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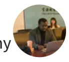
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Climate change–drylands–food security nexus in Africa: From the perspective of technical advances, challenges, and opportunities

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Climate change impacts on drylands pose more vexing risks to socio-ecological systems, resulting in food security issues, biodiversity loss, and livelihood shifts in Africa. This study critically reviewed relevant literature to evaluate the complexities and feedback loops between the climate–drylands–food security (CDF) nexus, which helps assess tactics to attain sustainable dryland ecosystem management under the changing environment. Comprehensive CDF frameworks are explored for dryland dynamics, ecosystem services, and food security (FS), and current high-precision ecosystem observation networks are used to detect regional-level climate variability and identify hotspots. In addition, this review also examines challenges and uncertainties for CDF systems and effective agrarian innovations as a way forward. To bridge the gap from science to policy making in the CDF nexus, it is vital to enhance the impacts and feedbacks of ecohydrological processes on agrarian production, ecosystem service tradeoffs and their effects on livelihoods, and regional development and preservation by optimization of the ecological water security pattern. This state-of-the-art assessment uses acquired information and knowledge to conceptually evaluate the past, current, and future impacts and risks and facilitates decision making through the delivery of long-term sustainability and socio-ecological resilience.

KEYWORDS

Africa, aridity index, CDF nexus, drylands, observation networks, sustainability

1 Introduction

Climate change is one of the world's most pressing real threats to the drylands, which may jeopardize food security (FS), that is, physical, social, and economic access to sufficient, safe, and nutritious food by people for an active and healthy life (Samuel et al., 2019) and other sectors of our civilization (Tachiiri et al., 2021; Ukhurebor et al., 2021). Drylands are areas where precipitation is balanced by evaporation from surfaces and evapotranspiration (Middleton and Thomas, 1997). They are generally characterized by sparse vegetation, water scarcity, and unpredictability (Berg and McColl, 2021). The distinct biophysical features of drylands make them highly susceptible (Robertson et al., 2018) and complex to unanimous climate change drivers (Berdugo et al., 2020). Upsurging temperatures, changes in precipitation and rainfall patterns, land use, nutrient availability, atmospheric CO_2 (Classen et al., 2015; Copeland et al., 2017; Schlaepfer et al., 2017; Leisner, 2020), and other greenhouse gases emissions (GHGs) are key driving factors of unprecedented dryland expansion (Maestre et al., 2012; Li et al., 2019; Lian et al., 2021). Drylands are associated with substantial land degradation and extremely vulnerable to severe environmental shocks and socioeconomic crises (Fraser et al., 2011; UNU-WIDER, 2017). Due to anthropogenic change and non-climatic stressors, in tandem with other stimuli, the mean global temperature has increased by ~1.0°C and is expected to further increase over the next century (IPCC, 2018). As a result, many dryland habitats are faced with severe threats that lead to reduced carbon sequestration and high water scarcity (UNEP, 2007; UNEP-WCMC, 2011; Bradford et al., 2020). Moreover, by the late 21st century, it is projected that ~78% of dryland expansion will befall under the representative concentration pathways (RCPs) 8.5 scenario in developing countries (Huang J et al., 2016; Huang et al., 2017). The impaired climate–drylands connection could impact FS in all four dimensions: availability, access, utilization, and food system stability, negatively influencing the efforts toward sustainability and ecosystem resilience in Africa (Connolly-Boutin and Smit, 2016; Niles and Brown, 2017; Mbow et al., 2019). Multi-disciplinary investigations are in need to identify effective techniques and practices, including coupled earth-anthropogenic processes in conjunction with careful management and adaptation measures of potential ecological risks, to enable mitigating the repercussions.

Meanwhile, the two dimensions of the nexus approach are interdisciplinary and transdisciplinary (Pahl-Wostl, 2019). By highlighting the trade-offs and synergies between the components, the primary dimension assesses the complexity of linkages among climate, dryland, and food systems. The second dimension strengthens driving forces such as population growth, socio-economic progress, and climate change, as well as innovation, technology, and policies (Endo et al., 2020). Nonetheless, a three-node nexus of climate change–dryland variation-FS leads to complexity. It also apprehends a "wide portrayal" and facilitates bringing in the socio-economic and ecological dimensions. This approach is considered a flexible and open option (Bleischwitz and Miedzinski, 2018). Tools and methodologies are varied and context-specific, but the linkages from climate change to social and environmental impacts are difficult to model, given the unpredictable anthropogenic activities affecting the outcomes (Devereux and Edwards, 2004). Conversely, new techniques are compelled to understand the complexities that lead to abrupt non-linear/correlation between Earth's systems (Randall et al., 2007; Stephens et al., 2020) and thresholds due to bulky and/or irretrievable effects (Devereux and Edwards, 2004). In addition to their implicitly multi-scale structure, linkage processes are difficult to simulate and/or emulate because they are rarely at the required spatial and temporal scale to establish specific reference as to the underlying changing aspects. To fully comprehend the CDF linkages, key factors (e.g., population growth, agricultural transformations and industrial development, technology and innovations, livelihood shifts, and governance and policy implementation) that drive those nexus complexities must be assessed and described for the entire system through the lens of climate change.

Correspondingly, a wide range of multi-spatiotemporal scale integrated frameworks focused on dryland changes, climate–land–energy–water (CLEW) nexus (Vinca et al., 2021), water–energy–food (WEF) nexus (Kogan et al., 2017; He et al., 2019; Kogan, 2019), water–energy–food–environment nexus (WEFE) (Malagó et al., 2021; Mirzaei et al., 2021), water–energy–food–biodiversity–health (WEFBH) nexus (Hirwa et al., 2021), and others have been set up. However, they are not sufficient anymore (Fernández-Ríos et al., 2021). Instead, current advances in climate change, dryland ecosystem management, and FS are hindered by the limitations of inadequate data on dryland environments and the methodologies commonly used for scientific data analysis, some of which are ill-equipped for capturing complex relationships present in the huge volumes of available data. Coupling large-scale field spatial observations with model simulations is now considered the most viable opportunity and accurate technique to identify dryland ecosystem shifts and evaluate dryland ecosystem stability. But, resistance and recovery after extreme events such as droughts, as a high priority needs urgent attention (Ruppert et al., 2015; Burrell et al., 2017; Wei et al., 2022). Development of using geospatial tools by multiscale frameworks continues to present key fundamental gaps (Fritz et al., 2019). In addition, various methods have been used to assess the influence of extreme events on dryland degradation (Wang et al., 2012; Dubovyk, 2017; He et al., 2019). Global FS requires transdisciplinary responses and interventions at different types of scale (Drimie and McLachlan, 2013), that is, globally (Schmidhuber and Tubiello, 2007; Yadav and Congalton, 2018), regionally (Ingram, 2011), and locally (Moore et al., 2012). With global climate change, dryland variation, and FS, there is the additional challenge of uncertainties, which is unlikely to decrease in the next coming decades (Campbell et al., 2016). There are gaps between research and technology transfer, research and implementation, research and practice, and science and policy. It is, therefore, urgent to seek alternative resources, efforts, and procedures that combine local with emerging scientific knowledge through more effective dissemination of information and technology, appropriate participatory learning, and partnerships.

