Chapter 9
Dryland Social-Ecological Systems in Africa

Fadong Li, Salif Diop, Hubert Hirwa, Simon Maesho, Xu Ning, Chao Tian, Yunfeng Qiao, Cheikh Faye, Birane Cissé, Aliou Guisse, Peifang Leng, Yu Peng, and Gang Chen

Abstract In Africa, dryland ecosystem is the largest biome complex, covering 60% of the continent and home to ~525 million people. Coupled with adverse climatic conditions and anthropogenic pressures make dryland highly vulnerable to environmental degradation. In this chapter, we elucidate an overview of dryland socio-ecological systems (DSES) in Africa. We examine dryland biodiversity as a basis for ecosystem services in Africa. Therefore, we investigate the research and technology

---

S. Diop died prior to the submission of this paper. This is one of the last works of him.

F. Li · H. Hirwa (✉) · S. Maesho · X. Ning · C. Tian · Y. Qiao · P. Leng · Y. Peng
State Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
e-mail: hhirwa2019@igsnrr.ac.cn

Shandong Yucheng Agro-Ecosystem National Observation Research Station, Ministry of Science and Technology of China, Yucheng, China

Yucheng Comprehensive Experiment Station, Chinese Academy of Sciences, Yucheng, China

F. Li · H. Hirwa · X. Ning · Y. Qiao
University of Chinese Academy of Sciences, Beijing 100049, China

S. Diop · B. Cissé
Department of Geography, Cheikh Anta Diop University, Dakar, Senegal

C. Faye
Department of Geography, U.F.R. Sciences and Technologies, Assane Seck University of Ziguinchor, Geomatics and Environment Laboratory, BP 523 Ziguinchor, Senegal

A. Guisse
Faculty of Science and Technology, University Cheikh Anta Diop of Dakar, P.O. Box 5005, Dakar-Fann, Senegal

P. Leng
Department of Lake Research, Helmholtz Centre for Environmental Research-UFZ, Magdeburg, Germany

G. Chen
Department of Civil and Environmental Engineering, College of Engineering, FL A&M University–Florida State University, Tallahassee, FL, USA

B. Fu and M. Stafford-Smith (eds.), *Dryland Social-Ecological Systems in Changing Environments*, https://doi.org/10.1007/978-981-99-9375-8_9

gaps in African drylands. Finally, we conclude and highlight the future perspectives for sustainable DSES management. Sustainable development requires an understanding of and adherence to the proper functioning of DSES. We recommend to promote sustainable agricultural best practices and innovations as a tool to enhance community resilience and cope with climate change impacts on food security, use modern observational data and develop idealistic models to better understand the climate-drylands-food security nexus approaches, and strengthen dryland research and management effectiveness through emerging and affordable technologies.

Keywords Socio-ecological systems · Land degradation · Dryland biodiversity · Resilience · Food security · Africa

9.1 Drylands and Socio-ecological Systems in Africa

Stretching latitudinally from 37°N to 35°S and longitudinally from 52°E to 17°W, Africa accounts for 6% of the Earth's surface area and 20% of its landmass. In Africa, drylands occupy over 60% of the total surface area (~30.37×10^6 km^2 including its adjacent islands) (Kolding et al. 2016). Overall, African drylands are biophysically and socially diverse, characterized by challenging agroclimatic conditions, thus a big part of the global heritage, in terms of the crops and livestock (Cervigni and Morris 2016). Therefore, African drylands include a constellation of widely differentiated resources at spatio-temporal scales (i.e., macroscales to microscales). In drylands, the availability of potential input expands and contracts dramatically through under unpredictable intervals between years. The potential productivity of these resources, as well as their efficient and sustainable use, depends largely, or even entirely, on producers' micro-management and real time adjustments (Kratli 2020).

The Agro-Ecological Zones (AEZs) of Africa are classified into seven types of ecosystems: cultivated lands, scrublands, shrublands, grasslands, savannas, semi-deserts, and deserts. Therefore, the major physical regions of Africa include the African Great Lakes, the Ethiopian highlands, the Sahara, the Sahel, the Swahili Coast, and the rainforest, as well as the Southern Africa savanna (Kay and Kaplan 2015). High temperatures and low precipitation of the dryland regions result in limited organic matter decomposition, minimal nutrient cycling, and subsequently reduced primary productivity (Hartley et al. 2007). The dryland agroecosystems provide the inhabitants with important ecosystem services including "hotspots" of hydro-biogeochemical activities. In these regions, ~70% of the population relies on rainfed agriculture for subsistence and is deeply intertwined with nature (Jalloh et al. 2012), in absence of climate change adaptation and mitigation measures, 40–80% of people are expected to be affected from 2010 to 2030 (Nyberg et al. 2019). Figure 9.1 shows the example of the degrading impacts of anthropogenic activities on dryland ecosystems and landscape restoration in Africa.

The dryland ecosystems are described by dryland socio-ecological systems (DSES), which dynamically couple society, culture, and natural capital quantitatively

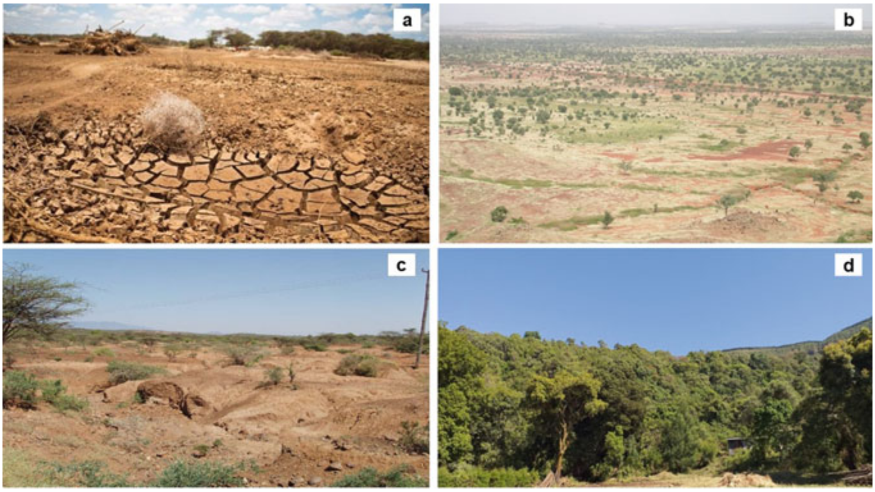


Fig. 9.1 Examples of dryland ecosystems in Africa. **a** Coupled changing weather patterns and over-abstraction are reducing river flows in Ewaso Ngiro River, Kenya. *Credit* Denis Onyodi/Kenya Red Cross Society. **b** West African Sahel and dry savannas, view of a degraded landscape in Niger. *Credit* Patrice Savadogo. **c** Degraded area by soil erosion in the rangelands near Lake Baringo, Kenya. *Credit* Lawrence M. Kiage. **d** Landscape restoration in Ethiopian highlands. *Credit* Mesfine

and qualitatively (Huber-Sannwald et al. 2012). Currently, DSES face challenges at different scales including climate variations, population growth, land degradation, desertification, water scarcity, economic and land-use changes, cultural perceptions, and governance and management practices that negatively affect DSES (Chapin et al. 2009; Linstädter et al. 2016; Villada-Canela et al. 2020). These challenges contribute to high levels of unpredictability, variability, and heterogeneity to shape the coupled human and nature co-adaptative process. For the sustainable management of natural resources, a comprehensive understanding of the complex relationships between human and natural systems is necessary (Aminpour et al. 2020). The DSES also provide guidelines for assessing the impact of social and ecological dimensions on resource use and management (Partelow 2018). There are two main conceptual pillars for DSES. Firstly, the first one is to understand the DSES function, taking into account the economic effect, and the second one is to consider all aspects related to the development, transformation, and implementation toward normative sustainability goals (Yu et al. 2021). Nowadays, in Africa, dryland management is one of the most pressing issues that need to be addressed. Presently, there is an urgent need to restore and protect the ecosystems in the semi-arid drylands of Sahel regions, Eastern Africa, Southern Africa, and Western Africa.

Using the DSES approach, this chapter aims to provide diagnostic information on Africa's drylands management. The chapter also reviews major features and trends of the DSES by assessing the driving factors of dryland change and their interactions. Attention is paid to potential future perspectives of sustainable dryland ecosystem management and efforts to enforce dryland community resilience in the face of adverse environmental changes. This chapter also addresses the research and innovation gaps in the reliable assessment of DSES assessment. This chapter could aid in enhancing the implementation of sustainability policy in Africa and worldwide.

9.2 Major Characteristics of Drylands and DSESs in Africa

9.2.1 African Dryland Distribution

Arid, semi-arid, and dry subhumid terrains in Africa make up 27% of the world's drylands and account for 11% of the Earth's land surface (Prăvălie 2016). The Sub-Saharan Africa (SSA) drylands cover ~13.9×10^6 km^2. According to a high-resolution assessment by UNDP/UNSO (1997), the total African aridity coverage is ~21.2×10^6 ha (equivalent two-thirds of the continent surface area) with three-fifths of its farming lands, and are home to two-fifths of its population. Insofar, the northern region comprises 38% of this area, which is largely in the hyper-arid category. Despite the fact that the economy of Central Africa lags behind Northern, Western, and Eastern Africa, they all share the similar aridity in their territories. The arid zone of Africa is barely 1% covered by forest in central Africa, which makes up a large part of the continent's forested areas (Kigomo 2003).

In Eastern Africa, the hyper-arid, arid, and semi-arid zones are mostly in Sudan, Djibouti, and Somalia. The semi-arid and arid zones are widespread in Kenya and Ethiopia, while the sub-humid drylands are the dominating ones in Tanzania and Uganda. Burundi has a dry sub-humid zone that covers only 5% of its land area. Nearly 51% of Tanzania is relatively dry, and over two-thirds of Kenya are in arid and semi-arid areas with 33.3, 51.8, and 12.3% land subject to degradation from slight, moderate to severe. Among the West African countries, six have a large dryland region including Cote d' Ivoire, Mali, Ghana, Niger, Nigeria, and Senegal with the index ranging between <0.03 and 0.5 (Fig. 9.2).

9.2.2 Climate, Soil, Land Uses, and Land Degradation

The Köppen-Geiger climate classification of Africa indicates three climate types for the land areas: the tropical A, arid B, and temperate C, representing 57.2%, 31%, and 11.8% of the land areas, respectively. The northern and southern fringes of Africa are dominated by deserts, and tropical rainforests, grasslands, and semi-arid climates are found in the central eastern regions of the continent (Fig. 9.3).

The Environmental Systems Research Institute (ESRI) digitized Africa soil data from the UNESCO/FAO Soils Map of the World at a scale of 1:5 m (sheets VI 1-2-3). From the original 1509 soil units of the World map, Africa's 106 units were increased

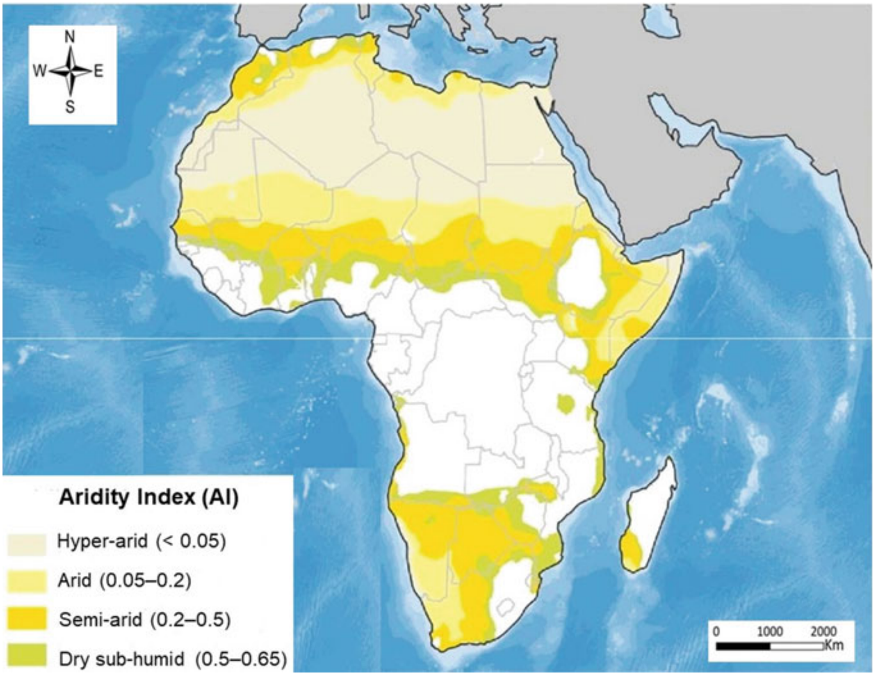


Fig. 9.2 A distribution of aridity classes in Africa based on global aridity index (AI) datasets (data from https://figshare.com/articles/Global_Aridity_Index_and_Potential_Evapotranspiration_ET0_Climate_Database_v2/7504448/3) (Trabucco and Zomer 2018). Drylands are demarcated based on the aridity index (AI), hyper-arid ($AI < 0.05$), arid ($0.05 < AI \leq 0.20$), semi-arid ($0.20 < AI \leq 0.50$), dry sub-humid ($0.50 < AI \leq 0.65$), and humid ($AI > 0.65$). Adapted from Wei et al. (2021)

to 133 to allow identification of associated soils (Batjes 2012). The major features of Africa soils are presented in Table 9.1.

The notable function of the soil in nutrient cycling. At the same time, it contributes to food production, water storage, and climate change mitigation in drylands (Safriel 2017). Soil organisms play a crucial role in the nutrient cycle of the land, contributing to its fertility and productivity through the accumulation of organic matter in the soil. Soil organisms include bacteria, fungi, insects, protozoa, worms, invertebrates, and vertebrates and all play an important role in the carbon, nitrogen, phosphorus, and water cycles by aiding decomposition processes that convert organically stored nutrients in plants like nitrogen to usable forms for living plants and maintaining the soil structure (Laban et al. 2018). The texture and structure of soil including the degree to which soil particles are bound together by organic matter, water holding properties, dissolved minerals, and oxygen contained in between the spaces are the rudimentary determinants of soil fertility (Safriel 2017). According to Parton et al. (1995), dryland soils typically have low organic carbon content due to primary productivity constrained by water scarcity, which affects the accumulation of soil organic content (SOC) and soil organic matter (SOM). Nevertheless, due to the longer residence

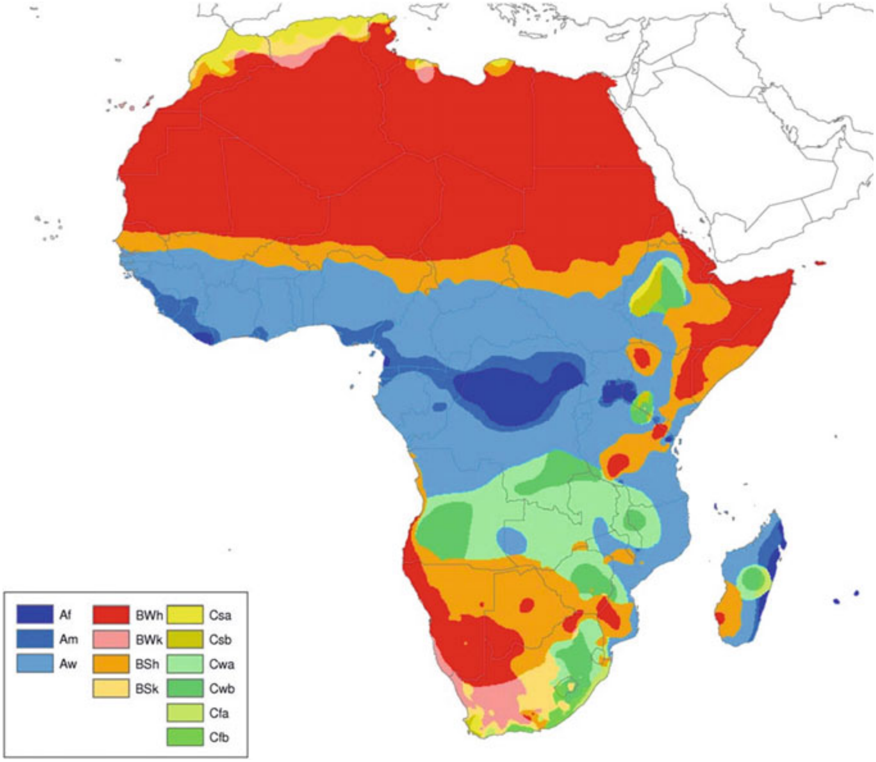


Fig. 9.3 Africa's major climates regions. The Equatorial (Af), Monsoon (Am), Tropical Savana (Aw), Warm Desert (Bwh), Cold Desert (Bwk), Warm Semi-Arid (Bsh), Cold Semi-Arid (Bsk), Warm Mediterranean (Csa), Temperate Mediterranean (Csb), Humid Subtropical (Cwa), Humid Subtropical/Subtropical Oceanic Highland (Cwb), Warm Oceanic/Humid Subtropical (Cfa), Temperate Oceanic (Cfb). *Source* Derived from World Köppen-Geiger classification (Peel et al. 2007)

time of soil carbon and low soil moisture, dryland ecosystems are quite significant for carbon sequestration and mitigation in comparison to other soils.

In Africa, land use patterns primarily depend on the population (Biswas 1986). More than 60% of the population of SSA is smallholder farmers, and agriculture contributes to about 23% of SSA's GDP (Bjornlund et al. 2020). Although 60% of the world's arable land is uncultivated in Africa (Gnacadja and Wiese 2016), but the continent's share remains low in global crop yields, therefore it has large rands in agricultural investment potential. Savannas, often known as grasslands, encompass about half of Africa, approximately 13 × 10^6 km^2 (Garrity et al. 2012). Grasslands cover the majority of central Africa, from south of the Sahara and the Sahel to north of the continent's southern point (Fig. 9.4).

Demographic growth, internal conflict, and wars with expanded refugee settlements, improper soil management, deforestation, shifting cultivation, insecurity in

Table 9.1 Main traits of African agro-ecological zones (AEZs) pertaining to land use (LU) and soil heterogeneity

FAO (AEZs)	Main soil type	Lus and agricultural systems
Hyper-arid (Kalahari, Karoo, Namib, and Sahara deserts)	Regosols and Arenosols	Oasis agricultural systems, nomadism, harvesting and hunting
Arid	Cambisols, Lixisols, and Leptosols	Millet based systems, semi-nomadism, and transhumance for livestock production
Dry and semi-arid (the Sahel and Sudan savannah)	Regosols, Solonetz, Arenosols, Lixisols, Plinthosols	Integrated crop (millet) and livestock production (agro-pastoralism) systems, transhumance sorghum, and maize
Sub-humid (Guinea Savannah)	Ferralsols, Acrisols, and Gleysols,	Agroforestry systems with sorghum, maize, root, and fruit plants
Humid (high rainforest)	Ferralsols, Acrisols, and Gleysols	Forest production (cocoa and coffee), agricultural systems with root and tuber crops
Mediterranean	Calcisols, Gypsisols, Regosols, Arenosols, Luvisols	Wheat-based system
Highlands	Ferralsols, Nitisols, Vertisols, Planosols	Grassland, pasture, cohffe, and tea plantations

Source Láng et al. (2016); Fischer et al. (2021); Garrity et al. (2012); Dewitte et al. (2013)

land tenure, variation in environmental conditions, and intrinsic characteristics of fragile soils in various agro-ecological zones are among the main causes of land degradation in Africa (Kiage 2013). According to the World Bank, Africa accounts for 65% of the total extensive cropland degradation of the world, negatively affecting ~485 × 10^6 people and resulting in ~US$ 9.3 billion annual costs (Fenta et al. 2020). Furthermore, among agricultural and non-agricultural land use, inadequate land-use planning and misuse of natural assets by the farming community, particularly poor farmers have significant negative impacts (Parikh and James 2012). For instance, 51% of the land in the Zambezi River basin, shared by Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe is moderately degraded and 14% is highly degraded. As a result of this deterioration, soil water-holding capacity (i.e., soil water retention) and infiltration decrease, lowering the amount of water in the soil accessible for the crops. It also has the potential to undermine large-scale water storage, particularly for irrigation schemes (Abrams 2018).

