Working Paper Report on Enhancing Climate Change Adaptation and Mitigation Actions on Land in Africa

The African Group of Negotiators Experts Support (AGNES) | Oppenheimer Research and Conservation| University of Witwatersrand | AUDA-NEPAD | Future Ecosystems for Africa

Supporting by:

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Executive summary

Introduction

This working paper report was commissioned by the African Group of Negotiators Experts Support (AGNES) and partners (Oppenheimer Research and Conservation, University of Witwatersrand, AUDA-NEPAD) with the overarching goal of enhancing climate actions on land in Africa. The report seeks to deepen understanding of the relationship between land and climate change adaptation in Africa. To achieve this goal, an extensive literature review was conducted to establish a framework for assessing climate actions in Africa (section 2). This review: 1) summarized climate trends in Africa, 2) identified key climate commitments made by African countries, and 3) highlighted the potential synergies and trade-offs between climate actions and sustainable development, including biodiversity conservation, rural development, land governance, climate securities and the concept of ecosystem degradation in the context of Africa.

Subsequently, a substantial number of case studies are reviewed (section 3) to evaluate available evidence for all the major land-based climate actions. Adequate case studies were selected for all the major land-based biomes of Africa (mangroves, forest, grassy ecosystems, and deserts) and land use types (conservation, agriculture, and urban). Climate change mitigation and adaptation actions considered include all emission reduction (ER) (ecosystem conservation and sustainable agriculture) and carbon-dioxide removal (CDR) (ecosystem management, ecosystem restoration, and agroforestry) pathways. The report particularly highlights and examine evidence across Africa’s grassy ecosystems, identifying leading case studies on climate change adaptation and mitigation. In addition, non-ecosystem-based climate actions, such as urban and desert-based climate interventions, were examined.

Finally, the report also highlights the main data and knowledge gaps (section 4) that need to be addressed to enhance climate actions on land in Africa. The report is therefore expected to become an important source of information for Africa experts and negotiators to define a common African position on climate actions that can be promoted and operationalized across the agriculture-forestry-biodiversity-climate nexus.

1. **Climate change, global warming, and related impacts represent the most significant threat to sustainable development in Africa**:

- Currently, global warming is leading to, among others, increasing mean and extreme temperatures, increased heatwaves, frequent and intense drought, and flooding in many parts of Africa. Climate models predict that global warming will lead to declines in agricultural productivity, decline in net primary productivity in rangelands, shift in species distribution, biodiversity loss, and potential escalation of conflicts in many regions of Africa. These changes are already being felt in key sectors across Africa and is likely to affect a huge proportion of the African population given the high dependence on natural resources and employment in climate-exposed sectors.

2. **Land-based climate mitigation and adaptation options are crucial to reducing global warming to within 1.5°C or 2°C of pre-industrial levels**.

- In recent years, there has been renewed interest and recognition of the importance of land-based ecosystems in climate change adaptation and mitigation. Actions targeting the protection, conservation, and restoration of forest and other natural ecosystems are essential component of global efforts – such as the Paris Agreement – to reduce global warming to within either 1.5°C or 2°C of pre-industrial levels. In addition, climate actions targeting or dependent on natural ecosystems can also contribute to other global goals such as the sustainable development goals through biodiversity conservation, social and environmental safeguards.

3. **Africa is uniquely positioned to become a major player in global climate actions**

- Africa is the world's second largest landmass with a total land area of approximately 30.37 million square kilometres and holds 60% of the world's arable land. The continent possesses highly diverse and unique ecosystems – comprising mangroves, forests, woodlands, savanna and grasslands, rangelands, arid lands, and deserts – as well as renewable energy potential. However, to realize its climate change mitigation and adaptation potential, Africa must advance a common position and interest on climate change in global fora.

4. **Framework for assessing climate actions in Africa**

- Africa's response to global warming is to prioritise adaptation while supporting mitigation efforts, particularly if they provide opportunities for achieving the goals of Agenda 2063. Consistent with this position, there is clear prioritization of adaptation actions in the NDCs of most African countries. The agriculture, water, and disaster risk management sectors which have high climate risks receive most of the adaptation actions. In contrast, mitigation actions mostly target the energy, conservation, transport, waste management, and the agriculture sectors.

- Land-based climate actions – both adaptation and mitigation actions – are likely to affect sustainable development and the achievement of Agenda 2063. Climate actions can have positive (synergies) or negative (trade-off) impact on society, economy, and ecology of Africa.

For instance, development of the renewable energy potential of Africa will trigger positive socio-economic growth. In contrast, some climate actions targeting natural ecosystems – e.g., large-scale afforestation in arid and grassy ecosystems – will have substantial negative impacts on both rural economy and ecology (see below).

- To reduce trade-offs and increase synergies, context-specific land-based climate actions are required in Africa. There is general acceptance that land-based climate actions, particularly those targeting natural ecosystems, must be implemented with caution to reduce trade-offs and maladaptation. In this respect, land-based climate actions in Africa should, at a minimum, meet the following criteria:
    - reduce climate threats and risks to socio-ecological systems
    - address sustainable development goals, particularly rural livelihoods
    - improve natural resources governance
    - reduce land inequalities and tenure constraints
    - improve climate securities
    - must be based on sound understanding of the ecology, structure, and function of the targeted ecosystem

5. How to enhance climate actions for mangroves

- Mangroves store substantial quantities of carbon and is fundamental to the livelihoods of many coastal communities. Conservation, improved management, and restoration of mangroves is crucial for coastal disaster risk management and preservation of fisheries-based livelihoods. Review of several case studies indicated avoided deforestation of mangroves can be achieved through financing mechanisms (REDD+ and blue carbon financing), local participation and stewardship, provision of alternative wood fuel sources, and improved regulatory framework. Several case studies also showed that mangrove restoration can be achieved using the community-based ecological restoration approach (CBERM). Importantly, case studies demonstrated that mangrove conservation, management and restoration lead to carbon storage, biodiversity conservation, and improved livelihoods

6. How to enhance climate actions for forests in Africa

- **Conservation**: African forests are diverse in composition, structure, and function. Forests in Africa store carbon, have high biodiversity, and are the source of livelihood for many people. However, the continent has the highest deforestation rate in the world. The case studies examined revealed that avoided deforestation can contribute to climate change mitigation through avoided emission and provision of ecosystem services. Although several REDD+ initiatives have been implemented, funding gaps constrain their success. Participatory and community-based forest management initiatives have proven successful. Political will and interest, adequate funding, provision of alternative livelihood activities, and adoption of technology are critical to forest conservation in Africa.

- **Improved forest management (IFM)**: IFM can contribute substantially to adaptation and mitigation efforts in Africa. However, disparities in benefits sharing and responsibilities can lead to significant trade-offs between livelihood and environmental goals especially in the absence of democratic decentralization. Trade-off between carbon, biodiversity, and livelihood benefits of IFM can be reduced through provision of alternative livelihood interventions. However, financial incentives for carbon offset from concession based IFM is relatively low in Africa.

- **Restoration**: Three distinct reforestation approaches exist in Africa. Generally, natural regeneration and mixed species plantations seems to perform better (in terms of biodiversity and carbon storage) than single species monocultures. However, quantitative assessment of the performance of the different approaches is constrained by lack of data. Reforestation in Africa is also constrained by agricultural expansion such that successful reforestation often leads to deforestation leakages. Here, novel forest landscape level sustainability initiatives may be the best option for integrating livelihood, biodiversity, and carbon goals.

- **Forest fires:** Fires have particularly damaging effect on forest composition, structure, and function. Reducing fire incidence in forest can contribute significantly to carbon storage, biodiversity conservation and rural livelihoods. Several examples showed that participatory fire management schemes involving relevant stakeholders can reduce fire incidence and impact on forests in Africa. However, to be successful, forest fire management must consider regional differences in vegetation types, climate, and local practices.

7. How to enhance climate actions for grassy ecosystems in Africa

Woodlands

- **Conservation**: Several woodland types exist in Africa including the *Isoberlinia* woodlands of the Sudanian region, the Acacia woodland of the Sahel and East Africa, and the Miombo woodlands of the Zambezian region. Substantial area of Africa's woodlands has been converted to agricultural lands with negative impacts on soil organic carbon, biodiversity, and provision of ecosystem services. Therefore, conserving existing woodlands is of critical importance to climate change adaptation and mitigation

- **Fire regime:** Regulating fire regime through changes in fire frequency or season have been proposed as climate action that can enhance carbon storage in woodlands. However, fire frequency across woodlands in Africa is quite variable and regulating fire frequency poses significant practical challenges. Importantly, there is a dearth of experimental evidence of the impact of combined fire season and frequency on woodlands making it difficult to assess the benefits of making large-scale changes to existing fire regimes.

- **Restoration:** Several case studies showed that degraded woodlands can be restored through either natural regeneration or introduction of indigenous trees on farm. However, species composition and soil organic carbon stocks in restored woodlands accumulate slowly and remain different from natural woodlands even after 60 years. Community participation is key to woodland restoration

Savannas and grasslands

- **Conservation:** Most of Africa's savannas and grasslands have been converted to farmlands with associated biodiversity and carbon loss. Cropland expansion has resulted in significant changes in fire frequency and intensity. Wildlife biomass has also declined and replaced by livestock driving changes in herbivory regime. In addition, bush encroachment of savannas and grasslands is widespread across the continent. Despite these trends, there is no global financing mechanism (e.g., REDD+ type initiative) for conservation of grasslands and savannas.

- **Afforestation:** There is a major push for afforestation in Africa's grasslands and savannas. Major large-scale afforestation projects, such as the Great Green Wall and AFR100, are currently being implemented. Afforestation is touted to have high carbon sequestration and livelihood benefits. The case studies examined provided inconclusive evidence for soil organic carbon (SOC) benefit of large-scale afforestation in grasslands and savannas. In contrast, the evidence clearly pointed to negative impact of afforestation on hydrology, ground water and biodiversity across Africa. Once afforested, grasslands and savannas are particularly difficult to restore. Inspite of this, there are several examples of successful local and community-based tree planting initiatives targeting land restoration, livelihood improvement, and carbon storage.

- **Fire regime:** Proposals for large-scale fire abatement or changes in fire seasons may be impractical and unlikely to deliver significant emission reduction benefits. Fire frequency and season affect emission characteristics. Recently, proposals have been made to alter fire frequency and season to reduce fire-based emissions. However, available evidence suggests that such fire-based climate actions are unlikely to deliver the projected emission reductions. This is due to several reasons including: 1) current trend of steady decline in annual burnt area, 2) difficulty in influencing some aspects of fire (e.g., fire-return interval), 3) there is little evidence that early dry season burning yield significant emission reduction across different types of savannas and grasslands, 4) early dry season fire is already extensively practiced across Africa.

- **Soil organic carbon (SOC):** Maintaining and enhancing soil organic carbon (SOC) in grasslands and savannas is an important climate change mitigation option. More than half of total ecosystem carbon (TEC) in grasslands and savannas is stored belowground as SOC. The case studies examined indicated that biome appropriate levels of fire and grazing have little impact on SOC whereas extremes – e.g., high frequency fire or fire exclusion and grazing exclusion or overgrazing – reduces SOC.

- **Biodiversity conservation:** Climate actions in savannas and grasslands must consider the impact of proposed interventions on biodiversity. For instance, proposals for changes in fire regime or increasing TEC and SOC have rarely considered the biodiversity implications. The evidence is clear that disturbance (fire and herbivory) is critical to maintaining open canopies which in turn is crucial for conserving the diversity and biomass of the herbaceous layer upon which variety of life-forms and ecosystem services depends.

- **Bush encroachment:** The impact of bush encroachment on TEC and SOC in grasslands and savannas is dependent on climate and topo-edaphic factors. Therefore, bush encroachment may increase TEC and SOC under some conditions while driving reduction under other conditions. However, the impact of bush encroachment on biodiversity is well-established with several studies reporting negative impacts on ecosystem services, mammalian and herpetofauna assemblage, termite activity, and mesocarnivore scavenging activity.

Rangelands

- **Grazing impact on SOC**: Most of the grassy ecosystems of Africa are grazed by wildlife and livestock. Africa is home to over 40 million pastoralists whose livelihood depends on healthy rangelands. Climate actions proposed for rangelands seeks to either reduce emissions or increase SOC in range soils. There are several lines of evidence that grazing affect SOC. However, the relationship between grazing and SOC is contingent on rainfall variability with grazing causing reduction in SOC only when annual rainfall is > 600mm. Current pastoral practice in Africa, which involves high seasonal mobility is likely to have minimal impact on SOC except when resource constraints lead to overgrazing.

- **Grazing systems**: Short-intense rotational grazing is promoted as a superior grazing system for climate change adaptation and mitigation relative to continuous grazing. Some experimental evidence lend support to this claim. However, under other conditions, continuous grazing perform as well as or better that short rotational grazing. These contrasting results suggests that context is critical when advocating for grazing systems in Africa.

- **Holistic management (HM)**: HM seeks to integrate ecology, economy, and society in grazing management. It advocates for grazing management that mimic native wildlife dynamics using short-intense grazing rotations. Although most of the predictions or central tenets of HM are contested, several case studies suggests that when properly practiced, HM do lead to positive ecological, social, and economic outcomes. The review also highlighted that most controversies on HM stems from miscommunication and inconsistent use of terminologies by both proponents and opposers. Therefore, clarifying the key concepts of HM may help reconcile some of the controversies associated with it approach and practices.

- **The wilder rangeland concept (WRC)**: WRC seeks to either replace managed livestock with harvestable communities of native wild herbivores or "rewild" livestock grazing practices. Climate change mitigation benefits of The WRC approach is linked to reduction in methane emission (through changes in size-class distribution), improvement in SOC, and changes in fire regime. Adaptation benefits from the WRC approach may accrue from increased and diversified revenue streams and improved resilience to economic and climatic shocks. Some case studies have demonstrated both mitigation and adaptation benefits of the WRC approach. However, only few case studies currently exist. Importantly, large-scale adoption of the WRC approach in Africa is likely constrained given existing land tenure system and potential for human-wildlife conflicts.

8. How to enhance climate actions for arid zones, deserts, and desertification

- **Contributions of deserts**: About one third of the land area in Africa is desert. Two major desert formations exist, namely, the Saharan and Namib deserts. Deserts in Africa provide important ecosystem services such as fertilization of the Amazon and Equatorial Atlantic Ocean. Deserts also have high albedo that play important roles in land-atmosphere feedback systems.

- **Desert greening**: Currently, deserts are getting greener and contributing to climate change mitigation naturally. Some climate actions in deserts in Africa also target increasing contribution to mitigation through increase in plant cover. However, existing evidence suggests that greening of deserts (naturally or through afforestation) may have negative effect on provision of other ecosystem services (e.g., reduced fertilization and decreased albedo). For instance, limited evidence suggests that greening of Africa's desert may even worsen local climatic conditions. Importantly, afforestation in deserts is likely ineffective due to high plant mortality.

- **Desert-based solar and wind farms:** Proposals have been made to deploy large-scale photovoltaic solar and wind farms to generate renewable energy for Europe and Africa. Proponents of such climate actions argue that such initiative will reduce fossil fuel consumption and generate local climate benefits. However, few studies exist that provides empirical evidence to support these claims. For instance, one study concluded that large-scale solar farms in the Sahara Desert may cause increase in local rainfall in the neighbouring Sahel region. However, another study indicated that such large-scale solar farms would have several negative impacts including drought in the Amazon, increased surface temperature, sea-ice loss, and enhanced tropical cyclones.

- **Desertification:** Many countries in Africa are experiencing desertification. Therefore, climate actions seek to reduce or reverse desertification. There is substantial scientific evidence that land degradation is a major problem in Africa and actions to halt this trend is essential for climate change adaptation. Indeed, Africa's flagship programme, the Great Green Wall initiative, is geared towards halting the southward expansion of the Sahara Desert. However, several case studies argued that conflating land degradation with desertification leads to promotion of climate actions (e.g., large-scale afforestation) that is decoupled from the root cause of the problem. Indeed, several case studies have shown that land degradation in Africa is driven mainly by over-exploitation of natural resources and is best addressed through local restoration efforts

9. How to enhance climate actions for agriculture

- **Climate change and agriculture:** Agriculture is the backbone of Africa's economy. Agriculture, fisheries, and forestry accounts for 14% of GDP and employs over 53% of Africans. However, agriculture in Africa is largely subsistence and rainfed. Therefore, the agricultural sector in Africa is highly exposed to climatic risks and climate change impact are already being experienced. Climate actions in agriculture in Africa mostly focuses on adaptation but several examples of mitigation interventions exist.

- **Climate actions in cropland:** In croplands, climate actions were mostly local in scale involving indigenous adaptation practices and other interventions such as climate smart agriculture (CSA), conservation agriculture (CA) and land intensification practices. Most of these interventions were geared towards maintaining soil fertility, improving yields, increasing resilience (e.g., to drought, flood, windstorm, etc) and reducing GHG emissions. Substantial evidence exists suggesting that indigenous and climate actions, such as CSA and CA, resulted in improvement in productivity, carbon storage and livelihoods. However, empirical evidence of cost-effectiveness of indigenous crop-based climate interventions are lacking and may constrain upscaling of innovative practices.

- **Climate actions in livestock (pasture):** Climate actions in livestock production under pasture focused on emission reduction through improved feeding practices and pasture management practices. Adaptation measures included cattle watering, fodder and pasture management and livestock management. In contrast mitigation interventions were limited to improved fodder, manure management and SOC. Both adaptation and mitigation measures had positive impacts on livestock productivity and GHG emissions. However, production of improved forage in Africa may increase GHG emissions unless driven by high fertilizer inputs.

- **Agroforestry:** Agroforestry was highlighted as a particularly promising climate action across all ecological zones. Substantial evidence exists in Africa demonstrating the utility of agroforestry in delivery carbon, biodiversity, and livelihoods gains. Indeed, several case studies showed that local agroforestry-based interventions can be a particularly powerful tool for land and ecosystem rehabilitation across diverse biomes, including in arid environments.

10. How to enhance climate actions for urban areas

- Africa is rapidly urbanizing. However, climate change is expected to have particularly high impact on urban centres in Africa. Most African urban areas have high exposure to climate change risks but have low adaptive capacities. Improving climate resilience in Africa's urban centres is fundamental to mitigate the negative impact of climate change. Despite this, there is dearth of case studies on successful climate change adaptation and mitigation approaches in urban centres in Africa. The existing case studies are mostly exploratory in nature and deal with issues such as drainage and flood management, urban green infrastructure, natural resource use, water and watershed management, spatial planning, and resource use. Importantly, examples of urban-based climate actions in Africa are mostly from South Africa, emphasizing a large regional disparity.

11. How to enhance climate actions for woodfules

- Wood harvest and wood fuels use is a major socio-economic activity for over 60% of Africans. Wood harvest from natural areas have significant impact on ecosystems in Africa, particularly in dry and arid environments. Climate actions targeting reduction in wood harvest and wood fuel consumption can have significant environmental, social (e.g., less time spent by women in looking for wood fuel) and carbon benefits. The case studies examined clearly demonstrated that provision of efficient cooking stoves can substantially reduce natural wood harvest, reduce CO_2 emissions, and improve health conditions of rural and urban households.

12. There are significant knowledge, information, and data gaps that needs to be addressed to enhance climate actions on land in Africa

Concerted efforts must be directed to addressing the following knowledge, information, and data gaps to enhancing climate actions on land in Africa.

***General and crosscutting themes*:**

- Estimate the mitigation potential across climate actions, ecosystems, land use types, and the five sub-regions.
- Determine the limit of climate change adaptation in Africa for various socio-ecological systems.

- Understand the cost-benefit of large vs. local-scale climate actions in Africa.
- Accumulate empirical evidence of the effectiveness of nature-based solutions (NbS) under different context in Africa.
- Understand gender and social gaps in climate change mitigation and adaptation in Africa.
- Evaluate the effectiveness of existing framework for genetic resources and biodiversity conservation in Africa.

Mangrove and forests

- Understand the response of distinct forests and mangrove types to climate change in Africa.
- Examine variations in trade-offs between carbon, biodiversity and livelihood goals across distinct forest and mangrove types and land use types.
- Evaluate the benefits and trade-offs associated with different forest restoration options (natural regeneration, mixed species plantation, and monocultures) across land use types.
- Assess the potential of novel forest landscape sustainability initiatives across distinct climatic zones in Africa.

Grassy ecosystems

- Map and quantify the extent of various grassy ecosystems in Africa to serve as baseline for appraising, monitoring, and evaluating climate actions.
- Quantify the total ecosystem value (TEV) of grassy ecosystems in Africa to enhance evaluation of the opportunity and trade-off cost associated with climate actions.
- Assess the effectiveness of existing international financing mechanisms for conservation, management, and restoration of grassy ecosystems.
- Develop improved and easy to use protocols and tools for carbon accounting in grassy ecosystems.
- Conduct more research to tease out the impact of grazing and fire on SOC stocks and dynamics across the various grassy ecosystem types in Africa.
- Document and assess the effectiveness of indigenous and traditional practices in supporting conservation, management, and restoration of grassy ecosystems in Africa.

Agriculture

- Identification and promotion of low-cost and best practices for tree regeneration under arid conditions.
- Establishing benchmarks for sustainable agriculture, traditional and indigenous practices.
- Evaluation of farm-based climate actions on biodiversity conservation
- Evaluation of the cost-effectiveness of local and indigenous adaptation practices across Agro-ecological zones

Urban areas

- Generate empirical evidence of cost-effectiveness of proposed urban climate action across Africa.
- Close the regional data and knowledge disparity on urban-based climate actions in Africa

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1.0 Introduction

This working paper report has been prepared with **the goal of enhancing climate actions on land in Africa**. The report seeks to address two recent calls made in relation to improving climate actions on land. Firstly, **paragraph 21** of the cover decision of the Glasgow Climate Pact (GCP) emphasizes the importance of protecting, conserving, and restoring nature and ecosystems, including forest and other terrestrial and marine ecosystems, to achieve the long-term global goal of the Convention by acting as sinks and reservoirs of greenhouse gases and protecting biodiversity, while ensuring social and environmental safeguards [1]. Paragraph 59 of the cover decision of the GCP further **invites parties to submit views on how to enhance climate action on land and under the existing UNFCCC programmes** and activities in paragraph 75 on the report on the dialogue on the relationship between land and climate change adaptation related matters. The Chair of the Subsidiary Body for Scientific and Technological Advice (SBSTA) is requested to prepare an informal summary report and make same available to the Conference of the Parties at its twenty-seventh session (COP27) [1].

Secondly, t**he African Union (AU) Agenda** 2063 envisions Africa participation in global efforts for climate change mitigation that support and broaden the policy space for sustainable development on the continent and specifically calls for "**Africa speaking with one voice and unity of purpose in advancing its position and interest on climate change**" in global fora [2]. Importantly, the draft African Climate Change Strategy (ACCS) document identifies the lack of a **coordinated and common Africa position** as one of the key challenges affecting the continents response to climate change [3]. The ACCS further indicates that "identifying, documenting and disseminating best practices and success stories" is fundamental to facilitate exchange of knowledge and experiences between regions, countries and communities for climate change adaptation and mitigation [3].

1.1 Objectives

The main objective of this working paper report is to **deepen understanding of the relationship between land and climate change mitigation and adaptation in Africa**. Africa is highly vulnerable to climate change, because of high exposure (e.g., continental warming greater than the global average) and low capacity to adapt to climate change and related impacts [4,5]. Inspite of this, the continent can play a crucial role in addressing global climate change given its **low historical contribution to GHG emissions, vast landmass**, **high renewable resources potential** (e.g., huge potential for solar energy), and **unique ecosystems** (including forests, mangroves, wetlands, savannas, grasslands, and deserts) [3]. However**, climate actions designed to harness Africa's climate change mitigation and adaptation potential requires careful consideration of co-benefits and trade-offs, particularly those linked to livelihood opportunities, biodiversity conservation, adaptation, and conflicts** [3,6,7]. This calls for context-specific climate actions that are fit for purpose and consistent with both the working of nature and society across all levels [3].

The report has been prepared considering the **current state of knowledge of climate actions across Africa's diverse ecosystems and land use practices**. Leading examples of climate actions on lands in Africa have been extensively reviewed to evaluate their **climate objectives** and other **environmental** and **social co-benefits** and **trade-offs**. The analyses took into consideration the different ecosystems, land use/management types across the five sub-regions of Africa (i.e., North, West, Central, Eastern, and Southern Africa). The report is therefore expected to become an important source of information for African experts and negotiators to **define a common African position on climate actions** that can be promoted and operationalized across the agriculture-forestry-biodiversity-climate nexus.

The report particularly highlights **the role of Africa's open ecosystems** in the context of climate change mitigation and adaptation options, identifying case studies of potential interest. Africa is predominantly a continent of grassy ecosystems. Approximately 55% of Africa's land mass is covered by grassy biomes (i.e., rangelands, woodlands, savannas, and grasslands) [8] that are fundamental to livelihoods. These grassy ecosystems contribute significantly to Africa's biodiversity and serves as important **net CO2 sink**. However, the structure and functions of these grassy ecosystems are currently threatened by over-exploitation (e.g., over-grazing), land-use changes (leading to changes in fire and herbivory regimes), and climate change [6]. Inappropriate climate actions in Africa's grassy ecosystems (e.g., large scale afforestation targeting carbon sequestration) are likely to exacerbate current threats on these systems and reduce their adaptation and mitigation potentials [9,10].

The report also highlights data, information and research gaps that need to be addressed for more Africa-appropriate climate change mitigation and adaptation solutions to be operationalized. These highlights include: 1) data and research gaps on climate solutions and country-level policies and processes (e.g., the Nationally Determined Contributions, NDCs), 2) impact of proposed climate solutions on aboveground and belowground carbon storage and emissions across the different ecosystems, 3) land use/ management types and CO_2 emissions, and 4) transboundary climate risk and impacts.

1.2 Report preparation

The African Group of Negotiators Experts Support (AGNES) and partners (Oppenheimer Research and Conservation, University of the Witwatersrand, AUDA-NEPAD) commissioned a working paper on climate actions on land in Africa in February 2022 with the aim of deepening understanding of the relationship between land and climate change mitigation and adaptation in Africa. The terms of reference (TOR) and concept notes were then sent to the lead author on 2nd February 2022. On 10th February 2022, an initial TOR meeting was conducted between the lead author, AGNES, and partners to provide detailed guidelines for the working paper report. Subsequently, the lead author submitted an inception report on 21st February 2022 and commenced developing a **framework for gathering the relevant case studies** for the report (see chapter 2 for details).

Four (4) main activities were undertaken to gather the relevant case studies and information for the preparation of the report. Firstly, the lead author attended the Savanna Science Network Meeting (SSNM) and post network meeting workshop on nature-based solutions in Kruger National Part, South Africa from 5th – 16th March 2022. The SSNM is an annual conference where scientist working **on open ecosystems across the world meet to share their latest research findings**. The 2022 SSNM conference therefore provided the lead author the opportunity to discuss the goal of the working paper report with several African grassy ecosystem scientists to solicit their views on the different land-based CCMA options for different ecosystem and to seek their recommendations on critical case studies to be included in the review.