Few current research on climate change, dryland variation, and FS in Africa have been published (Wheeler and von Braun, 2013; Cervigni and Morris, 2016; Guilpart et al., 2017; Li and Zhang, 2017; Leakey, 2018; Schouten et al., 2018; Nyberg et al., 2019; Chimwamurombe and Mataranyika, 2021). Consequently, developed and developing nations started focusing on new tools and strategies for boosting agricultural production to meet future challenges, and improving or advancing techniques that would help deal with food (in) security and monitor the expansion of drylands (Peng et al., 2021). The apparent potential for developing more holistic and cost-effective tactics, including using existing strategies and procedures as foundations, through developing novel methods that integrate RS and local participation, necessitates a suitable synopsis of dryland dynamics and FS on distinctive spatiotemporal scales.

In a nutshell, this succinct review aims to address both the vexing and progressive threats between climate change, dryland dynamics, and FS through the lens of novel systems approach, advances, challenges, and future opportunities. The CDF nexus provides a strong foundation for scientists, environmental decision-makers, and activists and actors who are interested in achieving all targets of the 17 sustainable development goals (SDGs), particularly SDG 13 (climate action), SDG 15 (use of ecosystem services), SDG 2 (zero hunger), and the Paris Climate Agreement, thereby devising effective policy for action and planetary well-being. This study also proposes a conceptual framework clarifying the interlinkages between influencing systems (i.e., drylands, climate, ecosystems, socio-ecological, and food systems) that consistently unravel and build greater resilience to the confounding vulnerabilities, shocks, and stresses within the food networks.

This study employs various research publications, books, reports, and case studies collected from official websites. Hence, we organize our review into four major aspects and then discuss them using past and current literature. These aspects are: 1) the CDF nexus, including dryland distribution and their associated impacts factors, the relationship between compounded climate, dryland, and FS; 2) technique advances in drylands monitoring methods, including regional observation networks and innovative technologies; 3) challenges and uncertainties for climate change, dryland dynamics, and FS measurements; and 4) future directions and research opportunities to improve dryland ecosystems management and cope with ongoing risks related to FS under climate change conditions.

2 Methodology

2.1 Study area

Africa's inhabited dryland areas (mainly arid, semi-arid, and subhumid zones) cover 11% of Earth's surface, 27% of the planet's drylands, and 40% of the continent's surface (Figure 1) (Wei et al., 2021). In these regions, the majority of the population (~85%) relies on subsistence rainfed agriculture and pastoralism (Kogo et al., 2021). The main staple subsistence crops are wheat, rice, maize, sorghum, and millet (Tsusaka and Otsuka, 2013). Increase of multiple climatic extreme events, including rainfall variability (Bradford et al., 2020), high temperatures (Webb et al., 2017), erratic droughts (Adhikari et al., 2015), and changing agro-ecological conditions (Schmidhuber and Tubiello, 2007; Scheelbeek et al., 2018) has significantly affected dryland agriculture with high uncertainties since the 1980s (Defrance et al., 2020). Ultimately, model simulations and other evidence clearly show that continued global warming will make the earth's drylands drier over time (Overpeck and Udall, 2010; Huang et al., 2012; Feng and Fu, 2013; Koutroulis, 2019). Climate models predict high evapotranspiration and lower soil moisture levels in arid and semi-arid regions of Africa (McCarthy et al., 2001; Bathiany et al., 2018), suggesting some tropical grasslands could become drier and unsuitable for farming (Schmidhuber and Tubiello, 2007).

2.2 Methods

VOSviewer, a software tool for constructing and visualizing bibliometric networks (Perianes-Rodriguez et al., 2016), was used to conduct the similarity analysis of high frequency terms in the titles and abstracts of the articles and to generate a keyword tagging map. Studies published from 1980 to 2022 were analyzed. The keywords were mainly categorized into four subjects: "climate change," "drylands," "food security," and "Africa". Databases used for extraction of studies, reports, and published articles included Web of Science™ (WoS) Core Collection database, Scopus, and ScienceDirect. In addition, reports on the impacts of climate change on either drylands or food security in Africa were also extracted from official websites of international organizations such as the Intergovernmental Panel on Climate Change (IPCC), Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), United Nations Framework Convention on Climate Change (UNFCCC), and the Food and Agriculture Organization (FAO). Moreover, 2,820 studies were

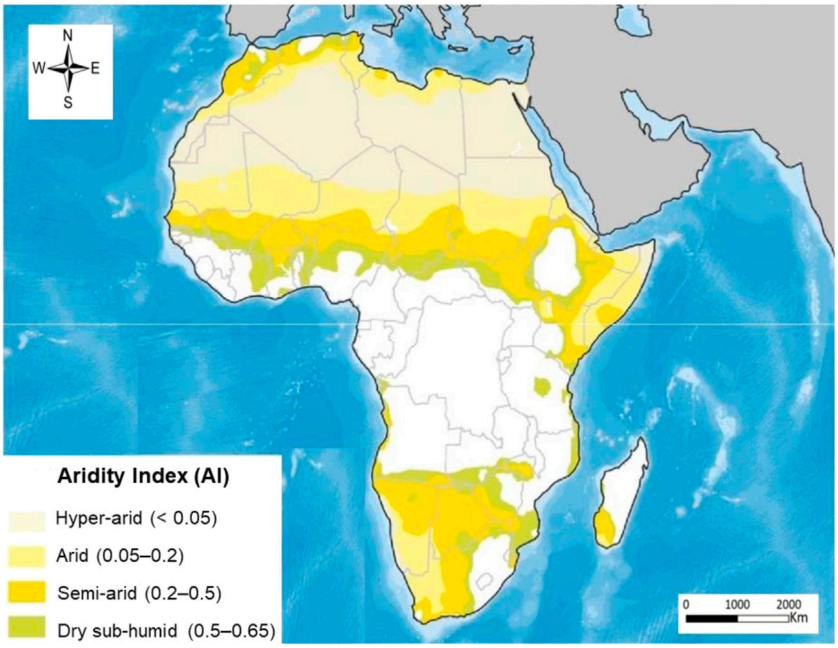

FIGURE 1
Distribution of Africa's drylands based on aridity index (AI). The AI was calculated using the annual precipitation (P) and potential evapotranspiration (PET) based on the 1970–2000 mean global-AI and global_ET0 datasets (Trabucco and Zomer, 2018). The hyper-arid zones are not considered in this study.

initially extracted. Referring to their abstracts, 152 studies were considered pertinent to this study. Out of the 152 publications, 88 studies were used to provide a summary of the nexus between the impacts of climate change on dryland variation, and food (in) security in Africa. In the context of interconnections, climate change, dryland ecosystem shifts, and food security in Africa are studied because there is a strong connection between the three systems to form a nexus. The analysis reveals that the dryland variation is mostly influenced by climate change, which results in food insecurity in Africa (Figure 2). As shown in Figure 2, it is clear that more prior research has been focused on climate change, household, and household food security.