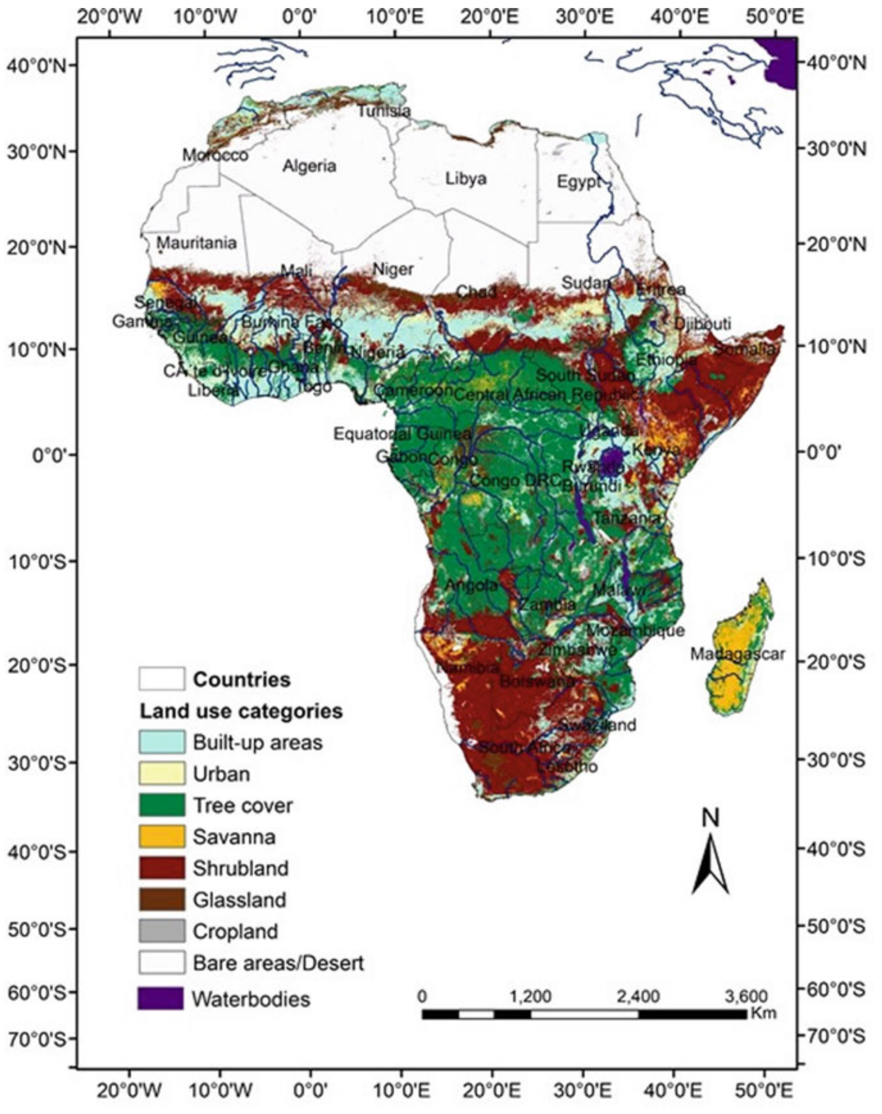


Fig. 9.4 Land use map of Africa. *Data source* European Space Agency (ESA 2017), Land Cover CCI Product User Guide Version 2

9.2.3 Water Resources

The considerable runoff typically benefits downstream regions. Rivers like the Nile, Niger, Senegal, and Orange carry water from rainy areas to arid areas that are often too arid to support life (Fig. 9.5). These high-elevation watersheds dubbed the “water towers of Africa”, provide water sources for many transboundary rivers, and offer

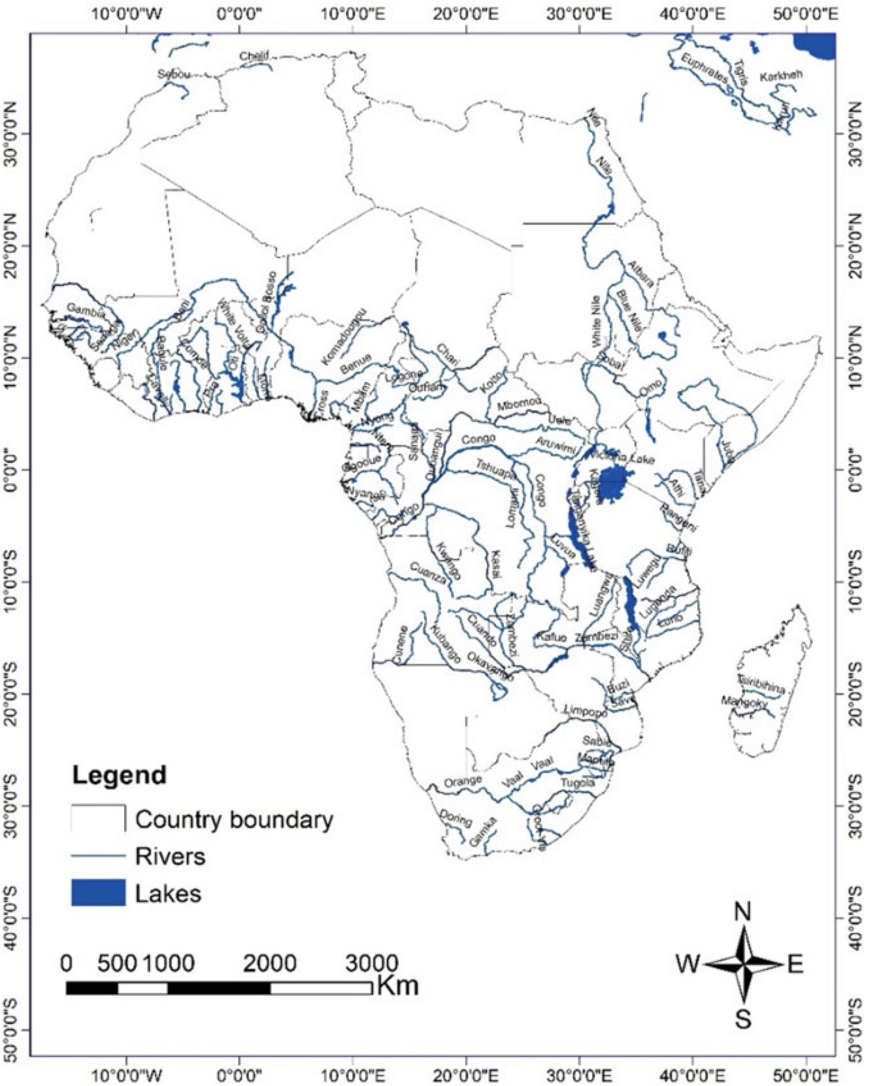


Fig. 9.5 Map of rivers and lakes in Africa. Data from WHYMAP GWR and UNESCO 2015—Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and UNESCO 2008. https://www.whymap.org/whymap/EN/Home/whymap-node.html. Accessed 10 October 2021

life-saving water to millions of people in downstream regions (MA 2005; UNEP 2010).

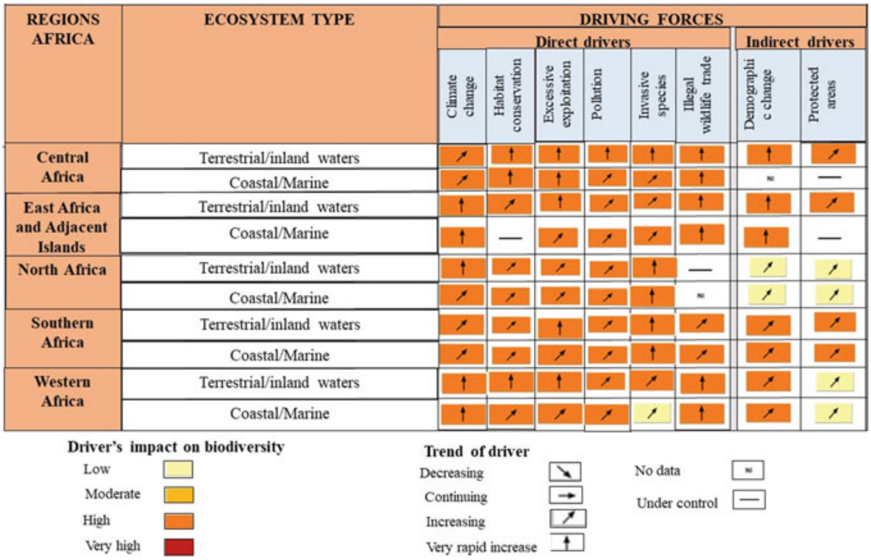
There are wide variations in average water availability (WA) per person among countries in the continent. For instance, the annual per capita WA for Nigeria, Africa's most populous country, is 1499.4 m^3, which is lower than that of fairly dry countries such as Botswana (5340 m^3) and Namibia (15,750 m^3) in Southern Africa. Annual per capita WA is high for countries such as Guinea (17,771 m^3), Sierra Leone (21,172 m^3), and Liberia (49,028 m^3) in West Africa; the Democratic Republic of Congo (15,773 m^3), Central African Republic (30,264 m^3) and Gabon (81,975 m^3) in Central Africa; and in the Indian Ocean Island of Madagascar (13,179 m^3). In the southern part of the continent, WA per capita is moderately low for South Africa (905 m^3), compared to North African countries such as Algeria (282 m^3) and Libya (110 m^3), as well as Kenya (618 m^3) in East Africa.

Likewise, most countries in Africa's desert regions, such as Libya, Egypt, Algeria, Tunisia, Namibia, and Botswana, usually have little rainfall and rely significantly on groundwater resources. In Botswana, for example, groundwater fulfils 80% of residential and livestock needs (Black 2016), and the same occurs in Namibia (Ndengu 2002). In North Africa, groundwater is the only source of water (Braune and Xu 2010). Some of Africa's important aquifers are losing water faster than recharge in large sedimentary basins of Lake Chad and under the Sahara Desert (Pham-Duc et al. 2020).

9.2.4 Understanding Dryland Biodiversity as a Basis for Ecosystem Services in Africa

Ecosystem multifunctionality (i.e., the interaction between biodiversity and different ecosystem functions) is context-dependent (Hu et al. 2021). Africa is home to a wide range of biodiversity and about one-quarter of the world's biodiversity is found in this region. Africa is also home to some of the largest intact concentrations of large mammals, which graze freely throughout many countries. African dryland biodiversity is unique and varies among ecosystems, species, genetic, and functional diversity (Bonkoungou 2001). The instant main threats to dryland biodiversity in Africa are the ecosystem and habitat degradation caused by new and powerful forces of environmental deterioration such as climate change, deforestation, desertification, mining operations, poverty-induced overexploitation of natural resources, and increased wildlife trade (Fig. 9.6) (Archer et al. 2021). Within each relative aridity category, the dryland ecosystems and species are highly heterogeneous with wide variations in topographic, climatic, geological, and biological situations and the most limiting factors are soil nutrients and hydrological resources. For instance, the findings of Hu et al. (2021) revealed that the microbial diversity (e.g., fungi) is positively associated with multifunctionality in more arid regions, whereas in less arid regions, there is a strong positive correlation between soil and species richness multifunctionality. Besides, the dryland biodiversification also comprises the seasonal rainfall pattern, fires, and herbivore pressure (Venter et al. 2017).

The dryland biodiversity in Africa mostly consists of Mediterranean systems, the Southern Africa region, the Saharan, and the Sahel of Africa. In 2014, 3148 plants



REGIONS AFRICA	ECOSYSTEM TYPE	DRIVING FORCES							
		Direct drivers						Indirect drivers	
		Climate change	Habitat conservation	Excessive exploitation	Pollution	Invasive species	Illegal wildlife trade	Demographic change	Protected areas
Central Africa	Terrestrial/inland waters	🟧 ↗	🟧 ↑	🟧 ↑	🟧 ↑	🟧 ↑	🟧 ↑	🟧 ↑	🟧 ↗
	Coastal/Marine	🟧 ↗	🟧 ↑	🟧 ↑	🟧 ↗	🟧 ↗	🟧 ↑	≈	—
East Africa and Adjacent Islands	Terrestrial/inland waters	🟧 ↑	🟧 ↗	🟧 ↑	🟧 ↗	🟧 ↗	🟧 ↑	🟧 ↑	🟧 ↗
	Coastal/Marine	🟧 ↑	—	🟧 ↗	🟧 ↗	🟧 ↗	🟧 ↑	🟧 ↑	—
North Africa	Terrestrial/inland waters	🟧 ↑	🟧 ↗	🟧 ↗	🟧 ↗	🟧 ↑	—	🟨 ↗	🟨 ↗
	Coastal/Marine	🟧 ↗	🟧 ↗	🟧 ↗	🟧 ↗	🟧 ↑	≈	🟨 ↗	🟨 ↗
Southern Africa	Terrestrial/inland waters	🟧 ↗	🟧 ↗	🟧 ↑	🟧 ↗	🟧 ↑	🟧 ↗	🟧 ↗	🟧 ↗
	Coastal/Marine	🟧 ↗	🟧 ↗	🟧 ↗	🟧 ↗	🟧 ↑	🟧 ↗	🟧 ↗	🟧 ↗
Western Africa	Terrestrial/inland waters	🟧 ↑	🟧 ↑	🟧 ↑	🟧 ↗	🟧 ↗	🟧 ↑	🟧 ↗	🟨 ↗
	Coastal/Marine	🟧 ↑	🟧 ↗	🟧 ↗	🟧 ↗	🟨 ↗	🟧 ↑	🟧 ↗	🟨 ↗

Driver's impact on biodiversity

Low	🟨
Moderate	🟡
High	🟧
Very high	🟥

Trend of driver

Decreasing	↘
Continuing	→
Increasing	↗
Very rapid increase	↑
No data	≈
Under control	—

Fig. 9.6 Trends in biodiversity, drivers associated with them per subregion, and ecosystem type

and 6419 animals in Africa were recorded as threatened with extinction on the International Union for Conservation of Nature (IUCN) Red List. Although 21% of all freshwater species are threatened, 58% of freshwater plant species and 45% of freshwater fish are over-harvested (Dulvy et al. 2014; Darwall et al. 2011). In addition, over the past two decades, African birds showed a decline, resulting in a high probability of extinction. The trends for other groups also revealed a negative correlation. Since 1970, the combined population of African vertebrate species have declined by around 39% (McLellan et al. 2014). Declines are more rapid in Western and Central Africa than in Eastern or Southern Africa (Craigie et al. 2010). On the contrary, smaller species' population trends (e.g., insects) are often unknown (UNEP-WCMC 2016). In 2020, the population of Africa grew by 2.49% (about 1.36 billion inhabitants) compared to that in the previous year (Anoba 2019), which results in an increased demand for natural resources, leading to land-use changes and unsustainable species utilization such as wetland drainage for agriculture, inappropriate and unsustainable fish harvesting (UNEP-WCMC 2016). As a result of these changes, natural areas, biodiversity, and ecosystem services provided by natural habitats are all under threat. Furthermore, the water contamination from excessive nutrients, domestic and industrial organic loads, pesticides and heavy metals, and the impacts of invasive species lead to the depletion of biodiversity in freshwater habitats, especially in East Africa's Lake Victoria, the Mediterranean and Atlantic coasts of Morocco, and numerous major African rivers (Darwall et al. 2011).

Biodiversity Conservation and Preservation

Many dryland societies have strong values of environmental custodianship and a rich knowledge of their environment and rely heavily on a range of biodiversity (Mortimore et al. 2009). Re-enabling communities to use this knowledge is a powerful way to enhance biodiversity and build resilience in Africa. Restoring biodiversity through ecological restoration contributes to major gains in ecosystem services (Cowie et al. 2011; Bonkoungou 2001). For instance, soil biodiversity is critical for the supply of ecosystem services, and its protection is central to achieving Land Degradation Neutrality in Africa (Von Maltitz et al. 2019). Sustainable land management (SLM) practices protect the ecosystem functions that sustain productivity. Clearing land for cultivation may initially increase food production, but it comes at a significant cost in terms of water supply, climate regulation, carbon sequestration, forest resources, pollination, and many more services. Vegetation cover can play a major role in reducing surface flows of water and improving infiltration of water. In return, soil biodiversity improves both infiltration and water storage in the soil (Cowie et al. 2011; Collentine and Futter 2018).

However, biodiversity conservation is not the exclusive preserve of environmental and wildlife agencies. Instead, a shared responsibility of many sectors, including agriculture and water is the key. Sustainable agriculture offers one of the most important ways to achieve sustainable development by simultaneously protecting biodiversity and ecosystem services, raising agricultural productivity, and promoting the resilience of people and ecosystems (Adenle et al. 2019; Agula et al. 2018). SLM practices often rely on protecting biodiversity to boost soil organic carbon, soil nitrogen, and soil moisture. Practices like agroforestry and low tillage agriculture are based on indigenous practices that have been revived and improved to protect soil moisture and fertility of croplands as well as provide supplementary benefits. Other SLM practices, such as contour bunds and zai, also contribute to building up soil moisture and organic matter to improve productivity and resilience (Cordingley et al. 2015; Adimassu et al. 2016). In Africa, there is a need to motivate new approaches and actions such as conserving, valuing, restoring, and preserving biodiversity and ecosystems. Considerable effort and endeavor are needed to promote and consolidate these approaches between all sectors.

9.2.5 Socio-economic Development Indicators

Economic growth will lessen the proportion of people in Africa’s drylands who are vulnerable to droughts and other stressors. However, it may not offset the effects of population growth. By 2030, the population living in rural areas of the dryland countries is projected to grow by 15–100% (Morris et al. 2016). By 2050, the human population in SSA will double (UNDP 2015). About 70% of Africans rely on dry and sub-humid lands for their livelihoods (UNEP 2007). With 10–20% of drylands already degraded, these drylands, which are mostly used for cattle production, are highly vulnerable to land degradation (FAO 2009).

In the past four decades, population growth in SSA was correlated to the corresponding economy with a rise in the number of people living in extreme poverty (Burian et al. 2019). Since the early 1990s, SSA's poverty rates have remained steady, and half of the global population now lives on less than US$ 1.90 day^{-1} (World Bank Group 2016). Africa's GDP is projected to gradually recover by ~3.4% and ~3.7% in 2021 and 2022, respectively, after shrinking by 2.1% in 2020 (IMF 2021). The per capita GDP is estimated to have contracted by 10% in nominal terms in 2020, which makes it insufficient to accelerate the socio-economic growth and reduce the poverty (Fig. 9.7). Drylands and poverty are interlinked at all scales of geography, from regional to subnational (Middleton and Sternberg 2013).

The COVID-19 pandemic will also exert a greater effect on African living conditions and socioeconomic prospects. In Ethiopia, Malawi, Nigeria, and Uganda, for example, the crisis is evidenced by increased unemployment, poverty, and inequality (Josephson et al. 2020). The health and economic problems facing dryland residents in Africa threaten to overwhelm the healthcare system, undermine livelihoods, and stain long-term prospects for economic growth.

