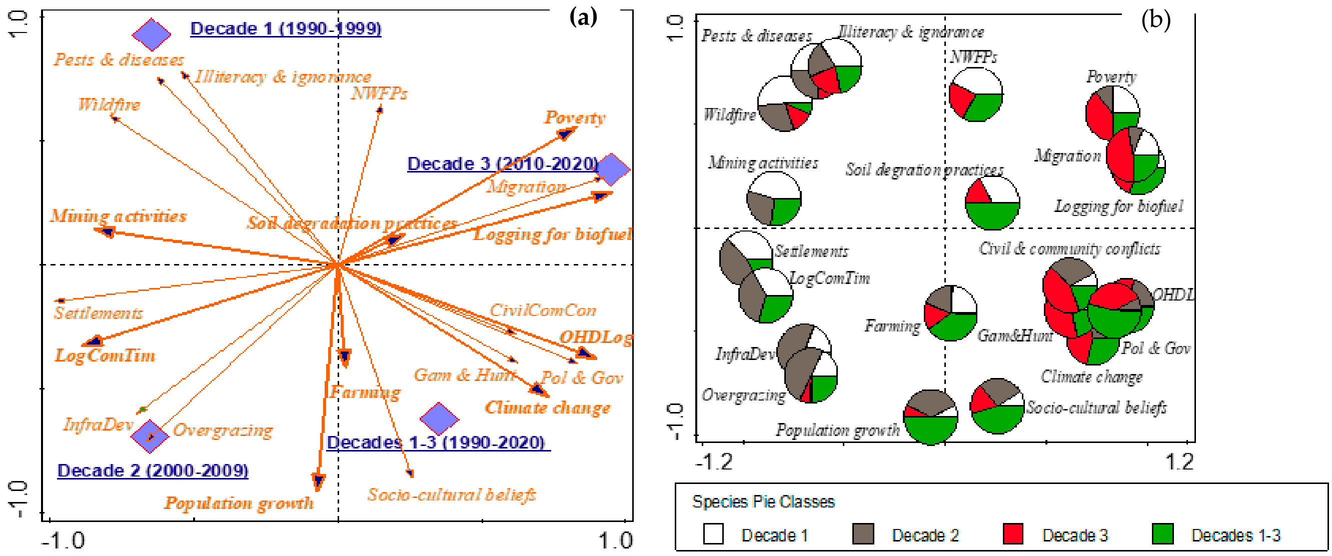

Figure 5. Multivariate analysis showing (**a**) the main drivers of carbon stock as an indicator of sustainable forest bioeconomy and the magnitude of their influence in the various decades, and (**b**) the sectoral proportion and the distribution of each driver of carbon stocks during the study periods. 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; CivilComCon = 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.