3 Overview on impacts of climate change on drylands and food security in Africa

3.1 Climatic changes in arid and semi-arid environments

Progressive shifts in climatic or weather variability influence both dryland biophysical and socioeconomic reciprocities (Berg et al., 2016; Greve et al., 2019; Overpeck and Udall, 2020). The main drivers of dryland variation include climatic factors (i.e., high temperature, changing rainfall patterns, and infertile soils) and anthromes (e.g., agriculture, urbanization, livestock grazing, and wildfires). The interconnected natural processes of degradation are water and wind erosion, salinization, and organic matter (OM) loss, which furtherance results in a decrease in soil health, agrarian productivity, and the ability to reduce carbon (C) emissions into the atmosphere (Reynolds et al., 2007). Over-exploitation and land degradation of ~4 × 10^9 ha (~73% of the total area of rangelands) resulted in soil loss of ~216 × 10^6 ha (~47% of SSA's drylands), degradation of 43 × 10^6 of irrigated croplands (~30% of total SSA's drylands) (UNEP, 2021). Nevertheless, dryland ecosystems and their biodiversity are strongly shaped by interdependent components such as topography, geology, rainfall, herbivores, fires, and human management (Davies et al., 2012). For instance, in Southern Africa, dry forests particularly, the Miombo woodland have the capability of storing ~100 tons of carbon/hectare. In addition, the coupled human biomes development leads to land degradation and a net loss of carbon storage, deteriorating the impacts of climate change (Stringer et al., 2012).

3.1.1 Increase in temperatures

Global warming trend has indeed been detected over drylands since the 1980s, with further warming predicted in the near future (Huang et al., 2016). Africa's drylands are known for their high temperatures (Put et al., 2004; Zhang et al., 2021). Climate change-induced temperature rises are likely to aggravate

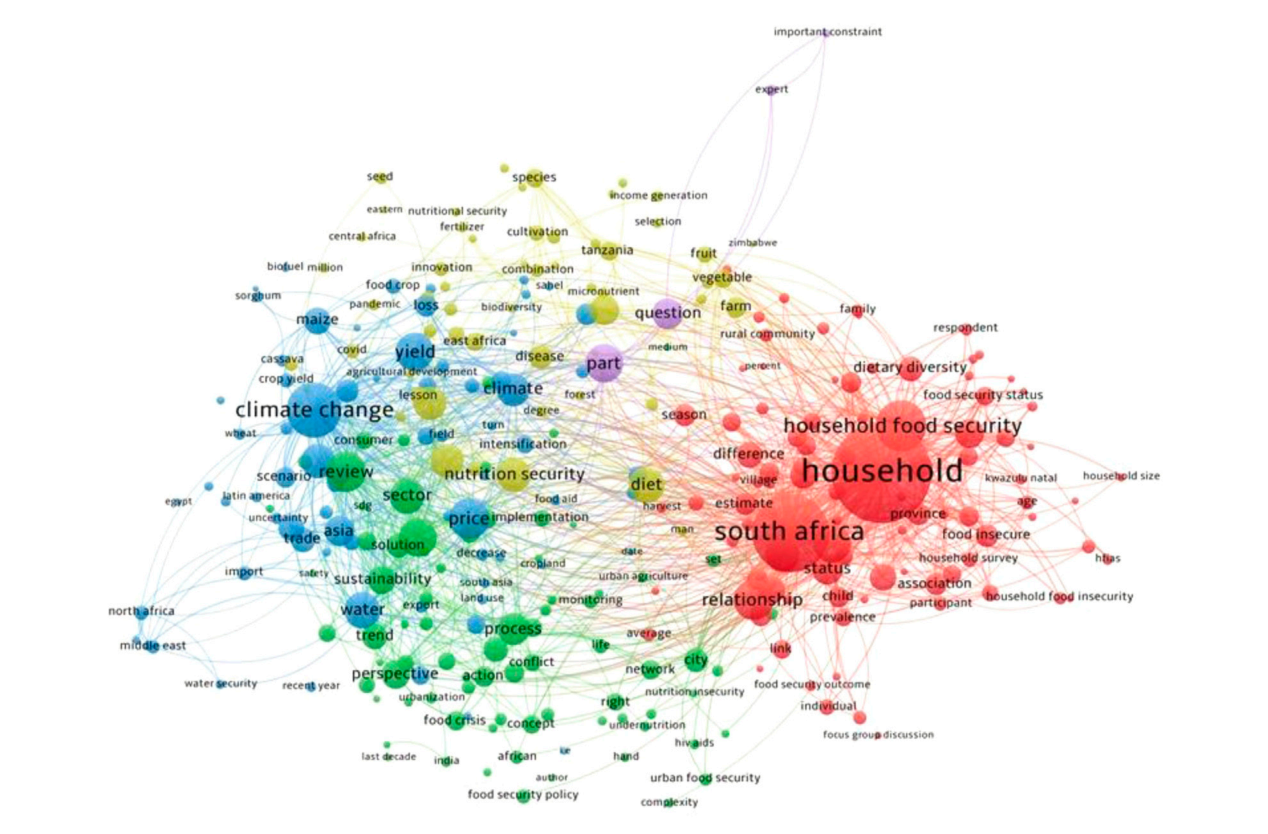

FIGURE 2
Diagram of clusters of topic terms for climate change, dryland variation, and food security nexus. The larger the node, the more frequently keywords appear in research. Lines stand for the co-citation relationship. Different colors denote research topics.

existing vulnerabilities of natural semiarid systems like droughts, water scarcity, and floods (Koohafkan and Stewart, 2008). The extreme variation in rainfall and the overall water shortage constrain nutrient accumulation in dryland ecosystems, impeding biogeochemical nutrient cycling (Laban et al., 2018). The study by Daramola and Xu (2021) reported that temperature generally increased across all dryland areas, with the warmest years identified between 2015 and 2017 except for the hyper-arid zones where the highest temperature increase occurred in 2010. 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 (Scholes et al., 2015).