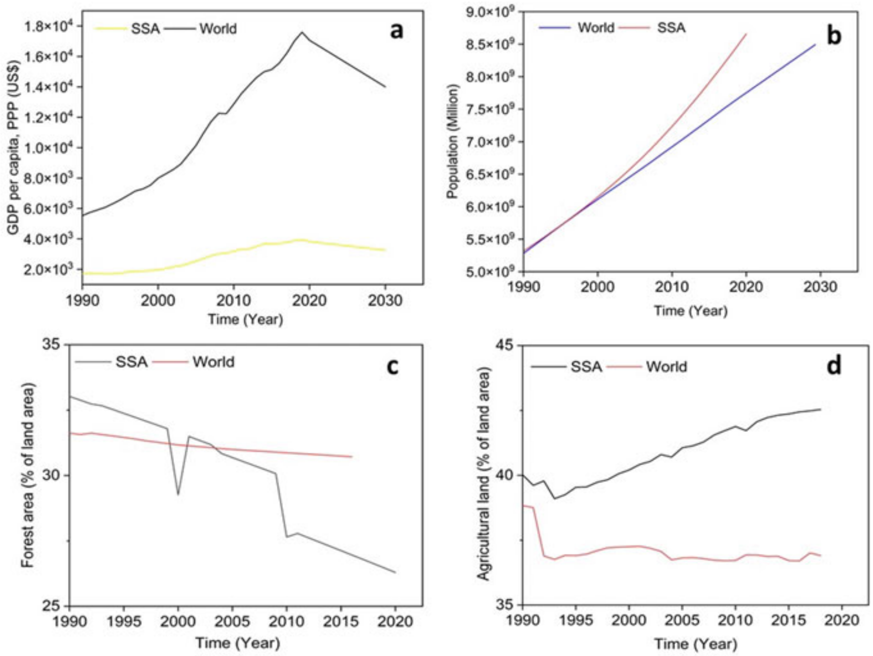


Fig. 9.7 Global and Sub-Saharan Africa (SSA) development indicators from 1990 to 2020, **a** GDP per capita, purchasing power parity (PPP), **b** population, **c** forest area, and **d** agricultural land. *Source* International Monetary Fund (IMF) database (World Bank 2021)

Table 9.2 The extent of African dryland

Sub-region	Hyper-arid		Arid		Semi-arid		Dry sub-humid		Total
	km^3	%	km^3	%	km^3	%	km^3	%	km^3
Central Africa	0	0	6	0	66	2	144	4	216
Eastern Africa	878	14	1670	27	1768	28	767	12	5083
Southern Africa	96	2	823	13	2579	42	924	15	4422
Western Africa	2363	33	1465	20	1278	18	514	7	5620
Total	8072	27	4604	16	6100	21	2392	8	21,170

Adapted from Koohafkan and Stewart (2008); UNDP/UNSO (1997)

9.3 Changing Aspects of African Drylands

9.3.1 *Dryland Dynamics in the Past Decades*

In the last four decades, the overall dryland temperature rose at a rate of 0.032 °C·year^{-1} and precipitation dropped at a rate of 0.074 mm·month^{-1}·year^{-1}, respectively. Although precipitation generally decreased over the drylands, summer precipitation increased over southern Africa as well as northern Africa's dryland areas (Daramola and Xu 2021). High precipitation years in southern Africa caused an initial spike in fire rates, which then declined in the subsequent years (Wei et al. 2020). Spatially, the North and Southern parts of Africa are dominated by hyper-arid regions (e.g., Sahara, Kalahari, and Namib desert) (FAO 2019). Most African regions are dominated by drylands, of which dry sub-humid, semi-arid, arid, hyper-arid dryland account for 8%, 21%, 16%, and 27%, respectively (Table 9.2).

9.3.2 *Structure and Functions*

It has been widely accepted that dryland function and structure are influenced by climatic factors (Maestre et al. 2016). The structure and function of drylands can be traced down to the basic processes that underpin the dryland ecosystem services that provide benefits to people (Hoover et al. 2019). Africa drylands ecosystem structural and functional dynamics consist of carbon dynamics, woody plant increase, and change in vegetation greenness (Ross et al. 2021). Therefore, in order to understand dryland carbon sequestration potentials, it is crucial to monitor spatiotemporal dynamics of dryland structure and function.

Auditing vegetation greenness is a key measure of photosynthetic activity and subsequent availability of green biomass for livestock feed (Diouf et al. 2015). Lu et al. (2016) indicated that over recent decades, changes in vegetation greenness were spatially diverse in African drylands despite overall greening trends (Wei et al. 2019). Over the last decades of the twentieth century, the field data and satellite observations commonly revealed a positive trend in vegetation greenness and rainfall across much of the Sahel (Brandt et al. 2015). Moreover, in recent decades, East Africa has been identified as a hotspot of vegetation browning driven by rising soil water shortage (Wei et al. 2019). As a result, in water-stressed southern Africa, vegetation greening has become common, which is linked to an increase in woody cover fueled by abundant rainfall and enhanced by CO_2 fertilization (Venter et al. 2018). Similarly, woody plants are becoming more common in African drylands (Stevens et al. 2017). In Southern Africa, for example, woody encroachment is displacing herbaceous vegetation (Skowno et al. 2017).

It has been observed that the Sahel's woody vegetation is shifting towards drought-resistant shrubs at the expense of forests (Brandt et al. 2015). The trend of rising leaf area index/vegetation greenness in African drylands mirrors the extensively reported increase in woody plant cover in tropical arid regions worldwide (Tian et al. 2017). Meanwhile, estimations of woody cover obtained from vegetation optical depth (VOD) have shown significant increases from 1992 to 2011 (Brandt et al. 2017). Further, from 2010 and 2016, there was a carbon loss in African drylands (Fan et al. 2019). With a climax in the unusually rainy year of 2011, African drylands were identified as a major carbon sink (Yue et al. 2017; Poulter et al. 2014). Consequently, due to intense El Niño event of 2015–2016 led to drylands being classified as a carbon source (Brandt et al. 2018), but the detailed mechanisms underlying this transition need to be investigated (Yue et al. 2017). In 2017, the carbon stock of African drylands (i.e., shrublands and savanna) had nearly restored to the pre-El Niño 2015–2016 levels (Wigneron et al. 2020). African drylands carry a huge amount of the continent's carbon stock, with soil carbon accounting for a significant portion (Robinson 2007). Nevertheless, widespread woody plant increase is often connected with an upsurge in aboveground carbon biomass (Venter et al. 2018). There is thus a need for observational evidence to identify the effects of woody intrusion on soil carbon (Mureva et al. 2018).

9.3.3 Ecosystem Services, Human Well-Being, and Resilience

Vegetation shifts and ecosystem resilience-related studies are increasing over time, which lead to accurate measurement at larger areas and enrich human understanding of the changes in the terrestrial ecosystem, carbon exchange system, and climate-biosphere interactions in the environment (Bao et al. 2014; Zhang et al. 2003). The usage of remote sensing approaches such as the Gross Primary Productivity (GPP) and evapotranspiration (ET) is becoming feasible to evaluate the ecosystem Water Use Efficiency (eWUE) and ecosystem resilience. The assessment of eWUE centered

Table 9.3 Ecosystem resilience using dimensionless ecosystem Resilience Index to drought (eRId)

No.	Resilience status	Range
1	Resilient	>= 1 *eRId*
2	Slightly non-resilient	0.9 <= *eRId* < 1
3	Moderately non-resilient	0.8 <= *eRId* < 0.9
4	Non-resilient	*eRId* < 0.8

on GPP and ET can be essential to understand the ecosystem carbon–water coupling (Sun et al. 2018), which further provides information for the accurate prediction of ecosystem resilience and ecosystem management (Huang et al. 2016). A recent study on eco-hydrological resilience over Africa using coarse spatial resolutions showed that 31.22% of the terrestrial ecosystems were non-resilient to ecosystem shifts (Kayiranga et al. 2020).

Ecosystem resilience to drought in the Horn of Africa (HA) (A case study): This case study highlights and demonstrates the status of the eWUE and ecosystem resilience to drought in the HA with higher spatial resolution and specific focus. The eWUE was extracted from daily Global GPP and annual ET datasets using MOD17 algorithm. The study generated the annual eWUE from the fraction of average annual MODIS GPP to the average annual ET for 15 years. The ecosystem resilience calculation was conducted using the dimensionless ecosystem Resilience Index to drought (*eRId*) from the ratio of mean values of multi-annual eWUE to the annual eWUE of the driest year as initially defined by Sharma and Goyal (2018), which was further applied in other studies (Sharma and Goyal 2018; Guo et al. 2019). The driest year of high drought severity in the Horn of Africa, i.e., 2009, was identified from the spatial and temporal patterns of the high-resolution annual SPEI images, which was consistent with the UN *Emergency Events Database* (EM-DAT) record of drought (EM-DAT 2018). Table 9.3 shows the four major classes of the *eRd*.

Figure 9.8 shows the spatial distribution maps for average annual GPP, ET, and eWUE across the HA during 2000–2014. The highest values of GPP and ET were concentrated in southwestern highlands of Ethiopia and Kenya with less extents in its southeastern coast. The accuracy evaluations of the mean annual GPP were achieved using GPP_{EC} from Global FLUXCOM observations with R^2 and RMSE values of 0.78 and 5.4 g C m^{-2}, respectively. By comparing the average annual MODIS-ET values to the annual averaged ET from the monthly evapotranspiration data of USGS early warning system for the study area, R^2 of 0.76 was obtained.

The mean annual eWUE in the HA was 1.58 g C kg^{-1} H_2O, which indicated a large spatial variability with a standard deviation of 0.51. The highest mean annual eWUE was in most regions of Ethiopia followed by Eritrea, while Somalia and Djibouti had the lowest mean annual eWUE. Based on Zonal statistics extractions using the ESA land cover types, the highest mean annual eWUE was in the croplands and forestlands, and the least mean annual eWUE was in the sparse vegetation and wetland areas. The shrubland, which had the overwhelming land cover (38.9%) in the HA, had relatively lower mean annual eWUE, whereas the grassland and sparsely vegetated lands had higher standard deviations and eWUE values.

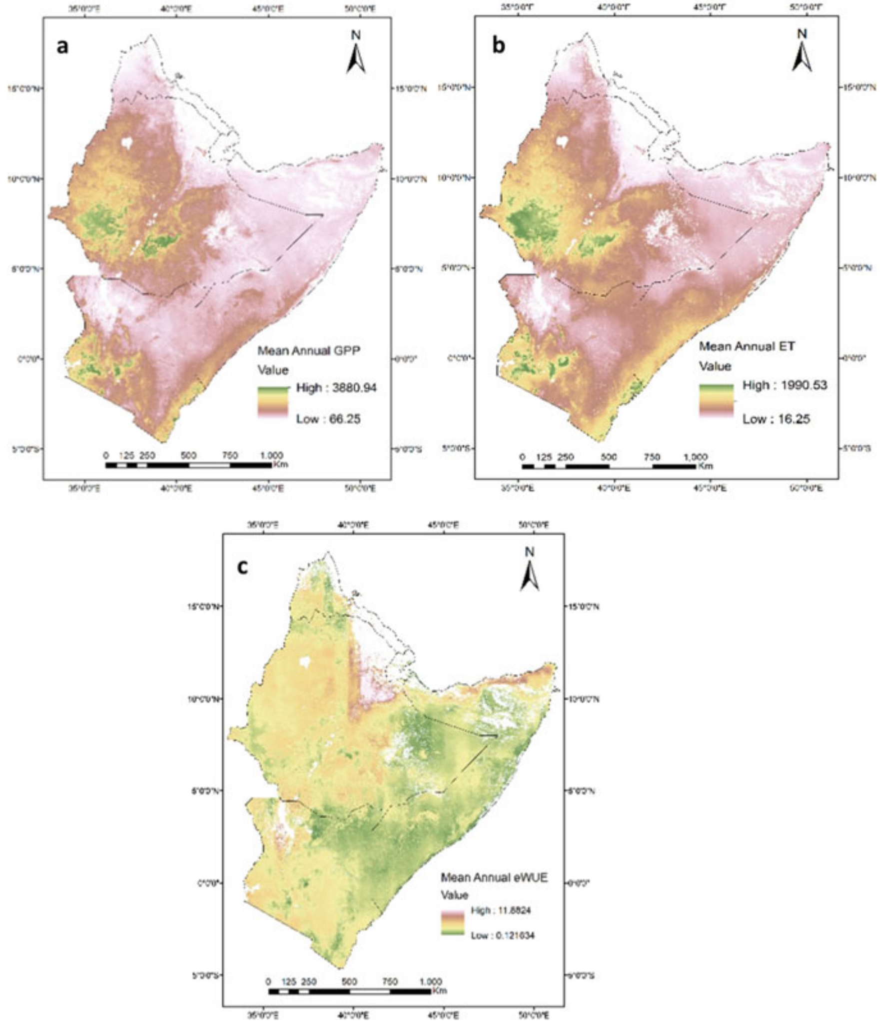


Fig. 9.8 Mean annual distributions of **a** GPP (g C m^{-2}), **b** ET (mm), and **c** eWUE (g C kg^{-1} H_2O) during 2000–2014 in the HA

Figure 9.9 shows the ecosystem resilience to drought (eRd) during 2000–2014. Overall, 54.9% of the study areas were found to be resilient to drought. Most of the resilient ecosystems were in the central highlands of Eritrea, southeast of Ethiopia, northeast Kenya, and large parts of Somalia. In contrast, 32.6%, 9.6% and 2.8% of the regions were non-resilient, moderately non-resilient, and slightly non-resilient, respectively. The strictly non-resilient ecosystems were mainly observed in southeast parts of Kenya, south-west of Eritrea, and areas near the triple junction of Ethiopia, Djibouti and Somalia.

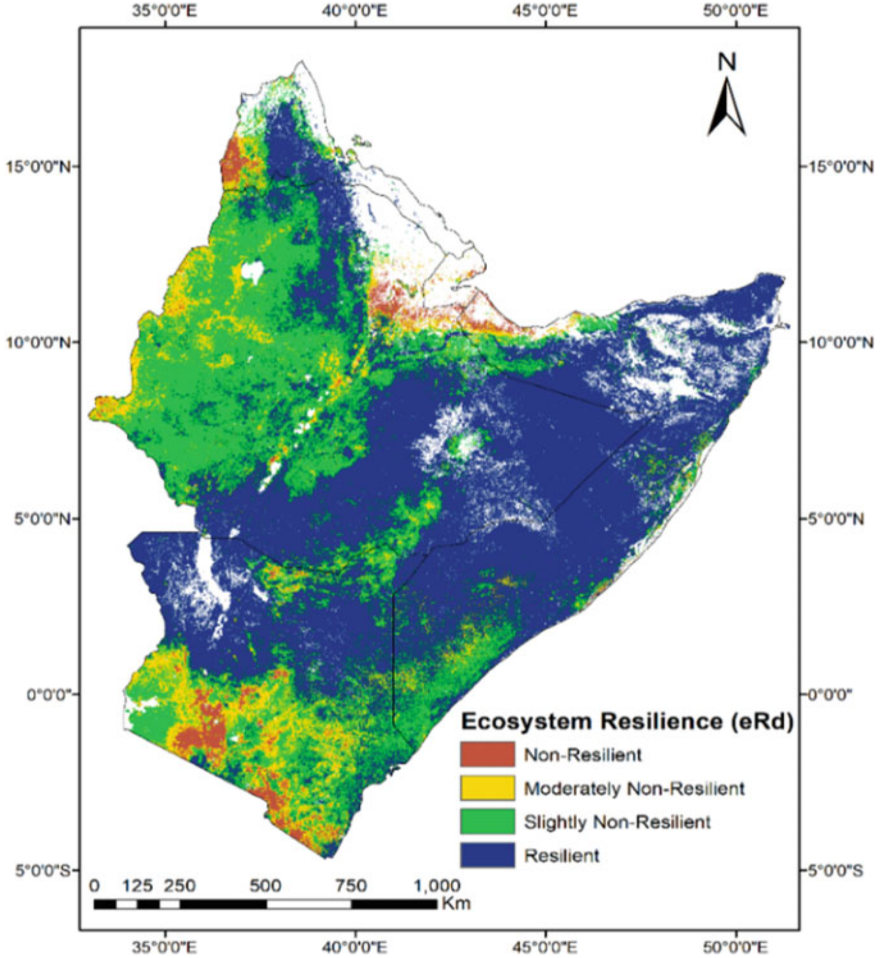


Fig. 9.9 Ecosystem resilience to drought (eRd) in the HA during 2000–2014

The aggregation of the final ecosystem resilience with multiple land cover types and agroecological zones of the region showed that the cropland and wetland were slightly non-resilient to drought with mean eRd values of 0.97 and 0.99, correspondingly. On the contrary, grassland and sparse vegetation were relatively the most resilient to drought with mean eRd values of 1.12 and 1.1, respectively. Likewise, the tropic warm-humid (eRd = 0.92) and the tropic cool-humid (eRd = 0.94) were slightly non-resilient to drought, whereas the tropic warm-arid (eRd = 1.13) and cool-arid agroecological zones showed relatively the highest resilience to drought in the region.

Even though the HA was considered as a drought-prone region, the final map of ecosystem resilience (Fig. 9.9) showed that 54.9% was resilient to drought, while

32.6% was completely non-resilient. This is mostly in agreement with the recent study on eco-hydrological resilience to ecosystem changes over the African continent (Kayiranga et al. 2020). However, this research showed that cropland and wetland were slightly non-resilient ecosystems to drought conditions rather than the savannahs and barren lands. The ecosystem resilience to drought revealed that the warm-humid and cool–humid agroecological zones were slightly non-resilient to the most severe drought conditions; this indicated the vulnerability of these ecosystems to the warming trends and climate variability impacts in the region. The variations in eWUE provide useful spatial and temporal information for policy and decision-makers and can play a vital role in rangeland and ranch management, vegetation degradation protection and management, and drought and climate change mitigation at national and regional levels.

9.3.4 Livelihoods and Food Security of Local Communities

The sustainability of livelihood in Africa's drylands is being jeopardized by a wide variety of environmental, political, and socioeconomic changes that are all intertwined (Fraser et al. 2011). The livelihoods of local communities are inextricably linked to the landscapes in which they live, which are especially sensitive to changes in these environments (Shackleton et al. 2019). Changes in livelihood activities could have detrimental consequences for ecological services. Environmental and socioeconomic development are putting increasing pressure on rural regions across much of Africa (Suich et al. 2015). Eventually, the food security both in developing and developed countries (e.g., the case of Tigray crisis) is compromised by political instability, conflicts or economic crises (García-Díez et al. 2021; Peng et al. 2021). Importantly, climate-related shifts are commonly overlaid on and feedback on a wide range of cross-scale socioeconomic stresses that relate to social vulnerability in the first instance (Niang et al. 2014). The detailed cross-cutting dimensions of resources and local livelihoods are shown in the Fig. 9.10.

