The Nexus of Climate Change and Land-use in Kenya

ABSTRACT

Land as a resource remains a useful in alleviating human risks through provision of food, water, energy and environmental goods/services. However, climate change has been perceived as a threat to land-use in mitigation of such risks. Meanwhile land-use has also been implicated in climate change in the world. This intertwined scenario portents an intricate link between climate change and land-use on one hand and land-use and climate change on the other. The interconnections between climate change and land appears to be direct in some cases but most cases, they are indirect and often subtle. The aim of this paper is to bring to light the interconnectedness between climate change and land, as well as assesses land impacts on climate change, in Kenya, and further suggests strategies needed to address these issues from a multidimensional perspective in the policymaking process. First the paper describe land-use and their influence on climate change such as agricultural expansion, urbanization, activities in catchment areas, large scale settlements, deforestation, manufacturing and industrial activities. The paper then looks at the impacts of climate change on land including: primary effects such as changes in land surface air temperature, GHG emissions, occurrence of extreme events, forest cover change, water quantity and quality, drought and desertification. The paper also looks at the indirect effects such as food production, forest cover changes, forest ecosystem services, biodiversity changes and socio-economic impacts on the population. To further this research, the study recommends ways of exploring land-sensitive approaches to climate change adaptation and/or mitigation. Further research should hence focus on developing conflict-sensitive approaches to climate-mitigation and adaptation measures which invite many communities in the climate governance debate. Ways of exploring climate-smart activities on land-based management is also recommended.

Keywords: Land, Land-Climate nexus, Kenya, Climate adaptation, climate change impacts

1. Introduction

The increasing global warming of the environment resulting from the long term sporadic increase in emissions of Greenhouse Gases (GHGs) that change the normal weather conditions clearly manifest climate change. Climate change has been reported over the last 100 years following records of 0.74ºC increase in the global average temperatures with a likelihood of further increase by 1.6–2.6ºC by the end of the 21st Century relative to the 1980 baseline [1]. At the continental level, warming in the African continent has always been greater than the global average with an increased average temperature expected to be 3–4ºC by the 21st Century [2]. The climate change cause differences in precipitation differentially across different regions of Africa where, high latitudes and the equatorial Pacific region have witnessed an increase in annual precipitation while regions in the dry mid-latitude and subtropics had reduced precipitation [3]. Sub-Saharan Africa is highly susceptible to climate change due to majority of the land lying across the warming tropics [4].

In Kenya, much of the climate change is caused by increasing GHGs, which has led to increasing ambient temperature, reduced rainfall, and increasing extreme events such as floods, droughts, strong winds and storms, with subtle gradual change in sea-level [5, 6]. It is also projected that ambient temperature will most likely increase by 2.5°C by the year 2050 leading to increasing frequency of extreme events such as flooding and droughts [7]. The climate change events appear more intense in the hot and dry regions of the Arid and Semi-Arid Lands (ASALs) which has seen massive reduction in levels of precipitation as well as a significant increases in frequency and severity of drought and floods [8].

Land-use patterns in Kenya has been changing since the beginning of the 1900s aiming mostly for economic or environmental benefits such as food production, energy, building materials, and industrial production etc [9, 10]. Land-use is one of the current drivers of climate change in Kenya [11, 12]. At the same time, the adverse climate change affects land and land resources [11, 13, 14]. Thus land and climate interact in a complex ways that is not unidimensional but multidimensional through multiple feedbacks. This situation therefore calls for a nexus approach that addresses the inter-connectedness, synergies, and trade-offs existing between climate change and land resources. Interesting studies on the nexus between climate change and land in Kenya are rather scarce. Therefore, the aim of this paper is to highlight the interconnectedness between land and climate change, and the need to address these issues from a multidimensional perspective.

2. METHODS

For this review, the principles of the systematic map methodology was used to describe the state of knowledge and map the available evidence of the role of indigenous knowledge for forest conservation and climate change adaptation in academic journal articles, book chapters, and conference papers. Scoping reviews are an established method for evidence synthesis, and are also increasingly applied in climate change adaptation research. The objective of scoping reviews is to provide a broad overview of the literature on a specific topic and identify patterns, trends, knowledge clusters, and gaps. While a scoping review approach usually does not include a critical appraisal of individual studies' results and their impacts, it is 'particularly valuable for broad, multi-faceted questions', and provides the basis for in-depth follow-up research on specific subsets of the identified evidence.

3. FRAMEWORK FOR CLIMATE-LAND-USE NEXUS

During the past few decades, land-use and climate changes are two major global issues [15], and proper research highly demands finding their relationships and impacts for the future. Forest and agricultural land are the main factors in the path of land-use affecting climate change, so they have become the focus of previous researches. However, the nexus of land and climate change have rarely been studies in a cause-consequences criterion especially for many local regions. The key conceptual framework that describes the pathways in research on climate change and land are impacts and vulnerability. Vulnerability is the propensity to be adversely affected. Fig. 1 shows the connections between climate change, including impacts and vulnerability on land and human security [16]. The purpose of Fig. 1 is to illustrate the complexity of links within the nexus of climate change and land.

