Chapter

Forests at the Crossroads: Biodiversity Conservation in the Era of Climate Change

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Abstract

Tropical forests are biodiversity-rich habitats on the globe because they host diversified flora and fauna species, provide a plethora of ecosystem goods and services to local communities, and sustain numerous ecological functions. The forest resources in Sudan are a vital aspect of the nation's ecological and economic framework. However, they face threats from agriculture, logging, and degradation, leading to loss of forest cover and reduced biodiversity. This chapter reviews Sudan's dryland forests, highlighting their importance, forest biodiversity, ecosystem services, environmental degradation, conservation challenges, biodiversity information gap, threats, and the urgent need for sustainable management strategies. It emphasizes the significance of protecting these forests to maintain ecological balance and promote socioeconomic development. Addressing these challenges requires urgent and effective conservation and management efforts to preserve these vital resources.

Keywords: forest biodiversity, ecosystem services, environmental degradation, conservation challenges, biodiversity information gap, threats, biodiversity conservation strategies

1. Introduction

Tropical forests contribute ecosystem services such as providing wildlife habitat, safeguarding against erosion and desertification, contributing to soil fertility, and many others [1]. Distribution patterns of plant species composition and diversity in natural habitats are issues of global interest today because environmental and anthropogenic factors greatly influence them. Forests in Sudan hold significant ecological, economic, and cultural value. They contribute to biodiversity, housing a variety of flora and fauna, and play a critical role in climate regulation. Economically, they support local and national economies through timber, medicinal resources, and tourism. Culturally, they are embedded in the country's heritage and traditions. However, Sudan's forests face considerable deforestation challenges. Approximately 28.4% of Sudan, or about 67,546,000 hectares, is forested. The primary drivers of deforestation include the conversion of natural forests to cropland and pasture, which significantly influences the country's deforestation rates. Additionally, fuelwood harvesting, constituting up to 80% of the national energy supply, has been a major cause of forest degradation [2].

Furthermore, Eltohami et al. [3] stated that the distribution of these resources is unbalanced (i.e., the greatest amount of the remaining forests is distributed in the south, whereas the poor and sparse woody formations characterize the northern part of Sudan where more people are concentrated and the need for forest goods and services is highest.) The areas free from human occupation such as reserved forests and national parks continue to represent habitats for an array of native flora. Maintaining reserved areas of natural vegetation within the human-dominated landscape is the only way to conserve native flora [4–7]. Therefore, habitat level analysis of vegetation becomes a vital for assessing the availability of plant resources, patterns of species diversity, and identification of botanical hot spots [8]. Conservation of biodiversity is crucial in a country, such as Sudan, where ecosystems are fragile, and renewable natural resources are endangered through over-exploitation. Ecosystems are rapidly deteriorating, primarily due to socioeconomic factors. Key contributors include agricultural expansion, logging, increased demand for livestock products, and urban development, particularly the construction of new transportation infrastructures. Additionally, economic and social pressures such as poverty and population growth are leading to harmful practices such as overgrazing, widespread tree cutting, soil erosion, desertification, overhunting, and overall land degradation. This environmental decline has led to the disappearance or severe endangerment of many aquatic and terrestrial species as their natural habitats are destroyed [2, 9].

Quantitative knowledge about basic stand diversity and structure and stand health indicators, such as canopy health and density of dead standing trees, are required for these current efforts toward attaining proper management and use of gum arabic-producing trees stands to be successful. Sudan faces a significant challenge in the management of its gum arabic-producing tree stands, primarily due to the absence of regular and long-term monitoring programs. This lack of systematic monitoring hinders the ability to track vital forest condition indicators in these areas. Despite the economic and ecological importance of gum arabic production, the country struggles to maintain a comprehensive understanding of the health and productivity of these forests. This situation is exacerbated by environmental stressors, such as climate change, which further affect these vital ecosystems. As a result, there is a pressing need for the establishment of robust monitoring systems to ensure sustainable management and conservation of Sudan's gum arabic-producing forest [3, 9–13]. Consequently, management and conservation planning are based on rough estimates. Baillie et al. [14] stated that to create effective forest management plans, it is obligatory to know which species present, consequently, management and conservation planning are based on rough estimates. Baillie et al. [14] stated that in order to create effective forest management plans, it is obligatory to know which species are present, their relative abundance and species-specific stages, and what factors control their future persistence and dynamics. Therefore, information about the current condition of natural reserved forests, including species composition, diversity, density, stage structure, and species-rich communities, are of primary importance in the planning and implementation of biodiversity conservation efforts [15].

2. Forest resources extent

Sudan's forests extend across several agroecological zones, which imply the existence of a variety of fauna and flora species that contribute directly or indirectly to the sustainable livelihood of local communities. In the period from 1980 to 1999, areas covered with forests in Sudan were estimated to be about 44 million acres, i.e., about 61% of the total

area of forests in arable lands, which equals about 73 million acres. In the mid-fifties, forests in Sudan constituted about 36% of the total area [16]. The forest resources in Sudan were estimated by FAO in 1990 to be about 19% of the total area of the country.