As the livelihoods of most people in drylands in Africa depend upon natural resource-based activities, including agriculture and animal husbandry, the capacity of the natural resources to generate stable and sufficient incomes is increasing (de Haan 2016). Hasty demographic growth increases the pressure on dwindling resources, creating conditions of extreme weather events, food price spikes, or other exogenous shocks that can trigger acute humanitarian crises and disasters and fuel violent social conflicts. Many households in Africa's drylands turn to unsustainable practices to address pressing short-term needs, resulting in significant land degradation, water scarcity, and massive biodiversity losses (Cervigni and Morris 2016). Vulnerability is thus expanding as a result of complex interactions between several causes, compromising the long-term livelihood prospects of hundreds of millions of people. Climate change is anticipated to compound the situation by increasing the frequency and severity of extreme weather occurrences (IPCC 2021). Food prices are predicted to

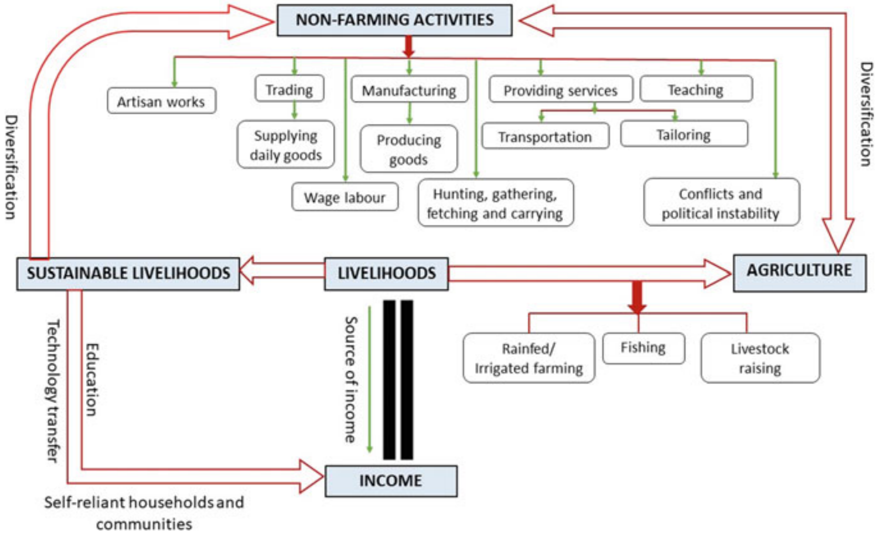


Fig. 9.10 Cross-cutting dimensions of rural resources and local livelihoods

rise dramatically, making food affordability an increasing concern for many African societies (Scholes et al. 2015).

SSA is plagued by food insecurity, with some cases reaching catastrophic proportions, for example, in the HA regions and southern Madagascar (Hirwa et al. 2021). Food insecurity is not just about availability, unsatisfactory food production, and intake, it is also about the poor food quality and nutritional value (Sasson 2012). Food riots and escalating food prices are two of the numerous signs of the current food crisis and instability. Nowadays, the key roots of food insecurity are inadequate food production and the influence of the COVID-19 crisis (Ayanlade and Radeny 2020). Africa's governments have enacted initiatives to promote staple crop cultivation and increase the productivity of local farmers, particularly smallholders.

9.3.5 Dryland Conservation and Effective Practices

The major conservation issues for drylands of Africa are habitat loss or degradation and habitat fragmentation, largely caused by agriculture, charcoal production, and infrastructural development (Githiru et al. 2017). Effective conservation methods are required to maintain crop output in arid regions (Hammel 1996). Adaptability and conservation strategies can help to offset dryland ecosystem service losses. Although the conservation status of dryland biodiversity is not well monitored, several recognized drivers of biodiversity of the African drylands have declined. As a result of population shifts and urbanization, agricultural expansion, land-use changes, weakening governance arrangements, and the introduction of alien invasive species, the declination of these drivers will become more obvious (IUCN 2012). It is crucial to foster sustainable intensification approaches based on conservation agriculture and community-based adaptation, with functioning support services and market access including the introduction of adapted cultivars (Mbow et al. 2014). In addition, identifying sustainable land management practices (e.g., agroforestry, crop rotation, and intercropping systems) for enhanced land-based climate change adaptation and mitigation (i.e., food production, biodiversity, GHG emissions reduction, soil carbon sequestration) is also important (Sanz et al. 2017; Francis 2016). Attention should also be paid to the food-energy-water-biodiversity-health (FEWBH) nexus, particularly water usage and re-utilization efficiency as well as the rainwater management (e.g., water harvest practices) (Albrecht et al. 2018; Hirwa et al. 2021) and water-energy-food (WEF) nexus security (Muhirwa et al. 2023). Obviously, establishing institutional designs centered on youth and women through new economic models that facilitate access to credit and loans to enact policies that balance cash and food crops will be beneficial (Palacios-Lopez et al. 2017). Last not least, enhancing local expertise, culture, and customs while exploring dryland ecosystem management innovations should be enhanced.

Uncertainties are quite crucial in agriculture because they influence decision-making and might potentially lead to inefficiencies as well as food poverty (Thornton and Wilkens 1998). Mortimore and Adams (2001) highlighted five key elements of the 1972–1974 drought catastrophe. Specifically, diversification of livelihood and crops, migration, negotiating the rain, managing biodiversity, animal integration, off-farm income-generating activities, and livestock integration were all prevalent among the mix of resilience techniques identified in the literature (Batterbury and Forsyth 1999; IPBES 2021). Additionally, as a reflection of the diversity, farmers grew multiple varieties of the same crop on the same field at the same time as insurance against future risks, which was a demonstration of system resilience (Jellason et al. 2021).

Diversification within and without agriculture has been used as a resilience management approach to help farmers endure extreme weather conditions (Ayana et al. 2021). In West Africa, household heads were discovered to be the decision-makers in terms of diversifying income sources (Ifeoma and Agwu 2014). Apart from livelihood diversification, food sources and farming systems were also diversified to serve as insurance against pest and disease infestations that could lead to losses or for balanced nutrition (Jellason et al. 2021). Research conducted in west Africa also illustrated the efficiency and the flexibility of livelihood and farming systems through the rationing of family labor for priority farm operations, which were determined by the variability of rainfall as to what and when to grow (Mortimore and Adams 2001). Some authors asserted that the current resilience strategies displayed by African smallholders were insufficient to tackle climate change impacts due to new dimensions of challenges such as increased poverty, population growth, and food insecurity (Awazi et al. 2021).

By 2030, structural changes driven by economic growth will enable a few dryland dwellers in Africa to switch to off-farm livelihood and thereby reduce their vulnerability. Many more will continue to depend on animal husbandry and the cultivation of the land. Advanced agricultural production technology can generate significant resilience improvements by enhancing the productivity of rain-fed agriculture. If nothing is done, households that depend on agriculture and are susceptible to droughts and other crises are anticipated to rise by roughly 60% in the Sahel and the HA by 2030. Interventions to improve the productivity of rain-fed crops can significantly mitigate this increase (Cervigni and Morris 2016). Enhanced agricultural production technology, soil fertility management, and the incorporation of trees into existing farming systems can all provide resilience benefits by increasing yields and crop drought and heat tolerance. Trees growing in farming fields, in fact, can function as fertilizer providers while also lowering crop water and heat stress. Trees can also improve household food security by providing food when crops and animal-source meals are in short supply, as well as increasing coping ability by offering assets that can be cut and sold in times of need.

In West Africa, among the current strategies for managing the resilience of arid zones, there is the very ambitious project of the Great Green Wall (GGWI). The GGWI's overarching goal is to combat desertification using established principles of sustainable land management, as well as the enhancement and preservation of natural resources and production and management systems. Through multipurpose activity platforms, transition is achieved while guaranteeing the socioeconomic development of local communities. For example, the Samise implements aim to (1) create income, (2) improve access to basic needs, (3) oversee the transition to a circular economy as a way to foster the emergence of rural production sites, (4) consolidate ecological sustainability to eradicate poverty and food insecurity, and (5) boost local population adaptation and resilience abilities (Diop et al. 2018). Since its creation in 2005, the Pan-African Agency of the Great Green Wall (with a total distance of ~7,775 km and total area of ~11,662,500 ha) has set up successful examples in its headquarter of Nouakchott. Now, it has transformed the arid areas of the Sahel into sustainable development hubs, which are integrated into the national economic fabric, an essential action for the entire Sahel region of West Africa (Fig. 9.11).

Furthermore, due to the fragility of Sahelian environment and its ability to adapt to climate variability and change, the choice of species to be reforested at the GGWI level is also influenced by two other factors: (1) they must not be edible to local fauna, and (2) they must have ecological relevance and economic worth (e.g., fruit and gum arabic production). The species should also meet criteria such as resistance to water stress, adaptability and plasticity, and multiple uses and utilities as perceived by local populations (Diop et al. 2018). The potential benefits from the construction of the GGWI to resolve biodiversity losses, environmental degradation, desertification, and climate change will have a legitimate chance of success if they are coherent with significant matters related to local communities' livelihoods such as satisfaction of domestic needs in terms of wood and non-wood products, raising

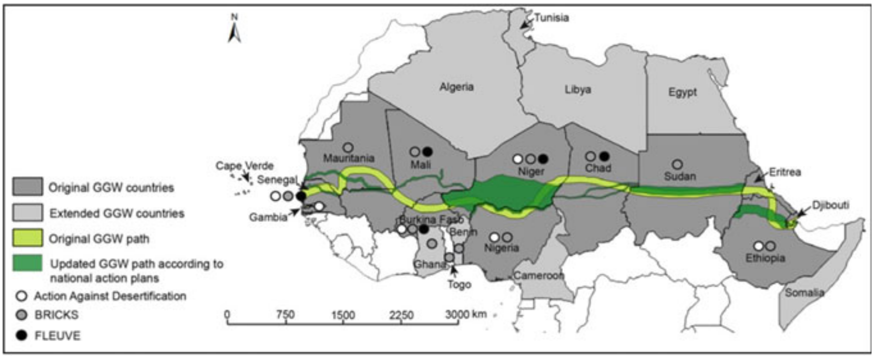


Fig. 9.11 The GGW situation map and participating countries. The Sahel and West Africa Program in Support of the *Great Green Wall* Initiative (SAWAP) consists of several transnational projects, e.g., Building Resilience through Innovation Communication and Knowledge Services (BRICKS) and Front Local Environmental pour une Union VertE (FLEUVE). Adapted from Goffner et al. (2019)

of household incomes through promotion of sustainable income-generating activities, and commitment to sustainable income-generating activities. Figure 9.12 shows exemplar tree nursery beds for the purpose of combating desertification in Senegal.

From this vantage point, "polyvalent" village gardens, as beneficiaries and focal points for practically all domestic and rural population activities, are a meaningful

Fig. 9.12 Nursery grounds in north Senegal—photo by A. Guisse, June 2009

method that is congruent well with GGWI program's goals. They supplement a regulated concentration of many activities that are frequently part of the inhabitants' ordinary everyday life. They may include new activities that rely on resources, as well as local dynamics and demographic proximity that allow for the formation of circumstances for self-sufficiency in the supply of services such as food, housing, medicinal plants, and other socioeconomic items (NAGGW 2016).

Dryland conservation practices in Ethiopia: The dryland area covers over 70% of the landmass in Ethiopia (Amanuel et al. 2019). According to a recent FAO guideline, dry forests account for 80% of Ethiopia's forests, and are a crucial element of Ethiopia's tropical forests, which span from the lush alpine forests of central Ethiopia's Bale Highlands to the hot and dry woods of southern Ethiopia's Borana rangelands (Atmadja et al. 2019). The dryland agro-ecological zone including the dry sub-humid areas of the country are under continuous human and livestock pressures, which are vulnerable to the effects of climate variability and climate change. In Ethiopia, traditional conservation practices reverted to 400 BC; however, established conservation activities such as soil and water conservation (SWC) became effective since the 1970s (Fig. 9.13) (Haregeweyn et al. 2015). Soil erosion (i.e., gully, rill, and sheet erosion) remains as one of the main environmental problems in large parts of Ethiopia, and it is likely to deteriorate with the predicted increase in population and climate variability in the twenty-first century (Field and Barros 2014). The SWC practices in Ethiopia showed mixed results as affected by the type of intervention involved and the agroecology considered for implementation, yet the relative performance of the interventions was effective in the dryland areas compared to the humid lands of the country (Haregeweyn et al. 2015).

The Federal Democratic Republic of Ethiopia has carried out some on-site conservation practices to conserve and promote sustainable utilization of its forest genetic resources in the dry forests managed by the civil society and/or the government (Atmadja et al. 2019). The Ethiopian Biodiversity Institute (EBI) has saved 2,000 accessions of 260 species of trees in its gene banks and created 15 in vivo locations in Ethiopia's three regional states (Atmadja et al. 2019). According to the EBI, a reduction in biodiversity at various spatial and temporal scales has become a concern in the country, necessitating national biodiversity protection and initiatives.

Fig. 9.13 Example of Ethiopia's common SWC measures; gully plugs constructed across gullies. **a** Gullies, **b** before (2012) and **c** after (2013) the interference. *Source* Haregeweyn et al. (2015)

Ethiopia has been very proactive in implementing the Participatory Forest Management (PFM) for conservation of its natural forests and forestry restoration. However, the rate of forest gain has been approximately 19,000 ha annually largely in the Dry Afromontane areas during 2000–2013, one-fifth of the annual forest loss in the country (Johnson et al. 2019).

An inception appraisal regarding the landscape restoration in Ethiopia's drylands elaborated that ~1 × 10^6 ha of degraded land were restored in northern Ethiopia over the past two decades (Sola et al. 2020). The main restoration practices and techniques implemented in the drylands of Tigray included area exclosures to enable for natural vegetation regeneration, conservation tillage, and water harvesting as well as building of small dams to hold water for infiltration or irrigation, tree planting, and pasture extension (Sola et al. 2020). Gebremeskel Haile et al. (2019) also highlighted the success and exemplary conservation practice In the Abraha Atsbaha watershed (Tigray, Ethiopia), where drought-prone degraded areas were converted into well-established sustainable landscapes as the groundwater levels amplified. The sustainable agricultural development practices have significantly contributed to diet self-sufficiency and economic benefits. The Government of Ethiopia built a dryland agriculture bureau to support research and development in the drylands, where the majority of Ethiopia's food is produced. A modern dryland management agenda calls for more participatory and collaborative planning and design of area enclosures, an unified landscape strategy engaging many sectors, and an endeavor to achieve socioeconomic sustainability guided by both professionals and knowledge systems (Sola et al. 2020).

9.3.6 Dryland Nature-Based Solutions (NbS) for Sustainable Management

NbS are facing challenges in semi-arid and arid lands in Africa including climate change, water security, food security, human health, socio-protection, socio-economic development, disasters, ecosystem degradation, and biodiversity loss (IISD 2022). NbS benefits and ecosystem services in African drylands include providing clean water to communities; maintaining diversity of plants and animals which are crucial for resilience to changes and shocks; stabilizing the soil while ensuring good quality soil and enhancing the carbon sequestration on agricultural lands and peatlands; providing flood control and regulate the quality of water; and promoting the aesthetic, spiritual and human well-being benefits such as ecotourism for the country and improved livelihood (Thorn et al. 2021). Moreover, NbS provide means for DSESs to successfully navigate the linkages between systems such as food, water, energy and climate, thus enhancing livelihood resilience and diversification. For instance, urban agriculture, as a form of NbS, can increase food security and improve human being livelihood. Immense benefits as well as the innovative governance, institutional, business, and finance models and frameworks inherent to NbS implementation provide a wealth of opportunity for social transformation and increased social inclusiveness in cities. Given the range of interventions by NbS and the cross-sectoral co-benefits, new processes and designs for informal area upgrading are interrogated and implemented. Opportunities for NbS implementation should be explored and, where relevant, upgrading activities should make use of NbS. Indeed, investing in NbS will let African drylands meet urgent global challenges sustainably as well as benefits biodiversity and livelihoods.

In summary, the NbS in arid and semi-arid lands (ASALs) can be grouped into five core principles as listed below (Cohen-Shacham et al. 2016; Seddon et al. 2020; Thorslund et al. 2017; Raymond et al. 2017).

(1) Environmental restorative capacity: Ecological rehabilitation (ER), forest landscape rehabilitation (FLR), ecological engineering (EE);
(2) Issue-specific: Ecosystem-based adaptation (EbA), Ecosystem-based mitigation (EbM), Ecosystem-based disaster risk reduction (Eco-DRR), and Climate adaptation services (CAS);
(3) Infrastructure development: Natural infrastructure (NI), Green infrastructure (GI);
(4) Managerial functions: Ecosystem-based management (EbMgt), e.g., Integrated coastal zone management (ICZM); Integrated water resources management (IWRM); and
(5) Protection measures: Area-based conservation (AbC).

The five categories of NbS are summarized as conceptual representation in Fig. 9.14.

To comply with the NbS principles (Fig. 9.14), there is a need for effective involvement of different actors with civil society organizations and the private sector (Leone et al. 2021), integration of hybridized approaches of green, blue, and grey infrastructure (Depietri and McPhearson 2017), maintain dryland soil biodiversity by planting indigenous trees along roads and in households (Thorn et al. 2021), linking informal transport networks with green spaces, shifting perspective from “unplanned” to “unserviced”, experimentation of “untried beginnings” (Cilliers et al. 2021), and generation of and use relevant data for evidence-based decision making (Frantzeskaki et al. 2019).

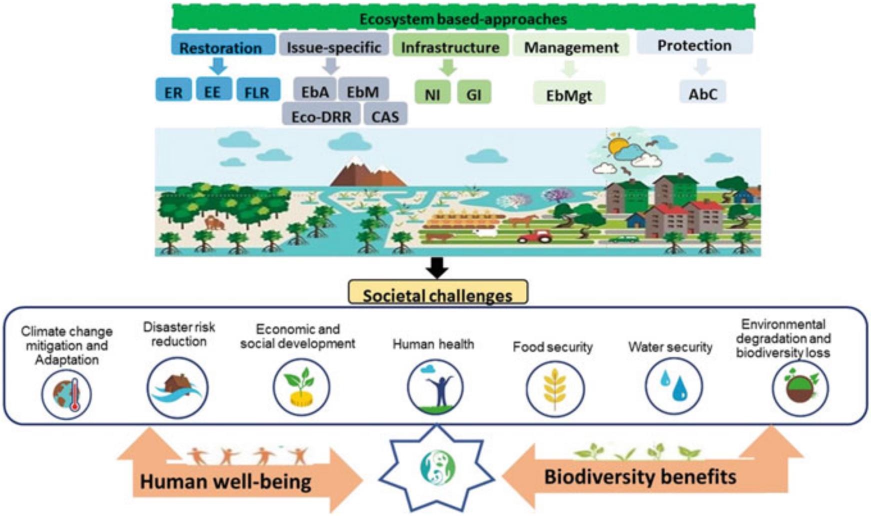


Fig. 9.14 Hypothetical representation (prototype) of NbS in drylands in Africa. Adapted from Cohen-Shacham et al. (2019)

9.4 Driving Forces of Dryland Change

9.4.1 Climate Change and Extreme Events

The World Meteorological Organization (WMO) declared the confrontation of a mix of changing precipitation patterns, increased temperatures, rising sea levels, and more frequent extreme weather and climate events (Blunden and Arndt 2020). Extreme weather events such as droughts, floods, and landslides, are likely to occur more frequently and/or with greater intensity in the twenty-first century according to climate measurements and models (Niang et al. 2014; Orimoloye et al. 2019). Extreme temperature occurrences have a severe impact on agriculture in Africa since many crops are already planted at the boundaries of their thermal tolerance and water stress resilience. Meanwhile, much of Africa's agricultural production takes place in semi-arid regions which are expected to get drier in the future (Scholes et al. 2015).