3.1.2 Decrease in rainfall patterns and poor nutrient soils

Prior research showed that precipitation generally decreased over the drylands and 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 subsequent years (Wei et al., 2020). Dryland soils are defined as having low organic matter (limiting microbial processing of nutrients for plants), weak structure and high salt content, and limited moisture retention capabilities (Safriel, 2017; Plaza et al., 2018). These, however, are enhanced by extreme variations in rainfall and overall water deficiency (Hartley et al., 2007).

3.1.3 Wildfires

Wildfires are an extreme threat to dryland environments (e.g., grasslands, savannas, or dry forests) and the threat is increasing due to increased ignition potentials by humans, the spread of fire-prone invasive grasses, and shrubs, surface temperature, and dry conditions. The dramatic increase in wildfire prevalence in recent decades poses serious threats to human safety, infrastructure, agricultural production, cultural resources, native ecosystems, and watershed functioning. It is especially prevalent in Africa, with up to 9% of the continent burnt on an annual basis (Andela et al., 2013), which contributes to 70% of the global burned area (Andela and van der Werf, 2014). More extensive dry season fires lead to wet season rainfall deficits of up to 30 mm (Saha et al., 2016). Subsequently, the occurrence and impacts of wildfires must be reduced through prevention, preparedness, and pre-fire management. The post-fire response such as erosion control and replanting in burned areas also helps reduce the immediate impacts of wildfire and establish non-native grasses, reducing the risk of future fires.

Variations in surface temperatures change the water dynamics in the soil, impacting crop yields directly. The warming trend will also lead to soil surface temperature increase, resulting in a decrease in rainfall patterns and soil nutrients. Although wildfire occurrence and extent have been linked to rainfall and temperature on regional scales, the atmospheric mechanisms that drive regional patterns of rainfall and temperature need to be further investigated.

3.2 Climate change and food security

3.2.1 Food availability

Availability refers to the physicality of food. Different foods can be produced in different ways. Agriculture in the drylands is dominated by small-scale and resource-poor farming, which is characterized by declining crop yields and livestock productivity and suffers from limited investments in agricultural technologies and inputs (Mortimore et al., 2009). Heat and drought stress, as well as increased insects (Salih et al., 2020), plant diseases (Graziosi et al., 2020), and flood damage (Atanga and Tankpa, 2021), thus have significant consequences for regional, national, and household food security and livelihoods (Blunden and Arndt, 2020). Under RCP 8.5, reductions of 13, 11, and 8% in mean cereal yields are projected in West and Central Africa, Northern Africa, and Southeastern Africa, respectively, based on the yield indicator of crop production per area of harvested land (WMO, 2020; Stuch et al., 2021). In addition, climate impacts the production of roots and tuber crops in different ways, such as changes in sowing time, pest and disease infestation of crops, and low crop yields (Owusu et al., 2020). 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). Livestock has both positive and negative effects on dryland resources. Nevertheless, about 25×10^6 pastoralists and 24×10^7 agro-pastoralists rely on livestock as their main source of income. In sub-Saharan Africa (SSA), 35% is permanent pasture (Kiage, 2013).

According to the study by Fischer et al. (2002), land suitable for double cropping would be reduced by 2×10^7 ha whereas for triple cropping would decrease from 5×10^6 to 1×10^7 ha (Grote et al., 2021) in SSA. From 2000 to 2050 in SSA, due to combined high temperatures and rainfall shortages, maize, millet, and wheat production is expected to decline by 5, 10, and 15%, respectively (Shiferaw et al., 2013). In Tanzania in eastern Africa, the maize yields will shrink by about 33% for the overall country. For the central regions, there will be an 84% decrease. Moreover, a decline in mean maize yields is projected for over 85% and 25% of harvested maize areas in Southern Africa and West Africa, respectively (Stuch et al., 2021). In many instances, crop production is not only affected by climate change and abiotic stresses, such as warmth and water scarcity (Cairns and Prasanna, 2018; Deutsch et al., 2018), but also biotic factors such as novel viral pests, insects, and diseases [e.g., Case of deserts locusts in Eastern Africa drylands (Kassegn and Endris, 2021)]. Finally, all these fluctuations continue to adversely affect food supplies, food prices, and malnutrition-related diseases (Levy et al., 2016). In light of these results, it is clear that there is much uncertainty regarding future forecasts of food production under climate change. Therefore, the implications for agro-socio-ecological linkages are important to accurately predict system dynamics from climate change.

3.2.2 Food accessibility

Generally, accessibility refers to the ease of acquiring foods in a form and location that enable their consumption. Weather-related shocks might undermine food security through various levels of change and food price volatility (Porter et al., 2014). Local food supply in many nations is mostly reliant on global food exchanges (or trade) and adverse climatic conditions such as floods, cyclones, and hailstorms alter agricultural commodities and transportation infrastructures at national to regional scales, thus influencing food supply at variable levels. However, changing climate affects food production, farmers' income, access to food, supply, and safety (Affoh et al., 2022). COVID-19 has had a vexing effect on food security and marginalized dryland communities across Africa, which serves as an external driver of FS (Ukhurebor et al., 2021). Food, livestock traders, and consumers have experienced restrictions on cross-border mobility and relations leading to a surge of spoiled goods due to prolonged transit times. For instance, in Eastern African countries, truckers regularly line up for miles when crossing the borders of neighboring countries. In addition, the effects of political instability in the Democratic Republic of Congo, Ethiopia, and South Sudan have caused the people to flee across the borders (O'Grady, 2021). From 2019 to 2020, the acute food insecurity induced by population change has increased to 1,033, 883, 600, 333, and 250% in Mali, Chad, Burundi, Sierra Leone, and Cameroon, respectively (WFP&FAO, 2020).

Climatic instability in SSA, however, could destabilize local markets, curb economic growth, and heighten the risk for agricultural investors in the north and south arid regions, which will lead to increased childhood hunger by rising food prices. It is projected that the price of maize will increase by 104% between 2005 and 2050 (Rosegrant et al., 2014), although the systematic analysis of the relationship between weather shocks and domestic food prices is rather limited (Mirzabaev and Tsegai, 2012). Advances in well-being may result from a more equitable allocation of benefits among many stakeholders and beneficiaries. Furthermore, a policy environment that fosters construction of better storage, and freer trade and promotes investments in transportation and irrigation infrastructure can help deal with these problems early on.