The national forest inventory, which was conducted by the Forest National Corporation (FNC) with the cooperation of FAO in 1995, documented that the forest cover was 24.9% of the total area of Sudan [17]. Sudan is classified as a moderately forested country with about 28% (67 million ha) forest and woodlands cover [18]. The scarcity of forest resources in Sudan is further aggravated by a high deforestation rate. FAO [19] ranked Sudan as the third country following Brazil and Indonesia in terms of net forest loss per year between 2000 and 2005. Deforestation in Sudan is attributed to many factors such as agricultural expansion, fires, overgrazing, and illicit felling of trees for fuelwood [20].

Forest resources in Sudan are inversely proportional to population density, 68% of Sudan's forests are in the south where 15% of the population live, and only 32% of the forests in the northern states in Sudan where 85% of the population lives [21]. In the year, 2005 forest resources were globally estimated and, accordingly, Sudan's forest cover found to be about 74 billion acres, which is equivalent to 29% of the area of the country. Nevertheless, there is an annual loss of these resources estimated to be about 589,000 acres. Yet, the global enumeration of forest resources, (2010), carried out by [22] in cooperation with different countries, presented a new profile for forest resource of Sudan. When completed in 2009, initial results of this assessment, noted that forest resources have dwindled from 74 million acres in the year 2005 to 69.949 million acres. Regrettably, this retraction of forest resources made the ratio of forest cover diminish from 29.6% in the year 2005 to 29.4% by late 2009 [23]. Based on the Afro-cover assessment and displayed in the NBSAP of 2015, the forest cover accounts for only 11.9% of the country's area with an annual deforestation rate exceeding 2.4%. Recent estimate based on FNC [24] report show that the forest cover occupies only 21.16% of total area of the country.

3. Forest diversity

The natural cover of Sudan is generally poor, sparse, and scanty vegetation due to its location in such arid environment of the country; except along the Nile banks and water courses where ephemeral herbs and grasses occur after the short rainy seasons. The reserved forests are about 837 forests distributed all over the country and occupy 85.90 million ha. This area represents 34.5% of the total land area of the country. These reserved forests are crucial for biodiversity conservation. They serve as vital habitats for a wide range of species, helping to preserve the ecological balance and biodiversity [25–27]. They constitute a great potential for biodiversity conservation and play vital role as an important component of natural resources and land use. Based on experts' opinions, these forests, including woodland savanna, are thought to be a home for over 500 unique species of trees and 185 species of shrubs, but this information have not been verified yet through field surveys [17, 28]. Al-Amin [29] is one of the prominent trees dendrology studies in Sudan has broadly classified the forest composition into three regions/ecosystems: (i) Arid and semiarid region (includes Northern, River Nile, Khartoum, White Nile, North Kordofan, North and West Darfur, and Red Sea states) where the vegetation is typical includes some scattered perennial vegetation, bushes and woody succulent thorny or leafless shrubs, and dominated by *Acacia tortilis, Capparis deciduas*, and *Maerua crassifollia* association. (ii) Dry Savanna ecosystem (includes Kassala, Gadaref, West Kordofan, and East and Central Darfur states) in which species richness

and stem density increase with noticeable abundance and dominance for species such as *Acacia seyal, Balanites aegyptiaca, Faidherbia albida, Ziziphus spina-chirsti,* and *Calotropis procera*. (iii) Wet Savanna ecosystem (Blue Nile, South Kordofan, and the South Darfur States) is essentially different and considered the richest and most dense region in Sudan in terms of trees and shrubs composition and diversity. Among the famous trees species occur at this zone are *Adansonia digitata, Balanites aegyptiaca, Borassus aethiopium, Cordia africana, Diospyros mespiliformis, Tamarindus indica, Prosopis africana, Sclerocarya birrea, Terminalia brownie, Crateva adansonii*, and *Comberetum* sp. In the basin and along the banks of the Nile and tributaries species, such as *Phoenix dactylifera*, *Acacia nilotica*, and *Tamarix aphylla*, are found.

4. Current status of biodiversity

4.1 Main ecosystems

Sudan's ecosystems are primarily categorized into two distinct types: aquatic and terrestrial ecosystems. Subsequent sections will provide detailed insights into both these ecosystems and their specific occurrences within the nation [30].

4.1.1 Aquatic (marine and freshwater) ecosystems

Contrary to its predominantly arid reputation, Sudan boasts a wealth of wetland ecosystems teeming with biological diversity and intriguing life forms. Notably, the eastern coast along the Red Sea harbors marine ecosystems characterized by lush mangrove forests and includes three protected marine areas, such as Senganeeb and Donganab. Additionally, Sudan is home to numerous inland freshwater habitats, including the river Nile and its tributaries, as well as various seasonal rivers, such as the Gash and Baraka, which originate in the Ethiopian highlands and create two inland deltas within the country. Furthermore, the nation is dotted with hundreds of lakes and ponds of varying sizes, each hosting a rich array of biodiversity [30].

4.1.2 Terrestrial ecosystems

4.1.2.1 Forests, grasslands, and mountains

According to Abdel Magid and Badi [31], Sudan's ecological landscape is categorized into five distinct vegetation zones, arranged from north to south based on rainfall patterns. They are: (i) desert, receiving 0–75 mm of precipitation, (ii) semidesert, with 75–300 mm, (iii) low rainfall savannah on clay and sand, with 300–800 mm, (iv) high rainfall savannah, receiving 800–1500 mm, and (v) mountain vegetation, ranging between 300 and 1000 mm of rainfall. These zones stretch from the arid desert in the far north to the lush savannahs (**Figure 1**). As per the recent land cover Atlas of Sudan, forests and rangelands together constitute 35.6% of Sudan's total land area [2, 28].