Secondly, the **authors conducted extensive literature review to** 1) identify the main land-based CCMA options proposed for the different ecosystems and land uses, 2) summarize current trend of climate change and impacts across Africa, 3) identify the key climate commitments made by African nations, 4) identify and characterize Africa's framework for climate change mitigation and Adaptation, 5) identify critical and topical issues of importance to CCMA and, 6) gather evidence for land-based CCMA actions across the diverse ecosystems, land uses, and sub-regions (North, West, Central, East, and Southern Africa) across Africa. For this exercise, and in addition to case studies gathered during the SSNM conference, the authors conducted search for specific land-based CCMA options in Africa on Scopus (https://www.scopus.com/) and Google Scholar (https://scholar.google.com/). Outputs generated from these searches – e.g., {Agroforestry} AND {Africa}- were reviewed individually and those providing evidence of land-based CCMA options (either quantitative or qualitative) were selected for more detailed examination. In addition to these searches, all NbS case studies provided by the Nature-based Solutions Evidence Platform Policy (https://www.naturebasedsolutionsevidence.info/) were included in the list of case studies.

Thirdly, the **lead author attended a working session meeting to develop common African position on how to enhance climate action on land**, held in Livingstone, Zambia from 30th March – 1st April 2022. The meeting brought together scientist, practitioners, policymakers, and negotiators across Africa, working on diverse ecosystems and land use to deliberate on existing land-based CCMA options and identify new and innovative approaches for enhancing climate actions for Africa. The output of this meeting (draft submission by the Republic of Zambia on behalf of the Africa Group on how to enhance climate action on land) greatly influenced the final structure of this report.

Finally, for land-based CCMA options lacking adequate case studies or with relatively few empirical studies in Africa, the lead author reached out to experts in the field through emails and zoom calls to obtain inputs.

1.4 Terminologies and scope of climate actions considered

Several concepts are used to **frame Climate Change Mitigation and Adaptation** (CCMA) on lands. Of these, the concept of "**nature-based solutions**" (NbS) has gained popularity in recent years [11–14]**. Nature-based solutions** is defined as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits"[15] . NbS interventions are generally geared towards 1) protecting and enhancing biodiversity, 2) mitigating and adapting to climate change, and 3) ensuring human well-being. The NbS concept builds on other earlier concepts – such as ecosystem approach, ecosystem-based adaptation/mitigation, etc. [16,17].

Inspite of its popularity and operating as a unifying concept, the use of the term "NbS" is still strongly contested in global climate change fora. Opponents of the NbS concept argue that:

1) framing of some climate actions as "natural" and others as "unnatural" limits the range of effective options available to policy makers [18]
2) there is likelihood of misunderstanding that NbS can provide a global solution to climate change [19]
3) "nature" being expressed as "solution" to climate change is inappropriate and detract attention from the need for urgent reduction of greenhouse gas emissions[1]
4) pledges for NbS often translate into target for afforestation, often with monocultures and non-native species[20]
5) there is limited proof that NbS actions are more desirable given existing technical limitations, risks and uncertainties, particularly in relation to actual carbon sequestration potential, land requirement and potential trade-offs (e.g., with biodiversity)[18].

In this working paper report, we use the term "land-based CCMA options" to encompass diverse CCMA concepts and actions that involves the use of ecosystems, biodiversity, and nature in climate change mitigation and adaptation [21,22]. Land-based CCMA options include diverse concepts and actions covering ecosystems-, agriculture-, urban-, and community-based interventions (Figure 1).

Land-based CCMA options are generally "supply-side measures" that seek to reduce emission, increase carbon sequestration of natural ecosystems, and improve community resilience [21]. Land-based supply-side measures include interventions to protect, manage and restore forests and other ecosystems; reduce emission and enhance carbon sequestration in agriculture; and enhance carbon sequestration using bioenergy. In contrast, "*demand-side*" measures for climate change mitigation encompasses strategies targeting consumption-based or lifestyle-based approaches such

[1] See here for detailed discussions on this during the approval of the Summary for Policymakers (SPM) of the assessment report of the Intergovernmental Panel on Climate Change (IPCC) Working Group 2 (WGII) on 'Climate Change: 2022: Impacts, Adaptation and Vulnerability'.

interventions targeting food waste, dietary changes towards less energy intensive diets, and efficient resource use in production of consumable products[23,24] .

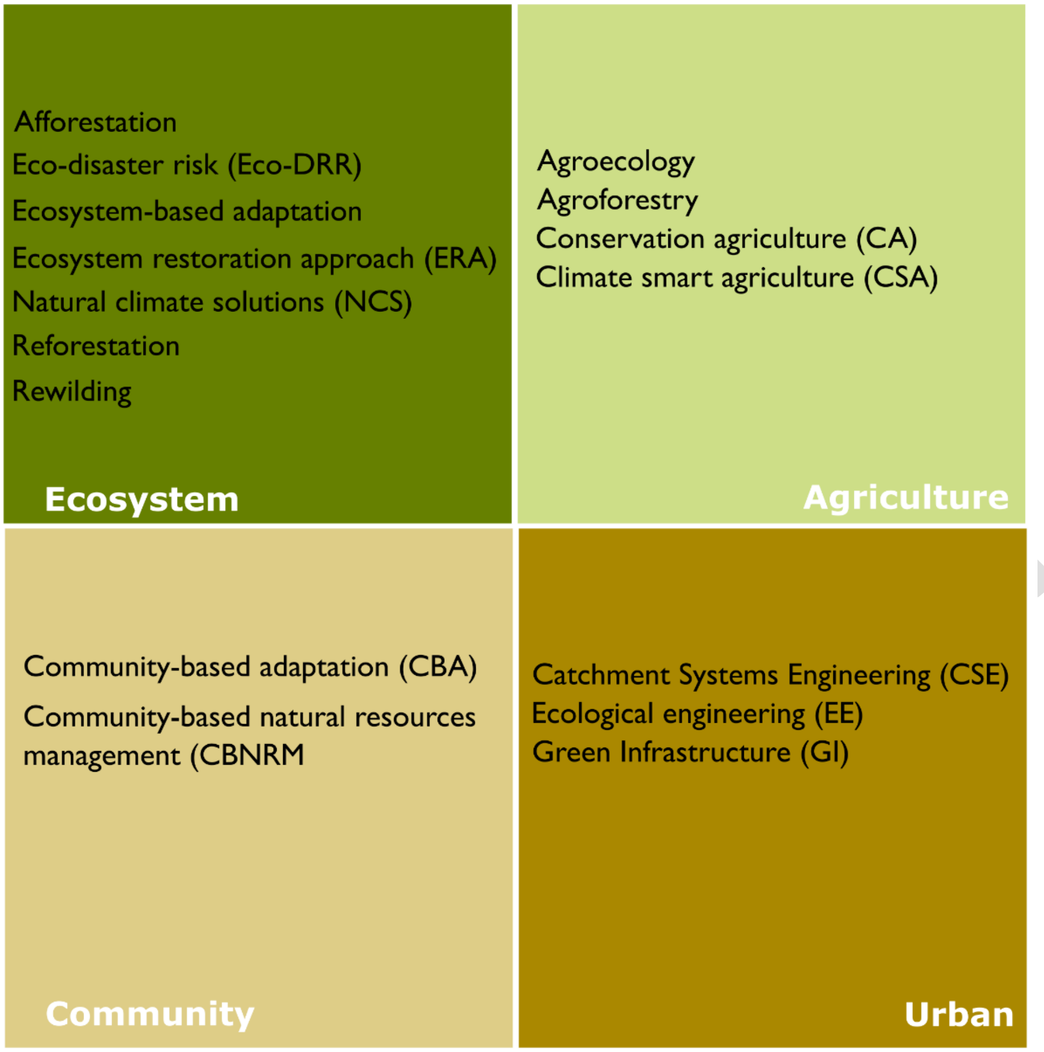

Figure 1: Examples of land-based CCMA options across ecosystems, agriculture, urban and community-based interventions. These interventions are also commonly referred to as nature-based solution (NbS) or natural climate solutions (NCS).

Land-based CCMA pathways can further be categorized into emission reduction (ER) and carbon dioxide removal (CDR) pathways (**Figure 2**) [25]. Land-based emission reduction interventions seek to reduce GHG emissions from forest and other ecosystems – by **conserving carbon-rich ecosystems** as well as adoption of **sustainable agricultural practices**. Land-based CDR pathways include **improved management of ecosystems**, **restoration of degraded ecosystems** and **agroforestry** [26]. Although both ER and CDR interventions can target any given ecosystem or land use, subtle variations exist with respect to where the different sub-pathways can be deployed. For instance, conservation, improved management, and restoration interventions can be deployed for all terrestrial ecosystems (e.g., forest, mangroves, and savanna/grassland). However, agroforestry and sustainable agriculture interventions are specifically designed for croplands and pastures.

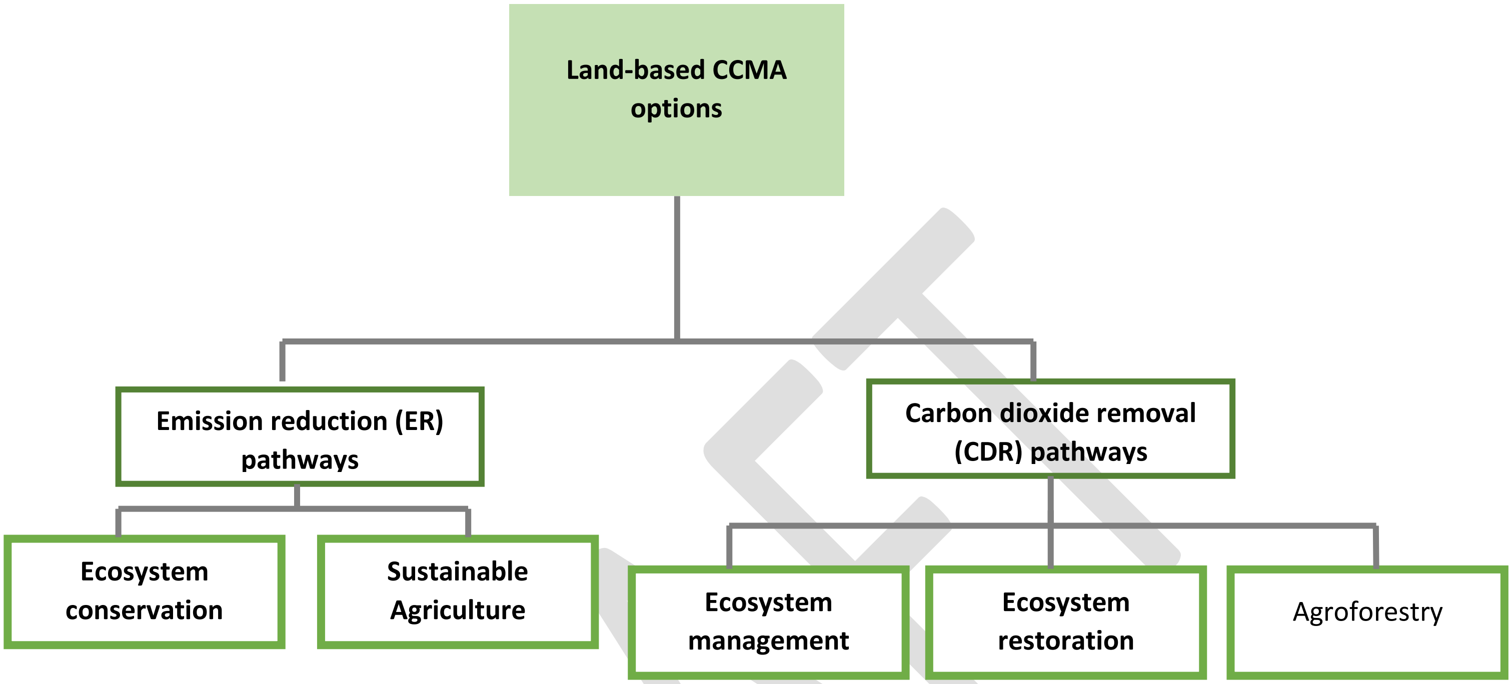

Figure 2: Overview of land-based CCMA options emphasizing different sub-pathways under emission reduction and carbon dioxide removal pathways.

Several components can be identified under each sub-pathway as follows: 1) Ecosystem conservation include avoided deforestation and avoided conversion of non-forest ecosystems such as grassy ecosystems, 2) Sustainable Agriculture encompass farm energy consumption, manure and fertilizer management and enteric fermentation., 3) Ecosystem management include interventions such as sustainable forest management, avoided burning (in grassy ecosystems) and soil carbon in grassland, 4) Ecosystem restoration include reforestation, afforestation and ecosystem restoration (for non-forest ecosystems), and 5) Agroforestry cover integration of variable tree cover on croplands and agropastoral systems [27].

2.0 Climate change adaptation and mitigation in Africa

We performed extensive literature review to establish a **framework for assessing climate actions in Africa**. The review below first provides an **overview of global actions and role of land-based CCMA options** for reducing global warming to within 1.5°C and 2°C of pre-industrial levels in this century. Subsequently, we summarize **climate trends in Africa** and identify the **key climate commitments made by African countries**. Given that Africa's focus is on climate change adaptation and sustainable development, the review highlights **potential synergies** and trade-offs between climate actions and sustainable development. The review shows that trade-offs and synergies between climate actions and sustainable development go beyond biodiversity conservation and rural development and include topical issues such as land governance, climate securities as well as the concept of ecosystem degradation.

2.1 Global climate actions – From Paris to Glasgow and beyond

There is a consensus among scientists that global warming above 2°C of pre-industrial levels will lead to significant societal, economic, and ecological damage [28]. Global warming above 2°C is predicted to usher in extreme climate risks such as frequent extreme weather events (e.g., flooding), significant species loss, increased drought, extreme heat waves, sea-level rise, lower agricultural productivity, and lower economic growth globally[26,28,29] .

Since 2015, there has been a concerted effort by the global community to combat global warming. In December 2015, at COP 21 in Paris, parties to the **United Nations Framework Convention on Climate Change** (UNFCCC) reached a landmark agreement ("The Paris Agreement" = PA) to combat the threats posed by climate change by keeping global temperature rise this century to below 2°C [1]. Indeed, the PA aims to further limit global temperature rise to within 1.5°C of pre-industrial level [1]. Limiting global temperature rise to within 1.5°C above pre-industrial levels is generally predicted to pose less climate-related risks compared to warming of 2°C [28].

According to the IPCC special report, reducing global warming to below 1.5°C and 2°C above pre-industrial levels requires substantial global emission reduction [28]. To reduce global warming to below 1.5°C of pre-industrial levels, global emission needs to decline by 45% from 2010 level by 2030 and should reach net zero by 2050. Similarly, to reduce global warming to within 2°C of pre-industrial level, there is the need to cut global emission by 25% by 2030 and attain net zero emission by 2070 [28,30].

To reach the common goals of climate risk reduction set in the PA, all parties are required to set commitments to cut their greenhouse gas emissions over time[1]. These commitments are Nationally Determined Contributions (NDCs) which are climate action plans pledged by nations to cut greenhouse gases emissions and adapt to climate effects[31] . Nations specifically set their targets to cut their emissions in NDCs with clear description of how to reach the target. Every five years, the new or updated NDCs are submitted to the office of UNFCCC secretariat. These commitment of climate actions are used to evaluate the progress made by each party which collectively enable to determine global commitments towards achieving the long-term goal of the PA.

Recent analysis of global climate actions suggest that current actions are falling short of the PA targets [30,32]. The United Nations Environment Programme's Emission Gap Report (2021) showed that the new and updated NDCs coupled with the announced pledges for 2030 have little impact to reduce global emissions[32]. Similarly, the NDCs synthesis report concluded that global emissions level in 2030 will be more than 16.3% of the 2010 level and that cumulative CO_2 emission in 2020 – 2030 would likely use up 89% of the remaining carbon budget consistent with reducing global warming to 1.5°C by 2050 [30].

2.2 Role of land-based CCMA in reducing global warming below 2°C

Limiting global warming to within either 1.5°C or 2°C above pre-industrial levels requires far reaching transformation across every sector of society. The United Nations Environment Programme estimates that 30 Gt of CO_2 equivalent emission reduction can be achieved across 6 sectors annually [33]. This includes 12.5 Gt of CO_2 equivalent from the energy sector; 7.3 Gt from Industry; 6.7 Gt **from Agriculture, food, and waste**; 5.9 Gt from **Nature-based solutions**; 5.9 Gt from buildings and cities; and 4.7 Gt from transport[33].

The importance of land-based activities in reducing global warming to within 1.5°C or 2°C have been particularly highlighted in global climate fora and scientific publications [25,26,34,35]. On one hand, land-based emissions account for about **14%** of net global anthropogenic CO_2 emissions through deforestation, agriculture, peatland drainage and mangrove clearance, livestock farming and rice paddies, and fertilizer use, etc. [36,37]. At the same time, land is a major CO_2 sink and is estimated to have absorbed about **one-third of CO_2** released since the first industrial revolution. It is estimated that significant CO_2 emission reduction and removals can be achieved by modifying land use, land use – change and forestry (LULUCF) activities [26]. Indeed, there is substantial evidence that agriculture, forestry, and other related land use (AFOLU) can provide up to 20 – 30% of the net emission reduction needed by 2050 to limit global temperature rise to 1.5°C [16,25,26,33,34].

2.3 Climate change trends in Africa

Africa has contributed among the least to historical global GHG emission, accounting for about 9% of total GHG emissions for the time period 1990 – 2019 [38]. Africa's GHG emission is mostly in the form of carbon dioxide (CO_2) and methane (CH_4) from the AFOLU and energy sectors but emissions from industry, transport and buildings are picking up in recent years [4,38]. Despite its low GHG contribution, Africa is predicted to experience the most severe impact of global warming and associated climate change [4,5,39]. The recent IPCC report on climate change in Africa indicated, among others, increasing mean and extreme temperature (greater than the global rate of warming), increased heat waves, frequent drought (particularly in West and Southern Africa), frequent and intense heavy rains across much of Africa [4,5]. The predicted impact of such warming and climate change includes increased risk of reduced food production due to decline in agricultural productivity and net primary productivity in rangelands, significant shifts in the range and distribution of plants and animals with associated loss of biodiversity, increasing conflicts particularly over land-based resources and rise in the proportion of Africans living under extreme poverty [4,5].

Climate change impacts are already being felt in key sectors across Africa [39]. Climate impacts such as water scarcity (e.g., Lake Chad), food insecurities (e.g., in Southern Africa), invasiveness, sea-level rise (especially in west Africa), and extreme weather events [5,39,40]. Given that majority of Africans are employed in climate exposed sectors – e.g., crop production, pastures, and pastoralism – the impact of climate change is predicted to unevenly affect the most disadvantaged groups (e.g., children, women, youth, and pastoralists) [5].

2.3 Key Commitments on Climate Change in Africa

Given the **high vulnerability**, **low adaptative capacity** and **resilience** of most African countries, global warming and climate change represent the ***most difficult bottleneck*** for economic growth and sustainable development [3]. Therefore, African countries and the continents intergovernmental bodies (e.g., the African Union, AU, and its sub-regional organizations) have demonstrated strong interest in climate change adaptation. Currently, **54 African Union Member States (AUMS)** have ratified the Paris Agreement and **53** of these have submitted their first NDCs.

At the continental level, several initiatives are promoted to contribute to climate mitigation, often with landscape restoration and job creation as co-benefits. These include the Great Green Wall initiative (https://www.greatgreenwall.org/about-great-green-wall), The African Resilient Landscape Initiative (ARLI), The African Forest Landscape Restoration Initiative (AFR100; https://afr100.org/), and several national initiatives (e.g., the Green Legacy Programme in Ethiopia).

2.4 Africa's Framework for Climate Change Adaptation and Mitigation

Figure 3 summarizes Africa's climate change adaptation and mitigation framework which is also partly set out in **Agenda 2063** ("The Africa We Want") [2]. **Agenda 2063** is Africa's blueprint and master plan for attaining inclusive and sustainable economic growth and development. Agenda 2063 is strongly aligned with the Sustainable Development Goals (SDGs) and envisions "*an integrated, prosperous and peaceful Africa, driven by its own citizens and representing a dynamic force in the international arena*". Agenda 2063 spells out the **7 Aspirations** of the "Africa We Want" by 2063 which ranges from a prosperous Africa based on inclusive growth and sustainable development to a united, strong, and resilient and influential global player and partner. **Aspiration 1** of Agenda 2063 outlines the goal of Africa's climate change response which are:

i) Africa shall address the global challenge of climate change by prioritizing adaptation in all our actions for sustainable development and shared prosperity
ii) Africa shall participate in global efforts for climate mitigation that support and broaden the policy space for sustainable development on the continent.

Therefore, Africa's response to global warming and climate change involves, first prioritizing adaptation, and supporting global efforts aimed at climate change mitigation particularly if they provide opportunities for achieving sustainable development.

Africa's response to climate change is further articulated in the "Draft African Climate Change strategy 2020 – 2030" [3]. The overall objective of the strategy is to ensure the achievement of the **vision of Agenda 2063 by building resilience of the African continent to the impacts of climate change** – a goal that is linked to SDG 13, "take urgent action to combat climate change and its impacts. The draft climate change strategy integrates relevant climate-oriented (e.g., the Sendai Framework for Disaster Risk Reduction, SFDRR; Convention on Biological Diversity, CBD) and non-climate commitments while providing flexible options for the sub-regional organizations to determine the exact nature of interventions to be implemented[3].

A central theme of both **Agenda 2063** and the **African Climate Change Strategy** is the fundamental role of **land and natural resources** in both sustainable development and climate change mitigation and adaptation. Africa is the world's second largest continental land mass – with total land area of 30.37 million square kilometers – with impressive ecological diversity including wetlands, lakes, forest, grassy ecosystems as well as extensive arable land (60% of the worlds arable land). This vast land and ecosystems can play important roles in both adaptation (on the continent) and mitigation (globally). Therefore, the strategy places the conservation and management of natural resources at the core of climate change adaptation and mitigation in Africa.

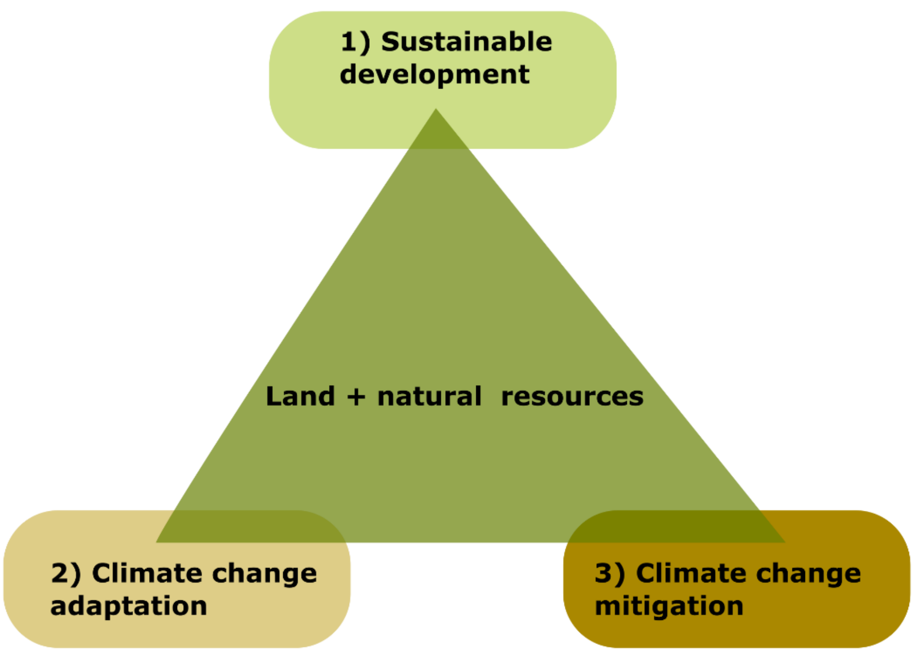

Figure 3: Interdependence between sustainable development, climate change adaptation and mitigation and the central role of land and natural resources in Africa.

2.5 Trends in climate actions in Africa

Consistent with the framework presented under **section 2.4**, two recent reviews of the NDCs of African countries shows a clear prioritization of adaptation measures relative to mitigation[41,42]. These reviews showed that adaptation actions are considered across multiple sectors and reflect perceived climate risks associated with these sectors[42]. The number of adaptation measures were highest for **agriculture** and include actions such as climate smart agriculture, provision of irrigation, land, and soil management with the goal of ensuring food security. The **water** sector had the second highest adaptation measures encompassing actions such as water management, water supply and quality, water conservation and reuse, water infrastructure and watershed management. Several adaptation measures were also found to be geared towards **disaster risk management** – e.g., disaster preparedness, monitoring, and evaluation, etc. – and health and disease surveillance[42].

In contrast, mitigation measures mostly targeted the energy, conservation, transport, waste management and the agriculture sectors[42]. Energy related mitigation measures targeted replacement of fossil fuel with renewable energy sources – mostly hydropower but also use of biofuels, solar and efficient cookstove – and enhanced energy efficiency. Mitigation actions in conservation focused broadly on reducing GHG emissions as well as carbon sequestration through actions linked to sustainable forestry, reducing emission from deforestation and forest degradation (REDD), afforestation, reforestation, and sustainable land management. Transport mitigation measures covered mostly improvement in urban and public transport and transport fuel use whereas waste management mitigation encompassed waste-to-energy, agricultural and water waste, recycling, and re-use. Mitigation measures in agriculture involve climate smart agriculture, agricultural waste, soil management, livestock and to a lesser extent fisheries and aquaculture [41,42].

2.6 Synergies and trade-offs in climate actions and sustainable development in Africa

Efforts to address climate change – through mitigation and adaptation – can affect sustainable development in Africa. On one hand, well designed and implemented mitigation measures can have significant positive influence on sustainable development. For instance, Africa has huge mitigation potential – untapped potential for clean and renewable energy – that can be leveraged for technology transfer and funding towards adaptation and sustainable development[3]. Indeed, mitigation measures such as renewable energy can offer strong synergies for sustainable development in Africa by stimulating growth of microenterprises through provision of cheaper off-grid power and hence contribute to poverty alleviation in rural areas [42].

In contrast, poorly designed and implemented mitigation measures can have adverse effect on sustainable development. For instance, several authors have pointed out the potentially negative ecological impacts of large-scale afforestation projects in Africa's grassy ecosystems on biodiversity and livelihood (e.g., through reduction of fodder for pastoralist)[9,43]. Indeed, even well-designed mitigation measures can have negative biodiversity and social impacts. For instance, Hussein et al. (2013) showed that forest carbon sequestration incentives can raise poverty levels in developing countries[44]. Importantly, given the high dependence of African countries on land- and natural resource-based sectors, adaptation, and mitigation actions, irrespective of how well-intended, will have consequences on equity[42].