3.2.3 Food utilization

Food utilization is closely linked with the general health environment, water, and sanitation (Vilakazi et al., 2019), which is indirectly impaired by climate change (Wheeler and von Braun, 2013). Climate change could have a direct effect on micronutrient consumption in three forms: by lowering important micronutrient source crop yields, altering the nutritional balance of a particular crop, or influencing crop selection decisions (Felix and Romuald, 2012). Due to uneven actual food distribution across Africa and diverse populations and households, food utilization is understudied (Myers et al., 2017). In response to food price shocks, urban and rural households adjust their consumption patterns in a number of ways such as decreasing caloric intake, decreasing the number of meals per day, decreasing food diversity, or substituting with less preferred foods (Matz et al., 2015; Kubik and May, 2018). Across most dryland areas in Africa, many poor people still face difficulties in obtaining adequate calorie intake and/or diverse quality diets. The proliferation of small-scale agro-processing industries and modern storage techniques in both rural and urban areas can increase food security by diversifying agrarian products and enhancing nutritional standards as well as creating the employment (Adeyeye, 2017). The “atta” for cowpea in Benin is a typical example (Kpossilande et al., 2020). Moreover, processed food can be purchased in various forms for each and every category of household (Reardon et al., 2021). Importantly, several studies revealed that agricultural policies have contributed in many SSA countries to increased food production, which helps the population to acquire more nutritious diets and improve livelihoods (Pernechele et al., 2018).

3.2.4 Food stability

Food stability is established when food supply and people’s ability to access and consume food remain stable and consistent over time (Bonuedi et al., 2020). The major causes of food instability include recurrent droughts, geopolitical instability, conflicts, lack of investments in agriculture, unstable markets, and poverty (WFP, 2019). More importantly, even temporary disruptions of food access resulting from food inflation can entail long-term, often irreversible nutritional damage, especially amongst infants and young children during the period of critical growth and development (Arndt et al., 2016). Because of the short-term supply fluctuations, the stability of complete food systems may be jeopardized as a result of climate change (Grote et al., 2021). Furthermore, abiotic (e.g., weather) and biotic (e.g., pests) shocks can compromise cereal stability. As staple crops like wheat and maize are planted in large areas, losses from pests, diseases, and climate change may be catastrophic (Conceição et al., 2016).

3.3 Feedbacks between climate–drylands–food security interactions and drivers

Dryland FS is driven by several factors. Changing climate is just one of many interconnected trends and drivers that shape dryland agricultural systems, including FS and nutrition (Brown et al., 2018). The dryland socio-ecological system comprises a food system, which is, furthermore, a complex adaptive system (Pereira, 2013; Allen and Prosperi, 2016). The most noteworthy technical advances and socio-economic factors that drive changes in food systems include technological and structural changes in the food system, food production, processing, distribution, and markets, population growth, wealth shifts, changing demographics, globalization, catastrophe management, and energy production, availability and use (Ingram, 2011; Pingali, 2012). Likewise, a sustainable food system is critical to the households’ survival and community resilience in Africa (Smit, 2016).

Bringing various fundamentals together, the integrated conceptual framework, illustrated in Figure 3, shows how climate, dryland, and food system give rise to a set of socioeconomic, ecosystem, food, livelihoods, and policy systems. The ecosystem services are stratified according to the livelihood outcome and other factors and the climate, in turn, shape-specific elements of dryland expansion and FS. Food system development must be evaluated not only in terms of economic efficiency and capacity to enhance FS but also in terms of their environmental impacts throughout the food chain. The climate change implications on drylands, ecosystem, food, and the socio-economic systems could gain from facets of all FS and improved livelihoods, thus providing a certain comprehensive understanding of the whole system as vividly illustrated in Figure 3.

4 Technical advances in climate change, dryland ecosystem monitoring, and food security

4.1 Progresses of dryland agroecosystem dynamics detection techniques

Over the past four decades, methods to detect and quantify the relative dryland expansion and land degradation have been developed (Wang et al., 2012; AghaKouchak et al., 2015). The RS techniques and spatial modeling are commonly used tools for quantifying spatio-temporal trends of LU/LC change in drylands (Ohana-Levi et al., 2019). Over the last four decades, the advent

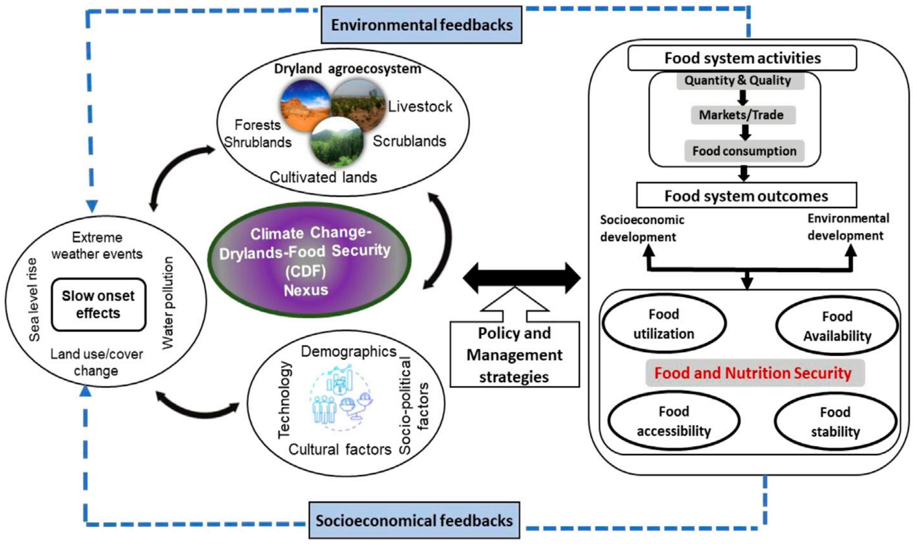

FIGURE 3
Interrelationship among the dryland agroecosystem, climate system, socio-economic system, and food system. Here, we present the CDF nexus (epicenter) from the viewpoint of environmental and socioeconomic feedback (above and below) and food system outcomes (right side). In particular, the anthropogenic activities, natural processes, and socioeconomic operations together drive dryland agroecosystem changes in African drylands. All these combined factors, however, positively/negatively impact the stability and income level, *via* effects on productivity, production costs, and market prices resulting in food insecurity and malnutrition.