4.1.2.2 Agroecological zones

The agricultural sector is pivotal for Sudan's food security, enhancing food production, and offering employment in rural areas. Sudan has about 86 million hectares

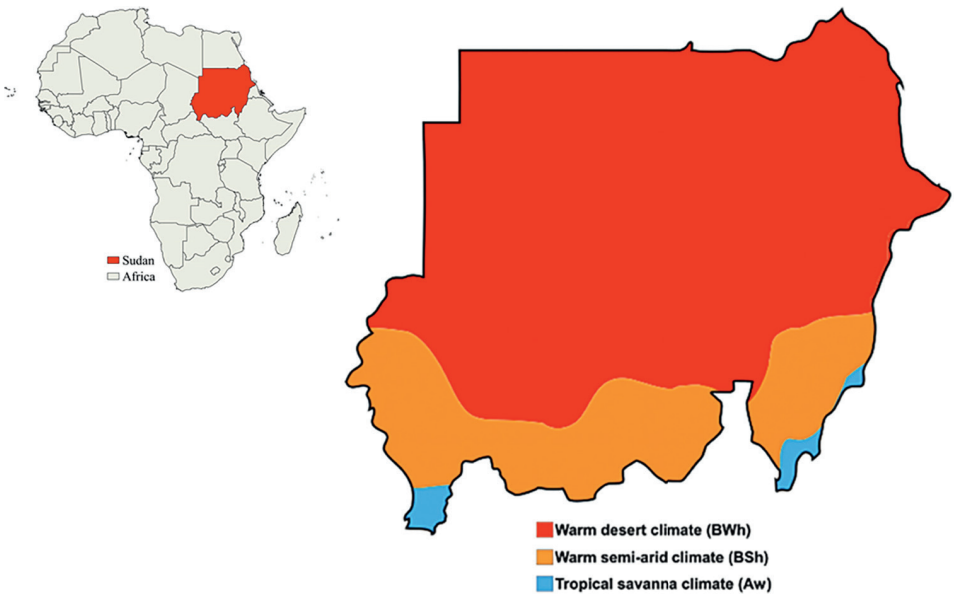

Figure 1.
Map of climatic zones of Sudan based on Köppen climate classification [30].

of cultivable land, yet less than 20% is utilized across three main farming subsectors. The irrigated sector, encompassing around one million hectares, contributes 21% to agricultural production value, including all wheat and a quarter of the country's sorghum. Despite its lower relative contribution to sorghum production compared to the rain-fed subsector, it offers stable output, especially critical during droughts for meeting consumption needs. The semi-mechanized rain-fed sector covers around 6 million hectares, primarily yielding sorghum and sesame, with crop success heavily reliant on rainfall. Additionally, the traditional rain-fed agropastoral sector spans about 9 million hectares in western, central, and southern Sudan, producing crops such as sorghum, millet, groundnuts, sesame, short-staple cotton, and gum Arabic.

Sudan's ecological zones, influenced by rainfall trends from north to south, dictate the distribution of its forests, transitioning from sparse bushland and shrubs in the arid north to dense, mixed forests in the southern savannah and mountain regions. The Nile basin cuts through Sudan from south to north, serving as a crucial water resource for agriculture, livestock, and forests. Forests and woodlands cover approximately 64.36 million hectares, while rangelands, providing 55–80% of the national herd's feed, span around 24 million hectares [27]. Livestock rearing is a significant livelihood for about 40% of the population, serving as a food source, wealth reserve, and a means of societal influence, particularly in areas underserved by banking and market systems (**Figure 2**) [2].

5. Socio-ecological services of forests

5.1 Ecological services of forests

The services provided by forests cover a wide range of ecological, economic, social, and cultural considerations and processes. Hence, ecosystem services are the

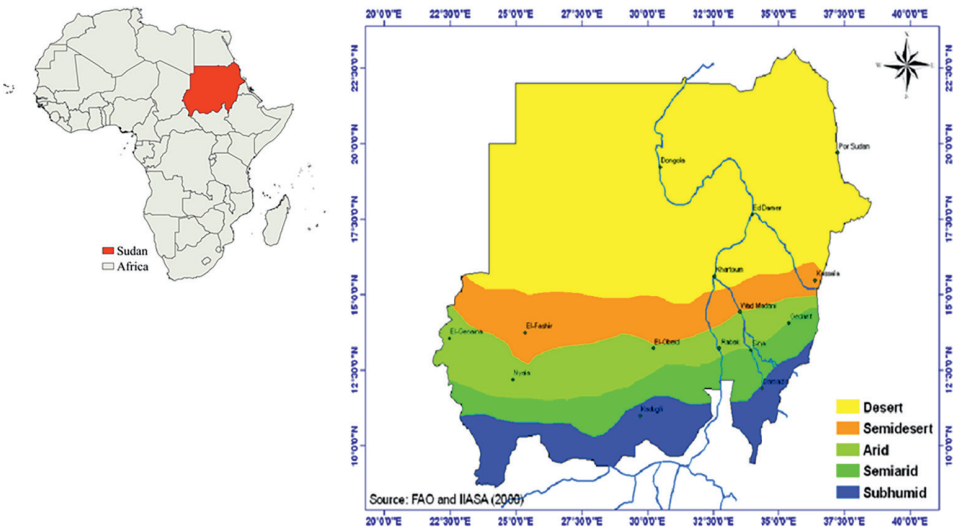

Figure 2.
Agroecological zones of the Sudan.