Reduced agricultural productivity as a result of heat and drought stress, as well as increased insect, disease, and flood damage will have significant consequences for regional, national, and household food security and livelihoods (Blunden and Arndt 2020). Under RCP 8.5, reductions in mean yield of 13, 11, and 8% are projected in West and Central Africa, Northern Africa, and East and Southern Africa. Wheat and rice are expected to be the worst-hit crops, while millet and sorghum are likely to be the least afflicted. Seasonal weather patterns are anticipated to be affected by global climate change. Concerns have been raised that converting Africa's dry tropical forests and savannahs to croplands for agricultural production may undermine the biomes' natural carbon reserves (IPCC 2019). According to a study based on 20,000 historical maize trials in Africa and daily weather data, the productivity of African maize declined by 1% for every 1 °C increase above 30. Under the same temperature situations, the yield was reduced by 1.7% in drought conditions (Lobell et al. 2011). To build the resilience of ecosystems and livelihoods in drylands, there is a need for a harmonized framework that integrates multiple hazards, including droughts, floods, and fires (Cervigni and Morris 2016). This will assist in determining the link between extreme climate occurrences and African populations' socioeconomic well-being.

9.4.2 Anthropogenic Activities

Agriculture

Agriculture in the drylands is dominated by small-scale and resource-poor farms, which suffers from limited investment in agricultural technologies and inputs, resulting in declined crop yields and livestock productivity. Dryland farming expansion is thus a leading stressor to biodiversity. Dryland economies and societies have always been driven by agriculture and related land use. African dryland operations face problems of failing in providing basic services due to rapidly rising population growth and economic development and are often unsuccessful in producing enough food. These issues are, therefore, compounded by socioeconomic and ecological factors of resource degradation (e.g., water, land, and biodiversity) (Twomlow et al. 2006). Over 94.5% of African food production is rainfed, with over 728×10^6 ha rainfed cultivable area. Maize, millet, and sorghum occupy the highest crop areas for all of Africa, but with significant diversity among regions. Even so, rainfed agriculture also has low productivity and yields. For example, maize yields are 1.8–2 tons ha^{-1} in Africa as compared to 5.11 tons ha^{-1} of the world average. The low productivity is due to improper farming techniques, including the impacts of land degradation, inadequate pest control, inefficient water usage, low fertilizer use, low mechanization, and poor support structure. The level of public expenditure on rainfed agriculture is insufficient to reinforce viable, productive, and sustainable rural lifestyles (Abrams 2018). The four intrinsic features of dryland agriculture that demonstrate its dynamism and potential are: (1) diversity, (2) people resiliency and adaptability, (3) sustainable intensification in a fragile ecosystem, and (4) complementary investments in infrastructure and policy reform (Bantilan et al. 2006). The need to increase the productivity of dryland agriculture is vital to ensure world food security.

Nitrogen Deposition

In drylands, the atmospheric concentration of greenhouse gases (GHGs) has abruptly augmented in the last decades, resulting in ongoing climate change (Pachauri et al. 2014). Therefore, assessing nitrogen (N) deposition to drylands is intricated by the manifold forms and paths of N loading from the atmosphere (Sickman et al. 2019). Many studies on soil N balance in Africa provided evidence of widespread soil N depletion through harvested crops, plant residues transported out of the fields,

Table 9.4 Nitrogen flows at the farm level in Africa's dryland smallholder farming system. Adapted from Dlamini et al. (2014)

Flows	Nutrients
Inputs	Mineral fertilizers Organic inputs including • Animal/farmyard manures • Applied composts • Crop residues application Biological N fixation • Intercropping • Inoculant application Atmospheric N Biomass transfer
Outputs	Harvested crops Crop residues removal Runoff and erosion Leaching below the root zone Gaseous losses • Volatilization • Denitrification

overgrazing and/or leaching, erosion, and volatilization, which altogether surpass the amount of nutrient inputs through fertilization, atmospheric deposition, biological fixation, and organic inputs (Manlay et al. 2004). Removal of crop products and residues, leaching, gaseous losses, runoff, and soil degradation are all examples of N output processes. Figure 9.15 represents the Nitrogen cycle or flows while Table 9.4 represents the summary of inputs and outputs.

GHG fluxes are projected to be low in dryland ecosystems, such as those in the Mediterranean Basin, due to water and nutrient limitations, particularly N (Dalal and Allen 2008). 80% of the agricultural system in SSA is composed of smallholder farms (farm size < 10 ha) with low N application and organic and/or synthetic fertilizer use. This type of agricultural crop production at the national level has low inputs, with mean annual synthetic N fertilizer use in SSA ranging from 7 kg N ha^{-1} to 13 kg N ha^{-1} in West Africa and East Africa respectively (van Bussel et al. 2015). Farmers in some countries, such as Burkina Faso, acquire government or assistance group help for using mineral N fertilizers to increase the crop productivity. N_2O emissions from the Africa's agriculture sector are estimated to account for about 6% of all global anthropogenic N_2O emissions (Pelster et al. 2017; Brümmer et al. 2008). Low N inputs cause soil N reserves to deplete, a process known as soil "N mining", which is one of the main causes of soil fertility loss and low crop yields (Vitousek et al. 2009). Land degradation/desertification also leads to adverse loss of soil nitrogen stocks (Dlamini et al. 2014). N_2O emissions from agriculture in SSA will possibly double the contemporary anthropogenic N_2O emissions if current yield gaps are addressed (Leitner et al. 2020). Further, it has been demonstrated in SSA that increasing fertilizer application rates beyond a particular threshold (between 100 and 150 kg N ha^{-1}) causes a non-linear rise in direct N_2O emissions (i.e., N_2O that is discharged on-site from soils to which N is added) (Shcherbak et al. 2014).

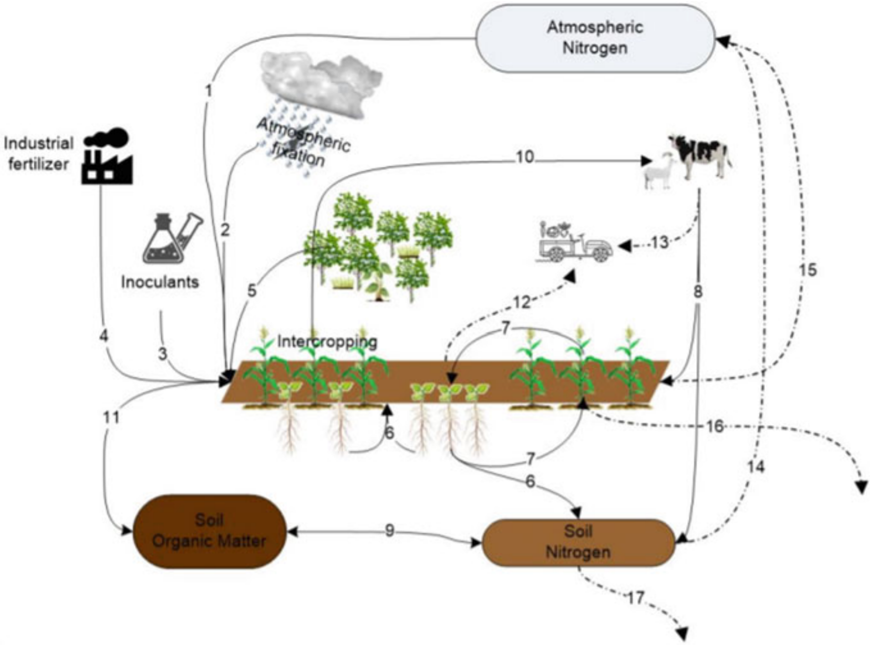


Fig. 9.15 Nitrogen and flows in smallholder farming system in drylands. Arrows represent flows, with solid lines representing N additions and exchanges, and dotted lines N losses. (Where 1 is biological nitrogen fixation, 2 atmospheric fixations, 3 microbial inoculations, 4 inorganic fertilizer application, 5 biomass transfer, 6 nutrient recovery, 7 crop rotation, 8 animal manure, 9 mineralization/immobilization, 10 animal feeds, 11 crop residues incorporated into the soil, 12 crops produce (goods), 13 livestock products, 14 denitrification, 15 volatilization, 16 runoff, and 17 leaching). Adapted from Kiboi et al. (2019)

Consequently, N is one of the foremost factors limiting agricultural thruput in African dryland agroecosystems (Rütting et al. 2018). Thus, this has had a great impact on the semi-arid cropping systems practiced in the continent. For instance, soil type together with the crops grown in the Sahel region, e.g., millet in Northern Burkina Faso largely contributes to N loss from the fields (Krogh 1997). To enhance or maintain the quality of the environment and conserve natural resources, alternative low-external-input approaches that involve the utilization of organic inputs have been developed for the farmers (De Jager et al. 2001) including the use of livestock manure for nutrient cycling and transformation of present agricultural land to other N-recycling efficient farming opinions in semi-arid conditions. However, fertilizer application results in higher soil fertility, together with the rise in N_2O emissions. Increased fertilization should be considered alongside GHG emissions that can be evaded (e.g., by deterring soil degradation and SOM mineralization), counterbalanced via C sequestration due to improved soil management (e.g., by building up additional SOM owing to enhanced residue input), and mitigated with emissions that would otherwise eventuate elsewhere due to cropland expansion (e.g., via deforestation, and grassland conversion).

Livestock Grazing and Fencing

Livestock is the main (and often only) land-use option in Africa's drylands. This sector is the keystone of the national economy in many of the countries of East and West Africa, the majority of which have a vast area of drylands (FAO 2018). Pastoralism is performed in Africa's major areas, covering 43% of the continent's territory. It covers about 36 countries (in 53 countries), elongating from the Sahelian West to the rangelands of Eastern Africa and the Horn and the nomadic populations of southern Africa (FAO 2018). About 25×10^6 pastoralists and 240×10^6 agro-pastoralists rely on livestock as their main source of income. In the SSA, 35% is permanent pasture (Kiage 2013). Further, in broad terms, pastoralism prevails in eastern Africa's drylands, whereas limited crop-livestock integration and agro-pastoralism prevail in western Africa's drylands, which can be traced in part to bi-modal against unimodal weather patterns (Milne et al. 2016).

Additionally, livestock has both positive and negative effects on the dryland resource base. In global drylands, livestock production sustains millions of livelihoods (Zhang et al. 2021), and pasturage is expected to increase in the next decades (Chillo et al. 2017). However, desertification occurs largely in drylands as a result of overgrazing (i.e., biodiversity loss and degradation of ecosystem functions). Grazing has been reported to create lower litter quality (i.e., low N and high secondary compound content) in drylands, which, when combined with a reduction in litter quantity and soil moisture, has a detrimental impact on the decomposition rate (Campanella and Bisigato 2010). Plant diversity changes also have an impact on animal communities by altering habitat structure and food security (Chillo and Ojeda 2014).

Nonetheless, in parts of SSA (especially Ethiopia), fencing or protecting an area for livestock fodder has become a useful strategy for supplying the animals with feed during times of stress (Catley et al. 2013). Pastoralists in drylands use livestock mobility as the primary strategy to deal with and exploit natural resource unpredictability (e.g., the case of Botswana McGahey (2011)). Pastoral mobility, diversification of livestock species, and maximization of herd numbers are some pastoralist insurance strategies that communities use to manage extreme uncertainty in their environment. In addition, while considering efforts to improve carbon management, pastoral organizations must be recognized and developed upon. Farmers and livestock keepers use a variety of management strategies across the varied land-use systems to obtain lucrative benefits (i.e., food and nutrition security, livelihoods, and revenue, etc.) as well as to improve the "condition/health" of the grazing areas. The main priorities of the management practices are to (a) decrease and combat land degradation, (b) restore or rehabilitate the land, and (c) increase land productivity for cattle production. Grazing management or pasture improvement (e.g., increased productivity, nutrient management, forest management, and species legumes), livestock management (e.g., improved feeding practices, precise agents, and nutritional additives), and restoration of degraded rangelands are examples of these management practices (e.g., erosion control, organic amendments, nutrient amendments).

There is a myriad of reasons why people in Africa's drylands face food insecurity and are unable to satisfy their nutritional needs and targets. Although there is no single reason why food shortages, insecurity, and the prevalence of malnutrition continue to plague Sub-Saharan Africa, failed internal economic policy tools and international policy prescriptions are identified as the culprits or causative factors (Dodo 2020). The main factors that have aggravated the problem of food production, supply, and accessibility are drought and conflict. Within an already tough setting of fragile ecosystems, high rates of population increase and ratio of poverty have also played a role. Because about 80% of the population in the region is rural and relies almost entirely on agriculture for consumption and income, solutions to the challenges of poverty and food insecurity must be predominantly found in the agricultural sector. The link between poverty and food insecurity is critical. Food production is important since agriculture is the primary source of income for the majority of the poor, and agriculture employs around 76% of the IGAD population. However, the level of food insecurity is lowered only when poverty is relieved or reduced. As a result, the long-term approach to food insecurity goes beyond increasing food production and involves the need to strengthen rural livelihoods in generally. Social safety nets of many kinds are also part of the solution to extreme poverty and food insecurity, not only in exceptional conditions like drought but also over the long periods needed to arrive at inclusive societies and as lasting solutions.

Chronic food insecurity is the most common and devastating consequence of these concerns in Africa's drylands. According to the African Union Commission's (AUC) Food Security Report, 27% of Africa's overall population is undernourished, nearly half of Africa's children are stunted, and acute malnutrition (>10%) is reported in more than 15 nations. Africa is currently attempting to cover its food insecurity with imports worth approximately US$ 20 billion per year, in addition to requesting food aid (AUC-NEPAD 2006). The majority of the victims of food insecurity in the region are the poor inhabiting the drylands who depend heavily upon natural resources for their livelihoods, either by growing crops or managing livestock.

Climate change impacts and continues to impair the subsistence of communities in Africa's drylands, which has now become a critical concern for the long-term development of the region (Epule et al. 2017). This challenge consists of the potential consequences of agroforestry systems on ecological services, agricultural productivity, and livelihoods. Agroforestry systems are traditional land-use methods that incorporate trees into agricultural grounds. These systems are widespread in Africa's drylands and have been practiced for generations. Unfortunately, Africa's dryland is highly susceptible to the effects of climate change (Epule et al. 2014) because of its reliance on rainfed agriculture. These areas' rural lifestyles are heavily reliant on agriculture and non-timber forest products, both of which are threatened by climatic changes. As a result, the regions are no longer able to provide good yields in ecological systems to sustain rural people's livelihoods.

9.4.3 Wildfires

Wildfires are an extreme threat to the dryland environments (e.g., grasslands, savannas, or dry forests) and are increasing due to increasing ignitions caused by humans, the spread of fire-prone invasive grasses and shrubs, and warming, drying climate. The dramatic increase in wildfire prevalence in recent decades poses serious threats to human safety, infrastructure, agricultural production, cultural resources, native ecosystems, watershed functioning, and others. Wildfires are especially prevalent in Africa, with up to 9% of the continent burnt on an annual basis (Andela et al. 2013), contributing to 70% of the global burned area (Andela and van der Werf 2014). More extensive and later dry season fires lead to wet season rainfall deficits of up to 30 mm (Saha et al. 2016). Recently, the MODIS tool on NASA's Aqua satellite detected multiple dozens of fires burning in southwestern Africa. Similarly, using the albedo model, the study of Saha et al. (2019) identified the strongest brightening in the Kalahari region as well as more intense and long-lived initial darkening in the Sahel region. In some biomes, the frequency of wildfires is widespread and alarming, such as in the forests and savannahs of West and East African countries. As fire frequency depends on fuel production, it is influenced in arid and semiarid regions by the total rainfall (Fig. 9.16).

Forest fires regimes are also responsible for woodland degradation in dry regions (Nichols et al. 2017). Fires, sometimes set to clear the land for agriculture, leave the soil susceptible to erosion and exposed to sunlight and other elements, which may change the makeup of the soil and prevent the tree species from regenerating (Fig. 9.17). Fires can also place neighboring stands at risk as grazing animals move into new areas to find forage, intensifying the pressure on resources and leading to overgrazing. Fires are a primary cause of desertification in the SSA regions, where the degradation of drylands is especially pronounced (Wei et al. 2020).

The occurrence and impacts of wildfire can be reduced through prevention, preparedness, and pre-fire management. The post-fire response such as erosion control and replanting in burned areas also helps to reduce the immediate impacts of wildfire and the establishment of nonnative grasses, which can reduce the risk of future fires. Given limited resources for land management and the ability of wildfires to cross property boundaries, building collaborative relationships among land managers, landowners, scientists, fire responders, and the public is key to addressing wildfires in African drylands.

9.4.4 Resource Conflicts in African Arid and Semi-arid Areas

The present state of natural resource degradation in the African drylands is explained in terms of factors related to ecological and demographic pressures, land-use conflicts, and inefficient land administration policies (Reda 2015). The armed conflicts strongly affect the agricultural activities (Demissie et al. 2022). Today, many

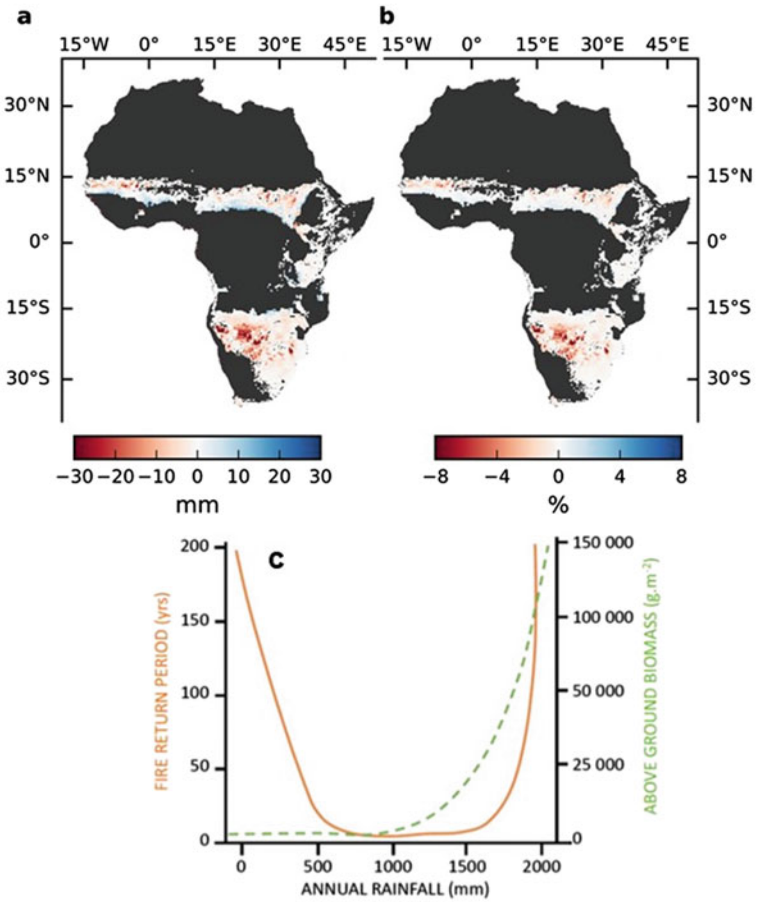


Fig. 9.16 Fire-induced rainfall suppression in drylands. **a** Rainfall lost as the difference between modeled wet season rainfall and wet season rainfall with no fire. **b** Rainfall modifications (expressed as a percentage of mean annual precipitation). Adapted from Saha et al. (2016). **c** The relationship between rainfall, fire frequency (continuous line), fuel accumulation (discontinuous line) in the southern Africa region. Adapted from Hély et al. (2019)

protected areas in SSA are located in areas of conflict (IUCN 2018). The potential conflictive areas in African drylands include the Senegal valley, the Niger Delta, the Kenyan highlands and wetlands, Tanzanian game-reserves and protected parks, and conflicts between Botswana and Namibia over the use of water resources as well as national politics and land tenure conflicts, the (Le Meur et al. 2006). Moreover, in the HA, i.e., Ethiopia, Eritrea, Somalia, and Djibouti, the first three countries are among the 20 countries in the world, where the most threatened herbivore species are found (Ripple et al. 2015; Sterzel et al. 2014; Pettersson and Öberg 2020), the case of Tigray (Balehegn et al. 2019). The HA has the highest conflict density in global drylands (8 out of 42 conflicts) (Fig. 9.18).