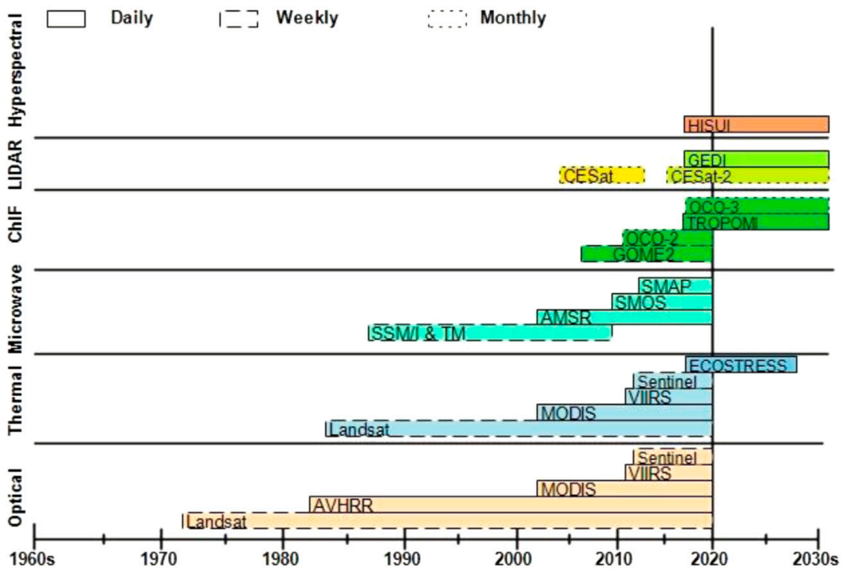

FIGURE 4
Advances in satellite imagery and multi-spectral RS of dryland vegetation dynamics. Historical milestones are provided from the 1960s to the 2030s. Timelines of LiDAR, chlorophyll fluorescence (ChIF), thermal infrared (TIR), microwave, optical, and hyperspectral earth observation satellites are shown. The progression of satellite capabilities from optical to hyperspectral indicates both the rising spatial and temporal resolution of sensor information as well as the extension of RS techniques in drylands. Modified and adapted from (Kuenzer et al., 2014; Smith et al., 2019). The color differentiates the type of satellite and its capability. The solid, semi-solid, and dash-dash lines represent daily, weekly, and monthly scales, respectively, as the data acquisition time.

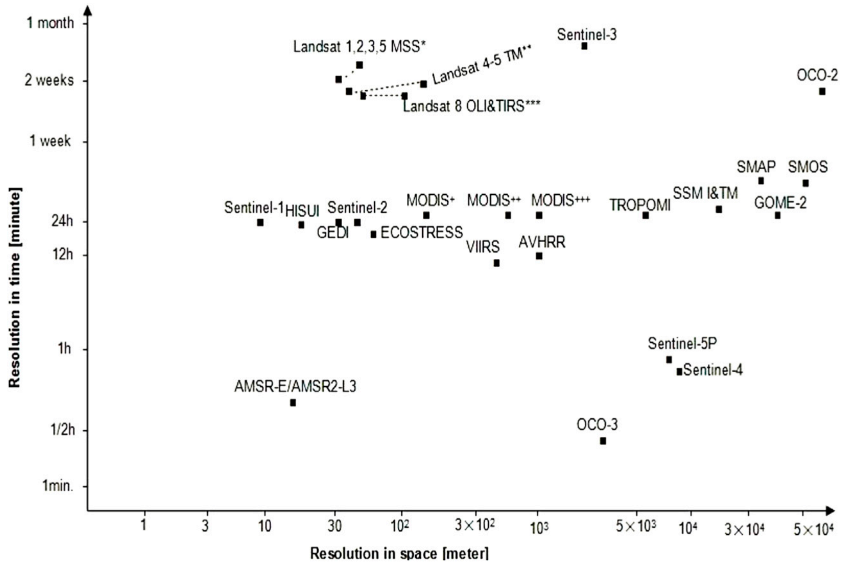

FIGURE 5
Comparison of RS satellites. The multispectral scanner (MSS)* its original pixel size was 79 m × 57 m, where the production systems now resampled the data to 60 m. The thematic mapper (TM)** band 6 was acquired at 120 m resolution, but products are resampled to 30 m pixels. Therefore, the Landsat 8 operational land imager (OLI) and thermal infrared sensor (TIRS)***, the TIRS bands are acquired at 100 m resolution but are resampled to 30 m in the delivered data product. The spectral band placement for each sensor is visually displayed. The MODIS consists of several bands, including bands 1–2^{+}, bands 3–7^{++}, and bands 8–36^{+++}.

of earth observations (EOs) has been highly relevant for enhancing data availability in drylands globally (Figure 4). Cost-effective atmospheric conditions in drylands complimented the extra huge need by providing the improved probability of high-quality data due to decreasing cloud cover for optical RS (Smith et al., 2019). Henceforward, several RS integrated tools have been introduced in drylands, including sensors such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Compact High-Resolution Imaging Spectrometer (CHRIS), Landsat thematic mapper (TM), Landsat multispectral scanner (MSS), Landsat operational land imager (OLI), and thermal infrared sensor (TIRS) with different multi-spectral satellite products such as atmospheric profiles product (MOD), Moderate Resolution Imaging Spectroradiometer (MODIS), modified atmospheric profiles from reanalysis information (MAPRI), and Atmospheric Correction Parameter Calculator (ACPC) (Kowalik et al., 1982; Jiménez-Muñoz et al., 2010; Fritz et al., 2019). Quantitative estimates of Vegetation Health and biomass dynamics based on the Visible Infrared Imaging Radiometer Suite (VIIRS) of Landsat MSS offer a dimensionless measure of greenness with normalized difference vegetation index (NDVI) (Rouse et al., 1974; Tian et al., 2016). Multi-source and multi-scale data sets, and fusion algorithms that intelligently integrate *in situ* data, remote sensing observations, and modeling results, are required to capture the complex spatial and temporal land and vegetation dynamics processes.

Dryland RS satellites are defined in terms of spatial and temporal resolution (Figure 5). Apart from the Advanced Very High-Resolution Radiometer (AVHRR) and Landsat, no sensor line allows for three to four decades of long-term monitoring of thermal patterns. While AVHRR provides two thermal observations per day on average, Landsat also has a 16-day repeat cycle. Thus, cloud-free data may only be accessible a few times annually, especially in overcast latitudes (Kuenzer et al., 2014). Several studies employed the AVHRR NDVI time series to assess the long-term patterns in regional vegetation heterogeneity and drivers in African drylands (Anyamba and Tucker, 2005; Donohue et al., 2009; Fensholt and Rasmussen, 2011).

4.2 Observational networks as essential to Africa dryland ecosystem management

Long-term ecological research (LTER) is a method of assessing biophysical interactions with human activities and how they affect the ecological integrity, particularly environmental processes and humanity's carrying capacity (Vanderbilt and Gaiser, 2017). These networks deal with climate and anthropological impacts on grassland, forests, freshwater, deserts, coasts, and other ecosystems that span a wide topographical range (Yevide et al., 2015). Some ecosystem research networks (ERNs) have been established in Africa (Table 1). These monitoring initiatives are intended to

TABLE 1 Examples of African Ecosystem Research Networks (AERNs) dealing with climate change, dryland monitoring, and FS.