outcome of ecosystem functions that benefit human beings [32]. There are numerous services that forests provide in addition to their values of basic goods. They contribute more than other terrestrial biomass to climate-relevant cycles and biodiversity-related processes. As stated by Dail [33], the major services provided by forests include regulation of water regimes, modulating climate, maintenance of soil quality, carbon sequestration, maintenance of biodiversity in themselves, and being a habitat for other species, biological control, cultural, aesthetic, and amenity services.

5.2 Socioeconomic services of forest

Forests, as a renewable natural resource, have a significant role to play in assuring present and future food security by improving both the economic and physical well-being of both rural and urban people. The significant role of non-timber forest products (NTFPs) in supporting rural economies is evident in various countries with notable differences in their contributions to household income. In Sudan, NTFPs contribute over 50% to the cash income of rural households, a higher percentage compared to other countries. For instance, in Cameroon, the contribution is 39% [34, 35], while in Tunisia, NTFPs account for only 0.33% of the agricultural gross domestic product but contribute significantly, 32.30%, to the income of local forest populations [35, 36]. In Iran, NTFPs make up 21% of rural income [37], and in northern Thailand, they contribute 6.35% to community income [38]. Additionally, the importance of NTFPs extends to providing edible fruits to rural populations and the use of trees in traditional medicine [12, 39]. The importance of forests is indisputable, especially in developing countries. For instance, these woody species are considered an important source of energy for providing a substantial supply of firewood and charcoal to the local communities, as well as people in urban areas [40]. National energy surveys indicated that forests contribute 70.8% of the country national energy balance (4.01 million tons of oil equivalents) [41]. Sudan's forests provide a variety of goods, including timber in round and sawn forms, arboreal biomass for domestic energy supplies and building materials, and great varieties of non-wood forest products (NWFPs),

which are consumed for a variety of uses and traded locally or exported for external markets to get hard currency [42]. The most important role played by forest in Sudan's' rural areas is food security and the creation of job opportunities outside the agricultural season.

The production of honey and wax, in addition to game hunting and gum collection, are complementary and seasonal activities. During the periods of drought that stroked the Sahel, the fruits of some tree species were used extensively by local people as famine foods. Rangeland resources, particularly forests, contribute substantially to the income and subsistence of a large sector of the population who are either pastoralists or agropastoralists. It supplies about 80% of total feed requirement of the national herd and provides habitats for wildlife as well [43, 44]. Moreover, forests' inhabitant wild animals exert a significant influence on food production systems and ecological systems.

In addition, forestry activities provide significant opportunities for employment and income generation in almost all rural areas of Sudan. It was estimated that one out of seven of the population is engaged in forest-related activities [45]. Prehistoric people got their food mainly by hunting and gathering wild plants. Many of these people lived in the forest and were a natural part of it. With current urban expansion, people settled in cities, but they still went to the forests to get timber and to hunt. Also, forests provide a wide range of ecosystem services. For example, they protect soils from erosion, regulate the water regime; capture and store carbon, produce oxygen; , provide freshwater and habitat, help to reduce fire risk (in the tropics), and produce wood and non-wood forest products [46, 47]. In fact, forest resources became of high importance to communities not only for their great environmental services but also for the provision of livelihoods.

6. The value of plant diversity

Various plant species have diverse uses based on the socioeconomic context of a community. Natural forests are crucial for providing non-timber forest products (NTFPs) such as fruits, fodder, honey, and medicinal herbs. They are also key sources of tools, construction materials, timber, and food for local communities. Forests are home to numerous animal species, including those unique to Sudan. Most woody species are economically valuable, leading to their unsustainable utilization. Particularly, the overuse of certain species for timber and fuelwood has endangered them. Consequently, awareness of sustainable forest management is limited in local communities.

Notably, forests are vital for the majority of rural inhabitants, particularly those living near them. These people depend on forests for food, fodder, fiber, medicines, and income from selling collected items [48]. However, forests serve broader purposes than just producing wood and non-wood products. NTFPs are essential for global sustainable development [49]. They provide solutions for poverty eradication, environmental sustainability, food security, agriculture, energy, clean water, watershed protection, biodiversity preservation, climate change mitigation and adaptation, combating desertification and land degradation, and disaster risk reduction [49].