Finally, economic development in Africa is driven by natural resources which are also important for climate change adaptation and mitigation[42,45]. Inspite of this, Africa's natural resources – land and soil, forest and mangroves, rangelands and their intact large mammal's assemblage, fisheries, and water resources – are currently under intense pressure and threats [6]. Unsustainable practices – such as habitat conversion, over-harvesting, poaching and illegal wildlife trade, pollution, and invasion by alien species – are resulting in land degradation, loss of habitat, loss of soil fertility and productivity and ultimately loss of economic opportunities for the most vulnerable groups [6].

Africa therefore faces two main challenges in relation to using it immense and diverse ecosystems and natural assets towards development and climate change adaptation and mitigation. First, and as noted by several analysis[6,42,45], there is the urgent need to reduce unregulated land cover changes, conversion of forest, rangelands, and other natural ecosystems to agriculture and other land use types. Second, selection of appropriate ecosystem-based CCMA options is critical to ensure delivery of benefits to people through the conservation and sustainable use of Africa's natural assets. In chapter 3, we analyze the different land-based CCMA options to identify promising climate actions for the different ecosystems and land use types across Africa.

2.7 Land governance and climate change actions in Africa

Land is an essential socio-economic resource in Africa. African lands are used for production crops, livestock, nature conservation, human settlements as well as other economic and socio-cultural purposes. Over 52% of African's are employed in agriculture, which accounts for about 19% of the continent's Gross Domestic Product (GDP)[46]. In Africa, land provides safety net because it is the ultimate source of income, food, shelter, and energy for most of the citizens[47]. Importantly, large areas of land in Africa – currently about 14-17% of the total land area – are already dedicated to conservation[48].

Land governance issues – land ownership, access, and tenure rights – are identified by the African Union Commission (AUC) as central to sustainable development, climate change mitigation and adaptation[47]. For instance, significant changes and investment in land use are required to reverse the negative impacts of climate change in Africa[47]. However, in the context of land-based CCMA in Africa**,** interventions will be implemented on lands that already have multiple ownership, access, and tenure claims[7]. Given that most interventions will be effective only when deployed at large scales (e.g., afforestation and tree planting), CCMA will likely compete with existing land uses that will have direct impact on livelihoods[43,49].

Existing knowledge from Lands System Studies (LSS)[7] suggests that while wins-wins can be crafted for CCMA and other co-benefits in some situations, trade-offs (between competing uses such as food production and biodiversity conservation, and within uses such as biodiversity and carbon sequestration) are often the norm. This suggests that **CCMA interventions in Africa will likely compound land governance issues**. This is particularly worrying given that land tenure systems in Africa are already under stress due to increasing population and climate induced disasters are expected to further disrupt land tenure systems[47].

Competition between land uses – both existing and new land uses – is likely to increase under current trends of climate change and will particularly affect the most vulnerable groups (e.g., women, migrants, and pastoralist). For instance, pastoral areas occupy about 40% of Africa's lands and operate on flexible, locally defined land tenure systems[47,50]. Climate change is increasingly bringing pastoralist in Africa into contact with farmers and often triggering conflicts[51]. These conflicts are likely to increase given that changes to tenure rights –which may be required to improve CCMA investment in lands – is likely to disproportionately affect such pastoral communities[47,50] due to loss of flexible customary grazing tenure.

2.8 Climate Securities in Africa

In Africa, where the economies and communities are heavily dependent on natural resources and rain-fed agriculture, localized violence and tensions on a smaller scale can be connected to the question of land-based resource availability and access[52,53], interacting with conditions like growing population, regional disparity, weak governance as well as the increasing impact of climate change (**see Fig. 4).** The recent IPCC Sixth Assessment Report acknowledges that climate change has already contributed to changes in terrestrial and freshwater ecosystems structures[29]. By impacting availability and access to natural resources, climate variability and extremes linked to climate change can disproportionately affect communities depending on those resources for their livelihoods such as farmers, herders, and fishermen, leading to decreased economic output and growth, and increased food insecurity, poverty, and inequality rates, which are often at the heart of conflicts and insecurity.

For instance, lack of access to water and pasture for livestock, induced by drought and desertification, can force pastoral communities to deviate from their usual migratory routes and seasons. This often brings them in closer proximity to farming communities, which are simultaneously trying to bring more land under cultivation in response to climatic stressors. In this situation, issues of limited availability and contested access to critical natural resources like land and water can contribute to risks of small-scale violent conflict between farmers and herders[54–56]. The dynamics of conflict and cooperation over natural resources connected to land systems can therefore emerge as a major pathway observable at regional scales within and across countries in Africa.

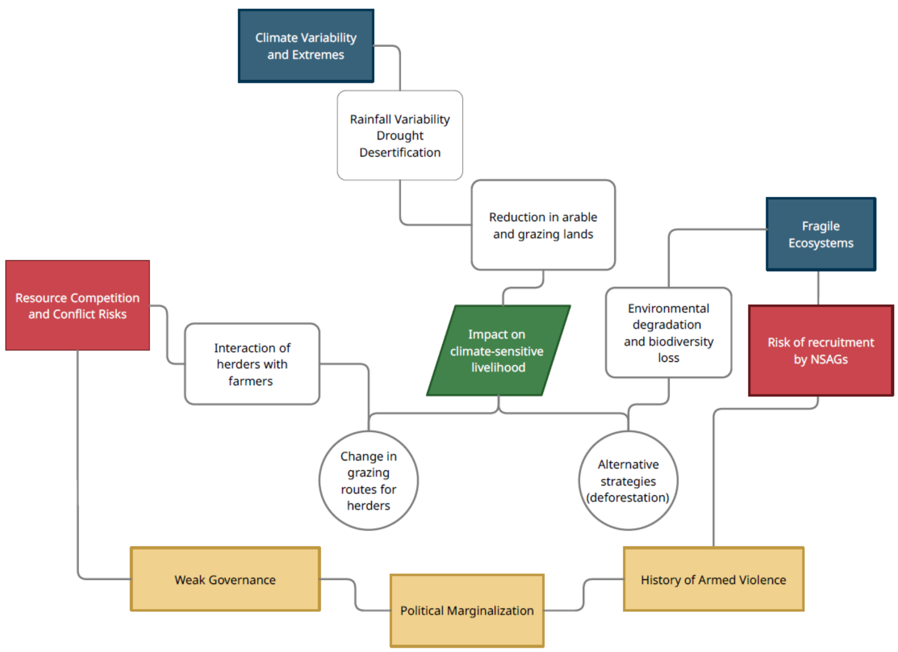

Figure 4: Climate-Natural Resources-Security nexus: Climate change can disrupt nature-based livelihoods, which in turn can perpetrate ecosystem degradation and trigger migration and land conflicts in Africa.

2.9 Ecosystem degradation in the context of Africa

Land-based CCMA options in Africa often emphasize protection, management, and restoration of ecosystems[3,42]. Defining and mapping out degraded ecosystems is a prerequisite for identifying restoration opportunities. Substantial scientific effort has been directed towards identifying areas of the world that are degraded and have potential for restoration[57]. However, **definition of ecosystem degradation is often viewed from a forest-based perspective** that are unsuitable for the extensive grassy ecosystems of Africa[58,59]**.** For instance, one recent study classifies substantial areas of Africa's grassy ecosystem as degraded and earmarked for restoration through afforestation[57]. Although several authors have pointed out these false claims [60–64] and improved framework for defining ecosystems degradation have been proposed[58,59,65] – that accommodates degradation in both forest and grassy ecosystems – they yet to be taken up into policy consideration.

The misreading and misclassification of Africa's grassy ecosystems[66] is driven by both methodological and historical definitional misconception. For instance, global assessment of degradation is often based on remote sensing data and focuses on productivity (above-ground biomass) within a landscape[57,67].For Africa's open ecosystems, fire and herbivore remove substantial amount of biomass that is likely to register on remotely sensed data as decreased productivity (and hence classified as degradation). However, these variabilities are perfectly normal for open ecosystems[59]. Importantly, long-standing debates about what constitute forest, woodland, savanna, and grasslands[68–70] have led to inconsistencies in the mapping of the different vegetation of Africa literature [70–74].

Inappropriate definition of ecosystem degradation, particularly in Africa's open ecosystems will likely lead to maladaptive climate change mitigation and adaptation interventions with great consequences for biodiversity and livelihoods[9,43,75]. For instance, fire and herbivory are important management tools for grassy ecosystems but fire suppression is strongly advocated as an important intervention for climate change mitigation and adaptation. Importantly, grassy ecosystems require open canopies and current push for more tree planting, which prioritises carbon sequestration, will have severe negative impacts on biodiversity and provision of ecosystem services.

3.0 Evidence for Land-based Climate Change Adaptation and Mitigation in Africa

We examined substantial number of case studies on climate change adaptation and mitigation in Africa. To ensure adequate representation in the selection and review of case studies, we first identified the major biomes of Africa (**Fig. 5**) using the “Bob Scholes Africa Ecoregion Map”. This map was derived by regrouping and smoothing the vegetation classification of the UNESCO/AETFAT/UNSO Vegetation Map of Africa [70] to follow the delineation of MAP-determined (“stable”) and disturbance-determined (“unstable”) savannas in Africa by Sankara et al., [76]. The Bob Scholes map identifies five (5) main ecoregions, namely, forest, Sub-humid savannas, semi-arid savannas, North Africa desert, and Southern Africa desert to semi-deserts. Here, we combined both the North Africa and Southern Africa deserts under “arid zones, deserts and desertification”. Similarly, we lumped sub-humid and semi-arid savannas into the “grassy ecosystem” category for ease of analysis and discussions. However, under the “grassy ecosystem” category, we further reviewed, reported, and discussed case studies under “woodlands”, “savannas and grasslands”, and “rangelands” to highlight issues that are specific to these sub-types. It is important to note that the Bob Scholes map does not cover mangroves, but we included mangroves in the analysis given their significance to climate mitigation and adaptation. We also reviewed case studies for the three (3) major land uses in Africa (i.e., conservation, agriculture, and urban). We considered three (3) sub-categories for agriculture, namely, cropland, livestock – pastures, and agroforestry.

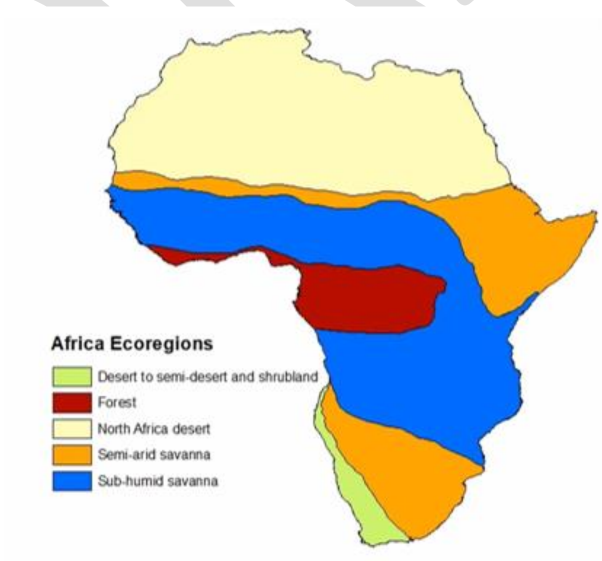

Figure 5: The Bob Scholes Africa Ecoregion Map.

3.2 Mangroves

Mangroves are complex coastal forest ecosystems that occur where the ocean, freshwater, and land meet. Mangrove trees have evolved special adaptations that allow them to live in waterlogged, salty, and often unstable conditions [77]. Globally, mangroves are found mostly in tropical regions covering an estimated area of about 150, 000 km^2 [77]. Southeast Asia (32% of the global mangrove area) hosts the highest coverage of mangroves followed by North and Central America and the Caribbean (15%) and West and Central Africa (14.5%) [77].

In Africa, mangroves are estimated to cover a land area of about 35,000 km^2 representing 19 – 23% of the global mangrove area [78,79]. Mangroves in Africa are mainly concentrated in West (10 of the 17 countries), Central and Eastern Africa [78,79]. Mangroves in Africa provide important ecological, social, and economic services. For instance, mangroves play a critical role in coastal fisheries in Africa by providing habitat for over 80% of commercial fisheries and other aquatic species [79]. African mangroves also provide wood and non-wood forest products, resource base for the salt industry, coastal protection, and biodiversity conservation [78].

Despite their importance, African mangroves are currently facing enormous degradation pressures with an estimated loss of 20 -30% of the mangroves in West and Central Africa over the past 25 years [79]. Main threats to mangroves in Africa include deforestation (linked to fish smoking), urbanization and urban infrastructure development, salt extraction and sand winning, quarrying, pollution, invasive species, and climate change [78–80].

Conservation, management, and restoration of mangroves is identified as one of the most promising land-based CCMA options. Generally, mangroves have remarkable carbon stocks and sequestration potential relative to tropical forest [77,81]. Therefore, conservation, management and restoration of mangroves represent a huge potential for carbon sequestration and emission reduction [81,82]. Conservation, management, and restoration of mangroves can also play vital roles in climate change adaptation improving coastal protection (and disaster risk reduction), biodiversity conservation and coastal livelihoods (e.g., fisheries habitat conservation, sustainable energy sources, etc.) [79,83].

Avoided deforestation

Avoided deforestation of mangroves ecosystem is generally of high priority given the high carbon stocks and livelihood implications. Carbon stocks in undisturbed mangroves is higher than degraded mangrove ecosystem in Central Africa [82]. Although mangrove have a limited extent in Africa [78,83], they seem to have particularly high carbon storage potential than even intact African rainforest [82]. Several examples of case studies on avoided deforestation initiatives – often linked to REDD+ and blue carbon financing – exist in Africa. These include the establishment of marine protected areas covering large areas in West Africa [80] , protection of mangroves in the Mikoko Pamoja carbon credit initiative in Kenya [84] as well as other initiatives combining mangrove conservation and restoration in Tanzania [85] and Guinea-Bissau [86] among others.

There is consensus from the case studies examined that successful "avoided deforestation" mangrove projects across Africa involves, among other things, those with: 1) local people involvement (e.g., co-management, participatory forest management, community-led sustainable forest management), 2) strengthening of institutional and individual capacity; 3) financial incentives are given for avoided deforestation (one study estimates between $6.69 – $7.20/t of CO_2 as the minimum amount required to be successful); 3) provide sustainable alternative energy sources (e.g., woodlots); 4) embedded in the larger framework of mangrove management (conservation, management and restoration) and 5) mainstreamed with national forest programs.

Improved mangrove management

Improved management of mangroves has been identified as one of the nature-based solutions to protect the structure, function, and ecosystems services of mangroves globally. Improved management of mangrove forests can provide wide range of ecological, social, and economic benefits in Africa [83]. For instance, the structure and regeneration of mangrove forests in Kenya were found to be greatly improved with important implication for carbon stock both in the soil and biomass [87]. Improved management of mangroves does not only enhance carbon storage but also improves the livelihood of local residents through community enterprises such as tomato farming, community micro-lending and fishing scheme and oyster cultivation [80]. Improved mangrove forest management could be sustained with provision of wood lots as alternative source of fuelwood to local residents and establishment of buffer zone to minimize sediment load and human pressure [88]. Such approach helps to reduce heavy human contacts with primary mangroves and reduce carbon emission through degradation and deforestation [82].

Mangrove restoration

Several examples of mangrove restoration initiatives exist in Africa and case studies were selected from Ivory Coast [89], Tanzania [85,90], Guinea-Bissau [86,91], Senegal [92], Kenya [84] among others. Most of the case studies suggested successful re-establishment of mangroves indicating carbon gains as well as other environmental and social co-benefits (e.g., alternative income sources from carbon credits, additional livelihood activities, and sustainable energy sources). However, not all mangrove restoration project yielded favorable results. Indeed, mangrove restoration efforts globally have low success rate of 15-20% [93,94]. For instance, restoration project focusing on tree planting obtained mixed results compared to those deploying community-based ecological mangrove restoration (CBEMR) approaches [85,86]. The CBEMR approach focuses on creating the enabling environmental conditions for natural recovery in disturbed sites [85]. This approach combines elements of hydrology, sediments dynamics and soil management to facilitate natural regeneration with active tree planting applied only when necessary [85]. The CBERM approach also addressed the socio-economic factors that are likely to compromise long-term sustainability of restored mangroves [86]. Indeed, one case study demonstrated that if the socio-economic factors of degradation are not addressed, efforts to restore mangroves will be viewed by local stakeholders "land-grabbing" or "green washing" attempts [92].

3.3 Forests

According to the FAO, Africa contributed 15.7% (636 million hectares) of the global forest cover in 2020 [95]. Africa's forest is diverse in composition, structure, and function, ranging from wet – dry types [74]. At the continental level, three prominent forest blocks exist, namely Upper Guinean (West Africa), Lower Guinean (Coastal Central Africa), and Congolia (Congo basin) forests that together form the Guinea-Congolian forest [74]. The Guinean Forest of West Africa is highly diverse – i.e., high species richness and endemism – and is one of the 36 global biodiversity hotspots [96,97].

Forests are of fundamental importance to African societies. They provide essential livelihood products (meat, food, medicine, etc.); serves as the resource base for many businesses (timber and non-timber forest products) and provide safety nets to rural communities, including provision of conducive microclimate for production of cash crops (e.g., cocoa in West Africa, tea in East Africa) [98]. African forests are also home to diverse species of plants and animals. They also ensure water supply, store substantial amount of CO_2, and purify the air [98].

Despite their importance, rate of forest loss (deforestation) in Africa is higher than anywhere in the world and continue to increase [95]. Human population growth, economic development (particularly in Asia) and changing demographic trends indirectly influence rate of deforestation in Africa. In Africa, agriculture (both subsistence and commercial) is the main direct driver of deforestation [99]. Tropical forest loss is particularly troubling given that they account for 8 – 15% of global greenhouse gas emissions [100]. Reversing forest loss in Africa has great potential for reducing GHG emissions, increasing adaptive capacity of local communities, and enhancing biodiversity conservation.

Avoided deforestation

Given the importance of forests in Africa, deforestation represents a significant threat to sustainable development. Intact African forests have higher carbon stocks [101–104] and are more diverse than degraded forest or any other land use type [95,105–107].

Several examples of effective avoided deforestation projects in different parts of Africa exist and demonstrate the workability of this option. Examples include: 1) participatory forest management in Zambia that is estimated to have saved 228,000 tons of CO_2 emission; 2) an externally verified 62% reduction in deforestation – relative to the national average – in the Bale Eco-region of East Africa [108]; and 3) a community-led sustainable forest management initiative in Senegal [109]. These and many other success stories reported elsewhere demonstrate that avoided deforestation works when the right approach is adopted [110].

The case studies examined indicated that avoided deforestation – through REDD+ initiatives – often provide both carbon [90,111] and other co-benefits – biodiversity and livelihoods [112–114]. As with mangroves, successful "avoided deforestation" projects across Africa involves those with 1) local people involvement (e.g., co-management, participatory forest management, community-led sustainable forest management), 2) alternative livelihood opportunities, particularly those that supplement on-farm income, 3) strong local political will and interest [110], 4) adequate funding and credits (in the form of carbon credits, payment for ecosystem services or grants), and 5) adoption of technology (e.g., near real time deforestation alerts) [115].

Improved forest management

Improved forest management (IFM) is an important tool for maintaining and increasing forest carbon stocks in Africa [116]. Many Africans communities heavily depend on forest for their livelihoods and both improved community-based and concession-based forest management are key for achieving sustainable forest management in Africa [117–119]. Case studies examined were selected from Democratic Republic of Congo [111,119], Ethiopia [120], Malawi [121], Morocco [122] and Madagascar [117] and spanned both community-based and concession-based [111] IFM in Africa.

The case studies analyzed indicated that there is huge potential for carbon storage, improved livelihood, and biodiversity through improved forest management in Africa [111,112,123]. Analysis of the available case studies indicates that IFM through community-based forest management (CBFM) creates positive incentives for appropriate behavior for sustainable forest management and works better if local communities play enforcement roles [90,118,120,122]. However, improved forest management involving local community indicates that 1) environmental, livelihood, and shared management responsibilities are not always reinforcing and may trade-off under some circumstances, 2) democratic decentralization are rarely established, and 3) environmental benefits (including carbon sequestration) often accrue to distant stakeholders but local communities carry the cost [113]. These observations suggest that carbon and biodiversity benefits of IFM may trade-off with local community livelihood if specific alterative livelihood interventions are not crafted as part of IFM [124,125].

Improved forest management in timber concessions – a common feature of forestry in Africa – can limit negative impacts of logging on biodiversity and improve carbon sequestration, particularly for concessions under certification initiatives [123,126–128]. Concession-based IFM can be achieved through reduced impact logging (RIL) or reduced logging intensity (RLI). However, the limited case studies available suggests that reduced logging intensity in Africa is only attractive where there is complete cessation of logging, in forest with low stocking and low profit forests [111,126]. Indeed, current carbon market prices are too low to be strong incentive for reduced impact logging or reduce logging intensity [111].

Reforestation

Technically speaking, reforestation is the restoration of forest cover on degraded or deforested lands. Reforestation is identified as an important land-based CCMA option for capturing carbon, improving biodiversity conservation, and providing green jobs in Africa [57,112]. Numerous past and ongoing reforestation projects are dotted across Africa. However, the feasibility and benefits of large-scale reforestation are often the subject of intense political and scientific debates [9,49,129,130].

Analysis of case studies on reforestation in Africa highlighted three main approaches namely, natural regeneration, mixed-species plantation, and single species plantation. Case studies across Africa showed that reforestation does not only provide climate benefits but also have significant environmental and social co-benefits. However, trade-offs were apparent and depended on the reforestation approach adopted.

A limited number of the examined case studies indicated that reforestation through natural regeneration – including assisted natural regeneration – achieve greater biodiversity success [131] , fast recovering of forest structure [132] , and agricultural productivity [133]. Combining natural regeneration with direct seeding – for large-seeded, late-successional trees – has been shown to further accelerate forest restoration [134]. Although natural regeneration is a cost-effective restoration pathway, it has limitation in addressing social needs such as providing wood products. In contrast, mixed-species plantations have higher aboveground biomass (high carbon storage), but lower abundance of understorey native saplings and liana (low biodiversity) compared to naturally established secondary forest and eucalyptus plantation [135–137] . Despite this, quantitative evidence of biodiversity and livelihood benefits are sparse for the different regeneration methods and often affected by positive site selection bias [138].

The case studies examined also highlighted major constraints on reforestation in Africa [139]. The major forest zone of Africa (e.g., Upper Guinean Forest in West Africa and Lower Guinean Forest in Central Africa) are also the centres of cash crop (e.g., cocoa, oil palm, coffee, tea) driven deforestation. Large scale deployment of reforestation in this region faces strong resistance from other land uses [7,49,129] and in some cases are perceived as "green grabbing" that disempower the local communities [49,140,141]. Reforestation, even if successful, can also indirectly drive deforestation leakage elsewhere in the region [142–145]. Importantly, existing customary land tenure represent significant bottleneck to large scale deployment of reforestation [7,129]. Several case studies show that reforestation efforts can be efficient if they are designed to accommodate traditional African customary tenure systems [49,129] . In this context, novel forest landscape level restoration approaches [146–149] may offer the best chance for integrating carbon, social and biodiversity benefits but its deployment in Africa is at its early stages and case studies on its effectiveness are lacking.

Fire management

Fire is an important driver of vegetation composition, structure, and function in most African ecosystems [150,151]. Forest fires can quickly destroy large amount of forest biomass, accelerate climate change, and biodiversity loss [152,153]. Increasing occurrence of fires in forest ecosystems in Africa will have significant negative consequences – on carbon storage, biodiversity conservation and rural livelihoods [154–156] – highlighting the importance of fire management as climate change adaptation and mitigation intervention [157]. We reviewed several case studies demonstrating effective fire management practices undertaken by the communities and other stakeholders that reduces the negative effect of fire on forest resources [158–161]. Generally, participatory fire management schemes that engaged residents, NGOs, government agencies, women's group, and farmers' organization - in South Africa, Congo Republic, Democratic Republic of Congo, Kenya, and Ghana – showed great promise [162,163] . However, regional differences were observed, particularly in north Africa suggesting that effectiveness of fire management interventions is context-dependent (e.g., vegetation type, drought conditions, etc.) [164]. Importantly, the case studies examined revealed that, in addition to climate change, forest degradation significantly made forests in Africa particularly prone to fire [165,166] . These findings suggest that effective fire management interventions deployed with other measures addressing degradation is likely to yield the highest carbon, biodiversity, and livelihood benefits.

3.4 Grassy Ecosystems

Africa is predominantly a grassy continent with about 55% of the land area composed of grassy vegetations such as grasslands/savannas, woodlands, and rangelands [70,151]. Africa's grassy ecosystems are distinct from forests in terms of vegetation composition, structure, functioning and management. Africa's grassy ecosystems have continuous cover of shade-intolerant herbaceous understorey with variable tree cover [167,168]. Fire and herbivory –by both intact wildlife fauna assemblage and livestock – exert significant control over the composition, structure, and function of Africa's grassy ecosystems [151,169–171].

Africa's grassy ecosystems are fundamental to the livelihoods of large population of people. The grassy ecosystems of Africa provide diverse ecosystem goods and services, including biodiversity; regulatory services such as water flow and quality, climate, and protection of soils; non-wood forest products (NWFPs) such as medicinal plants; wood fuels; timber and wood products; and wildlife and livestock. Indeed, in most countries in Africa, the major zone of crop production falls within the grassy ecosystems [98] highlighting the importance of this zone to food security. Importantly, Africa grassy ecosystems also store substantial amount of carbon [172,173], playing a vital role in global land-atmosphere feedback systems and hence climate change [174].

Despite their importance, the grassy ecosystems of Africa are threatened by unsustainable utilization (overexploitation), rapid conversion to other seemingly profitable land uses, drastic changes to fire regimes, and replacement of wildlife with livestock's [59,175]. Climate change and increasing population growth in Africa are projected to further accelerate the degradation of Africa's grassy ecosystems with severe consequences for biodiversity and livelihoods [59,174]. Coupled with this, the grassy ecosystems of Africa have historically been understudied and under-funded leading to widespread misconceptions about their structure, function, and management [176]. Indeed, several well-intended but ill-informed landscape restoration initiatives – e.g., large scale afforestation projects – are currently being promoted for Africa's grassy ecosystems under the guise of climate change mitigation and adaptation. Such initiatives are likely to adversely affect the structure and function of these grassy ecosystems leading to biodiversity loss and loss of economic opportunities [9,10,43,177].