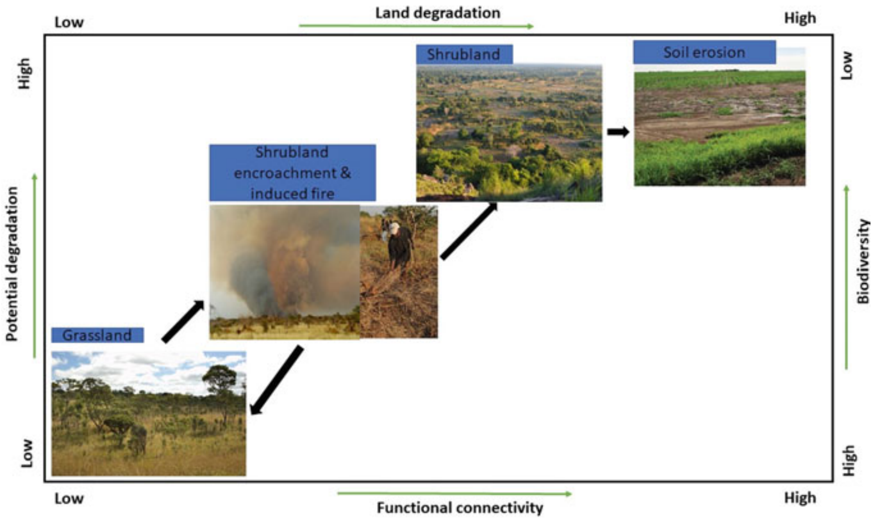


Fig. 9.17 Conceptual framework illustrating the stages of land degradation in typical Miombo woodlands, Southern Africa, with changes in biodiversity, functional connectivity, and soil erosion. Modified from Ravi et al. (2010)

Many researchers found that more than 70% of Africa's protected areas experienced conflicts during the last two decades. Several large nations experienced an average of 20 or more years of conflict per protected area, including Chad, Namibia, and Sudan (Daskin and Pringle 2018; Wigley et al. 2010). However, the large-mammal populations, including many threatened species have declined sharply (Ripple et al. 2015). Nowadays, almost all the countries in SSA experienced net encroachment, with only Congo, Kenya, Madagascar, Niger, and Somalia undergoing a net decline in woody cover. The highest rates of encroachment occurred in areas with moderate initial woody cover (i.e., 30–60%) in 1986. Areas with more than 75% initial cover experienced the highest rates of loss, probably due to human-induced clearing (Venter et al. 2018). Grazing herbivores, which dominate most African rangelands, reduce grass competition with woody plants and reduce fuel loads for fires, thereby releasing woody plants from the fire trap (Hempson et al. 2015; Roques et al. 2001). As result, shrub invasion is often associated with "overgrazing", and high browsing pressure can, in contrast, prevent the establishment of woody seedlings and retard the growth of shrubs, prolonging their exposure to fire and suppressing their recruitment into the mature stage (Roques et al. 2001). Figure 9.19 illustrates the major drivers of encroachments in protected areas (PAs) and their consequences on the dry environments.

The reasons for pAs encroachment in African drylands are still something of a puzzle. Multiple drivers likely interact to cause pAs encroachment. The uncertainty lies mainly in quantifying the importance of these drivers and understanding the extent to which they interact with one another. Factors such as herbivory, fire, and

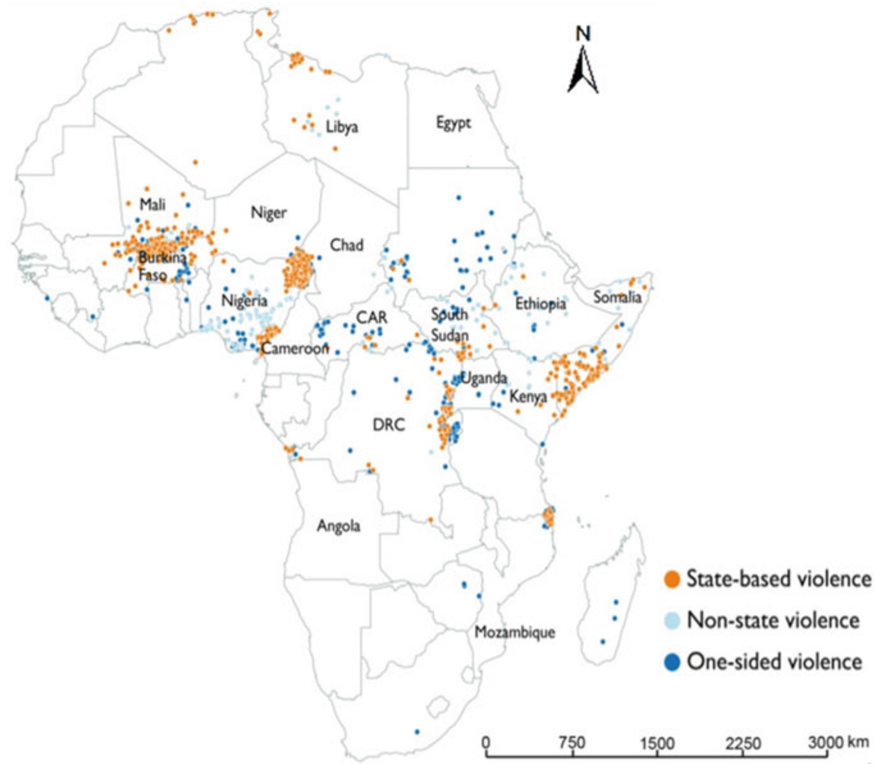


Fig. 9.18 Spatial distribution of armed conflicts and African drylands. Data from Uppsala Conflict Data Program (UCDP) georeferenced event dataset (GED). https://ucdp.uu.se/. Accessed 10 December 2021

soil properties are likely to alter woody cover and rates of encroachment in both wet and dry savannas at all levels (Devine et al. 2017). There is a need to enforce the best practices (BPs) approach and integrated conservation and development projects (ICDPs) to encourage conservation and development in rural communities adjacent to protected areas (Mutanga et al. 2015). The involvement of all stakeholders is very crucial. There is also a need for vastly elevated funding for PA management and research from both African and international governments and institutions.

9.4.5 Interactions Among Different Drivers

The DSES concept explicitly implies that humans and nature are inextricably linked. The effects of anthropogenic activities and climate change on ecosystems change their structure and function, thereby facilitating the provision of goods and services that contribute to human well-being (Fig. 9.20). For instance, livestock production in

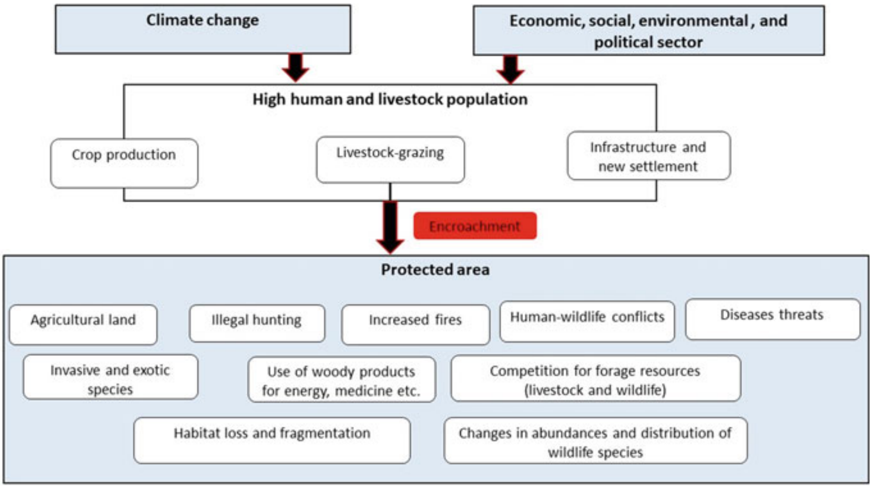


Fig. 9.19 Conceptual framework defining the major factors driving encroachments into a PA and their impacts in arid and semi-arid areas of Southeastern Africa

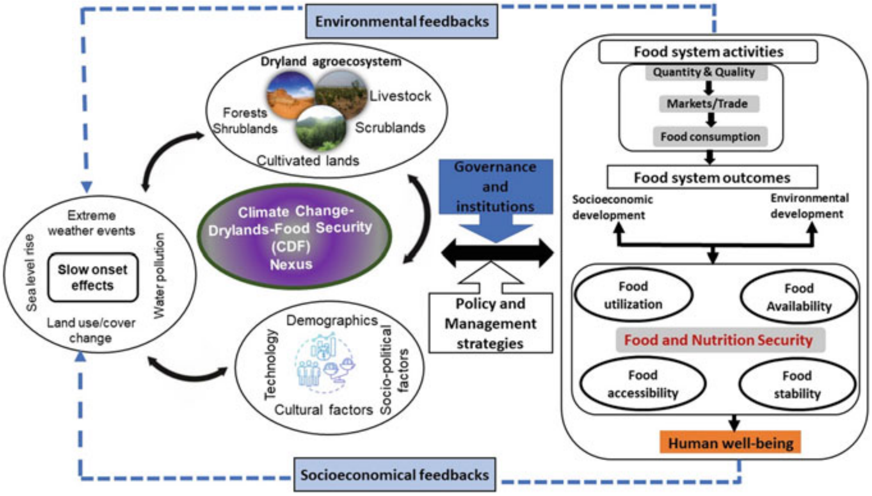


Fig. 9.20 Interconnection between food system, socioeconomic development, and dryland agroecosystem. Adapted from Hirwa et al. (2022)

drylands for semi-arid and arid societies, climate change mitigation by carbon sequestration, and cultural services such as distinctiveness and place for touristic activities (i.e., parks) all contribute to the well-being of dryland communities. However, drylands are directly affected by climate variability, human activities such as urbanization, and agricultural activities. The proximate drivers are influenced by distal socioeconomic dynamics, such as human population growth, technology, socioeconomic development, governance, institutional arrangements, and others. These indirect drivers do not always have direct effects on the dryland environment, but they do have an impact on the natural environment through moderating the effects of proximate causes.

Additionally, these interconnected ties between people and DSES can contribute to the community's resilience in different ways. Nonlinear dynamics and social and ecological feedbacks can promote negative system states. The proximate human actions such as overexploitation that directly influence ecosystems are shaped by underlying causes, or distal social, economic, cultural, and institutional forces. DSESs' assessments require understanding the factors that can help or hinder resilience. Likewise, the study of Cinner and Barnes (2019) indicated the adaptive capability were referred to six broad categories of social characteristics that contribute to dryland social-ecological change resilience: (1) the resources available to persons, (2) the ability to switch strategies, (3) the ability to plan and act collectively, (4) adaptation to changes and recognizing them, (5) the socio-cognitive structures that allow or limit social actions, and (6) the agency to decide whether or not to modify.

9.4.6 Research and Technology Gaps in African Arid Ecology

Long-term data series are important tools to answer ecological and evolutionary questions that need broad spatial and temporal monitoring. The lack of temporal information (i.e., long-term data series) leads to serious misjudgments that can interfere not only with attempts to understand and predict changes but also with efforts to manage the environments (Barbosa et al. 2020). Predictive models would be useful to understand and implement restoration programs that include the interactive effect of environmental variables and aquatic communities (Tessarolo et al. 2017). Several models have been built to prevent or reduce the adverse environmental impacts in arid and semi-arid zones. For instance, eutrophication (Mooij et al. 2010), flood forecasting and control (Refsgaard et al. 1988), drought prediction (Mishra and Singh 2011), crop growth modelling and crop yield forecasting (de Wit and van Diepen 2008; Khaki and Wang 2019; Di Paola et al. 2016), and among others have been developed and implemented.

The number of Earth Observation Networks (EONs) and Ecosystems Research Networks (ERNs) in Africa is relatively low compared to other regions worldwide. Therefore, this challenge results in huge uncertainties and subsequently affects decision-making at the international watershed levels, rendering the design of efficient adaptation measures much more difficult. These uncertainties are due to limited scientific understandings of the climate drivers and their interactions (e.g., West African (Klein et al. 2017), East Africa (Rowell and Chadwick 2018; Bornemann et al. 2019), and Southern Africa (Davis and Vincent 2017), resulting from a lack of high quality, long-term observation data, and specific data mining capabilities. For instance, Climate Risk and Early Warning Systems (CREWS) showed that the West African countries were most vulnerable to weather extremes because their national hydrological and meteorological services or agencies had limited early warning capabilities (i.e., the low infrastructure, observation systems, and human capacities), weak or non-existent dissemination systems, and a lack of effective emergency planning in case of alerts and warning information (Salack et al. 2015).

Therefore, there is an urgent need to enhance near-surface measurements and observation infrastructure in African drylands in order to develop coherent procedures of climate services delivery to national civil protection, humanitarian support agencies, and vulnerable communities. Droughts, flooding, air pollution, and dry spells, among other extreme events, can be detected using the network of near-surface observatories (Giannini et al. 2013; Knippertz et al. 2015; Salack et al. 2019), and to underpin climate services for mitigation, adaptation measures, and risks assessments (Ouedraogo et al. 2018; Jones et al. 2015). The strong commitment of African governments to ensure the sustainability and continuation of the transnational observation networks will empower African and world scientists as well as national meteorological and hydrological agencies to conduct research and deliver ecosystem services at a high level of accuracy and achieve Sustainable Development Goals (SDGs).

9.5 Summary and Perspectives

African DSES is considered as hotspots of vulnerability to environmental variability. African drylands have notably experienced change in land-use shifts and management in different regions of Africa. Therefore, understanding how Africa's drylands adapt to climate change and anthropogenic influence and maintaining the functional integrity of DSES is fundamental for sustainable development in the context of global environmental change.

This chapter provides a synopsis of African drylands as a DSES. The major features, trends, driving forces, potential future perspectives of drylands are reviewed, thereby informing policymakers, decision-makers, and stakeholders to harmonize strategies for DSES management in a sustainable way. The DSES are complex adaptive systems composed of connections between different people and dryland ecosystem factors. Biophysical and socioeconomic factors contribute to the emergence of DSES dynamics, which combine nonlinear and linear patterns with gradual yet abrupt developments. Comparing identical dryland DSES and diverse responses to global change, a better understanding of the context-specific DSES traits will be easier to be obtained. More study is needed to reduce the uncertainty in projecting system change trajectory and to investigate how synergies and trade-offs in drylands DSES are linked to spatial and temporal scales. Finally, this chapter highlighted the immediate future investment approaches and perspectives for climate-adapted development in Africa drylands:

- Empowerment of the local i.e., investing in infrastructure (e.g., communications and transport); investing in the development of governance systems that empower locally-led adaptation; prioritizing vulnerable stakeholders in order to provide the basis to address distributional outcomes and equity and improve community-level resilience.
- Supporting and exchange of local practices i.e., promoting investment in the demonstration of locally-led management practices that enable land resources restoration and sustainable production using NbS, carbon and biodiversity credit markets; implementation of participatory/joint research approaches to engage academic entities in supporting local knowledge, innovation, and technologies along with associated policies, so as to speed up the local adaptive learning.
- Involvement of the public in developing solutions: Building social and human capacity, fostering environmental mainstreaming education, and creating public awareness campaigns and trainings to educate citizens in dryland regions of Africa which provide the basis for adaptation to on-going future. Instead, providing the incentives and support for local communities to drive transformation and create job opportunities for youth and women.
- Providing enabling and integrated environment for strategic technical and operational partnerships and policy coordination and knowledge management. Undoubtedly, investing in major climate-adapted initiatives that run across multi-disciplinary sectors, people, and countries. Additionally, coordinate investor partnerships (i.e., dissolving climate finance mechanism) to drive free trade investments at large scale and over multiple funding cycles that accumulate to build resilience and reduce regional conflict.

In the final analysis, there is a need to promote sustainable agricultural best practices (e.g., NbS and Ecosystem-based Adaptation programs) and innovations as a tool to enhance community resilience and cope with climate change impacts on water-food security, use modern observational data and develop idealistic models to better understand the climate-drylands-food security nexus approaches, and strengthen dryland research and management effectiveness through emerging and affordable technologies. The above-mentioned recommendations should be seriously considered in future research and policy-making on DSES not only in Africa but also globally.

Acknowledgements We owe gratefulness to the reviewers whose insightful criticism significantly enhanced the paper. The third author was sponsored by Chinese Academy of Sciences (CAS)–The World Academy of Sciences (TWAS) President's Fellowship Programme for his Ph.D. study at University of Chinese Academy of Sciences (UCAS). This book chapter was funded by the National Natural Science Foundation of China (Grant No: 41761144053, 41561144011, U1906219, and U1803244).