Forest-derived medicine is the primary healthcare source for 80% of the population in developing countries [49]. Forests are crucial for developing green economies and industries and offer indirect yet reliable resources for sustaining rural livelihoods, particularly for vulnerable groups, such as women and indigenous tribes. Forests also

Use	Trees species
Timber and building materials	*Acacia nilotica*, *Albizia aylemeri*, *Ailanthus excelsa*, *Balanites aegyptiaca*, *Borassus aethiopium*, *Burkea africana*, *Cassia siamea*, *Celtis integrofolia*, *Cordia africana*, *Crateva adansonii*, *Dalbergia sissso*, *Dalbergia melanoxylon*, *Daniellia oliveri*, *Detarium microcarpum*, *Kigelia africana*
Antiques	*Dalbergia melanoxylon*
Fruits, oil, and honey bee production	*Acacia nioltica*, *Adansonia digitata*, *Balanites aegyptiaca*, *Borassus aethiopium*, *Cordia africana*, *Diospyros mespiliformis*, *Grewia tenax*, *Ficus sycamorus*, *Hyphaene thebaica*, *Gardenia lutea*, *Tamarindus indica*, *Prosopis africana*, *Sclerocarya birrea*, *Terminalia brownie*, *Moringa oleifera*, *Ximenia americana*
Medicinal uses	*Salvadora persica*, *Acacia polyacantha*, *Adansonia digitata*, *Cissus quadrangularis*, *Cordia sinensis*, *Crateva adansonii*, *Cymbogogon citratus*, *Tamarindus indica*, *Stereospermum kunthianum*, *Albizia anthelmintica*, *Faedharbia albida*, *Fagonia cretica*, *Grewia villosa*, *Hydnora abyssica*, *Psidum guajava*, *Sterculia setigera*
Gums	*Acacia senegal*, *Acacia seyal*, *Acacia polyacantha*, *Sterculia setigera*
Fodder	*Balanites aegyptiaca*, *Ficus sycamorus*, *Ziziphus spina-christi*, *Faedherbia albida*, *Acacia senegal*, *Acacia mellifera*, *Stereospermum kunthianum*, *Combretum aculeatum*, *Maerua crassifolia*, *Cadaba grandulosa*, *Bauhinia rufescens*

Table 1.
Common Sudanese trees species and their uses as described in the National Biodiversity Strategy Action Plan for 2015 [30].

directly contribute to food security. About 200 million people, including many indigenous people, rely directly on forests for their survival, and over 1.6 billion people globally depend on them for food, medicines, fuel, employment, and livelihoods [49]. See **Table 1**.

Forests harbor over 80% of the world's terrestrial biodiversity [48, 49]. They are vital sources of biodiversity, energy, water, livelihoods, and other ecosystem services essential for societal functioning [37]. Forested catchments provide most of the world is freshwater, critical for human survival and food production, in addition to supporting livelihoods [37]. Forests play a role in soil erosion prevention, soil moisture retention, desertification control, and flood protection. Resilient forests are key in combating and adapting to climate change. Although currently about 10% of global greenhouse gas emissions are attributed to deforestation, forests have the potential to absorb and store approximately one-tenth of the projected anthropogenic carbon emissions for the first half of this century in their biomass, soils, and products, making them the second largest carbon storehouse after the oceans [48, 49].

7. The threats to the conservation of forest resources

Forest resources in Sudan are under severe pressure because of inhabitants, the need for farmlands, and grazing lands. There is a severe and increasing fuelwood gap in the country, which leads to the depletion of the standing stock and hence, further degradation of the remaining forest stands [50].

Despite ongoing conservation initiatives and the establishment of new protected areas, Sudan continues to face a significant biodiversity crisis. The decline of plant and animal habitats is primarily attributed to a range of human and natural threats,

as highlighted in studies by [2, 44, 51–54]. Key human-induced disturbances include deforestation, habitat destruction, urbanization, excessive exploitation of flora and fauna, agricultural expansion, land clearance, forest fire, and pollution [1, 55]. The contribution of various factors to the biodiversity crisis is significant, each affecting ecosystems in unique ways:

- *Deforestation:* the removal of forests not only destroys habitats for myriad species but also disrupts entire ecosystems. Forests play a crucial role in absorbing carbon dioxide; thus, deforestation increases carbon emissions and accelerates climate change.

- *Habitat destruction*: this process, often driven by urban sprawl and industrial development, fragments and destroys the living spaces of many species, impeding their ability to survive and reproduce. The preservation of crucial habitats is key to safeguarding biodiversity.

- *Urbanization*: the expansion of cities and urban areas results in the conversion of natural habitats into developed land. This transformation often brings about pollution and alters local climates, posing additional stress to wildlife and plant populations.

- *Excessive exploitation of flora and fauna*: overharvesting for various human needs can decimate plant and animal populations, leading to extinction and disrupting the balance of ecosystems.

- *Agricultural expansion*: the transformation of forests and natural habitats into agricultural land leads to significant habitat loss. The use of chemicals, such as pesticides and fertilizers in agriculture, can pollute water sources and harm a broad range of species.

- *Land clearance*: similar to deforestation, clearing land for agriculture or development contributes to habitat destruction, soil erosion, and alterations in local water cycles.

- *Forest fires*: some ecosystems depend on periodic natural fires for regeneration. However, human-induced or exacerbated forest fires can be devastating, causing loss of habitats, reduction in biodiversity, and adding to greenhouse gas emissions.

- *Pollution*: various forms of pollution—air, water, soil—can have severe impacts on ecosystems. Pollutants can accumulate in the food chain, causing declines in species populations and affecting overall ecosystem health.