Woodlands

The woodlands of African are composed of an overstorey of small to medium-sized trees with loosely touching crowns (canopy cover ranging from 70 – 90%), a sparse woody undergrowth and continuous ground layer of sun-loving grasses [168,178,179]. The herbaceous ground layer of woodlands is generally compositionally distinct from the adjacent savanna's and reflect differences in tree cover [98,168,179]. Although tree densities are high in woodlands, grasses occur in sufficient density in the understorey to allow for annual fire occurrence [168,178]. The woodlands of Africa include the *Isoberlinia* woodlands of the Sudanian region, the *Acacia* woodlands of the Sahel and East Africa, and the extensive *Miombo* woodlands of the Zambezian region [98,168,178,180]. African woodlands have high diversity and endemism of plant species [98]. The woodlands are also crucial for water resources management given that most major water basins in sub-Saharan Africa are either located in or have their headwaters in woodlands [98]. Woodlands are also a source of diverse wild foods and medicinal plants, providing a safety net in times of crop failures [179]. African woodlands are currently threatened by policy failures, extensive conversion to cropland, over-exploitation, charcoal, and wood-based fuel use, changing fire regimes, climate change, and overgrazing [98,179].

Conservation

Given their socio-economic and carbon storage potentials, conservation of African woodlands is essential for climate change adaptation and mitigation [98]. Although only few woodland-specific climate actions exist [181] , the available literature suggests there is great potential for both mitigation and adaptation actions [182]. For instance, woodlands store substantial amounts of carbon with 40 - 70% of carbon stored in soils [98,172,178]. Conversion of woodlands to agriculture significantly reduces aboveground carbon stocks coupled with a narrowing of the range of soil C stock relative to intact woodlands [172,178]. Therefore, conserving existing woodlands is not only essential for continuous provision of ecosystem services, but also critical for reducing CO_2 emissions [98,179].

Improved Management

Improved management of woodlands is essential to securing the integrity and ecosystem services provided by woodlands, particularly under current regime of climate change. Climate change is predicted to affect woodland plant reproductive success, overall plant productivity and fire regimes that should lead to significant changes in the composition, structure, and functions of woodlands [183] and adaptative management approaches are required to ensure long-term sustainability [98]. Improved woodland management is particularly important given that even matured stands have potential to accumulate additional carbon [98,173].

Existing knowledge suggests that improved management of woodlands can promote biodiversity and carbon storage [98,168,178]. One proposed approach to increase carbon storage in woodlands is to either reduce fire frequency or season [184–186] . Early dry season fires tend to be less destructive compared to late dry season fires [178,187]. However, across natural woodland areas, a given site rarely burns every year and at the same time [178,188] suggesting that appropriate management should rather adopt variability in fire season and frequency. Importantly, experimental evidence of the impact of combined season and fire on composition, structure and dynamics of woodlands are lacking [178]. Notwithstanding, biome appropriate levels of grazing and fire tend to increase the diversity of forbs, with fire promoting species richness and abundance of annual and perennial grasses whereas grazing favored the diversity of perennial grasses [189,190].

Given their ecology and carbon sequestration potential, woodlands are particularly suitable for international government mechanisms such as payment for ecosystem services, REDD+, and other carbon trading instruments [98,186]. However, the effectiveness of these mechanisms in supporting improved woodland management and generating local socio-ecological benefits remains uncertain [191].

Restoration

Restoration of Africa's woodland also has great promise for both biodiversity, carbon sequestration and rural livelihoods. A significant area of the original woodland biome in Africa has been lost to other land uses or degraded [168,174]. Restoration of degraded or converted woodlands using natural regeneration and indigenous trees is considered the most promising adaptation strategy [192]. Indeed, allowing abandoned agricultural lands to regrow naturally has shown substantial aboveground carbon gains with carbon accumulation continuing even after 20 – 50 years [173] suggesting high mitigation potential. However, soil carbon stocks in regrowing woodlands remain low even after 60 years relative to intact woodland [98,173,193]. Importantly, woodlands can regenerate easily following abandonment of farm, but variations exist in the rate of recovering and is influenced by factors such as land use history and regeneration methods [98,194]. For instance, regrowing woodlands had similar species diversity compared to intact woodland, but woodland indicator species were missing from the regrowing site, suggesting slow recovery of matured woodland composition [173] and the need for some active planting interventions. Woodland restoration success is likely facilitated by reforms in natural resource governance that allows for decentralization of decision making and equitable benefit sharing [191,195].

Savannas and Grasslands

Savannas and Grasslands are the most dominant ecosystem type in Africa [8,71]. Africa's savannas and grasslands are species rich, store substantial amount of carbon and are home to and a source of livelihood for many people. Africa's savannas and grasslands are distinct from forest in terms of tree cover [196,197], composition and physiognomy [198–200], carbon stocks and energy budgets [201,202], functioning and management [59,203]. Regular disturbances, in the form of fire and herbivory, are important determinant of the structure and functioning of Africa's savannas and grasslands [59,167,169,204]. Although collectively treated as a single homogenous biome, Africa's grasslands and savannas are diverse in their composition, structure, and functioning and reflect sub-regional differences [69,73,205]. These differences have important implications for appropriate management of Africa's savannas and grasslands.

Conservation of savanna and grasslands

From grasslands/savannas to farm or croplands

A substantial area of Africa's savannas and grasslands have been converted to farmlands and other land use types [71]. All case studies examined – from Burkina Faso, Kenya, Uganda, Benin, Niger, and Zimbabwe – suggests that conversion of natural grasslands and savannas to farmlands are associated with drastic biodiversity loss [206–209] and entails high carbon cost [208,210,211]. The impact of conversion of natural grasslands and savannas to farmlands has far reaching consequences for whole ecosystem functioning. For instance, recent regional trends suggest significant declines in burnt area – i.e., changes in savanna fire regime – in Africa [212–214] driven by cropland expansion and human influence [215–217]. Similarly, decline in wildlife biomass and replacement by livestock in many parts of Africa is shifting historical herbivory regimes [171,175]. These changes in disturbance regimes are expected to and are already affecting species composition and structure of savannas and grasslands [59].

Afforestation

Afforestation involves planting trees or creating forests on lands that historically had no forest cover [218]. Afforestation and tree planting in savannas and grasslands has been proposed as an effective CCMA option with huge potential for carbon capture [57,219]. In response, several large-scale afforestation and tree planting initiatives – such as AFR100 and Great Green Wall – have been instituted across grasslands and savannas in Africa. The benefits of such large-scale afforestation projects in grasslands and savannas are strongly contested [9,10,61,64,220].

The case studies examined provided inconclusive SOC benefit of afforestation in grasslands and savannas. Net SOC benefit of afforestation ranged from positive [221], negative [221–224] to neutral [221,222]. However, the case studies examined were highly critical of afforestation of grasslands and savannas citing numerous negative impacts of such initiatives. For instance, several studies have demonstrated negative impact of afforestation in grasslands and savannas on hydrology and water availability in semi-arid and arid environment [225–227]. Large scale afforestation projects in savanna and grasslands are also predicted and observed to negatively impact biodiversity and local livelihoods, particularly through it impacts on rangeland resources [9,75,228–231]. Indeed, it has been demonstrated that once afforested, grasslands and savannas are particularly difficult to restore [232], highlighting the need for careful consideration of large-scale afforestation projects in Africa.

Inspite of this, several case studies showed spectacular examples of successful local and community-based tree planting initiatives targeting land restoration and livelihood improvement with carbon and biodiversity co-benefits [229,233–237]. These local examples demonstrate that tree planting integrated into local land-use practices can have huge carbon, biodiversity, and livelihood benefits. However, existing global finance mechanisms that focus primarily on tree cover and carbon stocks will be inappropriate for protecting Africa's savannas and grasslands. Rather, financing mechanisms – i.e., REDD$^+$ equivalent for savannas – that favour the management and conservation needs of Africa's grasslands and savannas will have significant positive impact on biodiversity conservation, carbon emission and livelihoods [238].

Improved management of savannas and grasslands

Improved management of savannas and grasslands is required to ensure the maintenance of vegetation structure, functioning, and the continuous provision of ecosystem services. Several climate change mitigation and adaptation options are proposed for savannas and grasslands often focusing on fire and grazing management with the goal of enhancing carbon stocks in these systems. However, sustainable management of Africa's savannas and grasslands ought to target not only carbon gains but also focus on conserving the unique biota of Africa as well as enhancing socio-economic and cultural needs of the local communities. Here, we review the major CCMA proposals made for Africa's savannas and grasslands.

Fire management

Fire is both a disturbance factor [203,239,240] and a management tool [161,241,242] for savannas and grasslands. A major proposal made for fire management in savannas and grasslands for climate change mitigation is to reduce or avoid savanna burning (i.e., fire frequency) and/or change fire season (i.e., promote early dry season burning over late dry season burning) [184,243,244]. Indeed, savanna burning emit substantial quantities of GHG emissions such as carbon dioxide, methane, and nitrous oxide [245,246] and under the Kyoto protocol, avoided "savanna burning" is identified as major GHG abatement activity [243]. Successful deployment of fire abatement projects in Australian savannas has led to calls for large-scale implementation of similar approach in Africa [243,244].

The case studies examined suggested that large-scale fire abatement or change in fire regime in Africa: 1) 1) is likely impractical to achieve [247] ; 2) does not consider current trend and changes in fire and burnt area [213,217] and the impact on savanna and grassland vegetation [248] ; 3) the scientific basis for such large-scale proposal is currently weak [247]; and 4) proposed fire regimes are decoupled from human livelihood activities in Africa [215]. Indeed, within the African context, there is an observed decline in savanna fires [213,217] due to human population growth and cropland expansion [248]. Given the importance of fire in reducing tree numbers in savannas [203,249,250], such decline in fire activity is currently driving widespread bush or woody encroachment of Africa's savannas and grasslands [248,251–254].

Fire frequency

Although savanna and grassland fires in Africa's are influenced by humans, not all aspects of fire can be easily controlled by humans or management practices, emphasizing the difficulty of deploying large-scale shift in fire regimes. For instance, fire-return interval and radiative power in Southern African is less influenced by human activity [216]. Similar, evidence is found in Kruger National Park. Here, although management activities affected spatial heterogeneity and seasonal distribution of fire, fire frequency and the area that burns in any given year were less influenced by management approach [241]. These and several other evidence point to the difficulty of enforcing drastic changes in fire use and management in Africa. Indeed, local communities and resource managers in Africa have adopted variable fire and burning practices suited to their local needs and management goals [161,247].

Fire season

There is substantial evidence that fire season affect emission characteristics in Africa, but the case studies examined lend little support to the emission reduction benefits of early dry season burning. Indeed, combustion efficiency, the type and quality of carbon emissions follow seasonal trends in Africa correlating with metrics of vegetation moisture [246,255–258]. However, emission ratios between early and late dry season burning differ significantly across savanna and grassland types. For instance, early burning in grasslands may lead to higher number of products of incomplete combustion compared to late dry season burning [257]. In contrast, early dry season burning in woodlands results in lower emissions in both products of complete and incomplete combustion [257]. Laris et al. [246] concluded, based on extensive analysis of methane gas emission from savanna fires of West Africa, that policies aimed at shifting savanna and grassland burning to early dry season fire will likely yield very little impact on emissions. Essentially, people in Africa already set large numbers of early dry season fire such that the proposal for shifting fire regime will not drastically change the current burning practices [161,242,247].

Soil carbon stocks

Soils of savannas and grasslands hold substantial amount of carbon and contribute significantly to global soil organic carbon (SOC) and total ecosystem carbon (TEC) [259]. In grasslands and savannas, about 50% of the total ecosystem carbon stocks are stored belowground [202,260]. Soil organic carbon is in a relatively stable form and once sequestered is less vulnerable to anthropogenic removals. Therefore, conserving existing soil carbon in savannas and grasslands and enhancing soil carbon accumulation is essential for climate change mitigation [259,261].

For both savannas and grasslands, the case studies examined indicates that moderate or biome-appropriate fire and grazing regimes do not adversely impact SOC and in some cases can improve SOC compared to extremes (e.g., high frequency fires, overgrazing or total fire/grazing exclusions). In the grasslands and savannas of Africa, disturbance (fire and herbivory) has variable effects on tree cover and grass biomass [262–264] and ultimately SOC and TEC. Broadly put, fire decrease [265], increase [266] or have no effect on SOC [267,268] depending on the vegetation type, climate and soil type. A recent study evaluating 60-year fire exclusion experiment in South Africa demonstrated that fire exclusion only marginally increased TEC, suggesting that frequently burned savannas in Africa store substantial belowground carbon, especially in biomass and deep soil layers [269]. Similarly, herbivory tend to have variable impact on SOC depending on vegetation, climate, and soil. However, overgrazing generally leads to a reduction of SOC across distinct grasslands and savannas in Africa [261,270–273].

Balancing carbon, ecosystem functioning and biodiversity objectives in savannas and grasslands

Climate actions targeting carbon storage (either SOC or TEC) by introducing large scale changes in fire and herbivory regimes are likely to trade-off with ecosystem functioning and biodiversity conservation. There is substantial scientific evidence that fire and grazing are required to reduce tree cover and maintain open canopies savannas in Africa [169,203,240,249,250,261,263,274,275]. Such open canopies are essential for maintaining grass biomass and the diversity of the herbaceous ground layer [199,202,276] upon which a variety of life-forms depends [275,277,278]. Indeed, the positive relationship between biome appropriate fire and grazing regimes on biodiversity in grassy ecosystems have been sufficiently demonstrated (W. J. Bond & Parr, 2010; Braithwaite, 1996; Maravalhas & Vasconcelos, 2014; Smit et al., 2010). Therefore, global climate actions designed to increase carbon storage in savannas and grasslands are unlikely to meet the management goals of grasslands and savannas which is mainly to balance carbon management priorities with ecosystem function, biodiversity, and socio-economic priorities (Hanan et al., 2021).

Bush and woody encroachment

Bush encroachment – i.e., increasing woody cover and biomass in savannas and grasslands – is currently widespread across Africa [248,253,279] and represent a major challenge to sustainable management of savannas and grasslands [252]. Although still debated, bush encroachment in savannas and grasslands is attributable to increase atmospheric CO_2, warmer and wetter climates, and declines in fire and herbivory [248,251,279,280]. There are ongoing debates on whether bush encroachment will have net positive or negative effects on grasslands and savannas, particularly considering the potential carbon gain from increased woody biomass [254].

The case studies examined indicates that TEC and SOC response to bush encroachment is variable and contingent on climate and topo-edaphic conditions. For instance, SOC increased under bush encroached sites in drier environment but decreased under wetter conditions [281] in a South African grassland. A meta-analysis involving 142 studies showed that woody encroachment resulted in significant changes in topsoil SOC, but this was contingent on soil type and rainfall [282]. Their study found that SOC, under bush encroachment, increased only in semi-arid and humid regions and that soil properties were the primary factors responsible for changes in SOC [282]. Generally, these observations suggests that carbon gain because of bush encroachment is highly variable and dependent on climate and rainfall conditions [283].

The case studies examined clearly pointed out that bush encroachment in grasslands and savannas is often associated with loss of biodiversity and ecosystem services. For instance, an evaluation of the impact of bush encroachment on the grassy ecosystems of South Africa concluded that bush encroachment leads to significant biodiversity loss and ecosystem services but yields overall carbon gain [252]. There is now increasing evidence that bush encroachment leads to declines in vertebrate, mammalian and herpetofauna diversity, especially at low net productivity [284] ; termite activity [285]; and mesocarnivore scavenging activity [286] in African grasslands and savannas. Importantly, a meta-analysis involving 43 studies of the impacts of bush encroachment globally concluded that shrub encroachment had negative effects on vertebrate richness and diversity particularly in Africa [284].

Several examples of successful management of bush encroachment in African savannas and grasslands exist [287–289]. Methods for controlling and managing bush encroachment include use of fire [290,291], mechanical and chemical shrub and tree removal [292], thinning [293], and variable livestock grazing [287,294]. These case studies suggest that often, single methods applied individually are less effective compared to integrated approaches such combination of fire, grazing and thinning [295].

Restoration of grasslands and savannas

Restoration of grasslands and savannas can contribute substantially to climate change adaptation and mitigation. Because they store substantial carbon [296] , there is a huge climate benefit of restoring degraded grasslands and savannas either through the conservation of existing carbon stocks [297] and or new sequestration by regrowing grasses [298]. Grassland and savanna restoration face several challenges including past land use practices (e.g., afforestation) [232,299] and climate change and variability [238,300]. Inspite of these challenges, several examples of successful grasslands and savannas restoration exist [301]. Examples of restoration approaches involve simply removing pressures and allowing natural recovery [302]; fire management [243,303] and grazing management [304,305]. Other successful restoration approaches include use of traditional and indigenous knowledge [306] and direct seeding [307,308]. In dry and arid climates, integrating irrigation with other restoration measures facilitates establishment and restoration [309].

Rangelands

Rangelands are lands on which the vegetation is composed predominantly of grasses, grass-like plants, forbs, or shrubs – often with or without trees – that are grazed or have the potential to be grazed by livestock and wildlife [67]. Most of the grassy ecosystems of Africa – i.e., grasslands, savannas, woodlands, and open forests – are grazed by livestock or wildlife and are therefore rangelands. Importantly, Africa is home to over 40 million pastoralist that depend on rangelands for their livelihood [3,50,56]. Rangelands provide substantial ecosystem services [310,311] carbon storage and CO_2 sequestration benefits [312,313]. All issues discussed under woodlands, savannas and grasslands are also applicable to rangelands. However, in this section, we highlight more of climate actions targeting grazing management on rangelands. We distinguish rangelands from pastures – which is treated under sustainable agriculture – and focus here on naturally occurring grazing lands.

Grazing management

Most climate actions on rangelands focus on conserving and increasing soil carbon stocks through changes in land use practices. Given that rangelands are rarely tilled, increased SOC generally relies on C inputs from plant roots and residues [314] . There are several ways by which C inputs can be enhanced for increased SOC. This includes regulating plant biomass removal by grazing, increasing forage production using improved species, irrigation, and fertilization [314]. A recent meta-analysis showed that improved land management – including grazing management – do lead to increase SOC [312,315]. Indeed, several studies demonstrated the impact of grazing management on SOC exist [229]. However, these case studies indicate that the effect of grazing management on SOC is dependent on rainfall variability (total quantity and variability) [316–318]. Under 600mm of annual rainfall, inter-annual variability in rainfall has larger impact on SOC than grazing [229,316]. Above 600mm of annual rainfall, grazing leads to a reduction of SOC [318,319]. Given that pastoralism – which is the dominant livestock production system – in Africa involves high mobility and opportunism and follows seasonal trends in resource available [305,306,320], the total impact on SOC is likely minimal.

Conservation and restoration of plant and soil resources are key to enhancing SOC in rangelands [312]. Therefore, there has been significant interest in promoting short-intense rotational grazing as a more viable grazing strategy for productivity and improved soil conditions [314]. Short-intense rotational grazing is thought to facilitate conservation and restoration of plant and soil resources as well as reduce rangeland degradation. Several experimental evidence suggest that intense-short rotational grazing do indeed increase SOC rapidly in abandoned farmlands [321] and under commercial pasture [322]. However, some case studies questioned the ecological efficiency of rotational grazing over continuous grazing [323,324] . For instance, a synthesis of several studies observed that plant production and animal production per head per area was either equal or higher for continuous grazing relative to rotational grazing [325]. These contrasting results suggest that differences among the two grazing systems are largely context dependent and that additional research is required for better understanding of grazing system and SOC [314] . In the African context, rotational grazing is the norm among both settled herders and pastoralists [50,306].

Holistic management (HM)

Holistic management (HM) has been proposed as an integrated sustainability concept with great promise and potential for grassland restoration, reversing desertification, climate change mitigation and adaptation as well as increased food and fibre production [326–328]. The HM approach is similar to all major global sustainability frameworks in that it advocates for integration of the ecological, economic, and social aspects of grazing management. It recognises that social and economic well-being of herders or pastoralists are linked to the health of the land [329]. It further identifies continuous movement and grazing actions – such as grazing, defecation, stomping, salivation, etc. – of native wildlife population as major determinants of grassland health [329,330]. Thus, loss and replacement of native wildlife with smaller sedentary livestock leads to biological decay of soils and grassland vegetation. In this respect, HM proposes mimicking native wildlife behaviors by strategically planning grazing using short-intense grazing rotations – referred to as Holistic Planned Grazing (HPG) [327,329].

Although HM is widely adopted and has been practiced for over half a century, its central tenet is still strongly contested in the scientific literature [330]. For instance, the claim that short-intense rotational grazing is ecologically efficient than continuous grazing is still widely debated [323–325]. Further, a recent review concluded that HM's intensive rotational grazing approach either had no effect or reduced production across farms in the united State, Argentina, and South Africa [331]. However, several published studies have also found that, if practiced appropriately, HPG results in positive ecological outcomes [321,330,332]. Importantly, controversies on the HM approach stems from miscommunication and inconsistent use of terminologies by both proponents and opposing camps [330]. Therefore, clarifying the key concepts of the HM approach and its associated practices is key to reconciling the differences and controversies [330].

The Wilder Rangeland Concepts (WRC)

The wilder rangeland concept is currently promoted as an innovative rangeland management approach with substantial climate change adaptation and mitigation benefits [333]. The WRC approach has two distinct forms. The first approach involves replacing managed livestock with harvestable communities of native wild herbivores [333]. The second approach involves "rewilding" of livestock grazing practices through learning from wild grazing systems. Two types of rewilding are also recognized. One form of rewilding involves adding herbivores and predators to places where they have been extirpated. In contrast, the second rewilding approach entails mixing livestock with wildlife [333,334].

The WRC approach is thought to have several climate change mitigation and adaptation benefits. For instance, species-rich wild grazing systems often have high numbers of non-ruminant species that directly reduces methane emission at the landscape level [333,334]. Further, large herbivores emit more methane per unit biomass than smaller ones [215], therefore changing size-class distribution of herbivores in a rangeland can reduce whole-landscape emission factors. However, there is little empirical data and examples in Africa [335].

There is also evidence that adding elephants to rangelands can improve SOC [336,337] despite significant reduction of aboveground woody biomass [250,338]. Importantly, adding wild grazers, such as elephants and rhinos, to rangelands reduce fire impacts through the consumption of grass phytomass [339–342] and thus contribute to methane and carbon dioxide emission reduction.

The WRC approach, particularly rewilding by adding wildlife to livestock systems is touted as an approach that improves farmers and herders' welfare. Some evidence exists that suggest rewilding may increase and diversify revenue streams and make livestock production more resilient to climate and economic shocks like droughts or changes in commodity prices [340,343]. Inspite of its potential benefits, large-scale adoption of WRC in Africa is likely to be constrained given existing land tenure system and human-wildlife conflicts [335].

Arid Zone, Deserts and Desertification

About a third of the land area of Africa is arid and deserts [70]. Africa host two main desert formations, namely the Sahara (in northern Africa) and Namib (southern Africa) deserts. Deserts are land areas with extensive bare grounds and sparse plant cover. Most species in desert occur at the physiological limit of their range. Inspite of this, variable plant growth forms – such as shrubs, forbs, succulents, etc. – and diverse desert vegetation types exist in Africa [344–346]. In addition to the existence of the two major desert systems in Africa, several Africa countries are also experiencing significant rate of desertification which is expected to have negative impacts on economy, ecology, and society [347–350]. Land use change and climate change are also expected to further accelerate desertification [6,26].

Although the core desert area in Africa has expanded over the twentieth century [351], projections indicate that it is likely to contract in the twenty-first century [352] due to potential increase in precipitation [353]. Such changes in Africa's desert cover will have significant consequences both regionally and globally. This is because the deserts of Africa provide important ecosystem services. For instance, dust transfer from the Sahara Desert is known to fertilize the Amazon Forest and the Equatorial Atlantic Ocean [354–356]. The high albedo of deserts also plays a key role in global land-atmosphere feedback system [357,358]. Importantly, across the world, arid areas and deserts are getting greener due to CO2 fertilization effect [359] and therefore contributing to climate change mitigation.

Generally, climate change adaptation and mitigation actions in respect of deserts and desertification focus on 1) increasing contribution of deserts to mitigation through increase in plant cover, 2) reducing and reversing desertification, and 3) harnessing the renewable energy potentials of deserts. Although some case studies suggest that afforestation in deserts can increase plant cover and improve climate [360], there is dearth of evidence in support of this claim in Africa. Instead, the limited evidence suggests that large scale afforestation in arid and desert environments is likely ineffective due to high mortality [237] and may even worsen climatic conditions in some cases [361].

Several case studies focusing on reducing or reversing desertification was reviewed. There is a consensus across the case studies that land degradation is a major challenge for most African countries [26,105,347,348,350]. Indeed, Africa's flagship programme, the Great Green Wall, is in direct response to the notion of increasing desertification [235,362]. However, several case studies were critical of the use of the term "desertification" and suggested that what is being experienced is land degradation arising from over-exploitation of natural resources rather than a southward expansion of the Sahara deserts [348,363,364]. These authors indicated that wrongly framing the issue as desertification leads to promotion of large-scale afforestation projects that are decoupled from the root cause [365]. Indeed, several examples exist that demonstrate that local level actions to restore degraded land tend to be more effective than large scale afforestation efforts [366–368].

Africa's population is rapidly growing, and energy need will continue to outpace supply. In this regard, most Africa countries have turned their attention to renewable energy sources such as photovoltaic solar and wind farms [42]. Several proposals have been made to deploy large-scale photovoltaic solar and wind farms in Africa's deserts to generate sustainable energy for both Africa and Europe [369]. The potential benefit, negative impacts, and appropriate technologies are still being discussed [370]. However, proponents of the project envision substantial climate benefits through reduction in use of fossil fuel in electricity generation and local climate benefits. For instance, one study concluded that large-scale solar farms in the Sahara Desert is likely to cause more local rainfall, particularly in the neighbouring Sahel region, [371] which should lead to increased vegetation cover and carbon sequestration. In contrast, another study observed that adverse remote effect of solar farms in the Sahara Desert will offset any regional benefit [372]. The study observed that such large-scale solar farms over the Sahara Desert will lead to substantial Amazon drought and forest degradation, increased surface temperature, sea-ice loss, reduced El Nino-Southern Oscillation and Atlantic Nino variability and enhanced tropical cyclones [372].

3.3 Agriculture

Agriculture is a major contributor to the economy, livelihoods, and lifestyle of Africa. Africa accounts for 15% of global cropland, 20% of global pasture, and 7% of global value of agriculture and fish production in 2018 – 2020 [373]. The agriculture sector of Africa is composed of four main subsectors, namely, crops, livestock, fisheries, and forestry. The crop subsector is made up of the industrial crops or cash crops (tree crops such as cocoa, oil palm, rubber, etc.), staples (starchy, tuber, roots, cereals, and legumes such as rice, maize, yam, cassava, etc.) and horticultural crops (fruits and vegetables). The livestock subsector includes poultry, sheep and goats, dairy, pork, beef, and other lesser reared species. The fisheries subsector encompasses marine fishery, inland fishery, and aquaculture. The forestry subsector includes logging and wood processing, ecotourism, and wildlife.

Agriculture, fisheries, and forestry accounts for 14% of Africa's Gross Domestic Product (GDP) but this is expected to decline by 2030 [373]. The crop subsector is dominant and accounted for almost 85% of total agricultural production value between 1990 to 2013 with West and Southern Africa contributing 60% and 22% of agricultural output in Sub-Sahara Africa over the same period [373]. Importantly, the agricultural sector employs more than half (53%) of the total labour force in Africa [374]. Given the high population growth rate in Africa, closing this huge yield gap is essential for ensuring food security and economic welfare. Closing the yield gap will require increase in agricultural inputs (e.g., organic, and inorganic fertilizer), improved germplasm, efficient agronomic and water management practices [375–377].