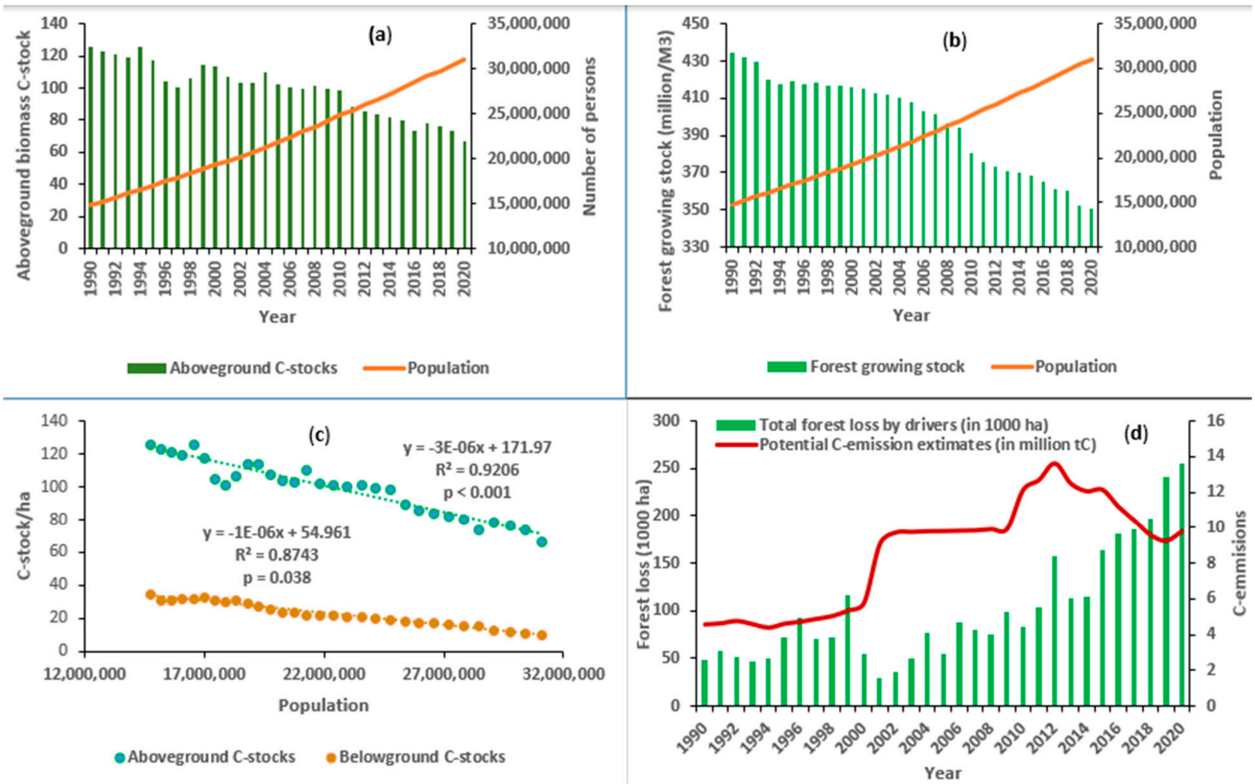

Figure 6. Relationships between (**a**) forest total carbon stocks and population, (**b**) forest growing stocks and population, (**c**) aboveground and belowground forest carbon stocks, and (**d**) the total forest loss caused by the drivers and carbon emission estimates covering the period from 1990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

Consistent with our findings, Cui et al. [102] found that the drivers of carbon sources increased by almost threefold (23,983.7 × 104 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 × 104 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 yr^{-1}) led to extensive AGB-Cstocks of 0.28 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 achieve this in Ghana because of the geometrically growing population.