References

Abrams L (2018) Unlocking the potential of enhanced rainfed agriculture. Report no. 39. SIWI, Stockholm. http://www.siwi.org/publications

Adenle AA, Wedig K, Azadi H (2019) Sustainable agriculture and food security in Africa: the role of innovative technologies and international organizations. Technol Soc 58:101143

Adimassu Z, Langan S, Johnston R (2016) Understanding determinants of farmers' investments in sustainable land management practices in Ethiopia: review and synthesis. Environ Dev Sustain 18(4):1005–1023

Agula C, Akudugu MA, Dittoh S et al (2018) Promoting sustainable agriculture in Africa through ecosystem-based farm management practices: evidence from Ghana. Agric Food Secur 7(1):1–11

Albrecht TR, Crootof A, Scott CA (2018) The water-energy-food nexus: a systematic review of methods for nexus assessment. Environ Res Lett 13(4):043002. https://doi.org/10.1088/1748-9326/aaa9c6

Amanuel W, Tesfaye M, Worku A et al (2019) The role of dry land forests for climate change adaptation: the case of Liben Woreda, Southern Oromia, Ethiopia. J Ecol Environ 43(1):11. https://doi.org/10.1186/s41610-019-0109-4

Aminpour P, Gray SA, Jetter AJ et al (2020) Wisdom of stakeholder crowds in complex social–ecological systems. Nat Sustain 3(3):191–199. https://doi.org/10.1038/s41893-019-0467-z

Andela N, Liu Y, Van Dijk A et al (2013) Global changes in dryland vegetation dynamics (1988–2008) assessed by satellite remote sensing: comparing a new passive microwave vegetation density record with reflective greenness data. Biogeosciences 10(10):6657–6676

Andela N, van der Werf GR (2014) Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition. Nat Clim Chang 4(9):791–795. https://doi.org/10.1038/nclimate2313

Anoba IB (2019) How a population of 42 billion could impact Africa by 2100: the possible economic. The SAIS Review of International Affairs. https://saisreview.sais.jhu.edu/how-a-population-of-4-2-billion-could-impact-africa-by-2100-the-possible-economic-demographic-and-geopolitical-outcomes/

Archer E, Dziba LE, Mulongoy KJ et al (2021) Biodiversity and ecosystem services on the African continent—what is changing, and what are our options? Environ Dev 37:100558. https://doi.org/10.1016/j.envdev.2020.100558

Atmadja S, Esthete A, Boissière M (2019) Guidelines on sustainable forest management in drylands of Ethiopia. FAO

AUC-NEPAD (2006) Towards a prioritised outcome-based approach to implementing Africa's food security commitments: beyond diagnosis and prescription to action summit on food security in Africa. Abuja, Nigeria. http://www.africa-union.org/root/AU/Conferences/Past/2006/December/REA/summit/doc/Food_Security_Summit_Eng_Final.doc. Accessed 24 Sept 2021

Awazi NP, Tchamba MN, Temgoua LF et al (2021) Farmers' adaptive capacity to climate change in Africa: small-scale farmers in Cameroon. In: Oguge N, Ayal D, Adeleke L et al (eds) African handbook of climate change adaptation. Springer International Publishing, Cham, pp 87–115. https://doi.org/10.1007/978-3-030-45106-6_9

Ayana GF, Megento TL, Kussa FG (2021) The extent of livelihood diversification on the determinants of livelihood diversification in Assosa Wereda, Western Ethiopia. GeoJournal. https://doi.org/10.1007/s10708-021-10379-5

Ayanlade A, Radeny M (2020) COVID-19 and food security in Sub-Saharan Africa: implications of lockdown during agricultural planting seasons. NPJ Sci Food 4(1):13. https://doi.org/10.1038/s41538-020-00073-0

Balehegn M, Haile M, Fu C et al (2019) Ecosystem-based adaptation in Tigray, Northern Ethiopia: a systematic review of interventions, impacts, and challenges. In: Leal Filho W (ed) Handbook of climate change resilience. Springer International Publishing, Cham, pp 1–45. https://doi.org/10.1007/978-3-319-71025-9_117-1

Bantilan M, Anand Babu P, Anupama G et al (2006) Dryland agriculture: dynamics, challenges and priorities. International Crops Research Institute for the Semi-Arid Tropics(ICRISAT)

Bao G, Qin Z, Bao Y et al (2014) NDVI-based long-term vegetation dynamics and its response to climatic change in the Mongolian Plateau. Remote Sens 6(9):8337–8358

Barbosa LG, Amorim CA, Parra G et al (2020) Advances in limnological research in Earth's drylands. Inland Waters 10(4):429–437. https://doi.org/10.1080/20442041.2020.1728179

Batjes NH (2012) ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver 12). ISRIC-World Soil Information

Batterbury S, Forsyth T (1999) Fighting back: human adaptations in marginal environments. Environ: Sci Policy Sustain Dev 41(6):6–9

Biswas AK (1986) Land use in Africa. Land Use Policy 3(4):247–259. https://doi.org/10.1016/0264-8377(86)90022-0

Bjornlund V, Bjornlund H, Van Rooyen AF (2020) Why agricultural production in sub-Saharan Africa remains low compared to the rest of the world—a historical perspective. Int J Water Resour Dev 36(sup1):S20–S53. https://doi.org/10.1080/07900627.2020.1739512

Black M (2016) The atlas of water: mapping the world's most critical resource. Univ of California Press

Blunden J, Arndt D (2020) State of the climate in 2019. Bull Am Meteor Soc 101(8):S1–S429

Bonkoungou EG (2001) Biodiversity in drylands: challenges and opportunities for conservation and sustainable use. Challenge Paper. The Global Drylands Initiative, UNDP Drylands Development Centre, Nairobi, Kenya

Bornemann FJ, Rowell DP, Evans B et al (2019) Future changes and uncertainty in decision-relevant measures of East African climate. Clim Change 156(3):365–384. https://doi.org/10.1007/s10584-019-02499-2

Brandt M, Mbow C, Diouf AA et al (2015) Ground-and satellite-based evidence of the biophysical mechanisms behind the greening Sahel. Glob Change Biol 21(4):1610–1620

Brandt M, Rasmussen K, Peñuelas J et al (2017) Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. Nat Ecol Evol 1(4):1–6

Brandt M, Wigneron J-P, Chave J et al (2018) Satellite passive microwaves reveal recent climate-induced carbon losses in African drylands. Nat Ecol Evol 2(5):827–835

Braune E, Xu Y (2010) The role of ground water in Sub-Saharan Africa. Groundwater 48(2):229–238

Brümmer C, Brüggemann N, Butterbach-Bahl K et al (2008) Soil-atmosphere exchange of N_2O and NO in near-natural savanna and agricultural land in Burkina Faso (W Africa). Ecosystems 11(4):582–600. https://doi.org/10.1007/s10021-008-9144-1

Burian A, Karaya R, Wernersson JEV et al (2019) A community-based evaluation of population growth and agro-pastoralist resilience in Sub-Saharan drylands. Environ Sci Policy 92:323–330. https://doi.org/10.1016/j.envsci.2018.10.021

Campanella MV, Bisigato AJ (2010) What causes changes in plant litter quality and quantity as consequence of grazing in the Patagonian Monte: plant cover reduction or changes in species composition? Aust Ecol 35(7):787–793

Catley A, Lind J, Scoones I (2013) Pastoralism and development in Africa: dynamic change at the margins. Routledge

Cervigni R, Morris M (2016) Confronting drought in Africa's drylands: opportunities for enhancing resilience. The World Bank

Chapin FS III, Kofinas GP, Folke C et al (2009) Principles of ecosystem stewardship: resilience-based natural resource management in a changing world. Springer Science & Business Media

Chillo V, Ojeda R (2014) Disentangling ecosystem responses to livestock grazing in drylands. Agr Ecosyst Environ 197:271–277

Chillo V, Ojeda RA, Capmourteres V et al (2017) Functional diversity loss with increasing livestock grazing intensity in drylands: the mechanisms and their consequences depend on the taxa. J Appl Ecol 54(3):986–996. https://doi.org/10.1111/1365-2664.12775

Cilliers J, Cilliers S, Lategan L (2021) Nature-based solutions for public green spaces in Sub-Saharan Africa—integrating place-making and green infrastructure. In: Faldi G, Fisher A, Moretto L (eds) African cities through local eyes. Springer, pp 91–110

Cinner JE, Barnes ML (2019) Social dimensions of resilience in social-ecological systems. One Earth 1(1):51–56. https://doi.org/10.1016/j.oneear.2019.08.003

Cohen-Shacham E, Andrade A, Dalton J et al (2019) Core principles for successfully implementing and upscaling nature-based solutions. Environ Sci Policy 98:20–29. https://doi.org/10.1016/j.envsci.2019.04.014

Cohen-Shacham E, Walters G, Janzen C et al (2016) Nature-based solutions to address global societal challenges. IUCN, Gland, Switzerland, p 97

Collentine D, Futter MN (2018) Realising the potential of natural water retention measures in catchment flood management: trade-offs and matching interests. J Flood Risk Manag 11(1):76–84

Cordingley JE, Snyder KA, Rosendahl J et al (2015) Thinking outside the plot: addressing low adoption of sustainable land management in sub-Saharan Africa. Curr Opin Environ Sustain 15:35–40

Cowie A, Penman T, Gorissen L et al (2011) Towards sustainable land management in the drylands: scientific connections in monitoring and assessing dryland degradation, climate change and biodiversity. Land Degrad Dev 22(2):248–260

Craigie ID, Baillie JE, Balmford A et al (2010) Large mammal population declines in Africa's protected areas. Biol Cons 143(9):2221–2228

Dalal RC, Allen DE (2008) Greenhouse gas fluxes from natural ecosystems. Aust J Bot 56(5):369–407. https://doi.org/10.1071/BT07128

Daramola MT, Xu M (2021) Recent changes in global dryland temperature and precipitation. Int J Climatol 42(2):1267–1282. https://doi.org/10.1002/joc.7301

Darwall W, Smith K, Allen D et al (2011) The diversity of life in African freshwaters: underwater, under threat: an analysis of the status and distribution of freshwater species throughout mainland Africa. IUCN, Gland, Switzerland and Cambridge, UK

Daskin JH, Pringle RM (2018) Warfare and wildlife declines in Africa's protected areas. Nature 553(7688):328–332. https://doi.org/10.1038/nature25194

Davis CL, Vincent K (2017) Climate risk and vulnerability: a handbook for Southern Africa. CSIR

de Haan C (2016) Prospects for livestock-based livelihoods in Africa's drylands. The World Bank

De Jager A, Onduru D, Van Wijk M et al (2001) Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. Agric Syst 69(1–2):99–118

de Wit AJW, van Diepen CA (2008) Crop growth modelling and crop yield forecasting using satellite-derived meteorological inputs. Int J Appl Earth Obs Geoinf 10(4):414–425. https://doi.org/10.1016/j.jag.2007.10.004

Demissie B, Nyssen J, Annys S et al (2022) Geospatial solutions for evaluating the impact of the Tigray conflict on farming. Acta Geophys 70(3):1285–1299. https://doi.org/10.1007/s11600-022-00779-7

Depietri Y, McPhearson T (2017) Integrating the grey, green, and blue in cities: nature-based solutions for climate change adaptation and risk reduction. In: Nature-based solutions to climate change adaptation in urban areas. Springer, Cham, pp 91–109

Devine AP, McDonald RA, Quaife T et al (2017) Determinants of woody encroachment and cover in African savannas. Oecologia 183(4):939–951. https://doi.org/10.1007/s00442-017-3807-6

Dewitte O, Jones A, Spaargaren O et al (2013) Harmonisation of the soil map of Africa at the continental scale. Geoderma 211:138–153

Di Paola A, Valentini R, Santini M (2016) An overview of available crop growth and yield models for studies and assessments in agriculture. J Sci Food Agric 96(3):709–714. https://doi.org/10.1002/jsfa.7359

Diop S, Guisse A, Sene C et al (2018) Combating desertification and improving local livelihoods through the GGWI in the Sahel region: the example of Senegal. J Resour Ecol 9(3):257–265

Diouf AA, Brandt M, Verger A et al (2015) Fodder biomass monitoring in Sahelian rangelands using phenological metrics from FAPAR time series. Remote Sens 7(7):9122–9148

Dlamini P, Chivenge P, Manson A et al (2014) Land degradation impact on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa. Geoderma 235–236:372–381. https://doi.org/10.1016/j.geoderma.2014.07.016

Dodo MK (2020) Understanding Africa's food security challenges. In: Food security in Africa. IntechOpen

Dulvy NK, Fowler SL, Musick JA et al (2014) Extinction risk and conservation of the world's sharks and rays. elife 3:e00590

EM-DAT (2018) The emergency events database. The International Disaster Database Brussels Belgium. https://www.emdat.be

Epule ET, Peng C, Lepage L et al (2014) The causes effects and challenges of Sahelian droughts: a critical review. Reg Environ Change 14(1):145–156

Epule TE, Ford JD, Lwasa S et al (2017) Climate change adaptation in the Sahel. Environ Sci Policy 75:121–137. https://doi.org/10.1016/j.envsci.2017.05.018

ESA (2017) Land cover climate change initiative product user guide version 2. T Rep 1992–2015. http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

Fan L, Wigneron J-P, Ciais P et al (2019) Satellite-observed pantropical carbon dynamics. Nat Plants 5(9):944–951

FAO (2009) Review of evidence on drylands pastoral systems and climate change: implications and opportunities for mitigation and adaptation. Land and Water Discussion Paper. Rome, Italy

FAO (2018) Pastoralism in Africa's drylands. Rome, Italy

FAO (2019) Trees forests and land use in drylands: the first global assessment-full report. FAO Forestry Paper No 184. Rome, Italy

Fenta AA, Tsunekawa A, Haregeweyn N et al (2020) Cropland expansion outweighs the monetary effect of declining natural vegetation on ecosystem services in sub-Saharan Africa. Ecosyst Serv 45:101154. https://doi.org/10.1016/j.ecoser.2020.101154

Field CB, Barros VR (2014) Climate change 2014—impacts adaptation and vulnerability: regional aspects. Cambridge University Press

Fischer G, Nachtergaele FO, van Velthuizen H et al (2021) Global agro-ecological zones (GAEZ v4)-model documentation. Rome, FAO. https://doi.org/10.4060/cb4744en

Francis C (2016) The carbon farming solution: a global toolkit of perennial crops and regenerative agriculture practices for climate change mitigation and food security by Eric Toensmeier. Agroecol Sustain Food Syst 40(9):1039–1040. https://doi.org/10.1080/21683565.2016.1214861

Frantzeskaki N, McPhearson T, Collier MJ et al (2019) Nature-based solutions for urban climate change adaptation: linking science policy and practice communities for evidence-based decision-making. Bioscience 69(6):455–466

Fraser ED, Dougill AJ, Hubacek K et al (2011) Assessing vulnerability to climate change in dryland livelihood systems: conceptual challenges and interdisciplinary solutions. Ecol Soc 16(3): 3

García-Díez J, Gonçalves C, Grispoldi L et al (2021) Determining food stability to achieve food security. Sustainability 13(13):7222. https://www.mdpi.com/2071-1050/13/13/7222

Garrity D, Dixon J, Boffa J-M (2012) Understanding African farming systems: science and policy implications. ACIAR, Sydney, Australia

Gebremeskel Haile G, Tang Q, Sun S et al (2019) Droughts in East Africa: causes impacts and resilience. Earth Sci Rev 193:146–161. https://doi.org/10.1016/j.earscirev.2019.04.015

Giannini A, Salack S, Lodoun T et al (2013) A unifying view of climate change in the Sahel linking intra-seasonal interannual and longer time scales. Environ Res Lett 8(2):024010. https://doi.org/10.1088/1748-9326/8/2/024010

Githiru M, Mutwiwa U, Kasaine S et al (2017) A spanner in the works: human–elephant conflict complicates the food–water–energy nexus in drylands of Africa (perspective). Front Environ Sci 5(69). https://doi.org/10.3389/fenvs.2017.00069

Gnacadja L, Wiese L (2016) Land degradation neutrality: will Africa achieve it? Institutional solutions to land degradation and restoration in Africa. In: Climate change and multi-dimensional sustainability in African agriculture. Springer, Cham, pp 61–95

Goffner D, Sinare H, Gordon LJ (2019) The Great Green Wall for the Sahara and the Sahel Initiative as an opportunity to enhance resilience in Sahelian landscapes and livelihoods. Reg Environ Change 19(5):1417–1428. https://doi.org/10.1007/s10113-019-01481-z

Guo L, Sun F, Liu W et al (2019) Response of ecosystem water use efficiency to drought over China during 1982–2015: spatiotemporal variability and resilience. Forests 10(7):598

Hammel JE (1996) Water conservation practices for sustainable dryland farming systems in the Pacific Northwest. Am J Altern Agric 11(2–3):58–63. https://doi.org/10.1017/S0889189300006779

Haregeweyn N, Tsunekawa A, Nyssen J et al (2015) Soil erosion and conservation in Ethiopia: a review. Prog Phys Geogr: Earth Environ 39(6):750–774. https://doi.org/10.1177/0309133315598725

Hartley A, Barger N, Belnap J et al (2007) Dryland ecosystems. In: Nutrient cycling in terrestrial ecosystems. Springer, pp 271–307

Hély C, Alleaume S, Runyan CW (2019) Fire regimes in dryland landscapes. In: D'Odorico P, Porporato A,Wilkinson Runyan C (eds) Dryland ecohydrology. Springer International Publishing, Cham, pp 367–399. https://doi.org/10.1007/978-3-030-23269-6_14

Hempson GP, Archibald S, Bond WJ (2015) A continent-wide assessment of the form and intensity of large mammal herbivory in Africa. Science 350(6264):1056–1061. https://doi.org/10.1126/science.aac7978

Hirwa H, Li F, Qiao Y et al (2022) Climate change-drylands-food security nexus in Africa: from the perspective of technical advances challenges and opportunities. Front Environ Sci 1535. https://doi.org/10.3389/fenvs.2022.851249

Hirwa H, Zhang Q, Qiao Y et al (2021) Insights on water and climate change in the Greater Horn of Africa: connecting virtual water and water-energy-food-biodiversity-health nexus. Sustainability 13(11):6483. https://doi.org/10.3390/su13116483

Hoover DL, Bestelmeyer B, Grimm NB et al (2019) Traversing the wasteland: a framework for assessing ecological threats to drylands. Bioscience 70(1):35–47. https://doi.org/10.1093/biosci/biz126

Hu W, Ran J, Dong L et al (2021) Aridity-driven shift in biodiversity–soil multifunctionality relationships. Nat Commun 12(1):5350. https://doi.org/10.1038/s41467-021-25641-0

Huang M, Piao S, Zeng Z et al (2016) Seasonal responses of terrestrial ecosystem water-use efficiency to climate change. Glob Change Biol 22(6):2165–2177

Huber-Sannwald E, Palacios MR, Moreno JTA et al (2012) Navigating challenges and opportunities of land degradation and sustainable livelihood development in dryland social-ecological systems: a case study from Mexico. Philos Trans R Soc Lond B Biol Sci 367(1606):3158–3177. https://doi.org/10.1098/rstb.2011.0349

Ifeoma I, Agwu A (2014) Assessment of food security situation among farming households in rural areas of Kano state Nigeria. J Cent Eur Agric

IISD (2022) Nature can help solve crises with investment: joint report. International Institute for Sustainable Development (IISD). https://sdg.iisd.org/news/nature-can-help-solve-crises-with-investment-joint-report/. Accessed 3 Feb 2022

IMF (2021) Regional economic outlook: Sub-Saharan Africa: one planet two worlds three stories. International Monetary Fund, Washington DC

IPBES (2021) Scoping report on assessing the interlinkages among biodiversity climate water food energy and health (nexus assessment). In: Plenary of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Eighth session. UN, UNEP, UNESCO, FAO, UNDP, p 11. https://ipbes.net/sites/default/files/2021-05/IPBES_8_3_nexus%20assessment_en.pdf

IPCC (2019) 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. Summary for policymakers. WMO, UNEP

IPCC (2021) Climate change 2021: the physical science basis. WMO, UNEP

IUCN (2012) Conserving dryland biodiversity. Nairobi, Kenya

IUCN (2018) Study on the interaction between security and wildlife conservation in Sub-Saharan Africa. Nairobi, Kenya

Jalloh A, Roy-Macauley H, Sereme P (2012) Major agro-ecosystems of West and Central Africa: brief description species richness management environmental limitations and concerns. Agr Ecosyst Environ 157:5–16

Jellason NP, Conway JS, Baines RN et al (2021) A review of farming challenges and resilience management in the Sudano-Sahelian drylands of Nigeria in an era of climate change. J Arid Environ 186:104398. https://doi.org/10.1016/j.jaridenv.2020.104398

Johnson BA, Dasgupta R, Mader AD et al (2019) Understanding national biodiversity targets in a REDD+ context. Environ Sci Policy 92:27–33. https://doi.org/10.1016/j.envsci.2018.11.007

Jones L, Dougill A, Jones RG et al (2015) Ensuring climate information guides long-term development. Nat Clim Chang 5(9):812–814. https://doi.org/10.1038/nclimate2701

Josephson A, Kilic T, Michler JD (2020) Socioeconomic impacts of COVID-19 in four African countries. The World Bank

Kay AU, Kaplan JO (2015) Human subsistence and land use in sub-Saharan Africa 1000 BC to AD 1500: a review, quantification, and classification. Anthropocene 9:14–32

Kayiranga A, Chen B, Trisurat Y et al (2020) Water use efficiency-based multiscale assessment of ecohydrological resilience to ecosystem shifts over the continent of Africa during 1992–2015. J Geophys Res: Biogeosci 125(8):e2020JG005749. https://doi.org/10.1029/2020JG005749

Khaki S, Wang L (2019) Crop yield prediction using deep neural networks. Front Plant Sci 10(621). https://doi.org/10.3389/fpls.2019.00621

Kiage LM (2013) Perspectives on the assumed causes of land degradation in the rangelands of Sub-Saharan Africa. Prog Phys Geogr: Earth Environ 37(5):664–684. https://doi.org/10.1177/0309133313492543

Kiboi MN, Ngetich FK, Mugendi DN (2019) Nitrogen budgets and flows in African smallholder farming systems. AIMS Agric Food 4(2):429–446