Agricultural growth in Africa is likely to interact with climate change which may amplify the challenges in the agriculture sector. On one hand, there is high potential for agricultural expansion in Africa in terms of both value addition and transition from traditional exports to high-value and processed commodity exports [378] as well as suitable land area for expansion [379]. However, such expansion is likely to increase direct emissions of GHG from agriculture in Africa. Indeed, GHG emissions from agriculture in Africa is expected to increase to 16% by 2030 and account for 62% of global increase in direct emissions from agriculture [373]. Importantly, Africa is the only region in the world where rural population is expected to increase (53% of population in rural areas) by 2030 [373]. This implies that rural labour will increase which may likely trigger shortages in agricultural lands. Under such conditions, climate change impact on productivity and rural livelihood may be severely threatened leading to a cycle of poverty and land degradation. Therefore, addressing issues related to agricultural productivity, climate change and rural livelihoods is critical to achieving the Agenda 2063 [2].

Cropland

Several case studies were examined to identify indigenous crop-based climate change adaptation and mitigation practices, the targeted impacts and actual results achieved. Case studies were mainly from East and West Africa and were from forest [380–382] , grassy [383–386] ,and multiple biomes [387–392]. Most of the case studies examined indigenous adaptation practices with a few focusing on both adaptation and mitigation [383,384,389]. Examined practices covered by the case studies range from Climate Smart Agriculture (CAS), Conservation Agriculture (CA) and land intensification. Analyzed practices include combinations of multiple cropping, intercropping, agroforestry/restoration, mulching, water harvesting, planting drought resistant species, local tillage practices, manure application, adaptive planting season, etc. Adaptation and mitigation practices generally targeted soil fertility, yield, GHG emissions and CO_2 sequestration, drought, flood, windstorm, bushfires, and crop income risks.

Generally, studies reported that adoption of SA practices had positive impacts on productivity (yield), carbon storage and livelihood gains. Most carbon and some livelihood benefits - in terms of aboveground biomass, SOC, and tree-based products – were linked to incorporation of trees in croplands [381]. However, some combination of practices, although delivering positive mitigation benefits (e.g., use of biochar) [384] may incur negative social (health impact) and overall environmental impacts [383]. Surprisingly, biodiversity conservation and gains are generally not evaluated and reported. Lack of finance was reported as the main bottleneck to adopting SA practices, as the initial cost (e.g., buying drought-resistant species or less harmful pesticides) can be extremely high [391]. Importantly, inspite of the benefit and importance of indigenous knowledge and practices in supporting adaptation in Africa, there is dearth of data and information on the cost-effectiveness of these practices, and they are currently not fully considered when designing modern adaptation and mitigation strategies [368,385,390].

Livestock - Pasture

Livestock production in Africa contributes to climate change through emission of GHGs such as carbon dioxide (from burning of pasture and rangelands), methane (by-product of ruminant digestive processes), and nitrous oxide (from mineral nitrogen fertilizer, manure, and decomposition of wildlife excreta). Removing or reducing these sources of emission can contribute substantially to global mitigation efforts [393]. Proposal for reducing livestock-based emissions include improved pasture, intensification of ruminant diet, changes in pasture and rangeland management practices, and changing livestock composition and breeds [393].

The case studies examined covered both mitigation and adaptation practices in the livestock sector used approaches such as emergency folder for drought adaptation, multi-species composition of herds, culling of weak livestock for food, changes in livestock type (e.g., from cattle to sheep or goat), and traditional grazing practices [193,388,394–399]. Adaptation measures from these case studies included cattle watering, fodder, and pasture management [394], rangeland productivity [395], and livestock management [399].Mitigation measures were mainly limited to improved feeding practices and manure management [396–398] and increase SOC [193].

Generally, all adaptation measures were found to have positive impacts on livestock productivity. Similarly, mitigation measures were found to reduce GHG emission and improve livestock productivity. However, production of improved/high quality forage may cause greater emission from land use unless driven by greater fertilizer input [396–398]. For livestock farmers that are unable to afford such high-fertilizer input, land scarcity will make it impracticable for adoption of high-quality forage production. Although there is dearth of data, one case study observed that measures to increase SOC – i.e., grazing and fire management – on pastures, may yield limited improvement. In this study, it was observed that 19 years of prescribed burning and grazing exclusion in West African savanna did not change SOC stocks [193]. One additional case study demonstrated that mixed livestock farms are less vulnerable to climate risk relative to specialized livestock farms, but the latter earn greater income per hectare [399].

Agroforestry

Agroforestry, the incorporation of trees on farmlands, is considered a major climate change adaptation and mitigation pathway [400–402]. The potential benefits of agroforestry are enormous and include provision of fruits and leaves for human consumption, fuel for cooking, fodder for animals, soil water conservation and fertility improvement, disease and pest management, and revenue diversification [234,403,404] . Adoption of agroforestry in Africa is an old practice [405] and variations in on-farm tree cover reflect local communities' experiences [234,406].

Several case studies from Ethiopia [388], Congo DRC [407], South Sudan [408], Nigeria [409], Benin [394], and Ghana [101,410] and across diverse biomes [403,404,406] were reviewed. These case studies examined the impacts of agroforestry on nature conservation, carbon stocks, crop yield, crop survival, pasture, and tree fodder with most assessing multiple environmental and social benefits. The case studies generally confirmed the utility off agroforestry in delivering carbon, biodiversity, and livelihood – linked to sale of tree products – gains across several biomes. Several examples showed that agroforestry practices can be an effective approach to land and ecosystem rehabilitation in both forest and non-forest ecosystems [103,233,237,390,409] and is often in harmony with local land tenure and use practices [129,405].

Inspite of this, a few case studies raised some important potential negative impacts and data gaps of agroforestry. For instance, one study showed that incorporation of some tree species on cocoa farms resulted in increased water stress and mortality of cocoa trees [410]. Similarly, Buxton et. al., [403] reported, inspite of the positive impacts of agroforestry on rural income and climate adaptation, trade-offs between carbon goals and crop yield in agroforestry in Kenya. Importantly, Cristina et al., [404], observed that, inspite of the general perception of the benefit of regenerating trees on farms, there is little mechanistic understanding relating how context conditions affect the diversity and abundance of regenerating trees and how this is related to ecosystem function and livelihood benefits. These observations suggest that inspite of its promise, more studies from different context are required to improve understanding of when agroforestry may be maladaptive.

3.7 Urban

Climate change is expected to have substantial impacts on Africa's cities and urban centres. Africa's cities and urban centres have low capacities to respond adequately to the threat of climate change due to a combination of high exposure (most key African cities are coastal), increasing urbanization, poor urban infrastructure, limited institutional and technical capacities, and limited adaptation opportunities. Given the high exposure and low adaptive capacities of African cities and urban centres, strengthening their climate resilience is fundamental to mitigate the negative impacts of climate change. Surprisingly, there is a dearth of case studies providing empirical evidence of successful adaptation and mitigation strategies for cities and urban centres in Africa.

The few case studies reviewed covered adaptation issues but were mostly exploratory providing analysis of potential approaches to sustainable climate change adaptation and mitigation. These included issues such drainage and flood management [411–415], urban green infrastructure and natural resource use [416–420], water and watershed use and management [421–425], spatial planning [426–428], and institutional and governance approaches [412,429].

Although from disparate viewpoints, these case studies generally suggested that successful climate change adaptation and mitigation in African cities requires multi-sectoral approaches. Such multi-sectoral approach needs to be built on strong coordination across all governmental levels and must involve all relevant stakeholder groups (local, national, and international). The role of local actors – such as local governments, community-based organization, non-profit organizations, etc. –, participatory learning and knowledge sharing, biodiversity actions, and integrated and sustainable resource management are particularly highlighted.

3.8 Cross-cutting themes

Wood harvest

Natural forests, woodlands and savannas provide wood products that are important to people's livelihoods. Reducing wood harvest from these sources through different techniques could maximize carbon sequestration while meeting people's demand for wood fuels. There is always an inherent trade-off between socioeconomic benefits and conservation across all land use types, particularly in the context of wood harvesting in Africa [430]. The production and use of wood fuel is a significant socio-economic activity in Africa with over 60% of the population relying on wood fuel as the primary source of household energy. Examination of cases studies across Africa shows that wood harvest from natural sources is substantially minimized when communities are provided with efficient cooking stoves. For instance, one case study showed that use of efficient cooking stove maximized the forest carbon store by avoiding emissions of 2.2 tons of CO_2 per household per year in Mali and 150,000 tons of CO_2 per year in Ghana [431]. Similarly, the use of cooking stoves and biogas in east Africa has huge potential to prevent 0.562–5.673 million tons of CO2e emissions per country per year from wood harvest [432]. Importantly, the provision of efficient stove also has the co-benefit of improved health conditions of rural households [433] and saving time for children and women [434]. Overall, the case studies examined across the continent showed that maximum carbon store in natural ecosystems could be attained with avoided wood harvest practices by providing alternatives to improve the socio-economic status of the local communities.

4.0 Data and knowledge gap in climate actions

Overview

Several climate actions have been proposed for Africa. In Chapter 3, we undertake extensive review of case studies to identify evidence supporting the appropriateness or otherwise of these climate actions. Through these reviews, we also identified significant knowledge and data gaps that need to be addressed to enhance climate actions on land in Africa. As pointed out in Chapter 2 and 3, Africa's ecosystems are unique – for instance, it is the only continent with complete wildlife assemblage – and diverse. Importantly, most Africans are employed in climate-sensitive sectors where impact of climate change or climate actions can have direct and significant impacts on their livelihoods. Therefore context-specific climate actions that improves ecosystem functioning, biodiversity and livelihoods are particularly desirable for Africa. Developing such context-specific actions requires climate data and information that have been verified and validated across Africa. Here, we highlight the main knowledge and information gaps that are critical for enhancing climate change adaptation and mitigation on lands in Africa.

Cross-cutting themes

1. **The mitigation potential of Africa** – As shown in Chapter 2 and 3, several climate actions proposed for Africa often emphasize the huge mitigation potential of the continent. For instance, climate action targeting reforestation, afforestation, fire in grassland or grazing management commonly tout the mitigation potential of these actions. However, data on exact figures or estimates of mitigation potential across climate actions, ecosystems and land use types, and sub-regions are lacking. Importantly, it is uncertain whether global estimates – e.g., GHGs emission reduction from changing fire frequency and season – are realistic for Africa given that such estimates and proposals are often met with fierce criticisms from African scientist and researchers.

2. **The limit of adaptation in Africa** – Africa's ecosystems, economy and livelihoods are all predicted to be significantly affected by ongoing climate change. The extent to which climate change will impact socio-ecological systems in Africa are still being investigated. A major concern for climate change adaptation and mitigation in Africa is the limit to adaptation with increasing global warming. Currently, data and knowledge of the climatic sensitivity and the tipping points for the various socio-ecological systems in Africa under different climate change scenarios remain unknown.

3. **Cost-benefit of large versus local scale climate actions** – Most climate actions proposed for Africa, particularly those driven by external agents, often target large-scale deployment. However, the evidence gathered from the case studies suggests that local-scale initiatives often work better, are cost-effective, suited to the context, and deliver multiple benefits

across all ecosystems and regions. However, studies assessing the effect of scale on cost-effectiveness of climate actions in Africa are lacking. Such knowledge is crucial to inform policy, planning and practice of climate actions in Africa.

4. **Evidence for effectiveness of nature-based solutions (NbS) is lacking** – currently NbS projects are highly recommended and widely practiced for climate change adaptation and mitigation. However, in Africa, there is limited evidence of the effectiveness of NbS. For instance, the NbS evidence ((https://www.naturebasedsolutionsevidence.info/evidence-tool/) platform currently list only few case studies from Africa. Given that NbS involves working with nature and people, understanding it effectiveness or trade-offs under different context is crucial for upscaling.

5. **Gender and social inclusion in climate actions** – In reviewing the various case studies, we observed that there is little to know consideration of gender and social issues in relation to most proposed climate actions in Africa. Some studies consider gender and age-based variations in climate change sensitivity and adaptation practices in Africa. However, there is complete silence on gender and social inclusion in relation to climate actions, particularly those linked to improved management and ecosystem restoration. Understanding the gender and social gap in climate change adaptation and how climate actions are likely to impact this gap is crucial for effective policy development in Africa.

6. **Conserving the genetic resources of Africa** – As pointed out in section 2.4, climate change adaptation and mitigation in Africa will rely heavily on natural the genetic resources of Africa are fundamental to climate change adaptation. However, there is inadequate information on the conservation status of plant genetic resources and utilization across Africa. Importantly, there is a critical knowledge gap on how current biodiversity conservation policies and plans relate to climate change adaptation and mitigation strategies. Evaluating existing policy framework for genetic resource conservation - e.g., storage of high biodiversity in DNA and seed banks, ex-situ, and in-situ conservation, etc – in Africa and their linkages with climate actions is crucial for effective climate change adaptation and mitigation policy development.

Data and research gaps for forest and mangrove climate actions.

7. **Forest and mangrove response to climate change in Africa** – As outlined in sections 3.2 and 3.3, climate actions for forest and mangroves are crucial for climate change adaptation and mitigation in Africa. However, there is insufficient data and understanding of forest response to climate change in Africa. Generally, African countries have limited research infrastructure and funding which significantly hamper climate research. For instance, Africa is often poorly represented in most global databases of inventoried and surveyed

plots (see for instance https://bien.nceas.ucsb.edu/bien/ and https://forestplots.net/). There is therefore limited understanding of current and future impact of climate change on forest and tree resources under varying land use context.

8. **Improved forest and mangrove management** – the case studies examined highlighted potential trade-off associated with prescriptions for improved forest and mangrove management. For instance, actions to enhance carbon sequestration or storage were found to trade-off with biodiversity conservation and livelihoods of local communities. Despite this, there is dearth of knowledge of how the strength of this trade-off varies across forest and land use types. Closing this knowledge gap is essential for improving synergies between climate, biodiversity, and livelihood goals through sustainable natural resource management.

9. **Forest and Mangrove restoration pathways** – Natural regeneration, mixed species plantation, and single-species monocultures were identified as the main forest and mangrove restoration options. However, the review only identified few studies on each of these restoration options. Currently, there is limited qualitative evidence of the benefits and trade-offs associated with each of these restoration options. More studies across forest and land use types are required to appropriately examine the carbon, biodiversity and livelihoods benefits of each of these restoration pathways.

10. **Landscape sustainability initiatives** – Novel landscape sustainability initiatives were highlighted in the review as being particularly promising for reducing conflict and trade-offs between carbon, biodiversity, and livelihood goals. However, only few such initiatives exist in Africa and so far, rigorous scientific analysis of their workability is lacking. Further studies are required to assess whether such initiatives can enhance climate actions on land in Africa.

Data and research gaps for climate actions in grassy ecosystems

11. **Extent of grassy ecosystems in Africa** – At the core of most scientific disagreements on climate actions in Africa is whether proposed actions are appropriate for the ecosystem targeted. There has been a long-standing disagreement on the definitions and classifications of Africa's ecosystems, particularly grassy ecosystems. Although biome maps – such as the UNESCO/AETFA/UNSO Vegetation Map of Africa exists – there is often disagreement on which vegetation types can be classified as "grassy" and "forest". For instance, there is strong disagreement on whether miombo woodlands are grassy ecosystems or forest. Ecosystem definition has implication for management and climate actions (see section 2.9). Therefore, it is essential to map and quantify the extent of various grassy ecosystems in Africa to serve as baseline for climate action appraisal, monitoring, and evaluation.

12. **Total ecosystem value (TEV) of Africa's grassy ecosystems** – Inspite of their enormous economic, social, and ecological contributions, the total ecosystem value of grassy ecosystem has been hardly estimated. As a result, most climate actions proposed for grassy ecosystems assume no value or low value of the existing ecosystem. For instance, Bastin et al., [57] identified several of Africa's pristine grassy ecosystems – for instance Kruger National Park – with remarkable levels of biodiversity as degraded and mapped them for restoration through tree planting. Quantifying the TEV of grassy ecosystems in Africa is critical to proper evaluation of the opportunity and trade-off costs associated with climate actions.

13. **Effectiveness of international government mechanisms** – International government mechanisms such as REDD+, PES (payment for ecosystem services) and other carbon trading mechanisms provide financial support and motivation for climate actions in Africa. These instruments have played significant roles particularly for climate actions in forest. However, it remains questionable whether these instruments are effective for Africa's grassy ecosystems. For instance, there is currently no REDD+ type arrangement for avoided conversion and degradation of grassy ecosystems. Importantly, there is dearth of information on whether such instruments or mechanisms can lead to improved management of grassy ecosystems and generate local socio-ecological benefits.

14. **Soil organic carbon (SOC) in grassy ecosystems** – most climate actions for Africa's grassy ecosystem target enhancing above- and belowground carbon (see section 3.4). Increasing SOC is seen as a more sustainable carbon sequestration approach given the relative stability of SOCs under arid and frequently disturbed conditions. SOC levels under different types of grassy ecosystems across Africa remains largely unmapped and GHGs emissions from grassy ecosystems under varying management regimes remains unknown. However, this information is essential to serve as a baseline to guide monitoring for carbon offset trade for grassy ecosystems.

15. **Carbon accounting for grassy ecosystems** – There is increasing understanding of fluxes in carbon capture and emission in grassy ecosystems. Although, tools and methodologies for total ecosystem carbon (TEC) and soil organic carbon (SOC) accounting are being developed and improved, large uncertainties still exist. With these uncertainties, it remains unclear how most proposed climate actions – especially NbS intervention types – will work. Reducing these uncertainties is central to improving carbon accounting and carbon offset trade in grassy ecosystems.

16. **Improved understanding of impact of disturbance on SOC stocks** – As pointed out under section 3.4, fire and grazing are both disturbance factors and management tools.

Unsurprising, climate actions seek to manipulate these factors to either enhance carbon capture or reduce emissions. However, data on impact of fire and grazing management in on SOCs in grassy ecosystems are relatively sparse and slowly accumulating over the past few years. Additional experimental evidence is required to achieve better understanding of the impact of grazing and fire management on SOCs. Importantly, more experimental evidence is required to better understand the effect of new innovative climate actions – such as rewilding and holistic management – on SOCs and other environmental and social co-benefits.

17. **Role of indigenous knowledge for managing grassy ecosystems** – Several case studies demonstrated that indigenous and traditional knowledge can be effective in conserving, managing, and restoring grassy ecosystems. However, rigorous scientific documentation and assessment of the effectiveness of indigenous and traditional practices across grassy ecosystem types and management regimes are currently lacking but is important for improving climate actions.

Data and research gaps for agriculture.

18. **Agroforestry in arid and dry lands** – As pointed out in section 3.6, agroforestry practices have unique value for nature conservation, carbon stocks and rural livelihoods. However, there is low adoption of agroforestry under arid conditions due to impact of climate change, browsing animals and fires on tree regeneration. Improving seedling establishment and growth under arid conditions is central to promoting adoption of agroforestry. Although information is generally available, effort to promote low-cost and best practices for tree regeneration under arid conditions is currently limited. Improved education and demonstration are required to motivate farmers interest in agroforestry in arid zones.

19. **Benchmarking sustainable agricultural practices** – Sustainable agriculture (SA) is promoted as an important climate change adaptation and mitigation pathway. Under the umbrella of SA are several practices including fertilizer management, agroforestry, improved germplasm, etc. The case studies reviewed in this report generally indicated that SA practices had positive impacts across multiple targets. However, adoption can be low if the specificity of the agricultural ecosystem is not taken into consideration. The concept of "benchmarking" has been proposed as an approach that can match SA technologies to the right site and farming context. However, benchmarks for many SA practices, including traditional and indigenous practices, are currently lacking.

20. **Impact of farm-based climate actions on biodiversity** – Conversion of natural ecosystems to agricultural lands generally leads to loss of biodiversity. Although some agriculture-based climate change adaptation and mitigation actions have potential to reduce

or ameliorate biodiversity loss, the review indicated lack of case studies reporting loss or gain of biodiversity in relations to climate actions on farm. This is a significant knowledge gap that constrains effective evaluation of climate actions on farm in Africa.

21. **Cost-effectiveness of local and indigenous adaptation practices** – We reviewed substantial number of case studies involving local and indigenous climate change adaptation practices. While some case studies indicated benefits of these practices, a substantial majority of case studies either failed to or reported benefits for only a single or few results areas (e.g., yield, drought impact, fertility, etc.). For most of the case studies, the cost-effectiveness of local and indigenous adaptation practices was generally non-existent. This is a significant knowledge gap that will hinder upscaling and promotion of innovative local and indigenous adaptation practices.

Data and research gaps for urban areas

22. **Cost-effectiveness of urban adaptation and mitigation strategies** – the urban case studies examined in this report were mainly exploratory in nature. There is dearth of empirical evidence of the benefits and trade-offs of urban-based adaptation and mitigation actions in Africa.

23. **Regional disparity in urban-based climate actions in Africa** – A significant majority of case studies on urban-based adaptation and mitigation were mainly from South Africa indicating lack of data and research on urban actions in other countries and regions.

24. **Limited scope of urban-based climate actions** – The case studies examined in this report indicated that only a limited number of urban-based climate actions have been explored in Africa. So far, important climate change adaptation and mitigation strategies that are potentially useful to the African context – e.g., include urban wastewater management for agriculture and power generation using urban waste – have been rarely examined.

5.0 Conclusions

Climate change and related impacts represent the most significant threat to sustainable development in Africa. Land-based mitigation and adaptation options will play a crucial role in reducing global warming to within 1.5°C and 2°C of pre-industrial levels. In this respect, Africa is uniquely positioned to become a major player in global climate actions. However, to realize this potential, Africa must advance a common position and interest on climate change in global fora.

This report examined all major climate actions across the diverse biomes, land use, and subregions of Africa. The report first reviewed and concluded that climate actions in Africa must not only address climate change risks and threats but must also meet the following minimum criteria:

- address sustainable development goals, particularly rural livelihoods
- improve natural resources governance
- reduce land inequalities and tenure constraints
- improve climate securities
- must be based on sound understanding of the ecology, structure, and function of the targeted ecosystem

Extensive review of climate actions on forests, mangroves, grassy ecosystems, and arid and deserts, and urban centres can be enhanced as follows:

- avoided deforestation of mangroves can be achieved through improved financing, local participation and stewardship, provision of alternative wood fuel sources, and improved regulatory framework. The community-based ecological restoration approach (CBERM) was highlighted as a promising restoration approach.

- Although REDD+ initiatives can contribute to avoided deforestation, there is an urgent need to close the funding gap. Community-based Forest management initiatives can support forest conservation if there is sustained political, adequate funding, provision of alternative livelihood activities, and adoption of technology.

- Significant trade-off between carbon, biodiversity, and livelihood goals exists for improved forest management and can be reduced through provision of alternative livelihood interventions.

- Natural regeneration and mixed species plantations are superior forest restoration options relative to monocultures. Irrespective of restoration option, novel landscape level sustainability initiatives present may be better at integrating livelihood, biodiversity, and carbon goals and hence reduce trade-offs.

- There is dearth of experimental evidence of the impact of fire frequency and season on woodlands making it difficult to assess the benefit of making large-scale changes to existing fire regimes.

- Decline in burnt area, changes in historical herbivory regime, and bush encroachment threaten savannas and grasslands of Africa. Despite this, there is no global financing mechanisms (e.g., REDD+ type initiative) for conservation of grasslands and savannas.

- There is no conclusive evidence that afforestation in savannas and grasslands leads to increase soil organic carbon (SOC) or total ecosystem carbon (TEC). In contrast, there is substantial evidence that afforestation in savannas and grasslands have negative impact on hydrology, ground water and biodiversity.

- Current evidence suggests that proposals to alter fire frequency and season in grasslands and savannas of Africa are unlikely to deliver the projected emission reductions.

- The case studies indicated that biome-appropriate levels of fire and grazing have little impact on SOC whereas extremes reduce SOC. However, the impact of grazing on SOC is dependent on rainfall. Despite this, there is clear evidence that fire and grazing (disturbance) are critical for maintaining open canopies which in turn is essential for conserving the diversity of the herbaceous layer.

- The impact of bush encroachment in savannas and grasslands on SOC is variable and contingent on climate and topo-edaphic factors. However, there is substantial evidence that bush encroachment leads to biodiversity loss.

- Short-intense rotational grazing is not superior to continuous grazing in rangelands.

- Although the central tenets of holistic management (HM) are challenged, some case studies suggests that when properly practiced, HM do lead to positive ecological, social, and economic outcomes.

- The wilder rangeland concept (WRC) has huge potential for climate change adaptation and mitigation in rangelands. However, existing land tenure systems and potential for increased wildlife-human conflict may constrain it adoption.

- Desert greening may have negative effect on provision of ecosystem services (e.g., reduced fertilization in the Amazon) and worsen local climatic conditions.

- There is inconclusive evidence of the climatic benefits of desert-based solar and wind farms.

- There is substantial evidence that land degradation is widespread in Africa and caused by over-exploitation of land and natural resources. However, conflating land degradation with desertification leads to promotion of climate actions that are decoupled from the root cause of the problem.

- Most crop-based climate actions result in improvement in yield, productivity, carbon, and livelihoods. However, there is limited understanding of the cost-effectiveness of indigenous and traditional adaptation practices.

- Climate actions in livestock production systems have positive impacts on productivity and GHG emissions. However, production of improved forage in Africa may increase land based GHG emissions unless driven by high fertilizer inputs.

- Agroforestry is highly promising for carbon sequestration, biodiversity, and livelihoods across all biomes and land uses.

- There is limited empirical evidence of the effectiveness of urban-based climate actions with most existing studies coming from South Africa.

- Provision of efficient cooking stoves is particularly promising for reducing natural wood harvest, reduce CO_2 emissions and improve health conditions of rural households.

- There are significant knowledge, information, and data gaps that needs to be addressed to enhance climate actions on land in Africa.