Station name	Time	Key technologies	References
Sahara and Sahel Observatory (ROSELT/OSS)	1992	25 clusters of observatories, geoportals, and instruments for monitoring environmental parameters. Open source and technologies (e.g., FOSS and OGC). Acquisition of low-resolution satellite images using NOAA/AVHRR and Spot 4–5/VEGETATION.	Ajmi et al. (2014)
Biodiversity Monitoring Transect Analysis in Africa (BIOTA-AFRICA)	2000	Automatic weather stations, temperature loggers, and research hut infrastructures	Jürgens et al. (2012)
South African Environmental Observation Network (SAEON)	2002	Arid lands node manages several sites using automatic weather stations, temperature loggers, and research hut infrastructures. Metadata models were developed with terrestrial sites	SAEON/NRF (2018)
Tropical Ecology Assessment and Monitoring Network (TEAM)	2002	17 sites. Data are collected using paper field forms, transcribed into digital form, or using a mobile EcoPDA device. Data acquisition data tools using automatic camera trap arrays, processed and curated data *via* technology partners San Diego Super Computer Center and the Hewlett Packard Enterprise at the University of California, San Diego	Rovero and Ahumada (2017), Team network (2011)
Global Observation Research Initiatives in Alpine environment (GLORIA)	2011	Field manual, field forms, online data input tool (e.g., Central GLORIA Database), photo documentation and management tool (PDM), and temperature data loggers	Yevide et al. (2015)

develop response strategies for any potential consequences such as biodiversity loss, land degradation, desertification, and extreme events (Li et al., 2015). Ecosystem monitoring *via* international LTER (ILTER) emerges in countries and is now applied all over the world (Yevide et al., 2016). Currently, the ILTER covers about 44 nations and 700 experimental stations, integrating observation of ecological aspects to serve the needs worldwide (Mirtl et al., 2018). Therefore, the advancement of dryland-specific models and novel assessment technologies for drylands cannot act without substantial and specialized observational networks (Smith et al., 2019). These networks currently exist in some regions, for example, HiWATER, OZFlux, and Semiarid ECohydrology Array (SECA). Africa is, however, one of the continents that owns continental and regional-scale monitoring networks, including the South African environmental observation network (SAEON) (Gray and Kalpers, 2005; Jürgens et al., 2012). Rapidly advancing technology will continue to impact LTER's tasks. The monitoring sites generally continue to be sparse, scattered, and biased toward dryland ecosystems. Development of ecotechnologies is needed. A need for scientifically-based peer-reviewed research using "bottom-up" rather than "top-down" help answer pressing.

In 1992, the Global Climate Observing System (GCOS) was created. All stakeholders that require climate information, from research to forecasting and impacts to mitigation and adaptation, are ensured to have access to adequate information and trends in the climate system. (Verstraete et al., 2009). Various technologies have also been developed to help address concerns about dryland expansion, climate variability, FS, and other environmental assessments (Smith et al., 2019). However, long-term ecological research infrastructures are often fragmented, unevenly distributed in space, and restricted to particular scientific objectives (Hass et al., 2018). Multiple global ecosystem research networks that help enhance investigations related to climate change, environment, and FS necessitate funds in research and development, human capital, knowledge flows, and infrastructure.

5 Challenges and uncertainties for climate change, dryland dynamics, and food security

Climate models (CMs) are weather forecasting extensions. Moreover, these models provide information on hydro-biogeochemical cycles (Foley, 2010; Wang et al., 2015). Scientists utilize the CMs to draw past, current, and future conclusions about complex earth systems (Huang et al., 2017). The most intricate and reliable models for understanding climate systems and forecasting climate change are General circulation models (GCMs) and regional climate models (RCMs), which may need bias corrections and model output statistics (MOS) (Eden and Widmann, 2014). For instance, Keenan et al. (2016) testified that during the last decades, in the warming break of drylands, a current hiatus of crop growth rate was linked to a rise of atmospheric CO_2 in the terrestrial sink, which was attributed to the effects of atmospheric CO_2 on vegetation (Ballantyne et al., 2017). Consequently, because global carbon cycle dynamics are not included in some CMIP5 models, CMIP5 cannot duplicate this trend without significant uncertainty (Huang et al., 2017). Even for state-of-the-art models of global carbon cycling, the carbon concentration still has a lot of uncertainty. The case of the West African monsoon is an example (Klein et al., 2017). Nonetheless, various models are built based on the same modeling institutions. Thus, the ensemble of CMs is not weighted. There are great uncertainties remaining in evaluations of the global trends in dryness and wetness under climate change conditions (Trenberth et al., 2014). To handle the uncertainties in aridity projections and the aridity index (AI) calculation against the hydro-ecological variables, there is a need to consider regions where the overwhelming of models agree in sign (Greve et al., 2019). Moreover, the use of time series precipitation and evapotranspiration datasets from meteorological stations could be helpful to reduce uncertainties in AI projections and regional dryland climate modeling (Tarek et al., 2021).

Dryland climate system uncertainty over human action possesses two main sources, including uncertainty due to unknown future emission concentrations of greenhouse gases and aerosols, and uncertainty of the climate system's response to our actions (Trenberth and Trenberth, 1992; Smith et al., 2009). This information, combined with climate models, allows decision makers at all levels of governance to determine how both natural and manmade influences have and will impact changes in our climate.

6 Future directions and research needs

In the past four decades, drastic population development has been observed in drylands (Smit, 2016; Ellis et al., 2021). Subsequently, modern dryland farming and intensive land use are necessary. Sustainable agriculture comprises multiple components, including the introduction of climate-adapted cultivars and sustainable environmental protection that integrates provision and preservation of ecosystem services by enhancing durable intensification programs based on conservation agriculture and community-based adaptation and mitigation with operational support services (e.g., biodiversity, food production, and reduction of GHG emissions) (Mbow et al., 2014; Sanz et al., 2017). Therefore, planning of the so-called food–energy–water–biodiversity–human health (WEFBH) nexus has revealed practicality in evaluating strategic policy to achieve the SDGs prior to the rising demands, dryland resource scarcity, and climate variability (Albrecht et al., 2018; Hirwa et al., 2021).