Each of these factors contributes to the biodiversity crisis by disrupting natural processes, destroying habitats, and directly threatening the survival of species. Efforts to mitigate these impacts are crucial for preserving biodiversity. In contrast, in regions such as Sudan, natural factors such as desertification, erosion, climatic changes (including droughts and floods), fires, and landslides also significantly affect biodiversity and protected areas. These natural challenges compound the pressures on ecosystems, making the conservation of biodiversity even more crucial.

Siddig [9] offers a detailed examination of the barriers to conserving biodiversity in Sudan, focusing on issues stemming from governance and political turmoil. The challenges identified are as follows:

1. Ongoing wars and conflicts have displaced thousands from their homes, forcing them to seek refuge in areas rich in biodiversity, including forests and protected zones. This movement has significantly contributed to the deterioration of ecosystems and a decline in plant and wildlife populations.

2. Inadequate management programs and insufficient budgets hinder the implementation of national biodiversity strategies.

3. Extreme weather patterns, including prolonged droughts and unpredictable rainfall, are becoming more common, affecting ecosystems, agriculture, and water resources.

4. Competition over limited natural resources, such as agricultural fields, rangelands, and water, often leads to conflicts among communities, further destabilizing the region and its ecosystems.

5. Slow enforcement of laws and regulations due to the inefficiency of institutional frameworks.

6. The absence of effective programs to raise public awareness about the significance of preserving biodiversity and encouraging community participation.

7. The presence of financial constraints, a shortage of necessary equipment, and a lack of opportunities for professional training in conservation practices.

8. A lack of comprehensive national plans for the integrated utilization of land and natural resources.

9. Inadequate facilities for proper environmental monitoring, research, and implementation of conservation strategies limit effective biodiversity preservation.

8. Impacts of climate change on biodiversity

Climate change is an acute peril to Earth and its life forms. Reports by the Intergovernmental Panel on Climate Change (IPCC) indicate that a continuous temperature rise of 0.2°C per decade could lead to an overall increase of 1.5°C above preindustrial levels between 2030 and 2052 [56]. Such increases are likely to exacerbate natural hazards worldwide, including droughts, floods, and extreme weather events, with more frequent and severe occurrences expected [57, 58]. In Sudan, for instance, projections suggest a substantial temperature increase by 2100, with summer temperatures rising by 1.5–3.0°C and winter temperatures by 1.1–2.1°C [59].

Precipitation patterns are also predicted to change significantly, with overall decreases in rainfall and greater variability—ranging from a 15% to 190% coefficient of variation (CV). These changes include shifts in rainfall up to 6mm and alterations in the duration and onset of the rainy season. Consequently, water scarcity is

expected to amplify, intensifying the risk of land degradation [58, 60, 61]. Such climatic shifts pose a profound risk to the biodiversity of Sudan's drylands, diminishing ecosystem productivity and leading to losses in species diversity, ecosystem functions, and vegetation variety [58, 62].

The impacts of climate change on biodiversity are profound and far-reaching, affecting ecosystems and species across the globe. As the climate continues to warm due to human activities, particularly the emission of greenhouse gases, natural habitats are altered, and the conditions necessary for survival and health of many species are being undermined. The intricate balance of biodiversity, which has been shaped over millions of years, is now being reshuffled in mere decades, leading to uncertain futures for many species and ecosystems.

Several effects of climate change on biodiversity have been documented. These include shifts in species distributions as organisms move to cooler areas or higher altitudes, changes in phenology such as altered timing of migration and reproduction, and direct impacts from extreme weather events such as cyclones, droughts, floods, and heatwaves. These changes not only affect individual species but also the interactions between species, which can alter food webs and ecosystem functioning. For instance, Shivanna [63] reviewed 519 studies on ecological responses to extreme climate events, covering a wide range of taxa including amphibians, birds, fish, invertebrates, mammals, reptiles, and plants, illustrating the broad scope of climate impacts on biodiversity.

Furthermore, climate-induced impacts on ecosystems and biodiversity affect the availability of nature's beneficial services to society. Ecosystem services, such as pollination, water purification, and disease regulation, are vital for human well-being, and their disruption can have cascading effects on food security, health, and economies. Understanding these linkages is crucial for developing strategies to adapt to changing conditions and mitigate further damage [64].

Projections of the effects of climate change on biodiversity typically involve estimating changes for a single future time point, often failing to capture the dynamic nature of ecological responses. This underscores the need for more nuanced and long-term studies that can provide a clearer picture of how climate change will reshape the natural world. Such knowledge is essential for conservation efforts and for predicting how ecosystems will function in the future [65]. See **Figure 3**.