References

1. UNFCCC. *Conference of the Parties, Twenty-first session - Adoption of the Paris Agreement*. (2015).
2. African Union (AU). *Agenda 2063: The Africa We Want*. (2013).
3. African Union (AU). *Africa Climate Change Strategy*. (2020).
4. IPCC. IPCC WGII Sixth Assessment Report: Africa. in *Climate Change 2022: Impacts, Adaptation and Vulnerability* (eds. Trisos, C. H., Adelekan, I. O. & Totin, E.) (2022).
5. WMO. *State of the Climate in Africa 2020*. vol. 1275 (World Meteorological Organization, 2020).
6. IPBES. *The regional assessment report on Biodiversity and Ecosystems Services for Africa*. (2018).
7. Meyfroidt, P. *et al.* Ten facts about land systems for sustainability. *Proceedings of the National Academy of Sciences* **119**, e2109217118 (2022).
8. White, F. The vegetation of Africa. *Natural Resources Research, UNESCO* **20**, 356 pp. (1983).
9. Bond, W. J., Stevens, N., Midgley, G. F. & Lehmann, C. E. R. The Trouble with Trees: Afforestation Plans for Africa. *Trends in Ecology & Evolution* **34**, 963–965 (2019).
10. Veldman, J. W. *et al.* Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *BioScience* **65**, 1011–1018 (2015).
11. Sowińska-Świerkosz, B. & García, J. What are Nature-based solutions (NBS)? Setting core ideas for concept clarification. *Nature-Based Solutions* **2**, 100009 (2022).
12. Seddon, N. *et al.* Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences* vol. 375 (2020).
13. Griscom, B. W. *et al.* Natural climate solutions. *Proc Natl Acad Sci U S A* **114**, 11645–11650 (2017).
14. Fargione, J. E. *et al. Natural climate solutions for the United States*. *Sci. Adv* vol. 4 https://www.science.org (2018).
15. UNEA. *Draft resolution on nature-based solutions for supporting sustainale development*. (2022).
16. Seddon, N. *et al.* Global recognition of the importance of nature-based solutions to the impacts of climate change. *Global Sustainability* **3**, (2020).
17. Eggermont, H. *et al.* Nature-based solutions: New influence for environmental management and research in Europe. *GAIA* vol. 24 243–248 (2015).
18. Bellamy, R. & Osaka, S. Unnatural climate solutions? *Nature Climate Change* vol. 10 98–99 (2020).

19. The Royal Society. Climate change and land: the science of working with nature towards net zero. in *Climate change: Science and Solutions* (eds. Peter Smith et al.) (The Royal Society, 2021).

20. Nathalie Seddon, Beth Turner, Pam Berry, Alexandre Chausson & Cecile A. J. Giradin. Grounding nature-based climate solutions in sound biodiversity science. *Nature Climate Change* **9**, 82–84 (2019).

21. Roe, S. *et al.* Land-based measures to mitigate climate change: Potential and feasibility by country. *Glob Change Biol* **27**, 6025–6058 (2021).

22. Frank, S. *et al.* Land-based climate change mitigation potentials within the agenda for sustainable development. *Environmental Research Letters* **16**, 024006 (2021).

23. Creutzig, F. *et al.* Towards demand-side solutions for mitigating climate change. *Nature Climate Change* **8**, 260–263 (2018).

24. Scherer, L. & Verburg, P. H. Mapping and linking supply- and demand-side measures in climate-smart agriculture. A review. *Agronomy for Sustainable Development* **37**, 66 (2017).

25. Roe, S. *et al.* Contribution of the land sector to a 1.5 °C world. *Nature Climate Change* **9**, 817–828 (2019).

26. IPCC. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. (2019).

27. Griscom, B. W. *et al.* Natural climate solutions. *Proceedings of the National Academy of Sciences* **114**, 11645–11650 (2017).

28. IPCC. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. (World Meteorological Organization, 2018).

29. IPCC. Summary for Policymakers. in *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. HO Portner et al.) (Cambridge University Press, 2022).

30. UNFCCC Secretariat. *Synthesis report on nationally determined contributions under the Paris Agreement*. (2021).

31. UNFCCC. Nationally Determined Contributions (NDCs). (2022).

32. United Nations Environment Programme. *Emissions Gap Report 2021: The Heat Is On – A World of Climate Promises Not Yet Delivered*. (2021).

33. United Nations Environment Programme. *Emissions Gap Report 2020.* (United Nations Environment Programme (UNEP) and UNEP DTU Partnership (UDP), 2020).

34. Griscom, B. W. *et al.* National mitigation potential from natural climate solutions in the tropics. *Philosophical Transactions of the Royal Society B: Biological Sciences* **375**, 20190126 (2020).

35. Roe, S. *et al.* Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology* **27**, 6025–6058 (2021).

36. Ogle, S. M. & Kurz, W. A. Land-based emissions. *Nature Climate Change* **11**, 382–383 (2021).

37. IPCC. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. (In press, 2019).

38. IPCC. WG III contribution to the Sixth Assessment Report: Chapter 2 - Emissions Trends and Drivers. in (eds. Shobhakar Dhakal, Jan Christoph Minx & Ferenc L Toth) (2022).

39. Niang, I. *et al.* Africa. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Barros, V. R. et al.) 1199–1265 (Cambridge University Press, Cambridge, 2014).

40. Sarr, B. Present and future climate change in the semi-arid region of West Africa: A crucial input for practical adaptation in agriculture. *Atmospheric Science Letters* **13**, 108–112 (2012).

41. Kennedy Mbeva, Cosmas Ochieng, Joanes Atela, Winnie Khaemba & Charles Tonui. *Intended nationally determined contributions as a means to strengthening Africa's engagement in international climate negotiations*. www.acts-net.org (2015).

42. Nyiwul, L. M. Climate change mitigation and adaptation in Africa: Strategies, synergies, and constraints. in *Contributions to Economics* 219–241 (Physica-Verlag, 2019). doi:10.1007/978-3-030-02662-2_11.

43. Naia, M. *et al.* Potential negative effects of the Green Wall on Sahel's biodiversity. *Conservation Biology* **35**, 1966–1968 (2021).

44. Zekarias Hussein, Thomas Hertel & Alla Golub. Climate change mitigation policies and poverty in developing countries. *Environmental Research Letters* **8**, (2013).

45. Scheren, P. *et al.* Defining pathways towards african ecological futures. *Sustainability (Switzerland)* **13**, (2021).

46. World Bank. World Development Indicators (WDI). *https://databank.worldbank.org/reports.aspx?source=2&series=NV.AGR.TOTL.ZS&country=SSF* (2022).

47. African Union Commission. *African Union Land Governance Strategy*. (2021).

48. UNEP-WCMC. Protected Area Profile for Africa from the World Database of Protected Areas. *www.protectedplanet.net* (2022).

49. Barbier, E. B. & Tesfaw, A. T. Tenure Constraints and Carbon Forestry in Africa. *American Journal of Agricultural Economics* **95**, 964–975 (2013).

50. African Union. *Policy Framework for Pastoralism in Africa: Securing, Protecting and Improving the Lives, Livelihoods and Rights of Pastoralist Communities*. (2010).

51. McGuirk, E. F. & Nunn, N. Transhumant Pastoralism, Climate Change, and Conflict in Africa. (2020) doi:10.3386/W28243.

52. J Barnett. *The Meaning of Environmental Security: Ecological Politics and Policy in the New Security Era*. (Zed Books, 2001).

53. Colin H Kahl. *States, Scarcity and Civil Strife in the Developing World*. (Princeton University Press, 2006).

54. C De Coning & F Krampe. *Mali - Climate, Peace and Security Fact Sheet*. (2001).

55. Ibrahim Yahaya Ibrahim & Mollie Zapata. *Region at risk: Preventing mass atrocities in Mali*. (2018).

56. UNOWAS. *Pastoralism and Security in West Africa and the Sahel: Towards Peaceful Coexistence. Dakar: United Nations Office for West Africa and the Sahel*. (2018).

57. Bastin, J.-F. *et al.* The global tree restoration potential. *Science (1979)* **365**, 76–79 (2019).

58. Veldman, J. W. Opinion piece Clarifying the confusion: old-growth savannahs and tropical ecosystem degradation. doi:10.1098/rstb.2015.0306.

59. Osborne, C. P. *et al.* Human impacts in African savannas are mediated by plant functional traits. *New Phytologist* **220**, 10–24 (2018).

60. Grainger, A., Iverson, L. R., Marland, G. H. & Prasad, A. Comment on "The global tree restoration potential." *Science* vol. 366 (2019).

61. Lewis, S. L., Mitchard, E. T. A., Prentice, C., Maslin, M. & Poulter, B. Comment on "The global tree restoration potential." *Science (1979)* **366**, 1–3 (2019).

62. Skidmore, A. K., Wang, T., de Bie, K. & Pilesjö, P. Comment on "The global tree restoration potential." *Science (1979)* **366**, (2019).

63. Friedlingstein, P., Allen, M., Canadell, J. G., Peters, G. P. & Seneviratne, S. I. Comment on "The global tree restoration potential." *Science* vol. 366 (2019).

64. Veldman, J. W. *et al.* Comment on "textquotedblleft}The global tree restoration potential." *Science (1979)* **366**, (2019).

65. Ratnam, J. *et al.* When is a 'forest' a savanna, and why does it matter? *Global Ecology and Biogeography* **20**, 653–660 (2011).

66. Fairhead, J. & Leach, M. *Misreading the African Landscape: Society and Ecology in a Forest-Savanna Mosaic*. (Cambridge University Press, 1996). doi:10.1017/CBO9781139164023.

67. ILRI *et al. Rangelands Atlas. Nairobi Kenya: ILRI*. (2021).

68. Bond, W. & Zaloumis, N. P. The deforestation story : testing for anthropogenic origins of Africa ' s flammable grassy biomes. *Philosophical Transactions of the Royal Society B: Biological Sciences* (2016).

69. Backéus, I. Distribution and vegetation dynamics of humid savannas in Africa and Asia. *Journal of Vegetation Science* **3**, 345–356 (1992).

70. White, F. *Vegetation of Africa—A Descriptive Memoir to Accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa*. (UNESCO, 1983).

71. Mayaux, P., Bartholomé, E., Fritz, S. & Belward, A. A new land-cover map of Africa for the year 2000. *Journal of Biogeography* **31**, 861–877 (2004).

72. Bond, W. J. Large parts of the world are brown or black: A different view on the 'Green World'hypothesis. *Journal of Vegetation Science* **16**, 261–266 (2005).

73. Fayolle, A. *et al.* A sharp floristic discontinuity revealed by the biogeographic regionalization of African savannas. *Journal of Biogeography* (2018) doi:10.1111/jbi.13475.

74. Droissart, V. *et al.* Beyond trees: Biogeographical regionalization of tropical Africa. *Journal of Biogeography* **45**, 1153–1167 (2018).

75. Vetter, S., Kerven, C., Davis, D. K. & Samuels, I. With Power Comes Responsibility-A Rangelands Perspective on Forest Landscape Restoration. *Front. Sustain. Food Syst* **4**, 549483 (2020).

76. Sankaran, M. *et al.* Determinants of woody cover in African savannas. *Nature 2005 438:7069* **438**, 846–849 (2005).

77. Global Mangrove alliance. *The State of the World's Mangrove 2021*. (2021).

78. Diop, E. S. *et al.* Mangroves of Africa. in *Mangrove Ecosystems: Function and Management* (ed. de Lacerda, L. D.) 63–121 (Springer Berlin Heidelberg, 2002). doi:10.1007/978-3-662-04713-2_2.

79. Ajonina G, Diamé A & Kairo J. Current status and conservation of mangroves in Africa: An overview. World Rainforest Movement Bulletin No 133. *World Rainforest Movement Bulletin* **133**, (2008).

80. Feka, Z. N. & Morrison, I. Managing mangroves for coastal ecosystems change: A decade and beyond of conservation experiences and lessons for and from west-central Africa. *Journal of Ecology and The Natural Environment* **9**, 99–123 (2017).

81. Bernal, B., Murray, L. T. & Pearson, T. R. H. Global carbon dioxide removal rates from forest landscape restoration activities. *Carbon Balance and Management* **13**, 1–13 (2018).

82. Kairo G.J.G. Ajonina *et al. Carbon pools and multiple benefits of mangroves in Central Africa: Assessment for REDD+*. (2014).

83. UNEP. *Mangroves of western and central Africa :* (2007).

84. United Nations Development Programme. *Mikoko Pamoja, Kenya. Equator Initiative Case Study Series*. (2020).

85. Menno De Boer, Lilian Nyaega, Elizabeth Wamba & Emmanuel Japhet. To plant or not to plant? Insights from mangrove restoration in Rufiji Delta. *The Wiomsa Magazine: People & the environment* **2020**, (2020).

86. Wetland International. *Conserving the biodiversity of the Cacheu Mangroves National Park: Our achievements*. (2018).

87. Kumari, P., Pathak, B. & Singh, J. K. Potential contribution of multifunctional mangrove resources and its conservation. *Biotechnological Utilization of Mangrove Resources* 1–26 (2005) doi:10.1016/B978-0-12-819532-1.00001-9.

88. Adams, J. B. & Rajkaran, A. Changes in mangroves at their southernmost African distribution limit. *Estuarine, Coastal and Shelf Science* **247**, 106862 (2020).

89. GEF. Protection of Mangroves through the creation of a firewood plantation. https://sgp.undp.org/fact-sheets-190/47-mangrove-project/file.html (2010).

90. Robinson, E. J. Z., Albers, H. J., Meshack, C. & Lokina, R. B. Implementing REDD through community-based forest management: Lessons from Tanzania. *Natural Resources Forum* **37**, 141–152 (2013).

91. Vasconcelos, M. J. *et al.* Can blue carbon contribute to clean development in West-Africa? The case of Guinea-Bissau. *Mitigation and Adaptation Strategies for Global Change* **20**, 1361–1383 (2015).

92. Cormier-Salem, M. C. & Panfili, J. Mangrove reforestation: greening or grabbing coastal zones and deltas? Case studies in Senegal§. *http://dx.doi.org/10.2989/16085914.2016.1146122* **41**, 89–98 (2016).

93. Kodikara, K. A. S., Mukherjee, N., Jayatissa, L. P., Dahdouh-Guebas, F. & Koedam, N. Have mangrove restoration projects worked? An in-depth study in Sri Lanka. *Restoration Ecology* **25**, 705–716 (2017).

94. Primavera, J. H. & Esteban, J. M. A. A review of mangrove rehabilitation in the Philippines: successes, failures and future prospects. *Wetlands Ecology and Management 2008 16:5* **16**, 345–358 (2008).

95. FAO & UNEP. *The State of the World's Forests 2020. Forest, biodiversity and people*. (FAO and UNEP, 2020).

96. IUCN. *Ecosystem Profile : Guinean Forests of West Africa Biodiversity Hotspot*. (2015).

97. Russell A. Mittermeier *et al. Hotspots revisited: Earth's Biological Richest and Most Endangered Terrestrial Ecoregions*. (CEMEX, 2005).

98. Chidumayo, E., Okali, D., Kowero, G. & Larwanou, M. *Climate Change and African forest and wildlife resources in African forestry*. (African Forest Forum, 2011).

99. Seymour, F. & Harris, N. L. Reducing tropical deforestation. *Science (1979)* **365**, 756–757 (2019).

100. Seymour, F. & Busch, J. *Why Forests, Why Now? The Science, Economics, and Politics of Tropical Forests and Climate Change*. (2014).

101. Asase, A. & Tetteh, D. A. Tree diversity, carbon stocks, and soil nutrients in cocoa-dominated and mixed food crops agroforestry systems compared to natural forest in southeast Ghana. *http://dx.doi.org/10.1080/21683565.2015.1110223* **40**, 96–113 (2015).

102. Girmay, G., Singh, B. R., Mitiku, H., Borresen, T. & Lal, R. Carbon stocks in Ethiopian soils in relation to land use and soil management. *Land Degradation & Development* **19**, 351–367 (2008).

103. Olorunfemi, I. E., Komolafe, A. A., Fasinmirin, J. T. & Olufayo, A. A. Biomass carbon stocks of different land use management in the forest vegetative zone of Nigeria. *Acta Oecologica* **95**, 45–56 (2019).

104. Wasige, J. E. *et al.* Contemporary land use/land cover types determine soil organic carbon stocks in south-west Rwanda. *Nutrient Cycling in Agroecosystems 2014 100:1* **100**, 19–33 (2014).

105. Maitima, J. M. *et al.* The linkages between land use change, land degradation and biodiversity across East Africa. *African Journal of Environmental Science and Technology* **3**, 310–325 (2010).

106. Alroy, J. Effects of habitat disturbance on tropical forest biodiversity. *Proc Natl Acad Sci U S A* **114**, 6056–6061 (2017).

107. Barima, Y. S. S. *et al.* Deforestation in central and West Africa: Landscape dynamics, anthropogenic effects and ecological consequences. *Advances in Environmental Research* **7**, 95–120 (2011).

108. Mulugeta Lemenih & Yvan Biot. *Reducing deforestation and emissions in Bale*. (2017).

109. The World Bank. Community-Led Sustainable Forest Management Program Creates Wealth for Rural Families and New Energy Sources in Senegal. https://www.worldbank.org/en/news/feature/2014/06/10/community-led-sustainable-forest-management-program-creates-wealth-for-rural-families-and-new-energy-sources-in-senegal (2014).

110. Boucher, D., Elias, P., Faires, J. & Smith, S. *Deforestation Success Stories Tropical Nations Where Forest Protection and Reforestation Policies Have Worked*. www.ucsusa.org/forestsuccess. (2014).

111. Rossi, V. *et al.* Could REDD+ mechanisms induce logging companies to reduce forest degradation in Central Africa? *Journal of Forest Economics* **29**, 107–117 (2017).

112. Zhang, Q. & Justice, C. O. Carbon Emissions and Sequestration Potential of Central African Ecosystems. *AMBIO: A Journal of the Human Environment* **30**, 351 – 355 (2001).

113. Ribot, J. C., Lund, J. F. & Treue, T. Democratic decentralization in sub-Saharan Africa: its contribution to forest management, livelihoods, and enfranchisement. *Environmental Conservation* **37**, 35–44 (2010).

114. Skutsch, M. M. & Ba, L. Crediting carbon in dry forests: The potential for community forest management in West Africa. *Forest Policy and Economics* **12**, 264–270 (2010).

115. Moffette, F., Alix-Garcia, J., Shea, K. & Pickens, A. H. The impact of near-real-time deforestation alerts across the tropics. *Nature Climate Change 2021 11:2* **11**, 172–178 (2021).

116. Chow, J., Doria, G., Kramer, R., Schneider, T. & Stoike, J. Tropical Forests Under a Changing Climate and Innovations in Tropical Forest Management: *http://dx.doi.org/10.1177/194008291300600302* **6**, 315–324 (2013).

117. Rasolofoson, R. A. *et al.* Impacts of Community Forest Management on Human Economic Well-Being across Madagascar. *Conservation Letters* **10**, 346–353 (2017).

118. Shreya Dasgupta & Zuzana Burivalova. Does community-based forest management work in the tropics? *Mongabay Series: Conservation Effectiveness* https://news.mongabay.com/2017/11/does-community-based-forest-management-work-in-the-tropics/ (2017).

119. Vermeulen, C. & Karsenty, A. Towards a community-based concession model in the DRC. *International Forestry Review* **19**, 80–86 (2017).

120. Kedir, H., Negash, M., Yimer, F. & Limenih, M. Contribution of participatory forest management towards conservation and rehabilitation of dry Afromontane forests and its implications for carbon management in the tropical Southeastern Highlands of Ethiopia. *https://doi.org/10.1080/10549811.2017.1414614* **37**, 357–374 (2017).

121. Mazunda, J. & Shively, G. Measuring the forest and income impacts of forest user group participation under Malawi's Forest Co-management Program. *Ecological Economics* **119**, 262–273 (2015).

122. Melhaoui, Y. *Protection and participatory management of forest ecosystems of the RIF, Morocco*. (2003).

123. Sharma, S. K., Telfer, M., Phua, S. T. G. & Chandler, H. A pragmatic method for estimating greenhouse gas emissions from leakage for Improved Forest Management projects under the Verified Carbon Standard. *https://doi.org/10.1080/20430779.2012.696237* **2**, 22–32 (2012).

124. Israel, F. & Murugan, P. *Livelihood Impacts of Forest Carbon Project and its Implications for Forest Sustainability: the Case of Regenerated Forest in Humbo District, Southwestern Ethiopia*. (2015).

125. Sandbrook, C., Nelson, F., Adams, W. M. & Agrawal, A. Carbon, forests and the REDD paradox. *Oryx* **44**, 330–334 (2010).

126. Claey Florian *et al.* Could IFM REDD+ projects incentivize forest concessionaires to reduce greenhouse gases emissions in Central Africa? A lesson from the FORAFAMA project. in *Our Common Future under Climate Change* (CIRAD, 2015).

127. Griscom, B. W. & Cortez, R. The Case for Improved Forest Management (IFM) as a Priority REDD+ Strategy in the Tropics: *http://dx.doi.org/10.1177/194008291300600307* **6**, 409–425 (2013).

128. Kalonga, S. K., Midtgaard, F. & Eid, T. Does Forest Certification Enhance Forest Structure? Empirical Evidence from Certified Community-Based Forest Management in Kilwa District, Tanzania. *International Forestry Review* **17**, 182–194 (2015).

129. Unruh, J. D. Carbon sequestration in Africa: The land tenure problem. *Global Environmental Change* **18**, 700–707 (2008).

130. Abiodun, B. J., Adeyewa, Z. D., Oguntunde, P. G., Salami, A. T. & Ajayi, V. O. Modeling the impacts of reforestation on future climate in West Africa. *Theoretical and Applied Climatology 2012 110:1* **110**, 77–96 (2012).

131. Crouzeilles, R. *et al.* Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. *Science Advances* **3**, (2017).

132. Poorter, L. *et al.* Multidimensional tropical forest recovery. *Science (1979)* **374**, 1370–1376 (2021).

133. Kpolita, A., Dubiez, E., Yongo, O. & Peltier, R. First evaluation of the use of assisted natural regeneration by central african farmers to restore their landscapes. *Trees, Forests and People* **7**, 100165 (2022).

134. Cole, R. J., Holl, K. D., Keene, C. L. & Zahawi, R. A. Direct seeding of late-successional trees to restore tropical montane forest. *Forest Ecology and Management* **261**, 1590–1597 (2011).

135. Warner, E. *et al.* Higher aboveground carbon stocks in mixed-species planted forests than monocultures – a meta-analysis. *bioRxiv* 2022.01.17.476441 (2022) doi:10.1101/2022.01.17.476441.

136. Nichol, J. E. & Abbas, S. Evaluating Plantation Forest vs. Natural Forest Regeneration for Biodiversity Enhancement in Hong Kong. *Forests 2021, Vol. 12, Page 593* **12**, 593 (2021).

137. Bonner, M. T. L., Schmidt, S. & Shoo, L. P. A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations. *Forest Ecology and Management* **291**, 73–86 (2013).

138. Reid, J. L., Fagan, M. E. & Zahawi, R. A. Positive site selection bias in meta-analyses comparing natural regeneration to active forest restoration. *Science Advances* **4**, 9143–9159 (2018).

139. Reynolds, T. W. Institutional Determinants of Success Among Forestry-Based Carbon Sequestration Projects in Sub-Saharan Africa. *World Development* **40**, 542–554 (2012).

140. Cormier-Salem, M. C. & Panfili, J. Mangrove reforestation: greening or grabbing coastal zones and deltas? Case studies in Senegal. *Printed in South Africa-All rights reserved* **41**, 89–98 (2016).

141. Kansanga, M. M. & Luginaah, I. Agrarian livelihoods under siege: Carbon forestry, tenure constraints and the rise of capitalist forest enclosures in Ghana. *World Development* **113**, 131–142 (2019).

142. Pfeifer, M. *et al.* Protected Areas: Mixed Success in Conserving East Africa's Evergreen Forests. *PLOS ONE* **7**, e39337 (2012).

143. Fisher, B. *et al.* Implementation and opportunity costs of reducing deforestation and forest degradation in Tanzania. *Nature Climate Change 2011 1:3* **1**, 161–164 (2011).

144. Bare, M., Kauffman, C. & Miller, D. C. Assessing the impact of international conservation aid on deforestation in sub-Saharan Africa. *Environmental Research Letters* **10**, 125010 (2015).

145. Ford, S. A. *et al.* Deforestation leakage undermines conservation value of tropical and subtropical forest protected areas. *Global Ecology and Biogeography* **29**, 2014–2024 (2020).

146. Rainforest Alliance. Sustainable Landscapes Projects. https://www.rainforest-alliance.org/business/tailored-services/sustainable-landscapes/ (2019).

147. IDH. Initiative for Sustainable Landscapes - Kenya : The sustainable trade initiative. https://www.idhsustainabletrade.com/initiative/isla-kenya/ (2022).

148. Landscale. Powering Landscape Sustainability. https://www.landscale.org/ (2022).

149. Diaw, M. C. A whole-landscape approach to green development in Africa. *IIED Briefing Papers* (2015).

150. Midgley, G. F., Woodward, F. I. & Bond, W. J. The global distribution of ecosystems in a world without fire. *New Phytologist* **165**, 525–537 (2004).

151. Bond, W. J. & Keeley, J. E. Fire as a global "herbivore": the ecology and evolution of flammable ecosystems. *Trends Ecol Evol* **20**, 387–94 (2005).

152. Koppmann, R., von Czapiewski, K. & Komenda, M. Natural and human-induced biomass burning in Africa: an important source for volatile organic compounds in the troposphere. *Climate Change and Africa* **9780521836340**, 69–78 (2005).

153. Ramo, R. *et al.* African burned area and fire carbon emissions are strongly impacted by small fires undetected by coarse resolution satellite data. *Proceedings of the National Academy of Sciences* **118**, e2011160118 (2021).

154. Zhao, Z. *et al.* Fire enhances forest degradation within forest edge zones in Africa. *Nature Geoscience 2021 14:7* **14**, 479–483 (2021).

155. Dwomoh, F. K. & Wimberly, M. C. Fire regimes and forest resilience: alternative vegetation states in the West African tropics. *Landscape Ecology 2017 32:9* **32**, 1849–1865 (2017).

156. Lindenmayer, D. B. & Sato, C. Hidden collapse is driven by fire and logging in a socioecological forest ecosystem. *Proc Natl Acad Sci U S A* **115**, 5181–5186 (2018).

157. Bowman, D. M. J. S. *et al.* Forest fire management, climate change, and the risk of catastrophic carbon losses. *Frontiers in Ecology and the Environment* **11**, 66–67 (2013).

158. Mike Jurvelius. *Community-based fire management in southern Africa*. https://www.fao.org/3/y5507e/y5507e04.htm (2004).

159. Scott Posner, David Maercklein & Ronald Overton. *USDA Forest Service Mission to the Republic of Congo and the Democratic Republic of Congo: In Support for the Development of Community Fire Management and Restoration in the Congo Basin*. (2009).

160. Nyongesa, K. W. & Vacik, H. Fire Management in Mount Kenya: A Case Study of Gathiuru Forest Station. *Forests 2018, Vol. 9, Page 481* **9**, 481 (2018).

161. van Wilgen, B. W., Everson, C. S. & Trollope, W. S. W. Fire Management in Southern Africa: Some Examples of Current Objectives, Practices, and Problems. 179–215 (1990) doi:10.1007/978-3-642-75395-4_11.

162. Johann G. Goldammer *et al.* Community participation in integrated forest fire management: experiences from Africa, Asia and Europe. in *Communities in flames: proceedings of an international conference on community involvement in fire management* (eds. Peter Moore, David Ganz, Lay Cheng Tan, Thomas Enters & Patrick B Durst) (FAO and United Nations Regional Office for Asia and the Pacific, 2002).