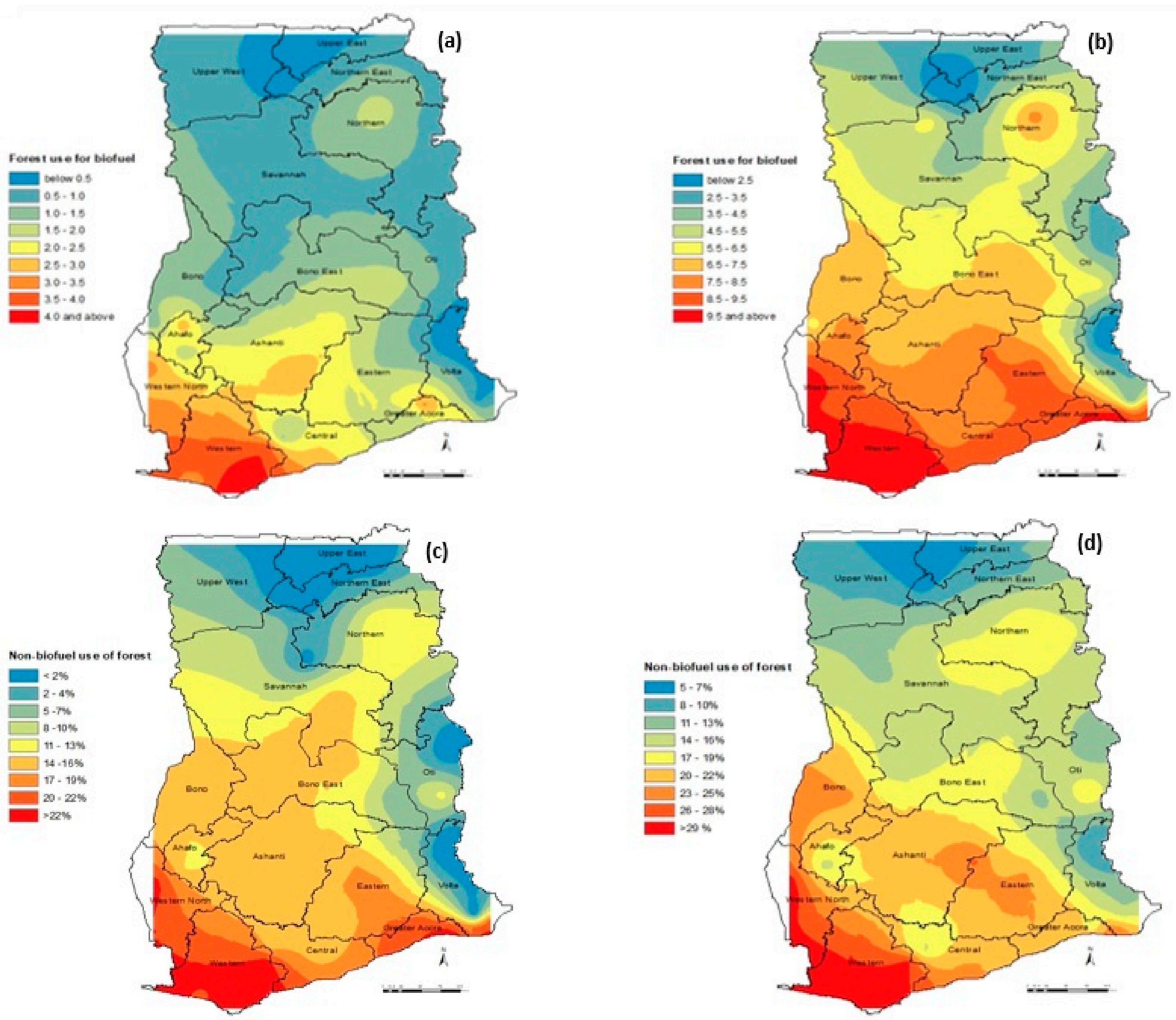

Figure 7. Ordinary kriging model showing the spatial distribution and variability (%) in the use of forest and its resources as (**a**) biofuel from 1990–1999, (**b**) biofuel from 2010–2020, (**c**) non-biofuel from 1990–1999, and (**d**) non-biofuel from 2010–2020.

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 macrophlla*, *Letestua durissima*, *Lophira alata*, *Milicia excels*, *Baphia kirkii*, *Cleistanthus mildbraedii*, *Cylicodiscus gabonensis*, *Desbordesia pierreana*, *Manilkara cuneifolia*, *Parinari glabra*, *Strombosia glaucescens*, *Tessmania africana*, *Klainedoxa gabonensis*, *Afzelia 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 *Afzelia*, *Diospyros bejaudi Lecomte*, *Diospyros crumenata*, *Diospyros nitida*, *Diospyros helferi*, and

Parinarium 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].