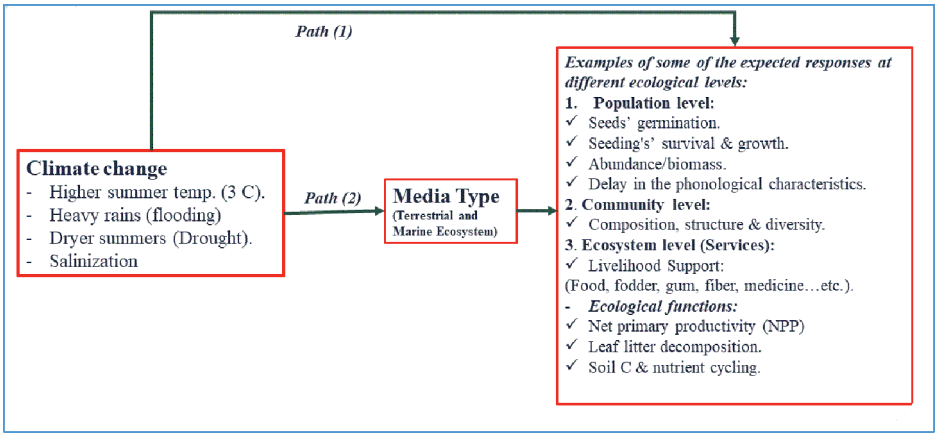

Figure 3.
Potential paths and responses for impact of climate change on biodiversity.

9. Understanding the deficit in biodiversity knowledge

Sudan's environment is predominantly harsh and dry, yet it is purported to host a rich array of plant, animal, and microbial life vital for the livelihoods of its inhabitants. This richness, largely based on expert knowledge or regional estimates, lacks substantiation from in-depth and policy-driven field research. Consequently, detailed information on the status and trends of these organisms and their environments is significantly lacking [9, 53]. Consensus among local conservationists and scientists points to a steady decline in biodiversity due to ongoing human pressure, conflict, governmental neglect, and the impacts of drought and desertification.

Additionally, Sudan faces challenges in gathering and disseminating scientific data, especially concerning biodiversity. There is a marked deficit in electronically available details about the diversity, numbers, and distribution of various life forms, including plants, microbes, insects, amphibians, fish, and birds. This gap extends to understanding ecosystems and genetic diversity [10].

While there is some awareness of Sudan's forestry, agriculture, and certain animal populations, considerable gaps remain, particularly regarding microbes, arthropods, amphibians, and reptiles. Most protected areas, critical for conservation, are understudied, and knowledge about their current state and threats is scarce. Notably, over 80% of wildlife research is focused on Dinder National Park, neglecting other protected areas [30].

To address this, initiatives to create new protected areas, ratify international conventions, and devise national biodiversity strategies should incorporate comprehensive biodiversity monitoring and assessment programs. These programs are vital for deepening understanding, enhancing documentation, and fostering policy-driven conservation. However, their success hinges on foundational efforts such as strengthening institutions, building capacity, establishing long-term monitoring, embracing technology, raising awareness, and enforcing laws.

10. Urgent management interventions and future directions

According to [28], Sudan adopted the global 20 Aichi Biodiversity Targets as its national strategic objectives. The NBSAP's key elements include the biodiversity of plants, forests, ranges, domestic animals, wildlife, marine life, and inland waters, as well as aspects of biotechnology and biosafety. Tailored and achievable targets for each of these components were established in alignment with the global objectives. The resulting proposed actions stem directly from these specific targets. Sudan demonstrates a political resolve to prioritize the integration of biodiversity and ecosystem considerations into major developmental agendas. Various channels for this integration exist, including the National Constitution, and diverse policies, strategies, and legislation. See **Figure 4**.

The Proposed National Constitution, especially highlights the need to weave biodiversity and ecosystem management into sustainable development policies, encompassing areas such as macroeconomics, agricultural policies, and climate change responses. The strategies for managing and conserving biodiversity and ecosystems have been woven into the broader fabric of sustainable development planning [30]. Recommendations to further these efforts are subsequently identified:

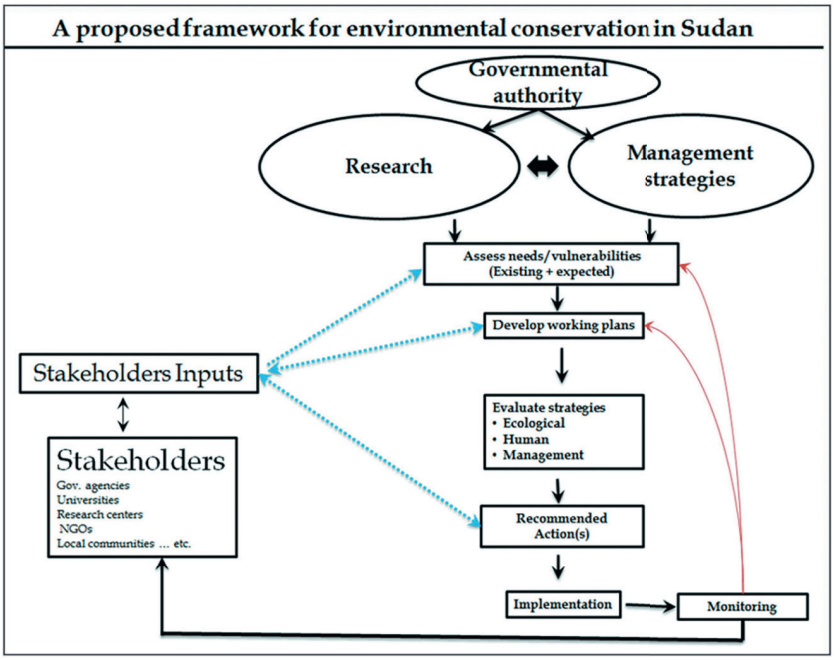

Figure 4.
A proposed framework for environmental conservation in Sudan based on the role of the government in initiating research and management plans with consideration of environmental stakeholders [9].