163. FAO. Global Forest Resources Assessment 2005 – Report on fires in the Sub-Saharan Africa Region. *Fire Management Working Paper 9* (2005).

164. Curt, T., Aini, A. & Dupire, S. Fire Activity in Mediterranean Forests (The Algerian Case). *Fire 2020, Vol. 3, Page 58* **3**, 58 (2020).

165. Dwomoh, F. K. & Wimberly, M. C. Fire Regimes and Their Drivers in the Upper Guinean Region of West Africa. *Remote Sensing 2017, Vol. 9, Page 1117* **9**, 1117 (2017).

166. Reddad, H. *et al.* Fire activity in North West Africa during the last 30,000 cal years BP inferred from a charcoal record from Lake Ifrah (Middle atlas-Morocco): Climatic implications. *Journal of African Earth Sciences* **84**, 47–53 (2013).

167. Scholes, R. J. & Archer, S. R. TREE-GRASS INTERACTIONS IN SAVANNAS1. *Ann. Rev. Ecol. Syst.* **28**, 517–544 (2011).

168. Menaut, J.-C., Lepage, M. & Abbadie, L. Savannas, woodlands and dry forests in Africa. in *Seasonally Dry Tropical Forests* 64–92 (Cambridge University Press, 1995). doi:10.1017/CBO9780511753398.004.

169. Archibald, S. & Hempson, G. P. Competing consumers: contrasting the patterns and impacts of fire and mammalian herbivory in Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150309 (2016).

170. Bond, W. J. What Limits Trees in C 4 Grasslands and Savannas? *Annual Review of Ecology, Evolution, and Systematics* **39**, 641–659 (2008).

171. Hempson, G. P. *et al.* A continent-wide assessment of the form and intensity of large mammal herbivory in Africa. *Science (1979)* **350**, 1056–61 (2015).

172. Ryan, C. M., Williams, M. & Grace, J. Above- and Belowground Carbon Stocks in a Miombo Woodland Landscape of Mozambique. *Biotropica* **43**, 423–432 (2011).

173. Williams, M. *et al.* Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. *Forest Ecology and Management* **254**, 145–155 (2008).

174. Chidumayo, E. Climate chnage and the woodlands of Africa. in *Climate change and African forest and wildlife resources* (eds. Chidumayo, E., Okali, D., Kowero, G. & Larwanou, M.) (African Forest Forum, 2011).

175. Hempson, G. P., Archibald, S. & Bond, W. J. The consequences of replacing wildlife with livestock in Africa. *Scientific Reports* **7**, 17196 (2017).

176. Waldron, A. *et al.* Targeting global conservation funding to limit immediate biodiversity declines. *Proceedings of the National Academy of Sciences* **110**, 12144–12148 (2013).

177. Holl, K. D. & Brancalion, P. H. S. Tree planting is not a simple solution. *Science (1979)* **368**, 580–581 (2020).

178. Frost, P. The ecology of miombo woodlands. in *The Miombo in Transition: Woodlands and Welfare in Africa* (ed. Campbell, B.) (Centre for International Forestry Research, 1996).

179. Campbell, B. & Byron, N. Miombo woodlands and rural livelihoods: Options and opportunities. in *The Miobo in Transition: Woodlands and Welfare in Africa* (ed. Campbell, B.) (Center for International Forestry Research, 1996).

180. Assédé, E. S. P., Azihou, A. F., Geldenhuys, C. J., Chirwa, P. W. & Biaou, S. S. H. Sudanian versus Zambezian woodlands of Africa: Composition, ecology, biogeography and use. *Acta Oecologica* **107**, 103599 (2020).

181. Jindal, R., Swallow, B. & Kerr, J. Forestry-based carbon sequestration projects in Africa: Potential benefits and challenges. *Natural Resources Forum* **32**, 116–130 (2008).

182. J Grace *et al.* A pilot project to store carbon as biomass in African woodlands. (2010) doi:10.4155/cmt.10.22.

183. Opere, Alfred., Olago, Daniel., Chidumayo, Emmanuel. & Osman-Elasha, Balgis. Climate change processes and impacts. in *Climate Change and African Forest and Wildlife Resources* (eds. Chidumayo, E., Okali, D., Kowero, G. & Larwanou, M.) (African Forest Forum, 2011).

184. Russell-Smith, J. *et al.* Opportunities and challenges for savanna burning emissions abatement in southern Africa. *Journal of Environmental Management* **288**, 112414 (2021).

185. Russell-Smith, J. *et al.* Improving estimates of savanna burning emissions for greenhouse accounting in northern Australia: limitations, challenges, applications. *International Journal of Wildland Fire* **18**, 1–18 (2009).

186. Ribeiro, N. S. *et al.* Prediction of forest parameters and carbon accounting under different fire regimes in Miombo woodlands, Niassa Special Reserve, Northern Mozambique. *Forest Policy and Economics* **133**, 102625 (2021).

187. Trapnell, C. G., Friend, M. T., Chamberlain, G. T. & Birch, H. F. The Effects of Fire and Termites on a Zambian Woodland Soil. *The Journal of Ecology* **64**, 577 (1976).

188. Tarimo, B., Dick, Ø. B., Gobakken, T. & Totland, Ø. Spatial distribution of temporal dynamics in anthropogenic fires in miombo savanna woodlands of Tanzania. *Carbon Balance and Management* **10**, 1–15 (2015).

189. Savadogo, P., Tiveau, D., Sawadogo, L. & Tigabu, M. Herbaceous species responses to long-term effects of prescribed fire, grazing and selective tree cutting in the savanna-woodlands of West Africa. *Perspectives in Plant Ecology, Evolution and Systematics* **10**, 179–195 (2008).

190. Nghalipo, E., Joubert, D., Throop, H. & Groengroeft, A. The effect of fire history on soil nutrients and soil organic carbon in a semi-arid savanna woodland, central Namibia. (2018) doi:10.2989/10220119.2018.1526825.

191. Zulu, L. C. *et al.* Governance and Institutional Arrangements for Sustainable Management of Miombo Woodlands. *Miombo Woodlands in a Changing Environment: Securing the Resilience and Sustainability of People and Woodlands* 139–189 (2020) doi:10.1007/978-3-030-50104-4_5.

192. Desanker, P. v. & Magadza, C. Africa. in *Climate Change 2001: Impacts, Adaptation and Vulnerability, IPCC Working Group II, Third Assessment Report* (eds. McCarthy, J. J., Canziani, O. F., Leary, N. A., Doken, D. J. & White, K. S.) (Cambridge University Press, 2001).

193. Aynekulu, E. *et al.* No changes in soil organic carbon and nitrogen following long-term prescribed burning and livestock exclusion in the Sudan-savanna woodlands of Burkina Faso. *Basic and Applied Ecology* **56**, 165–175 (2021).

194. Andrew Wardell, D., Reenberg, A. & Tøttrup, C. Historical footprints in contemporary land use systems: forest cover changes in savannah woodlands in the Sudano-Sahelian zone. *Global Environmental Change* **13**, 235–254 (2003).

195. G., K., B.M., C., U.R., S. & eds. Policies and governance structures in woodlands of Southern Africa. *Policies and governance structures in woodlands of Southern Africa* (2003) doi:10.17528/CIFOR/001408.

196. Sankaran, M., Ratnam, J. & Hanan, N. Woody cover in African savannas: The role of resources, fire and herbivory. *Global Ecology and Biogeography* **17**, 236–245 (2008).

197. Staver, A. C., Archibald, Sa. & Levin, S. Tree cover in sub-Saharan Africa : Rainfall and fire constrain forest and savanna as alternative stable states. *Ecology* **92**, 1063–1072 (2011).

198. Aleman, J. C. *et al.* Floristic evidence for alternative biome states in tropical Africa. *Proc Natl Acad Sci U S A* **117**, 28183–28190 (2020).

199. Torello-Raventos, M. *et al.* On the delineation of tropical vegetation types with an emphasis on forest/savanna transitions. *Plant Ecology & Diversity* **6**, 101–137 (2013).

200. Charles-Dominique, T., Midgley, G. F., Tomlinson, K. W. & Bond, W. J. Steal the light: shade vs fire adapted vegetation in forest–savanna mosaics. *New Phytologist* **218**, 1419–1429 (2018).

201. Williams, C. *et al.* Africa and the global carbon cycle. *Carbon Balance and Management* **2**, 1–13 (2007).

202. Scholes, R. J. & Hall, D. The carbon budget of tropical savannas, woodlands and grasslands. in *Global Change: Effects on Coniferous and Grasslnds* (eds. Breymeyer, A. I., Hall, D. O., Melillo, J. M. & Agren, G. I.) 69–100 (John Wiley, 1997).

203. Bond, W. J. What Limits Trees in C4 Grasslands and Savannas? *http://dx.doi.org/10.1146/annurev.ecolsys.39.110707.173411* **39**, 641–659 (2008).

204. Archibald, S., Hempson, G. P. & Lehmann, C. A unified framework for plant life-history strategies shaped by fire and herbivory. *New Phytologist* **0**, (2019).

205. Menault, J. C. & Cesar, J. The structure and dynamics of West African savannas. in *Ecology of tropical Savannas* (eds. Huntley, B. J. & Walker, B. H.) 80–100 (Springer Berlin Heidelberg, 1982).

206. Homewood, K. *et al.* Long-term changes in Serengeti-Mara wildebeest and land cover: Pastoralism, population, or policies? *Proc Natl Acad Sci U S A* **98**, 12544–12549 (2001).

207. Balima, L. H., Nacoulma, B. M. I., Bayen, P., Kouamé, F. N. G. & Thiombiano, A. Agricultural land use reduces plant biodiversity and carbon storage in tropical West African savanna ecosystems: Implications for sustainability. *Global Ecology and Conservation* **21**, e00875 (2020).

208. Searchinger, T. D. *et al.* High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. *Nature Climate Change 2014 5:5* **5**, 481–486 (2015).

209. Baudron, F., Corbeels, M., Monicat, F. & Giller, K. E. Cotton expansion and biodiversity loss in African savannahs, opportunities and challenges for conservation agriculture: a review paper based on two case studies. *Biodiversity and Conservation 2009 18:10* **18**, 2625–2644 (2009).

210. Woomer, P. L. The impact of cultivation on carbon fluxes in woody savannas of Southern Africa. *Water, Air, and Soil Pollution 1993 70:1* **70**, 403–412 (1993).

211. Dimobe, K. *et al.* Predicting the Potential Impact of Climate Change on Carbon Stock in Semi-Arid West African Savannas. *Land 2018, Vol. 7, Page 124* **7**, 124 (2018).

212. Earl, N. & Simmonds, I. Spatial and Temporal Variability and Trends in 2001–2016 Global Fire Activity. *Journal of Geophysical Research: Atmospheres* **123**, 2524–2536 (2018).

213. Andela, N. & van der Werf, G. R. Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition. *Nature Climate Change 2014 4:9* **4**, 791–795 (2014).

214. Ramo, R. *et al.* African burned area and fire carbon emissions are strongly impacted by small fires undetected by coarse resolution satellite data. *Proc Natl Acad Sci U S A* **118**, (2021).

215. Archibald, S. Managing the human component of fire regimes: lessons from Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, (2016).

216. Archibald, S. *et al.* Southern African fire regimes as revealed by remote sensing. *International Journal of Wildland Fire* **19**, 861–878 (2010).

217. Barbosa, P. M., Stroppiana, D., Grégoire, J. M. & Pereira, J. M. C. An assessment of vegetation fire in Africa (1981–1991): Burned areas, burned biomass, and atmospheric emissions. *Global Biogeochemical Cycles* **13**, 933–950 (1999).

218. Putz, F. E. & Redford, K. H. Dangers of carbon-based conservation. *Global Environmental Change* **19**, 400–401 (2009).

219. Zomer, R. J., Trabucco, A., Bossio, D. A. & Verchot, L. v. Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems and Environment* **126**, 67–80 (2008).

220. Grainger, A., Iverson, L. R., Marland, G. H. & Prasad, A. Comment on "The global tree restoration potential." *Science (1979)* **366**, (2019).

221. d'Annunzio, R. *et al.* Pairwise comparison of soil organic particle-size distributions in native savannas and Eucalyptus plantations in Congo. *Forest Ecology and Management* **255**, 1050–1056 (2008).

222. Berthrong, S. T., Jobbágy, E. G. & Jackson, R. B. A global meta-analysis of soil exchangeable cations, pH, carbon, and nitrogen with afforestation. *Ecological Applications* **19**, 2228–2241 (2009).

223. Berthrong, S. T., Piñeiro, G., Jobbágy, E. G. & Jackson, R. B. Soil C and N changes with afforestation of grasslands across gradients of precipitation and plantation age. *Ecological Applications* **22**, 76–86 (2012).

224. Nouvellon, Y. *et al.* Soil CO2 effluxes, soil carbon balance, and early tree growth following savannah afforestation in Congo: Comparison of two site preparation treatments. *Forest Ecology and Management* **255**, 1926–1936 (2008).

225. Allen, A. & Chapman, D. Impacts of afforestation on groundwater resources and quality. *Hydrogeology Journal 2001 9:4* **9**, 390–400 (2001).

226. Jackson, R. B. *et al.* Trading water for carbon with biological carbon sequestration. *Science (1979)* **310**, 1944–1947 (2005).

227. van Wyk, D. B. Some effects of afforestation on streamflow in the Western Cape Province, South Africa. *Water SA* **13**, (1987).

228. Herrmann, S. M. & Tappan, G. G. Vegetation impoverishment despite greening: A case study from central Senegal. *Journal of Arid Environments* **90**, 55–66 (2013).

229. Hanan, N. P., Milne, E., Aynekulu, E., Yu, Q. & Anchang, J. A Role for Drylands in a Carbon Neutral World? *Frontiers in Environmental Science* **9**, (2021).

230. del Campo, A. D. *et al.* Assessing reforestation failure at the project scale: The margin for technical improvement under harsh conditions. A case study in a Mediterranean Dryland. *Sci Total Environ* **796**, (2021).

231. Coleman, E. A. *et al.* Limited effects of tree planting on forest canopy cover and rural livelihoods in Northern India. *Nature Sustainability 2021 4:11* **4**, 997–1004 (2021).

232. Zaloumis, N. P. & Bond, W. J. Grassland restoration after afforestation: No direction home? *Austral Ecology* **36**, 357–366 (2011).

233. Sendzimir, J., Reij, C. P. & Magnuszewski, P. Rebuilding Resilience in the Sahel: Regreening in the Maradi and Zinder Regions of Niger. *Ecology and Society* **16**, 08 (2011).

234. Hanan, N. P. Agroforestry in the Sahel. *Nature Geoscience 2018 11:5* **11**, 296–297 (2018).

235. Goffner, D., Sinare, H. & Gordon, L. J. The Great Green Wall for the Sahara and the Sahel Initiative as an opportunity to enhance resilience in Sahelian landscapes and livelihoods. *Regional Environmental Change* **19**, 1417–1428 (2019).

236. O'Connor, D. & Ford, J. Increasing the Effectiveness of the "Great Green Wall" as an Adaptation to the Effects of Climate Change and Desertification in the Sahel. *Sustainability 2014, Vol. 6, Pages 7142-7154* **6**, 7142–7154 (2014).

237. Morrison, J. The "Great Green Wall" Didn't Stop Desertification, but it Evolved Into Something That Might | Science| Smithsonian Magazine. https://www.smithsonianmag.com/science-nature/great-green-wall-stop-desertification-not-so-much-180960171/ (2016).

238. Dudley, N. *et al.* Grasslands and savannahs in the UN Decade on Ecosystem Restoration. *Restoration Ecology* **28**, 1313–1317 (2020).

239. Higgins, S. I. *et al.* Which traits determine shifts in the abundance of tree species in a fire-prone savanna? *Journal of Ecology* **100**, 1400–1410 (2012).

240. Higgins, S. I., Bond, W. J. & Trollope, S. W. Fire, reprouting and variability: a recipt for grass-stepe coexistence in savanna. *Journal of Ecology* **88**, 213–229 (2000).

241. van Wilgen, B. W., Govender, N., Biggs, H. C., Ntsala, D. & Funda, X. N. *Response of Savanna Fire Regimes to Changing Fire-Management Policies in a Large African National Park*. vol. 18 (2004).

242. Nieman, W. A., van Wilgen, B. W., Leslie, A. J. & Nieman, W. African Protected Area Conservation and Science. (2021) doi:10.4102/koedoe.

243. Lipsett-Moore, G. J., Wolff, N. H. & Game, E. T. Emissions mitigation opportunities for savanna countries from early dry season fire management. *Nature Communications 2018 9:1* **9**, 1–8 (2018).

244. Tear, T. H. *et al.* Savanna fire management can generate enough carbon revenue to help restore Africa's rangelands and fill protected area funding gaps. *One Earth* **4**, 1776–1791 (2021).

245. Sinha, P. *et al.* Emissions from miombo woodland and dambo grassland savanna fires. *Journal of Geophysical Research: Atmospheres* **109**, 11305 (2004).

246. Laris, P. *et al.* Methane gas emissions from savanna fires: what analysis of local burning regimes in a working West African landscape tell us. *Biogeosciences* **18**, 6229–6244 (2021).

247. Laris, P. On the problems and promises of savanna fire regime change. *Nature Communications 2021 12:1* **12**, 1–4 (2021).

248. Venter, Z. S., Cramer, M. D. & Hawkins, H. J. Drivers of woody plant encroachment over Africa. *Nature Communications 2018 9:1* **9**, 1–7 (2018).

249. Gignoux, J., Lahoreau, G., Julliard, R. & Barot, S. Establishment and early persistence of tree seedlings in an annually burned savanna. *Journal of Ecology* **97**, 484–495 (2009).

250. Stevens, N., Archibald, S. A. & Bond, W. J. Transplant experiments point to fire regime as limiting savanna tree distribution. *Frontiers in Ecology and Evolution* **6**, 1–13 (2018).

251. Ward, D. DO WE UNDERSTAND THE CAUSES OF BUSH ENCROACHMENT IN AFRICAN SAVANNAS ? *African Journal of Range & Forage Science* **22**, 101–105 (2005).

252. Department of Environmental Affairs. *Towards a policy on indigenous bush encroachment in South Africa*. (2019).

253. Mitchard, E. T. A. & Flintrop, C. M. Woody encroachment and forest degradation in sub-Saharan Africa's woodlands and savannas 1982-2006. *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**, 20120406 (2013).

254. Stevens, N., Lehmann, C. E. R., Murphy, B. P. & Durigan, G. Savanna woody encroachment is widespread across three continents. *Global Change Biology* **23**, 235–244 (2017).

255. Ward, D. S., Shevliakova, E., Malyshev, S. & Rabin, S. Trends and Variability of Global Fire Emissions Due To Historical Anthropogenic Activities. *Global Biogeochemical Cycles* **32**, 122–142 (2018).

256. Scholes, R. J., Ward, D. E. & Justice, C. O. Emissions of trace gases and aerosol particles due to vegetation burning in southern hemisphere Africa. *Journal of Geophysical Research: Atmospheres* **101**, 23677–23682 (1996).

257. Korontzi, S. Seasonal patterns in biomass burning emissions from southern African vegetation fires for the year 2000. *Global Change Biology* **11**, 1680–1700 (2005).

258. Korontzi, S., Justice, C. O. & Scholes, R. J. Influence of timing and spatial extent of savanna fires in southern Africa on atmospheric emissions. *Journal of Arid Environments* **54**, 395–404 (2003).

259. Scharlemann, J. P. W., Tanner, E. V. J., Hiederer, R. & Kapos, V. Global soil carbon: Understanding and managing the largest terrestrial carbon pool. *Carbon Management* **5**, 81–91 (2014).

260. Awé, D. V., Noiha, N. V. & Zapfack, L. Carbon management for savannah ecosystems in Central Africa: a case study from Cameroon. *International Journal of Low-Carbon Technologies* **16**, 1290–1298 (2021).

261. Venter, Z. S., Hawkins, H. J., Cramer, M. D. & Mills, A. J. Mapping soil organic carbon stocks and trends with satellite-driven high resolution maps over South Africa. *Science of The Total Environment* **771**, 145384 (2021).

262. Smit, I. P. J. *et al.* Effects of fire on woody vegetation structure in African savanna. *Ecological Applications* **20**, 1865–1875 (2010).

263. Devineau, J. L., Fournier, A. & Nignan, S. Savanna fire regimes assessment with MODIS fire data: Their relationship to land cover and plant species distribution in western Burkina Faso (West Africa). *Journal of Arid Environments* **74**, 1092–1101 (2010).

264. Sankaran, M., Ratnam, J. & Hanan, N. Woody cover in African savannas: the role of resources, fire and herbivory. *Global Ecology and Biogeography* **17**, 236–245 (2008).

265. Pellegrini, A. F. A. *et al.* Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. *Nature 2018 553:7687* **553**, 194–198 (2017).

266. Findlay, N. *et al.* Long-term frequent fires do not decrease topsoil carbon and nitrogen in an Afromontane grassland. *https://doi.org/10.2989/10220119.2021.2016966* **39**, 44–55 (2022).

267. Jones, R., Chambers, J. C., Johnson, D. W., Blank, R. R. & Board, D. I. Effect of repeated burning on plant and soil carbon and nitrogen in cheatgrass (Bromus tectorum) dominated ecosystems. *Plant and Soil 2014 386:1* **386**, 47–64 (2014).

268. Manson, A. D., Jewitt, D. & Short, A. D. Effects of season and frequency of burning on soils and landscape functioning in a moist montane grassland. *https://doi.org/10.2989/102201107780178177* **24**, 9–18 (2009).

269. Zhou, Y. *et al.* Limited increases in savanna carbon stocks over decades of fire suppression. *Nature* **603**, 445–449 (2022).

270. Bouvet, A. *et al.* An above-ground biomass map of African savannahs and woodlands at 25 m resolution derived from ALOS PALSAR. *Remote Sensing of Environment* **206**, 156–173 (2018).

271. Munjonji, L. *et al.* Disentangling Drought and Grazing Effects on Soil Carbon Stocks and CO 2 Fluxes in a Semi-Arid African Savanna. (2020) doi:10.3389/fenvs.2020.590665.

272. Dlamini, P., Chivenge, P. & Chaplot, V. Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: A meta-analysis shows. *Agriculture, Ecosystems & Environment* **221**, 258–269 (2016).

273. Morris, C. D., Everson, C. S., Everson, T. M. & Gordijn, P. J. Frequent burning maintained a stable grassland over four decades in the Drakensberg, South Africa. *https://doi.org/10.2989/10220119.2020.1825120* **38**, 39–52 (2020).

274. Charles-Dominique, T. *et al.* Spiny plants, mammal browsers, and the origin of African savannas. *Proceedings of the National Academy of Sciences* **113**, E5572–E5579 (2016).

275. Thoresen, J. *et al.* Fire and herbivory shape soil arthropod communities through habitat heterogeneity and nutrient cycling in savannas. *Global Ecology and Conservation* **25**, e01413 (2021).

276. Geiger, E. L. *et al.* Distinct roles of savanna and forest tree species in regeneration under fire suppression in a Brazilian savanna. *Journal of Vegetation Science* **22**, 312–321 (2011).

277. Bond, W. J. & Parr, C. L. Beyond the forest edge: Ecology, diversity and conservation of the grassy biomes. *Biological Conservation* **143**, 2395–2404 (2010).

278. van Coller, H. & Siebert, F. Herbaceous biomass–species diversity relationships in nutrient hotspots of a semi-arid African riparian ecosystem. *https://doi.org/10.2989/10220119.2014.951394* **32**, 213–223 (2015).

279. Mitchard, E. T. a., Saatchi, S. S., Gerard, F. F., Lewis, S. L. & Meir, P. Measuring Woody Encroachment along a Forest–Savanna Boundary in Central Africa. *Earth Interactions* **13**, 1–29 (2009).

280. Wiegand, K., Ward, D. & Saltz, D. Multi-scale patterns and bush encroachment in an arid savanna with a shallow soil layer. *Journal of Ve* **16**, 311–320 (2005).

281. Mureva, A., Ward, D., Pillay, T., Chivenge, P. & Cramer, M. Soil Organic Carbon Increases in Semi-Arid Regions while it Decreases in Humid Regions Due to Woody-Plant Encroachment of Grasslands in South Africa. *Scientific Reports 2018 8:1* **8**, 1–12 (2018).

282. Li, H. *et al.* Effects of shrub encroachment on soil organic carbon in global grasslands. *Scientific Reports 2016 6:1* **6**, 1–9 (2016).

283. Coetsee, C., Gray, E. F., Wakeling, J., Wigley, B. J. & Bond, W. J. Low gains in ecosystem carbon with woody plant encroachment in a South African savanna. *Journal of Tropical Ecology* **29**, 49–60 (2013).

284. Stanton, R. A. *et al.* Shrub encroachment and vertebrate diversity: A global meta-analysis. *Global Ecology and Biogeography* **27**, 368–379 (2018).

285. Leitner, M., Davies, A. B., Parr, C. L., Eggleton, P. & Robertson, M. P. Woody encroachment slows decomposition and termite activity in an African savanna. *Global Change Biology* **24**, 2597–2606 (2018).

286. Lima, K. A. *et al.* Landscape Heterogeneity and Woody Encroachment Decrease Mesocarnivore Scavenging in a Savanna Agroecosystem. *Rangeland Ecology & Management* **78**, 104–111 (2021).

287. de Klerk, J. N. *Bush Encroachment in Namibia: Report on Phase 1 of the Bush Encroachment Research, Monitoring, and Management Project*. (Ministry of Environment and Tourism, Directorate of Environmental Affairs, 2004).

288. Fulbright, T. E. Viewpoint: A theoretical basis for planning woody plant control to maintain species diversity. *Journal of Range Management* **49**, 554–559 (1996).

289. Angassa, A. & Oba, G. Bush encroachment control demonstrations in southern Ethiopia: 1. Woody species survival strategies with implications for herder land management. *African Journal of Ecology* **47**, 63–76 (2009).

290. Ditomaso, J. M. *et al.* Control of Invasive Weeds with Prescribed Burning. *Weed Technology* **20**, 535–548 (2006).

291. Trollope, W. S. W. Role of fire in preventing bush encroachment in the Eastern Cape. *http://dx.doi.org/10.1080/00725560.1974.9648722* **9**, 67–72 (2010).

292. Kahumba, A. Comparison of the rehabilitative effects of mechanical and chemical methods of bush control on degraded highland savanna rangelands in Namibia. (University of Namibia, 2010).

293. Smit, G. N. An approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment. *Journal of Environmental Management* **71**, 179–191 (2004).

294. Hester, A. J., Scogings, P. F. & Trollope, W. S. W. Long-term impacts of goat browsing on bush-clump dynamics in a semi-arid subtropical savanna. *Plant Ecology 2005 183:2* **183**, 277–290 (2005).

295. Hare, M. L., Xu, X., Wang, Y. & Gedda, A. I. The effects of bush control methods on encroaching woody plants in terms of die-off and survival in Borana rangelands, southern Ethiopia. *Pastoralism* **10**, 1–14 (2020).