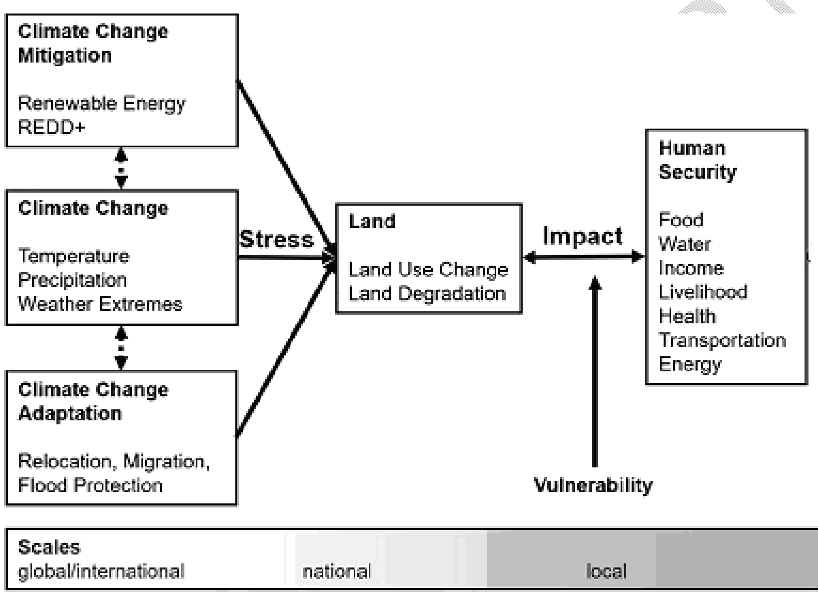

Fig. 1 Conceptual framework of effects of climate change on land resource dynamics [16]

4. LAND-USE AS DRIVER OF CLIMATE CHANGE

At the global, regional and local scale, there has been an increase in human activities on land that often results in the increase in emission of GHGs causing localized changes in weather related events [17, 18]. Aggregated over large areas, these changes have the potential to influence climate change at the regional and global levels. The activities on land that drive climate change are therefore discussed on this section.

4.1 Expansion of agricultural activities

Climate change is driven by multiple climate pollutants consisting of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) which are largely associated with agriculture [19]. Cropland and livestock based agriculture, contributes to climate change by releasing CO_2, CH_4 and N_2O [20]. In this regard agriculture emitted 5.5–6.5 billion tons of CO_2 equivalent in 2021 (10–12% of all GHGs in that year). Its share of CH_4 and N_2O emissions was much greater: agriculture contributes about 47% of global CH_4 and 58% of N_2O. These figures are devoid of GHGs from electricity and fuel used in agriculture for machinery, processing, and transport. Also, emissions vary widely among countries, with more industrialized countries producing more GHGs than developing countries but deriving much less of their GHGs from agriculture.

In Kenya, agriculture was the leading source of GHG emissions, contributing 62.8% of total 80,000 kT of GHG emissions, followed by emission from energy (31.2%) [21, 22]. Agriculture is also one the main reason for a change in land-use that take up and store carbon dioxide (CO_2) from the atmosphere, to farmland.

4.2 Urbanization/urban development

There is rapid increase in urban areas together with urban populations [23] leading to numerous activities in the urban areas that tend to increase warming. Urbanization is related to the climate change issue in two ways. Firstly, a significant amount of energy is used in urban areas which is, a major source of greenhouse gases [24]. Secondly, the increase in population of the urban areas result into more use of marginal land, thereby which exacerbate the potential impacts of climate change [25]. Cities are usually 2-3°C warmer than their surrounding environments a phenomenon known as Urban Heat Islands (UHI) [26]. UHI is a localized climate phenomenon whereby urban areas experience warmer temperatures than their surrounding non-urban areas (Fig. 2). The magnitude or intensity of this so-called urban heat island (UHI) depends on various factors, such as the size and morphology of the city.

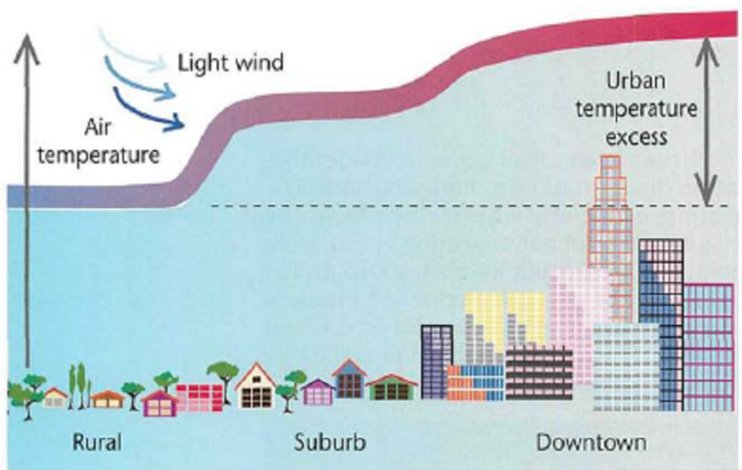

Fig 2. Generalized cross-section of a typical urban heat island (UHI)

The rapid urbanization in Kenya over the past decades seems to have been accompanied by extensive land-use and land cover changes, which potentially affect local or regional climate [27]. One of the major consequences of these modifications is the increase in land surface temperature in urban areas, such as those reported in Nairobi City, which strengthens the urban heat island (UHI) effect [28, 29]. Land-use changes in urbanization, creating an urban heat island (UHI), have been implicated for the observed warming in Kenya urban areas during the last few decades [30, 31].