Remote sensing data have been utilized to provide information in data-scarce areas to address climate variability and FS induced by shifts in foundational dynamic ecosystems. The extension of dryland-specific modern observation models, networks, and evaluations of new RS technologies is a key to successful dryland ecosystem management. These technologies exist in some areas across Africa (e.g., AngoSat-2, NileSat-301, and NARSSCube-2) (Woldai, 2020). Owing to advances in model development from the late 1990s until now, modeling efforts have inspired more current observational investigations. In this instance, measurements are frequently provided apropos of regression models, and multidecadal aerial images are used to identify vegetation changes, for example, in the case of Niger over a forty-year interval. Nonetheless, some models (e.g., Brusselator model) can be overly mechanistic in their representation of many processes at hand, resulting in a high dimensionality that must be calculated from data. As a result, this modeling approach is frequently linked to observation and involves comparisons to field-based assessments (Figure 6). Ultimately, we recommend close collaboration between geo-information data-driven modeling approaches and terrestrial ecosystem modelers to more swiftly categorize model structural deficiencies and hence intrinsically empower more precise dryland ecosystem functioning model projections with the social and ecological system.

Commonly known technologies are categorized into two main types of hardware and software resources, including open-source and affordable tools and scanners, sensors, and platform networks. Therefore, an increasingly growing pool of comparatively low-cost innovations is spurring the transition from catchment to subnational measures (Richardson et al., 2018). The ecosystem phenology camera network can be used to estimate the carbon flux, photosynthesis, and canopy greenness in dryland vegetation (Richardson et al., 2013), and mobile devices can be redeployed to record and capture ecological data. For instance, the Land-Potential Knowledge System (LandPKS) recognizes soil and land types, monitors soil health and vegetation, and identifies management options (Herrick et al., 2016). This could be used to verify remote sensing products, assess earth surface model projections, seasonally explain ecosystem-scale data, and investigate the climate change effects on the terrestrial ecosystem (Seyednasrollah et al., 2019). Public and private institutions can reduce expenditures on design, research, and development, *via* surplus non-custom devices that are relatively inexpensive and widely available.

7 Conclusion

At present, dryland ecosystem degradation meets increasingly severe climate change. Increasingly, widespread, frequent, and extreme weather events substantially impact food security, especially the sufficiency and regularity of food production. In this review, the bibliometric approach was used to assess the research trends, which identified that research demand on the impacts of climate change on drylands and FS has been increasing. African drylands harbor enormous exceptional levels of biodiversity *via* diverse land-use systems and provide a variety of ecosystem services. However, they are ecologically fragile in a plethora of ways. There is a strong relationship between climate change, dryland change, and food systems. With regards to the digital revolution in the RS field, in addition to continuing to use conventional methods to detect the impact of climate change on arid and semi-arid regions, technical innovations (e.g., ecosystem observational/research networks) and modern practices (e.g., climate modeling tools) focusing on dryland changes and FS in Africa are very rare across all sectors. Novel methods, such as coupling different vegetation indices, are urgently needed and

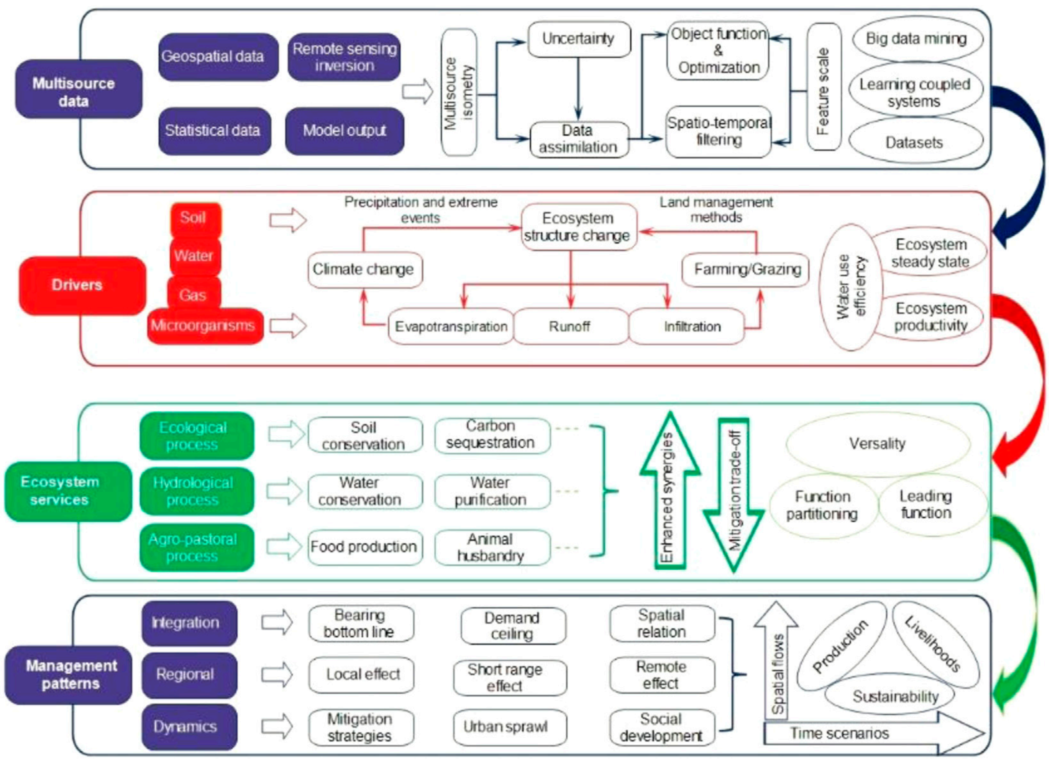

FIGURE 6
Research directions of climate change, dryland variation, and food security nexus.

encouraged to support conventional dryland RS and FS assessment, from basin to regional scales. With particular efforts to the tactically explored studies, we propose an integrated conceptual framework of different systems (i.e., drylands, climate, ecosystem, socio-economic, and food system) (Figure 3). The foresight and prediction assessment of driving forces of the climate, drylands, and FS needs further research (Section 6). The framework has the potential to reveal new insights into climate change, dryland ecosystem dynamics, and FS with the availability and accuracy of data in the entire system. The nexus approach combines intradisciplinary sections involving all socioeconomic and ecological fields to better understand the regional impacts and develop adaptive strategies while mitigating the climate change impacts on drylands. Herein, we propose new research opportunities to strengthen the CDF nexus: ① promoting sustainable agricultural best management practices and innovations as a tool to enhance community resilience and cope with climate change impacts on FS, ② using modern observational data and developing idealistic models to better understand the CDF nexus approaches, and ③ strengthening dryland research and management effectiveness through emerging and affordable technologies. By combining these research directions, we may gain new insights into dryland dynamics, ecosystem services, and FS. We recommend decision makers design policy instruments that consider CDF fields as a multidisciplinary nexus.

Author contributions

HH: conceptualization, methodology, investigation, acquisition of data, formal analysis, writing—original draft, and review and editing. FL: conceptualization, methodology, formal analysis, writing—original draft, review and editing, supervision, and funding acquisition. YQ, SM, FM, CT, PL, AI, RI, GC, and BT: writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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