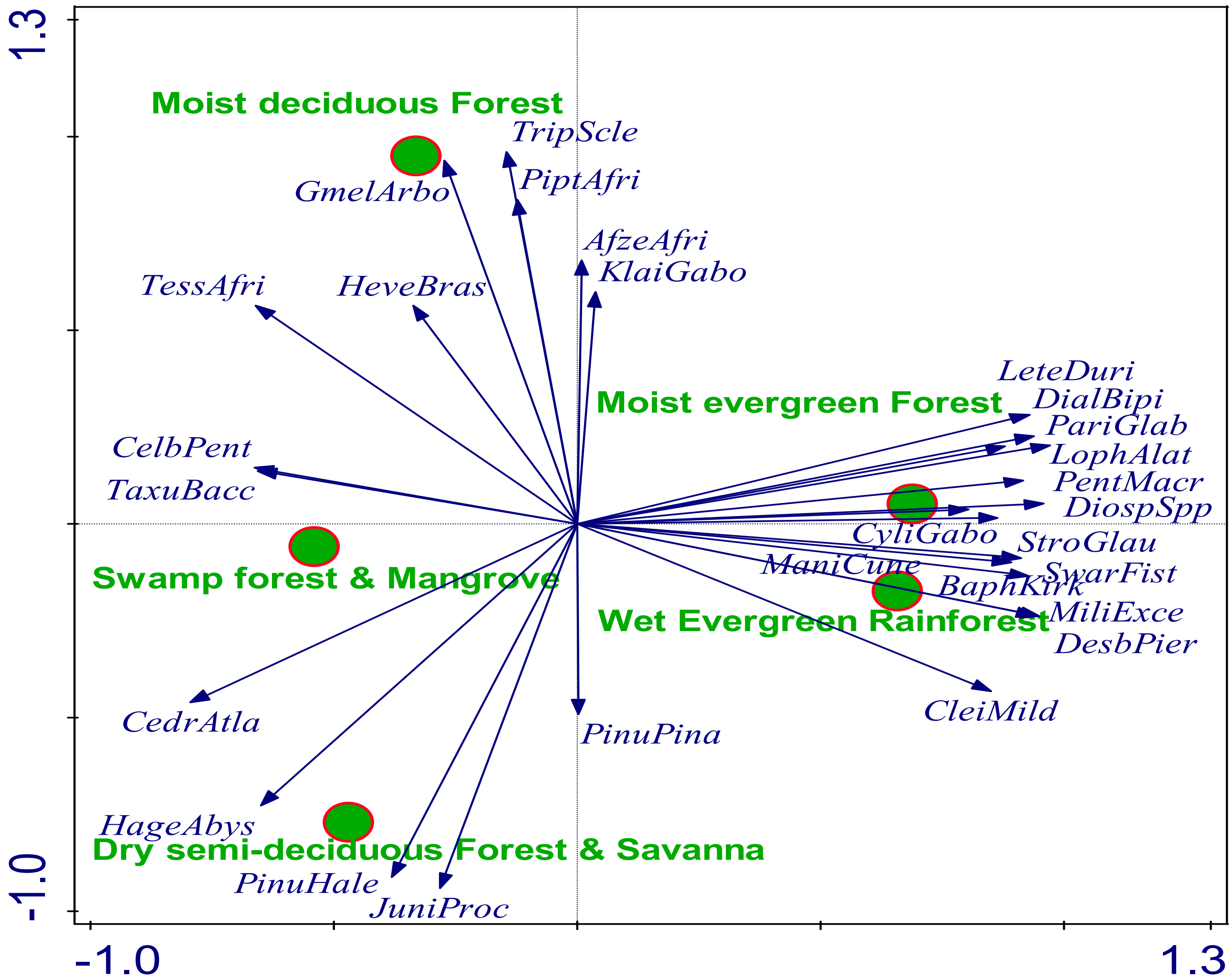

Figure 8. Multivariate ordination plot showing the vegetation zones and their associated common tree species, which promoted carbon fluxes vis-à-vis sustainable forest bioeconomy for each vegetation zone during the study period. Description of the abbreviations are as follows for each species: *Dialium 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; Afzelia 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.*