Kigomo BN (2003) Forests and woodlands degradation in dryland Africa: a case for urgent global attention. Paper presented at the XII world forestry congress, Quebec City, Canada

Klein C, Bliefernicht J, Heinzeller D et al (2017) Feedback of observed interannual vegetation change: a regional climate model analysis for the West African monsoon. Clim Dyn 48(9):2837–2858. https://doi.org/10.1007/s00382-016-3237-x

Knippertz P, Evans MJ, Field PR et al (2015) The possible role of local air pollution in climate change in West Africa. Nat Clim Chang 5(9):815–822. https://doi.org/10.1038/nclimate2727

Kolding J, van Zwieten PA, Marttin F et al (2016) Fisheries in the drylands of Sub-Saharan Africa—“fish come with the rains”. Building resilience for fisheries-dependent livelihoods to enhance food security and nutrition in the drylands. FAO, Rome, Italy

Koohafkan P, Stewart BA (2008) Water and cereals in drylands. Earthscan

Kratli S (2020) Valuing variability—new perspectives on climate resilient dryland development. International Institute for Environment and Development (IIED), London

Krogh L (1997) Field and village nutrient balances in millet cultivation in northern Burkina Faso: a village case study. J Arid Environ 35(1):147–159

Laban P, Metternicht G, Davies J (2018) Soil biodiversity and soil organic carbon: keeping drylands alive. IUCN, Gland, Switzerland

Láng V, Fuchs M, Szegi T et al (2016) Deriving world reference base reference soil groups from the prospective global soil map product—a case study on major soil types of Africa. Geoderma 263:226–233. https://doi.org/10.1016/j.geoderma.2015.07.005

Le Meur P-Y, Hochet P, Shem M et al (2006) Conflict over access to land and water resources within Sub-Saharan dry lands. Underlying factors, conflict dynamics and settlement processes. GRET-FAO LEAD Final Report

Leitner S, Pelster DE, Werner C et al (2020) Closing maize yield gaps in sub-Saharan Africa will boost soil N_2O emissions. Curr Opin Environ Sustain 47:95–105. https://doi.org/10.1016/j.cosust.2020.08.018

Leone M, Miranda MG, Knoblauch D et al (2021) Governance analysis for planning and implementation of urban NBS: governance practices, challenges and needs of INTERLACE cities. Deliverable 2.2. INTERLACE project

Linstädter A, Kuhn A, Naumann C et al (2016) Assessing the resilience of a real-world social-ecological system lessons from a multidisciplinary evaluation of a South African pastoral system. Ecol Soc 21(3). http://www.jstor.org/stable/26269980

Lobell DB, Bänziger M, Magorokosho C et al (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat Clim Chang 1(1):42–45. https://doi.org/10.1038/nclimate1043

Lu X, Wang L, McCabe MF (2016) Elevated CO_2 as a driver of global dryland greening. Sci Rep 6(1):20716

MA (2005) Ecosystems and human well-being. Island Press, USA

Maestre FT, Eldridge DJ, Soliveres S et al (2016) Structure and functioning of dryland ecosystems in a changing world. Annu Rev Ecol Evol Syst 47:215–237. https://doi.org/10.1146/annurev-ecolsys-121415-032311

Manlay RJ, Ickowicz A, Masse D et al (2004) Spatial carbon, nitrogen and phosphorus budget in a village of the West African savanna—II. Element flows and functioning of a mixed-farming system. Agric Syst 79(1):83–107

Mbow C, Van Noordwijk M, Luedeling E et al (2014) Agroforestry solutions to address food security and climate change challenges in Africa. Curr Opin Environ Sustain 6:61–67. https://doi.org/10.1016/j.cosust.2013.10.014

McGahey DJ (2011) Livestock mobility and animal health policy in southern Africa: the impact of veterinary cordon fences on pastoralists. Pastor: Res Policy Pract 1(1):14. https://doi.org/10.1186/2041-7136-1-14

McLellan R, Iyengar L, Jeffries B et al (2014) Living planet report 2014: species and spaces, people and places. WWF International

Middleton NJ, Sternberg T (2013) Climate hazards in drylands: a review. Earth Sci Rev 126:48–57. https://doi.org/10.1016/j.earscirev.2013.07.008

Milne E, Aynekulu E, Bationo A et al (2016) Grazing lands in Sub-Saharan Africa and their potential role in climate change mitigation: what we do and don't know. Environ Dev 19:70–74

Mishra AK, Singh VP (2011) Drought modeling—a review. J Hydrol 403(1):157–175. https://doi.org/10.1016/j.jhydrol.2011.03.049

Mooij WM, Trolle D, Jeppesen E et al (2010) Challenges and opportunities for integrating lake ecosystem modelling approaches. Aquat Ecol 44(3):633–667

Morris M, Cervigni R, Guo Z (2016) The central role of drylands in Africa's development challenge. Confronting drought in Africa's drylands: opportunities for enhancing resilience, pp 27–36. https://doi.org/10.1596/978-1-4648-0817-3_ch1

Mortimore M, Anderson S, Cotula L et al (2009) Dryland opportunies: a new paradigm for people ecosystems and development. International Union for Conservation of Nature (IUCN)

Mortimore MJ, Adams WM (2001) Farmer adaptation change and 'crisis' in the Sahel. Glob Environ Chang 11(1):49–57

Muhirwa F, Shen L, Elshkaki A et al (2023) Alert in the dynamics of water-energy-food production in African countries from a nexus perspective. Resour Conserv Recycl 194:106990

Mureva A, Ward D, Pillay T et al (2018) Soil organic carbon increases in semi-arid regions while it decreases in humid regions due to woody-plant encroachment of grasslands in South Africa. Sci Rep 8(1):1–12

Mutanga CN, Vengesayi S, Muboko N et al (2015) Towards harmonious conservation relationships: a framework for understanding protected area staff-local community relationships in developing countries. J Nat Conserv 25:8–16

NAGGW (2016) Strategic plan of development of the NAGGGW (2016–2020). Dakar, Senegal

Ndengu S (2002) International shared aquifers in Namibia. In: B Managing shared aquifer resources in Africa Paris (IHP-VI series on groundwater 8), pp 117–122

Niang I, Ruppel O, Abdrabo M et al (2014) Africa: climate change 2014: impacts adaptation and vulnerability. Part B: regional aspects. In: Barros VR et al (eds) Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change, pp 1199–1265

Nichols CA, Vandewalle ME, Alexander KA (2017) Emerging threats to dryland forest resources: elephants and fire are only part of the story. For: Int J For Res 90(4):473–484. https://doi.org/10.1093/forestry/cpx010

Nyberg G, Mureithi SM, Muricho DN et al (2019) Enclosures as a land management tool for food security in African drylands. J Land Use Sci 14(1):110–121

Orimoloye IR, Mazinyo SP, Kalumba AM et al (2019) Implications of climate variability and change on urban and human health: a review. Cities 91:213–223. https://doi.org/10.1016/j.cities.2019.01.009

Ouedraogo I, Diouf NS, Ouédraogo M et al (2018) Closing the gap between climate information producers and users: assessment of needs and uptake in Senegal. Climate 6(1):13. https://www.mdpi.com/2225-1154/6/1/13

Pachauri RK, Allen MR, Barros VR et al (2014) Climate change 2014: synthesis report. In: Contribution of working groups i ii and iii to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC)

Palacios-Lopez A, Christiaensen L, Kilic T (2017) How much of the labor in African agriculture is provided by women? Food Policy 67:52–63. https://doi.org/10.1016/j.foodpol.2016.09.017

Parikh SJ, James BR (2012) Soil: the foundation of agriculture. Nat Educ Knowl 3(10):2

Partelow S (2018) A review of the social-ecological systems framework. Ecol Soc 23(4): 36

Parton W, Scurlock J, Ojima D et al (1995) Impact of climate change on grassland production and soil carbon worldwide. Glob Change Biol 1(1):13–22

Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11(5):1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Pelster D, Rufino M, Rosenstock T et al (2017) Smallholder farms in eastern African tropical highlands have low soil greenhouse gas fluxes. Biogeosciences 14(1):187–202. https://doi.org/10.5194/bg-14-187-2017

Peng Y, Hirwa H, Zhang Q et al (2021) Dryland food security in Ethiopia: current status opportunities and a roadmap for the future. Sustainability 13(11):6503. https://www.mdpi.com/2071-1050/13/11/6503

Pettersson T, Öberg M (2020) Organized violence 1989–2019. J Peace Res 57(4):597–613

Pham-Duc B, Sylvestre F, Papa F et al (2020) The Lake Chad hydrology under current climate change. Sci Rep 10(1):5498. https://doi.org/10.1038/s41598-020-62417-w

Poulter B, Frank D, Ciais P et al (2014) Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. Nature 509(7502):600–603. https://doi.org/10.1038/nature13376

Prăvălie R (2016) Drylands extent and environmental issues. A global approach. Earth Sci Rev 161:259–278. https://doi.org/10.1016/j.earscirev.2016.08.003

Ravi S, Breshears DD, Huxman TE et al (2010) Land degradation in drylands: interactions among hydrologic–aeolian erosion and vegetation dynamics. Geomorphology 116(3):236–245. https://doi.org/10.1016/j.geomorph.2009.11.023

Raymond CM, Frantzeskaki N, Kabisch N et al (2017) A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environ Sci Policy 77:15–24

Reda KT (2015) Natural resource degradation and conflict in the East African pastoral drylands. Afr Secur Rev 24(3):270–278. https://doi.org/10.1080/10246029.2015.1059350

Refsgaard JC, Havnø K, Ammentorp HC et al (1988) Application of hydrological models for flood forecasting and flood control in India and Bangladesh. Adv Water Resour 11(2):101–105. https://doi.org/10.1016/0309-1708(88)90043-7

Ripple WJ, Newsome TM, Wolf C et al (2015) Collapse of the world's largest herbivores. Sci Adv 1(4):e1400103. https://doi.org/10.1126/sciadv1400103

Robinson D (2007) Implications of a large global root biomass for carbon sink estimates and for soil carbon dynamics. Proc R Soc B: Biol Sci 274(1626):2753–2759

Roques KG, O'Connor TG, Watkinson AR (2001) Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. J Appl Ecol 38(2):268–280. https://doi.org/10.1046/j.1365-2664.2001.00567.x

Ross CW, Hanan NP, Prihodko L et al (2021) Woody-biomass projections and drivers of change in sub-Saharan Africa. Nat Clim Chang 11(5):449–455. https://doi.org/10.1038/s41558-021-01034-5

Rowell DP, Chadwick R (2018) Causes of the uncertainty in projections of tropical terrestrial rainfall change: East Africa. J Clim 31(15):5977–5995

Rütting T, Aronsson H, Delin S (2018) Efficient use of nitrogen in agriculture. Nutr Cycl Agroecosyst 110(1):1–5. https://doi.org/10.1007/s10705-017-9900-8

Safriel U (2017) Land Degradation Neutrality (LDN) in drylands and beyond–where has it come from and where does it go. Silva Fennica 51(1B):20–24

Saha MV, D'Odorico P, Scanlon TM (2019) Kalahari wildfires drive continental post-fire brightening in Sub-Saharan Africa. Remote Sens 11(9):1090. https://www.mdpi.com/2072-4292/11/9/1090

Saha MV, Scanlon TM, D'Odorico P (2016) Suppression of rainfall by fires in African drylands. Geophys Res Lett 43(16):8527–8533. https://doi.org/10.1002/2016GL069855

Salack S, Bossa A, Bliefernicht J et al (2019) Designing transnational hydroclimatological observation networks and data sharing policies in West Africa. Data Sci J 18(1):33. https://doi.org/10.5334/dsj-2019-033

Salack S, Sarr B, Sangare SK et al (2015) Crop-climate ensemble scenarios to improve risk assessment and resilience in the semi-arid regions of West Africa. Climate Res 65:107–121

Sanz MJ, Vente Jd, Chotte J-L et al (2017) Sustainable land management contribution to successful land-based climate change adaptation and mitigation. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany

Sasson A (2012) Food security for Africa: an urgent global challenge. Agric Food Secur 1(1):2. https://doi.org/10.1186/2048-7010-1-2

Scholes M, Scholes RB, Lucas M (2015) Climate change: briefings from Southern Africa. NYU Press

Seddon N, Chausson A, Berry P et al (2020) Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos Trans R Soc B 375(1794):20190120

Shackleton S, Hebinck P, Speranza CI et al (2019) Livelihood and landscape change in Africa: future trajectories for improved well-being under a changing climate. MDPI: A special issue of Land

Sharma A, Goyal MK (2018) Assessment of ecosystem resilience to hydroclimatic disturbances in India. Glob Change Biol 24(2):e432–e441

Shcherbak I, Millar N, Robertson GP (2014) Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. Proc Natl Acad Sci 111(25):9199–9204. https://doi.org/10.1073/pnas1322434111

Sickman JO, James AE, Fenn ME et al (2019) Quantifying atmospheric N deposition in dryland ecosystems: a test of the Integrated Total Nitrogen Input (ITNI) method. Sci Total Environ 646:1253–1264. https://doi.org/10.1016/j.scitotenv.2018.07.320

Skowno AL, Thompson MW, Hiestermann J et al (2017) Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers. Glob Change Biol 23(6):2358–2369

Sola P, Oduol J, Hagazi N et al (2020) Landscape restoration is more than land restoration: dryland development in Ethiopia and Kenya. Tropenbos International, Wageningen, The Netherlands

Sterzel T, Lüdeke M, Kok M et al (2014) Armed conflict distribution in global drylands through the lens of a typology of socio-ecological vulnerability. Reg Environ Change 14(4):1419–1435. https://doi.org/10.1007/s10113-013-0553-0

Stevens N, Lehmann CE, Murphy BP et al (2017) Savanna woody encroachment is widespread across three continents. Glob Change Biol 23(1):235–244

Suich H, Howe C, Mace G (2015) Ecosystem services and poverty alleviation: a review of the empirical links. Ecosyst Serv 12:137–147. https://doi.org/10.1016/j.ecoser.2015.02.005

Sun S, Song Z, Wu X et al (2018) Spatio-temporal variations in water use efficiency and its drivers in China over the last three decades. Ecol Ind 94:292–304

Tessarolo G, Ladle R, Rangel T et al (2017) Temporal degradation of data limits biodiversity research. Ecol Evol 7(17):6863–6870. https://doi.org/10.1002/ece3.3259

Thorn JPR, Hejnowicz AP, Marchant R et al (2021) Dryland nature based solutions for informal settlement upgrading schemes in Africa. ICLEI Africa

Thornton PK, Wilkens PW (1998) Risk assessment and food security. In: Tsuji GY, Hoogenboom G, Thornton PK (eds) Understanding options for agricultural production. Springer, Dordrecht, pp 329–345. https://doi.org/10.1007/978-94-017-3624-4_16

Thorslund J, Jarsjo J, Jaramillo F et al (2017) Wetlands as large-scale nature-based solutions: status and challenges for research, engineering and management. Ecol Eng 108:489–497

Tian F, Brandt M, Liu YY et al (2017) Mapping gains and losses in woody vegetation across global tropical drylands. Glob Change Biol 23(4):1748–1760

Trabucco A, Zomer RJ (2018) Global aridity index and potential evapotranspiration (ET0) climate database v2. CGIAR Consort Spat Inf

Twomlow SJ, Steyn JT, Du Preez CC (2006) Dryland farming in southern Africa. Dryland Agric 23:769–836

UNDP (2015) World population prospects: the 2015 revision. United Nations Econ Soc Aff 33(2):1–66

UNDP/UNSO (1997) Aridity zones and dryland populations: an assessment of population levels in the world's drylands. UNSO/UNDP, New York

UNEP-WCMC (2016) The state of biodiversity in Africa: a mid-term review of progress towards the Aichi Biodiversity Targets. UNEP-WCMC, Cambridge, UK, p 104. https://www.cbd.int/gbo/gbo4/outlook-africa-en.pdf

UNEP (2007) Biodiversity and climate change. Montreal

UNEP (2010) Africa water atlas. United Nations Environment Programme (UNEP) Division of Early Warning Assessment, African Ministers' Council on Water, African Union Commission, United States Department of State, European Union

van Bussel LGJ, Grassini P, Van Wart J et al (2015) From field to atlas: upscaling of location-specific yield gap estimates. Field Crop Res 177:98–108. https://doi.org/10.1016/j.fcr.2015.03.005

Venter Z, Cramer M, Hawkins H-J (2018) Drivers of woody plant encroachment over Africa. Nat Commun 9(1):2272

Venter ZS, Hawkins HJ, Cramer MD (2017) Implications of historical interactions between herbivory and fire for rangeland management in African savannas. Ecosphere 8(10):e01946

Villada-Canela M, Camacho-López R, Muñoz-Pizza DM (2020) The socio-ecological systems approach to research the integrated groundwater management in an agricultural dryland in Mexico. In: Lucatello S, Huber-Sannwald E, Espejel I et al (eds) Stewardship of future drylands and climate change in the global south: challenges and opportunities for the agenda 2030. Springer International Publishing, Cham, pp 79–95. https://doi.org/10.1007/978-3-030-22464-6_5

Vitousek PM, Naylor R, Crews T et al (2009) Nutrient imbalances in agricultural development. Science 324(5934):1519–1520. https://doi.org/10.1126/science.1170261

Von Maltitz GP, Gambiza J, Kellner K et al (2019) Experiences from the South African land degradation neutrality target setting process. Environ Sci Policy 101:54–62

Wei F, Wang S, Brandt M et al (2021) Responses and feedbacks of African dryland ecosystems to environmental changes. Curr Opin Environ Sustain 48:29–35. https://doi.org/10.1016/j.cosust.2020.09.004

Wei F, Wang S, Fu B et al (2020) Nonlinear dynamics of fires in Africa over recent decades controlled by precipitation. Glob Change Biol 26(8):4495–4505. https://doi.org/10.1111/gcb.15190

Wei F, Wang S, Fu B et al (2019) African dryland ecosystem changes controlled by soil water. Land Degrad Dev 30(13):1564–1573

Wigley BJ, Bond WJ, Hoffman MT (2010) Thicket expansion in a South African savanna under divergent land use: local vs global drivers? Glob Change Biol 16(3):964–976. https://doi.org/10.1111/j.1365-2486.2009.02030.x

Wigneron J-P, Fan L, Ciais P et al (2020) Tropical forests did not recover from the strong 2015–2016 El Niño event. Sci Adv 6(6):eaay4603

World Bank (2021) Indicator: data development indicator. Washington DC. https://data.worldbank.org/indicator

World Bank Group (2016) Poverty and shared prosperity 2016: taking on inequality. World Bank. http://www.worldbank.org/en/publication/poverty-and-shared-prosperity

Yu P, Qiuying Z, Yuanzhan C et al (2021) Resilience, adaptability, and regime shifts thinking: a perspective of dryland socio-ecology system. J Resour Ecol 12(3):376–383. https://doi.org/10.5814/j.issn.1674-764x.2021.03.007

Yue C, Ciais P, Bastos A et al (2017) Vegetation greenness and land carbon-flux anomalies associated with climate variations: a focus on the year 2015. Atmos Chem Phys 17(22):13903–13919. https://doi.org/10.5194/acp-17-13903-2017

Zhang R, Wang J, Niu S (2021) Toward a sustainable grazing management based on biodiversity and ecosystem multifunctionality in drylands. Curr Opin Environ Sustain 48:36–43. https://doi.org/10.1016/j.cosust.2020.09.005

Zhang X, Friedl M, Schaaf C et al (2003) Monitoring vegetation phenology using MODIS. Remote Sens Environ 84(3):471–475. https://doi.org/10.1016/S0034-4257(02)00135-9