1. Conduct surveys and documentation of the current state of plant, wildlife, and microbial populations in Sudan to inform conservation decisions.

2. Prioritize attention to endangered species, those in need, and lesser-studied groups, such as microbes and amphibians.

3. Examine various ecosystems and agricultural zones, including those involving cultivated and natural plants, wild edibles, and weeds across different farming systems.

4. Create a national information system for sharing data on the status of biodiversity in both natural and controlled environments and consider integrating an early warning system.

5. Enhance the capacity of existing institutions in terms of coordination, staffing, and infrastructure.

6. Improve breeding capabilities within research and academic institutions to extend germplasm enhancement effectively.

7. Foster connections between the preservation and practical use of conserved genetic resources. Promote and support on-farm conservation for agricultural species.

8. Review and update the nation's strategies, policies, and laws concerning animal, forest, and agricultural sectors.

9. Empower rural communities by enhancing their ability to cooperatively manage natural resources, which will lead to improved forest and tree resource management.

10. Implement programs with local communities to safeguard forest resources, recognizing them as both impacted by and contributors to environmental change.

11. Apply sustainable practices for non-wood forest products (NWFP) through improved management, *in situ* conservation, agroforestry, legal reforms, conservation actions, reforestation, controlled grazing, energy-efficient household solutions, and community-based forest management. Utilize integrated land management to enhance agricultural stability and productivity.

12. Initiate national research initiatives to study and domesticate wild food varieties.

13. Establish in situ conservation sites for wild plant species, including crop wild relatives and native range plants.

14. Increase the number of protected areas to encompass over 17% of Sudan's land and ensure at least one protected area per state.

15. Ensure sustainable use of natural resources by indigenous and local communities.

16. Develop and implement robust systems and tools for monitoring, evaluating, and managing invasive alien species.

17. Future research should aim to understand the abundance and distribution of key indicator species and evaluate the impacts of human activity and climate change on ecosystems and these species.

18. Intensify research and data collection efforts on understudied aquatic ecosystems, focusing on freshwater and marine biodiversity, to fill existing knowledge gaps.

19. Establish partnerships with international conservation organizations to bring in expertise, resources, and global best practices for biodiversity management.

20. Develop and implement educational programs and campaigns to raise public awareness about the importance of biodiversity and the role individuals can play in its conservation.

21. Encourage community-led initiatives and participatory approaches in conservation projects to ensure that local knowledge and needs are integrated into biodiversity management.

22. Foster interdisciplinary research combining biological sciences with socioeconomic studies to understand the human impact on biodiversity and devise socioeconomically viable conservation strategies.

23. Promote ecotourism as a sustainable development strategy to generate revenue while preserving natural habitats and species.

24. Implement strict regulations and enforcement mechanisms to curb illegal activities such as poaching, logging, and unregulated fishing that threaten biodiversity.

25. Encourage the restoration of degraded habitats through reforestation, wetland restoration, and other rehabilitation projects to increase biodiversity and ecosystem resilience.

26. Monitor and address the impact of climate change on biodiversity by developing adaptive management strategies to help species and ecosystems cope with changing conditions.

27. Support genetic research and conservation to preserve the genetic diversity within species, crucial for their adaptability and survival.

11. Conclusion

Biodiversity and ecosystems provide crucial services to local communities. Often, policymakers focus only on the direct economic benefits of ecosystems, neglecting other significant values such as educational, social, and cultural aspects. This narrow view underestimates the ecosystems' true economic potential. Recognizing this potential is essential for the wise and effective use of ecosystem goods and services, considering their total economic value, which encompasses various functions and uses. The threats to biodiversity often stem from a limited understanding of its economic, cultural, spiritual, and social significance. For instance, South Sudan's secession led to a loss of diverse ecosystems, including forests, pastures, protected areas, and valuable wetlands. However, the remaining ecosystems still represent a rich biological diversity, forming a crucial part of the nation's heritage and assets. These ecosystems and biodiversity are under threat from multiple pressures and drivers. Agricultural expansion, at the expense of natural resources, has significantly impacted core resources such as forests, rangelands, and wildlife. Heavy land clearance machinery has caused widespread destruction of forests, resulting in large areas of bare land and loss of natural vegetation. This environmental degradation has led to a rapid decrease in forest biodiversity, including a reduction in the number and abundance of species across various ecosystems. Additional factors contributing to this degradation include traditional farming practices, human activities, overgrazing, drought, climate change impacts, land degradation, and the activities of the petroleum and gold mining industries. Conflicts, decentralization, and inadequate funding for conservation have also played a role. These issues have led to a decrease in forest and rangeland areas, forcing livestock to encroach on protected areas, leading to competition with wildlife for resources and disease transmission. Wildlife faces threats from poaching, becoming increasingly rare and endangered, exacerbated by the proliferation of arms due to civil conflicts and the resettlement of people around protected areas. The primary responsibility lies in conserving Sudan's natural heritage, including its ecosystems, species, and genetic diversity, while striving for sustainable benefits. Conservation efforts must prioritize the protection of biodiversity before considering its exploitation.

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Conflict of interest

The authors declare no conflict of interest.

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