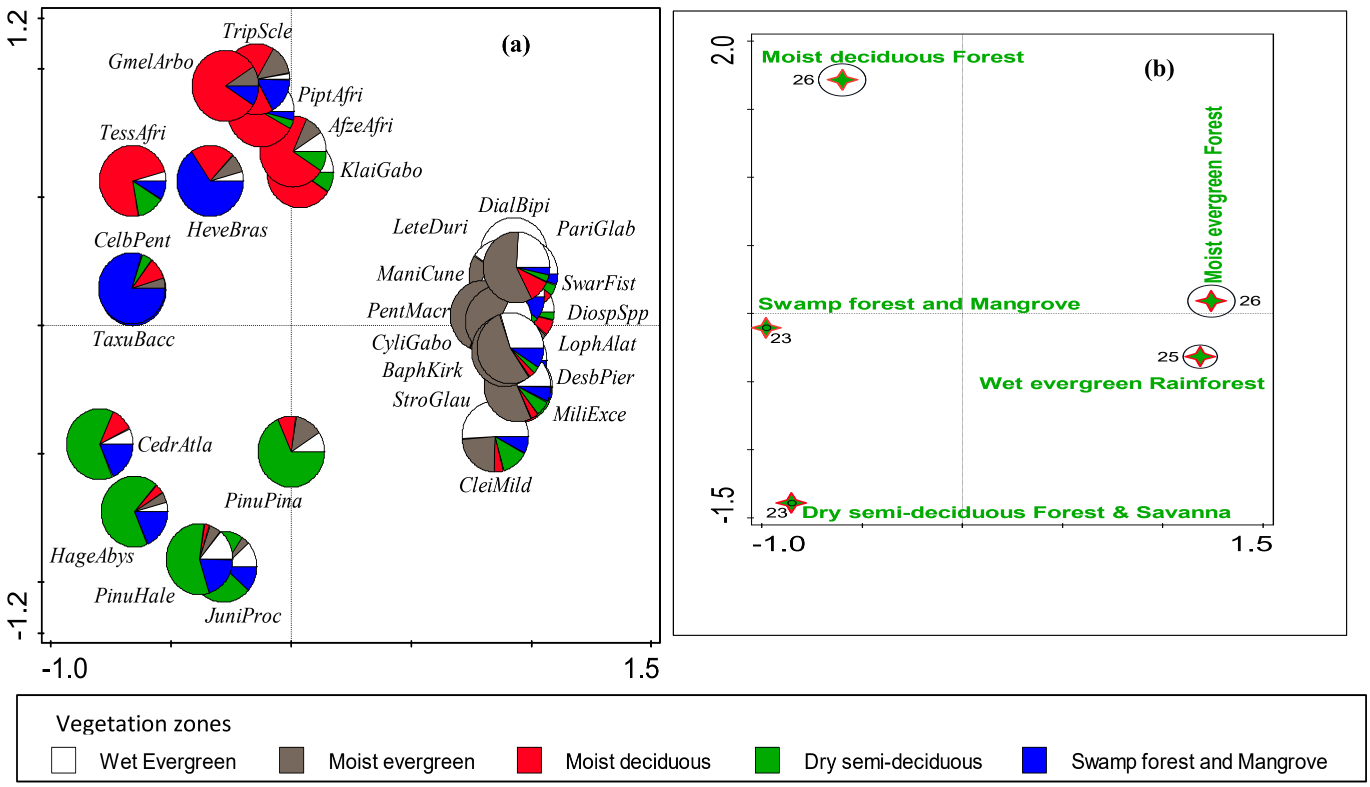

Figure 9. Multivariate ordination plot showing (**a**) the proportion of the major forest tree species that contribute substantially to peoples' livelihood and the forest bioeconomy, and (**b**) an ordination plot showing the vegetation zones and the associated common tree species that promote carbon 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%.

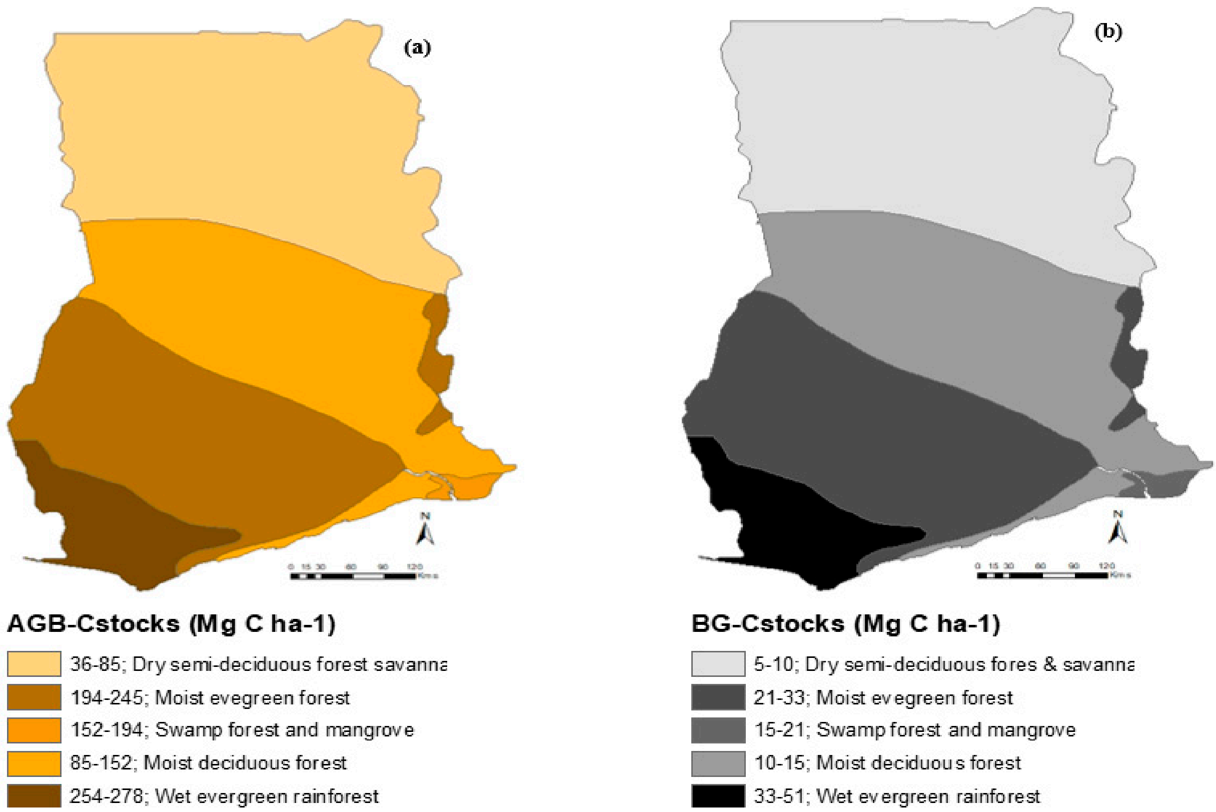

Figure 10. Average carbon stocks in (**a**) aboveground biomass and (**b**) belowground (soil) in the forest-vegetation zones from 1990 to 2020.

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 liter 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-Emision	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_2 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.

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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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