296. Epple, C., Garcia, R. S. & Jenkins, M. *Managing ecosystems in the context of climate change mitigation: A review of current knowledge and recommendations to support ecosystem-based mitigation actions that look beyond terrestrial forests*. *Technical Series* vol. 86 (2016).

297. Dass, P., Houlton, B. Z., Wang, Y. & Warlind, D. Grasslands may be more reliable carbon sinks than forests in California. *Environmental Research Letters* **13**, 074027 (2018).

298. Yang, Y., Tilman, D., Furey, G. & Lehman, C. Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature Communications 2019 10:1* **10**, 1–7 (2019).

299. Buisson, E. *et al.* Resilience and restoration of tropical and subtropical grasslands, savannas, and grassy woodlands. *Biological Reviews* **94**, 590–609 (2019).

300. Falk, D. A. & Millar, C. I. The Influence of Climate Variability and Change on the Science and Practice of Restoration Ecology. *Foundations of Restoration Ecology: Second Edition* 484–513 (2016) doi:10.5822/978-1-61091-698-1_17.

301. Pellizzaro, K. F. *et al.* “Cerrado” restoration by direct seeding: field establishment and initial growth of 75 trees, shrubs and grass species. *Brazilian Journal of Botany 2017 40:3* **40**, 681–693 (2017).

302. Wang, L. *et al.* Grazing exclusion—An effective approach for naturally restoring degraded grasslands in Northern China. *Land Degradation & Development* **29**, 4439–4456 (2018).

303. Davis, M. A. & Miller, A. Savanna Restoration Using Fire Benefits Birds Utilizing Dead Trees, Up to a Point. *https://doi.org/10.1674/0003-0031-179.1.94* **179**, 94–104 (2018).

304. Manning, G. C., Baer, S. G. & Blair, J. M. Effects of Grazing and Fire Frequency on Floristic Quality and its Relationship to Indicators of Soil Quality in Tallgrass Prairie. *Environmental Management* **60**, 1062–1075 (2017).

305. Galvin, K. A. Transitions: Pastoralists Living with Change. *http://dx.doi.org/10.1146/annurev-anthro-091908-164442* **38**, 185–198 (2009).

306. Selemani, I. S. *et al.* The role of indigenous knowledge and perceptions of pastoral communities on traditional grazing management in north-western Tanzania. *African Journal of Agricultural Research* **7**, 5537–5547 (2012).

307. Bissett, N. J. Restoration of Dry Prairie by Direct Seeding: Methods and Examples. in *Land of Fire and Water: The Florida Dry Pairie Ecosystem. Proceedings of the Florida Dry Prairie Conference* (ed. Noss, R. F.) (2006).

308. Sampaio, A. B. *et al.* Lessons on direct seeding to restore Neotropical savanna. *Ecological Engineering* **138**, 148–154 (2019).

309. Slodowicz, D., Humbert, J. Y. & Arlettaz, R. The relative effectiveness of seed addition methods for restoring or re-creating species rich grasslands: a systematic review protocol. *Environmental Evidence 2019 8:1* **8**, 1–7 (2019).

310. de Groot, R. *et al.* Global estimates of the value of ecosystems and their services in monetary units. *Ecosystem Services* **1**, 50–61 (2012).

311. Bengtsson, J. *et al.* Grasslands—more important for ecosystem services than you might think. *Ecosphere* **10**, e02582 (2019).

312. Conant, R. T., Cerri, C. E. P., Osborne, B. B. & Paustian, K. Grassland management impacts on soil carbon stocks: a new synthesis. *Ecological Applications* **27**, 662–668 (2017).

313. Henderson, B. B. *et al.* Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. *Agriculture, Ecosystems & Environment* **207**, 91–100 (2015).

314. Wilcox, J. *et al.* Soil C Sequestration as a Biological Negative Emission Strategy. *Frontiers in Climate | www.frontiersin.org* **1**, (2019).

315. Morgan, J. A. *et al.* Carbon sequestration in agricultural lands of the United States. *Journal of Soil and Water Conservation* **65**, 6A-13A (2010).

316. Derner, J. D. & Schuman, G. E. Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation* **62**, (2007).

317. Ellis, J. E. & Swift, D. M. Stability of African Pastoral Ecosystems: Alternate Paradigms and Implications for Development. *Journal of Range Management* **41**, 450 (1988).

318. Wehrden, H. von, Hanspach, J., Kaczensky, P., Fischer, J. & Wesche, K. Global assessment of the non-equilibrium concept in rangelands. *Ecological Applications* **22**, 393–399 (2012).

319. Koerner, S. E. *et al.* Change in dominance determines herbivore effects on plant biodiversity. *Nature Ecology & Evolution 2018 2:12* **2**, 1925–1932 (2018).

320. Vetter, S. With Power Comes Responsibility – A Rangelands Perspective on Forest Landscape Restoration. *Frontiers in Sustainable Food Systems* **4**, 225 (2020).

321. Machmuller, M. B. *et al.* Emerging land use practices rapidly increase soil organic matter. (2015) doi:10.1038/ncomms7995.

322. Teague, W. R. *et al.* Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *Agriculture, Ecosystems & Environment* **141**, 310–322 (2011).

323. Venter, Z. S., Hawkins, H. J. & Cramer, M. D. Does defoliation frequency and severity influence plant productivity? The role of grazing management and soil nutrients. *https://doi.org/10.2989/10220119.2020.1766565* 1–16 (2020) doi:10.2989/10220119.2020.1766565.

324. O'Reagain, P. J. & Turner, J. R. An evaluation of the empirical basis for grazing management recommendations for rangeland in southern Africa. *http://dx.doi.org/10.1080/02566702.1992.9648297* **9**, 38–49 (2010).

325. Briske, D. D. *et al.* Rotational Grazing on Rangelands: Reconciliation of Perception and Experimental Evidence. *Rangeland Ecology & Management* **61**, 3–17 (2008).

326. van Amburgh, P. & Cooke, S. *Less Stress, More Grass by Managing Holistically: A dairy case study*. (2017).

327. Savory, A. & Parsons, S. D. The Savory Grazing Method. *Rangelands* **2**, 234–237 (1980).

328. Savory Institute. *Restoring the climate through capture and storage of soil carbon through holistic planned grazing*. (2013).

329. Savory, A. & Butterfield, J. *Holistic Management: A New Framework for Decision Making*. (Island Press, 1999).

330. Gosnell, H., Grimm, K. & Goldstein, B. E. A half century of Holistic Management: what does the evidence reveal? *Agriculture and Human Values 2020 37:3* **37**, 849–867 (2020).

331. Hawkins, H. J., Venter, Z. S. & Cramer, M. D. A holistic view of Holistic Management: What do farm-scale, carbon, and social studies tell us? *Agriculture, Ecosystems and Environment* **323**, (2022).

332. Cassidy, L. R. & Kleppel, G. *The Effect of Grazing Regime on Grassland Bird Abundance in New York State*. vol. 86 (2017).

333. Kerley, G. I. H. & Cromsigt, J. From reindeer to rhino: Reflections on "Climate change mitigation and adaptation benefits of wilder rangelands." *South African Journal of Science* **116**, (2020).

334. Cromsigt, J. P. G. M. *et al.* Trophic rewilding as a climate change mitigation strategy? *Philosophical Transactions of the Royal Society B: Biological Sciences* **373**, (2018).

335. Svenning, J.-C. *et al.* Science for a wilder Anthropocene: Synthesis and future directions for trophic rewilding research. *Proceedings of the National Academy of Sciences* **113**, 898–906 (2016).

336. Sitters, J., Kimuyu, D. M., Young, T. P., Claeys, P. & Olde Venterink, H. Negative effects of cattle on soil carbon and nutrient pools reversed by megaherbivores. *Nature Sustainability 2020 3:5* **3**, 360–366 (2020).

337. Sandhage-Hofmann, A., Linstädter, A., Kindermann, L., Angombe, S. & Amelung, W. Conservation with elevated elephant densities sequesters carbon in soils despite losses of woody biomass. *Global Change Biology* **27**, 4601–4614 (2021).

338. Davies, A. B. & Asner, G. P. Elephants limit aboveground carbon gains in African savannas. *Global Change Biology* **25**, 1368–1382 (2019).

339. J Smit, I. P., Archibald, S. & Izak J Smit, C. P. Herbivore culling influences spatio-temporal patterns of fire in a semiarid savanna. *J Appl Ecol* **56**, (2019).

340. Goheen, J. R. A win–win for wildlife and ranching. *Nature Sustainability 2018 1:10* **1**, 535–536 (2018).

341. Waldram, M. S., Bond, W. J. & Stock, W. D. Ecological Engineering by a Mega-Grazer: White Rhino Impacts on a South African Savanna. *Ecosystems 2007 11:1* **11**, 101–112 (2007).

342. Johnson, C. N. *et al.* Can trophic rewilding reduce the impact of fire in a more flammable world? *Philosophical Transactions of the Royal Society B: Biological Sciences* **373**, (2018).

343. Snyman, S. *et al. State of the Wildlife Economy in Africa*. https://www.alueducation.com (2021).

344. Ozenda, P. *Flora and vegetation of the Sahara.* (CNRS, 1991).

345. le Houérou, H. N. Biogeography of the arid steppeland north of the Sahara. *Journal of Arid Environments* **48**, 103–128 (2001).

346. van Damme, P. Plant Ecology of the Namib Desert. *Afrika Focus* **7**, 355–400 (1991).

347. Tolba, M. K. Desertification in Africa. *Land Use Policy* **3**, 260–268 (1986).

348. Reich, P. F., Numbem, S. T., Almaraz, R. A. & Eswaran, H. Land resource stresses and desertification in Africa. in *Response to Land Degradation* 101–116 (CRC Press, 2019). doi:10.1201/9780429187957-12.

349. UNCCD. *Summary for Decision Makers: Global Land Outlook, second edition*. (2022).

350. Gonzalez, P. Desertification and a shift of forest species in the West African Sahel. *Climate Research* **17**, 217–228 (2001).

351. Thomas, N. & Nigam, S. Twentieth-century climate change over Africa: Seasonal hydroclimate trends and sahara desert expansion. *Journal of Climate* **31**, 3349–3370 (2018).

352. Kurukulasuriya, P. & Mendelsohn, R. O. How Will Climate Change Shift Agro-Ecological Zones and Impact African Agriculture? *World Bank Policy Research Working Paper* **4717**, (2008).

353. Pausata, F. S. R. *et al.* The Greening of the Sahara: Past Changes and Future Implications. *One Earth* **2**, 235–250 (2020).

354. Evan, A. T., Flamant, C., Gaetani, M. & Guichard, F. The past, present and future of African dust. *Nature 2016 531:7595* **531**, 493–495 (2016).

355. Yu, H. *et al.* The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. *Geophysical Research Letters* **42**, 1984–1991 (2015).

356. Bristow, C. S., Hudson-Edwards, K. A. & Chappell, A. Fertilizing the Amazon and equatorial Atlantic with West African dust. *Geophysical Research Letters* **37**, (2010).

357. Bonfils, C., de Noblet-Ducoudré, N., Braconnot, P. & Joussaume, S. Hot Desert Albedo and Climate Change: Mid-Holocene Monsoon in North Africa. *Journal of Climate* **14**, 3724–3737 (2001).

358. Oleson, K. W. *et al.* Assessment of global climate model land surface albedo using MODIS data. *Geophysical Research Letters* **30**, 1443 (2003).

359. Donohue, R. J., Roderick, M. L., McVicar, T. R. & Farquhar, G. D. Impact of CO2 fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters* **40**, 3031–3035 (2013).

360. Branch, O. & Wulfmeyer, V. Deliberate enhancement of rainfall using desert plantations. *Proc Natl Acad Sci U S A* **116**, 18841–18847 (2019).

361. Huebner, L. *Large Scale Afforestation in Arid and Semi-Arid Climate: Hydrologic-Ecological Lessons Learned and Concept of Modular Hydrologic Connectivity of Vegetation*. *Journal of Agriculture Food and Development* vol. 6 (2020).

362. O'Connor, D. & Ford, J. Increasing the Effectiveness of the "Great Green Wall" as an Adaptation to the Effects of Climate Change and Desertification in the Sahel. *Sustainability 2014, Vol. 6, Pages 7142-7154* **6**, 7142–7154 (2014).

363. Behnke, R. & Mortimore, M. Introduction: The End of Desertification? in *The End of Desertification?* (eds. Behnke, R. & Mortimore, M.) 1–34 (Springer, Berlin, Heidelberg, 2016). doi:10.1007/978-3-642-16014-1_1.

364. Olsson, L. Desertification in Africa — A critique and an alternative approach. *GeoJournal 1993 31:1* **31**, 23–31 (1993).

365. Akhtar-Schuster, M. *et al.* Unpacking the concept of land degradation neutrality and addressing its operation through the Rio Conventions. *Journal of Environmental Management* **195**, 4–15 (2017).

366. Rastgoo, M. & Hasanfard, A. Desertification in Agricultural Lands: Approaches to Mitigation. *Deserts and Desertification* (2021) doi:10.5772/INTECHOPEN.98795.

367. Hammouzaki, Y. Desertification and its control in Morocco. *Combating Desertification in Asia, Africa and the Middle East: Proven practices* 91–111 (2013) doi:10.1007/978-94-007-6652-5_5.

368. Nyong, A., Adesina, F. & Osman Elasha, B. The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change 2007 12:5* **12**, 787–797 (2007).

369. Komoto, K. *et al. Energy from the Desert: Very Large Scale PV Power Plants for Shifting to Renewable Energy Future*. (International Energy Agency, 2015).

370. Loumakis, G. Sustainable Solar Energy. *Lecture Notes in Energy* **77**, 139–167 (2020).

371. Li, Y. *et al.* Climate model shows large-scale wind and solar farms in the Sahara increase rain and vegetation. *Science (1979)* **361**, 1019–1022 (2018).

372. Lu, Z. *et al.* Impacts of Large-Scale Sahara Solar Farms on Global Climate and Vegetation Cover. *Geophysical Research Letters* **48**, e2020GL090789 (2021).

373. OECD/FAO. *OECD-FAO Agricultural Outlook 2021-2030*. (OECD, 2021). doi:10.1787/19428846-en.

374. The World Bank. Employment in agriculture (% of total employment) (modeled ILO estimate) - Sub-Saharan Africa | Data. https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=ZG (2019).

375. Bjornlund, V., Bjornlund, H. & van Rooyen, A. F. Why agricultural production in sub-Saharan Africa remains low compared to the rest of the world – a historical perspective. *https://doi.org/10.1080/07900627.2020.1739512* 1–34 (2020) doi:10.1080/07900627.2020.1739512.

376. Diallo, A. *AGRA Feeding Africa's soils whitepaper*. (2019).

377. Gilbert, N. African agriculture: Dirt poor. *Nature* **483**, 525–527 (2012).

378. Fukase, E. & Martin, W. *Agro-processing and Horticultural Exports from Africa*. (2017).

379. Pfister, S., Bayer, P., Koehler, A. & Hellweg, S. Projected water consumption in future global agriculture: Scenarios and related impacts. *Science of The Total Environment* **409**, 4206–4216 (2011).

380. Didas Kimaro *et al.* Adaptation by Smallholders in Eastern Africa to Climate Change through Conservation Agriculture. in *Soil Management of Smallholder Agriculture* 292–323 (CRC Press, 2014). doi:10.1201/B17747-16/ADAPTATION-SMALLHOLDERS-EASTERN-AFRICA-CLIMATE-CHANGE-CONSERVATION-AGRICULTURE-RATTAN-LAL-STEWART.

381. Nyagumbo, I. *et al.* Evaluating the merits of climate smart technologies under smallholder agriculture in Malawi. *Soil Use and Management* **38**, 890–906 (2022).

382. Bedeke, S., Vanhove, W., Gezahegn, M., Natarajan, K. & van Damme, P. Adoption of climate change adaptation strategies by maize-dependent smallholders in Ethiopia. *NJAS - Wageningen Journal of Life Sciences* **88**, 96–104 (2019).

383. Sparrevik, M., Field, J. L., Martinsen, V., Breedveld, G. D. & Cornelissen, G. Life cycle assessment to evaluate the environmental impact of biochar implementation in conservation agriculture in Zambia. *Environmental Science and Technology* **47**, 1206–1215 (2013).

384. Cornelissen, G. *et al.* Biochar Effect on Maize Yield and Soil Characteristics in Five Conservation Farming Sites in Zambia. *Agronomy 2013, Vol. 3, Pages 256-274* **3**, 256–274 (2013).

385. Ngwese, N. M., Saito, O., Sato, A., Boafo, Y. A. & Jasaw, G. Traditional and Local Knowledge Practices for Disaster Risk Reduction in Northern Ghana. *Sustainability 2018, Vol. 10, Page 825* **10**, 825 (2018).

386. Adzawla, W. & Alhassan, H. Effects of climate adaptation on technical efficiency of maize production in Northern Ghana. *Agricultural and Food Economics* **9**, 1–18 (2021).

387. Arouna, A. & Akpa, A. K. A. Water Management Technology for Adaptation to Climate Change in Rice Production: Evidence of Smart-Valley Approach in West Africa. *Sustainable Solutions for Food Security: Combating Climate Change by Adaptation* 211–227 (2019) doi:10.1007/978-3-319-77878-5_11.

388. Nigussie, Y., van der Werf, E., Zhu, X., Simane, B. & van Ierland, E. C. Evaluation of Climate Change Adaptation Alternatives for Smallholder Farmers in the Upper Blue-Nile Basin. *Ecological Economics* **151**, 142–150 (2018).

389. Branca, G. *et al.* Assessing the economic and mitigation benefits of climate-smart agriculture and its implications for political economy: A case study in Southern Africa. *Journal of Cleaner Production* **285**, 125161 (2021).

390. Enete, A. A., Madu, I. A. & Onwubuya, E. A. Climate Change and the Profitability of Indigenous Adaptation Practices in Smallholder Agriculture in South East Nigeria: *http://dx.doi.org/10.5367/oa.2012.0092* **41**, 179–185 (2012).

391. Bozzola, M. & Smale, M. The welfare effects of crop biodiversity as an adaptation to climate shocks in Kenya. *World Development* **135**, 105065 (2020).

392. Muroyiwa, B., Masinda, N. & Mushunje, A. Smallholder farmers' adaptation strategies to mitigate the effect of drought on maize production in OR Tambo District municipality. *https://doi.org/10.1080/20421338.2020.1847385* **14**, 459–471 (2021).

393. Thornton, P. K. & Herrero, M. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc Natl Acad Sci U S A* **107**, 19667–19672 (2010).

394. Baba, C. A. K. & Hack, J. Economic valuation of ecosystem services for the sustainable management of agropastoral dams. A case study of the Sakabansi dam, northern Benin. *Ecological Indicators* **107**, 105648 (2019).

395. Belgacem, A. O., Salem, F. ben, Gamoun, M., Chibani, R. & Louhaichi, M. Revival of traditional best practices for rangeland restoration under climate change in the dry areas A case study from Southern Tunisia. *International Journal of Climate Chanage Strategies and Management* (2019) doi:10.1108/IJCCSM-02-2018-0019.

396. Hawkins, J., Yesuf, G., Zijlstra, M., Schoneveld, G. C. & Rufino, M. C. Feeding efficiency gains can increase the greenhouse gas mitigation potential of the Tanzanian dairy sector. *Scientific Reports 2021 11:1* **11**, 1–15 (2021).

397. Brandt, P., Herold, M. & Rufino, M. C. The contribution of sectoral climate change mitigation options to national targets: a quantitative assessment of dairy production in Kenya. *Environmental Research Letters* **13**, 034016 (2018).

398. EADD, CGIAR, CCAFS & ICRAF. *East African Dairy Development Program adopts Climate Smart Agriculture*. (2014).

399. Otieno, J. & Muchapondwa, E. *Agriculture and adaptation to climate change: The Role of wildlife ranching in South Africa*. (2016).

400. Kuyah, S. *et al.* Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agronomy for Sustainable Development* **39**, 1–18 (2019).

401. Schoeneberger, M. *et al.* Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. *Journal of Soil and Water Conservation* **67**, 128A-136A (2012).

402. Nair, P. K. R. Climate Change Mitigation: A Low-Hanging Fruit of Agroforestry. 31–67 (2012) doi:10.1007/978-94-007-4676-3_7.

403. Buxton, J. *et al.* Community-driven tree planting greens the neighbouring landscape. *Scientific Reports |* **11**, 18239 (2021).

404. Cristina Rother, D. *et al.* Opportunities and Constraints for Using Farmer Managed Natural Regeneration for Land Restoration in Sub-Saharan Africa. (2020) doi:10.3389/ffgc.2020.571679.

405. Mbow, C. *et al.* Agroforestry solutions to address food security and climate change challenges in Africa. *Current Opinion in Environmental Sustainability* **6**, 61–67 (2014).

406. Brandt, M. *et al.* Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands. *Nature Geoscience 2018 11:5* **11**, 328–333 (2018).

407. Batsi, G., Sonwa, D. J., Mangaza, L., Ebuy, J. & Kahindo, J. M. Preliminary estimation of above-ground carbon storage in cocoa agroforests of Bengamisa-Yangambi forest landscape (Democratic Republic of Congo). *Agroforestry Systems 2021 95:8* **95**, 1505–1517 (2021).

408. Joseph Mayindo Mayele. Agroforestry practices for enhancing food security and climate change resilience in Rajaf county, South Sudan. *Master Thesis* http://196.43.133.114/handle/10570/7540 (2019).

409. Oke, D. & Olatiilu, A. Carbon Storage in Agroecosystems: A Case Study of the Cocoa Based Agroforestry in Ogbese Forest Reserve, Ekiti State, Nigeria. *Journal of Environmental Protection* **02**, 1069–1075 (2011).

410. Abdulai, I. *et al.* Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. *Global Change Biology* **24**, 273–286 (2018).

411. Mbuya, E., Jean-Baptiste, N. & Kyessi, A. G. Climate Adaptation Practices in Building Constructions: Progress and Limitations in Dar es Salaam, Tanzania. *Climate Change Management* 507–520 (2018) doi:10.1007/978-3-319-72874-2_29.

412. Vedeld, T., Coly, A., Ndour, N. M. & Hellevik, S. Climate adaptation at what scale? Multi-level governance, resilience, and coproduction in Saint Louis, Senegal. *Natural Hazards* **82**, 173–199 (2016).

413. Campion, B. B. & Venzke, J. F. Rainfall variability, floods and adaptations of the urban poor to flooding in Kumasi, Ghana. *Natural Hazards 2012 65:3* **65**, 1895–1911 (2012).

414. Adekola, O., Lamond, J., Adelekan, I. & Eze, E. B. Evaluating flood adaptation governance in the city of Calabar, Nigeria. *https://doi.org/10.1080/17565529.2019.1700771* **12**, 840–853 (2019).

415. Busayo, E. T. *et al.* Rediscovering South Africa: Flood disaster risk management through ecosystem-based adaptation. *Environmental and Sustainability Indicators* **14**, 100175 (2022).

416. Hugo, J., du Plessis, C. & Masenge, A. Retrofitting Southern African cities: A call for appropriate rooftop greenhouse designs as climate adaptation strategy. *Journal of Cleaner Production* **312**, 127663 (2021).

417. Biconne, R. Knowledge Sharing on Climate Change as a Resource for Adaptation Processes: The Case of Malika, Senegal. *Springer Climate* 125–140 (2014) doi:10.1007/978-3-319-00672-7_8.

418. Mugwedi, L. F. *et al.* Restoration planning for climate change mitigation and adaptation in the city of Durban, South Africa. *International Journal of Biodiversity Science, Ecosystem Services and Management* **14**, 132–144 (2018).

419. Monteverdi, M. C. *et al.* Re-use of wastewater for a sustainable forest production and climate change mitigation under arid environments. *Annals of Silvicultural Research* **38**, 22–31 (2014).

420. Koura, I. B., Dossa, L. H., Kassa, B. D. & Houinato, M. Adaptation of Periurban Cattle Production Systems to Environmental Changes: Feeding Strategies of Herdsmen in Southern Benin. *http://dx.doi.org/10.1080/21683565.2014.953662* **39**, 83–98 (2014).

421. Heath, T. T., Parker, A. H. & Weatherhead, E. K. Testing a rapid climate change adaptation assessment for water and sanitation providers in informal settlements in three cities in sub-Saharan Africa: *http://dx.doi.org/10.1177/0956247812453540* **24**, 619–637 (2012).

422. Bender, M. v. Water for Bongo: Creative Adaptation, Resilience & Dar es Salaam's Water Supply. *Daedalus* **150**, 48–63 (2021).

423. Machado, A. A. S., Valyi, K. & Rillig, M. C. Potential Environmental Impacts of an "Underground Revolution": A Response to Bender et al. *Trends in Ecology & Evolution* (2016) doi:10.1016/j.tree.2016.10.009.

424. Yéo, W. E., Goula, B. T. A., Diekkrüger, B. & Afouda, A. Vulnerability and adaptation to climate change in the Comoe River Basin (West Africa). *Springerplus* **5**, (2016).

425. Ziervogel, G., Shale, M. & Du, M. Climate change adaptation in a developing country context: The case of urban water supply in Cape Town. *https://doi.org/10.3763/cdev.2010.0036* **2**, 94–110 (2011).

426. Brown, D. Making the linkages between climate change adaptation and spatial planning in Malawi. *Environmental Science & Policy* **14**, 940–949 (2011).

427. Pierer, C. & Creutzig, F. Star-shaped cities alleviate trade-off between climate change mitigation and adaptation. *Environmental Research Letters* **14**, 085011 (2019).

428. Anguelovski, I., Chu, E. & Carmin, J. A. Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South. *Global Environmental Change* **27**, 156–167 (2014).

429. Roberts, D. Prioritizing climate change adaptation and local level resilience in Durban, South Africa: *http://dx.doi.org/10.1177/0956247810379948* **22**, 397–413 (2010).

430. Robertson, J. & Lawes, M. J. User perceptions of conservation and participatory management of iGxalingenwa forest, South Africa. *Environmental Conservation* **32**, 64–75 (2005).

431. Lambe, F., Jürisoo, M., Wanjiru, H. & Senyagwa, J. *Bringing clean, safe, affordable cooking energy to households across Africa: an agenda for action*. www.newclimateeconomy.report (2015).

432. Wassie, Y. T. & Adaramola, M. S. Potential environmental impacts of small-scale renewable energy technologies in East Africa: A systematic review of the evidence. *Renewable and Sustainable Energy Reviews* **111**, 377–391 (2019).

433. Thakur, M. *et al.* Impact of improved cookstoves on women's and child health in low and middle income countries: a systematic review and meta-analysis. *Thorax* **73**, 1026–1040 (2018).

434. Petrokofsky, G., Harvey, W. J., Petrokofsky, L. & Adongo Ochieng, C. The importance of time-saving as a factor in transitioning from woodfuel to modern cooking energy services: A systematic map. *Forests* **12**, (2021).