4.3 Large scale settlements and climate change

A great variety of settlements exist today reflecting human needs, abilities, and aspirations, as well as social, political, and economic relations [32]. The conundrum of large scale settlements comes with forest clearing for agricultural production, city expansion causing clearance of land, water abstraction, pollution of the land, energy use and transport which are the main drivers of greenhouse gas emissions.

In Kenya, since the onset of missionary evangelism and colonization, human settlements have taken two distinct patterns: the rural and urban settlements. After independence saw Kenya give back much of forest and densely vegetated lands to the locals which earmarked the onset of land-use change followed by large scale settlement of people [33, 34]. Each of these patterns has been greatly influenced by politics, administrative and the socio-economic development of the time. There are scenarios where large parts of forest ecosystems is hived off and given to the people for settlement. Settlements schemes have also been established in forested areas by authorities in a bid to settle landless people, reduce population in highly populated area, increase food production and settle people displaced by different disasters [35, 36]. Perhaps one of the most controversial settlements is in the Mau Forest in the last 20 years [37]. Over the past 20 years, this forest has faced destruction from illegal loggers and encroachers who have extended their farming and grazing lands deep into the forest.

4.4 Deforestation and climate change

There has been large scale clearance of forests to allow for humans settlement, agriculture, mining, road construction or industrial development in the past especially in the tropics [38, 39]. In Kenya, closed forests are crucial water catchments. Among these forests, the five largest blocks are Mt. Kenya, the Aberdare Range, the Mau Complex, Mt. Elgon and the Cherangani Hills. These montane forests are surrounded by the most densely populated areas of Kenya. Notwithstanding the services they provide to the people of Kenya, these forests have been and remain the target of uncontrolled and unplanned development activities that has led to massive deforestation which tend to cause climate change concern. There are also settlement schemes that were hived off from forested areas in Kenya that have led to massive deforestation in Kenya [35]. As people clear forests to pave way for settlements, deforestation and land degradation sets in which further leads to negative impacts on climate change.

Efforts to increase afforestation and reforestation activities have been observed since 2002 (average of 326,794 ha/year from 2002-2018 as outlined in the 2019 FRL), these can be attributed largely to the establishment of private commercial plantations and Government-led initiatives. However, deforestation and forest degradation (average 338,863ha/year) still occur at slightly higher rates: there is therefore a net loss of forest in Kenya [40]. Kenya is one of the countries which has documented reduction forests cover the past 30 years within the gazetted forest, trust lands as well as in the private land [41] including in gazetted and protected water towers [37, 42]. Loss of forests through excision, population pressures and climate change is estimated at close to 5,000 ha per year. Kenyan forest cover during independence was over 10% of the land mass [43]. The Kenya forest cover in 2020 was 6.2% of the total land area which is a reduction from 6.9% in 1990 [44]. Therefore it is clear that Kenya has lost 0.8% of forest cover over the same period of time. Forest cover in Kenya including the area of publicly owned plantations, which has been the backbone of Kenya's once thriving wood based industry, has progressively reduced over the years and currently some of the drivers of climate change [45].

5. CLIMATE CHANGE IMPACTS ON LAND AND LAND-USE

Analysts of climate impacts identified three main land based sectors that are impacted by climate change: agriculture, forestry, water, and indirectly human life [46-48]. Agriculture and forestry are key land-uses. Water is important to land because its availability affects the viability of agriculture through irrigation. The impacts are discussed in this section.

5.1 Impacts on agriculture and food production

Agriculture is one of the largest climate-sensitive sector due to response to increasing temperature and precipitation on crop yields and livestock production [49]. In regions of where temperature are low, increasing temperatures lead to improved crop growth due to temperature optima being higher in cold environments. However, in region where there is high temperature then warming may have little impact or adverse impacts. The temperature and precipitation variations due to climate change also affect crops and livestock more depending on aridity of the area. Indirect effect of climate change on land is also probable where such as arable land being left fallow or abandoned completely when there is severe drought or converted to open water during periods of extremely high precipitation, that may negatively affect the land production or production capacity.

Agriculture is an important sector in Kenya due to its significant contribution to the economy, livelihoods and food security [50]. The sector is constantly affected by climate change causing seasonal alterations in rainfall and temperature of varying magnitude and duration over the years [5, 51]. Erratic weather events characterized by frequent droughts were experienced in 1951, 1952–1955, 1957–1958, 1974–1976, 1980–1981, 1983–1985, 1987, 1992–1993, 1995–1996, 1999–2001, 2004–2006 and 2008–2009 [52, 53]. Agricultural production during the years of droughts has always been low (Fig. 3).

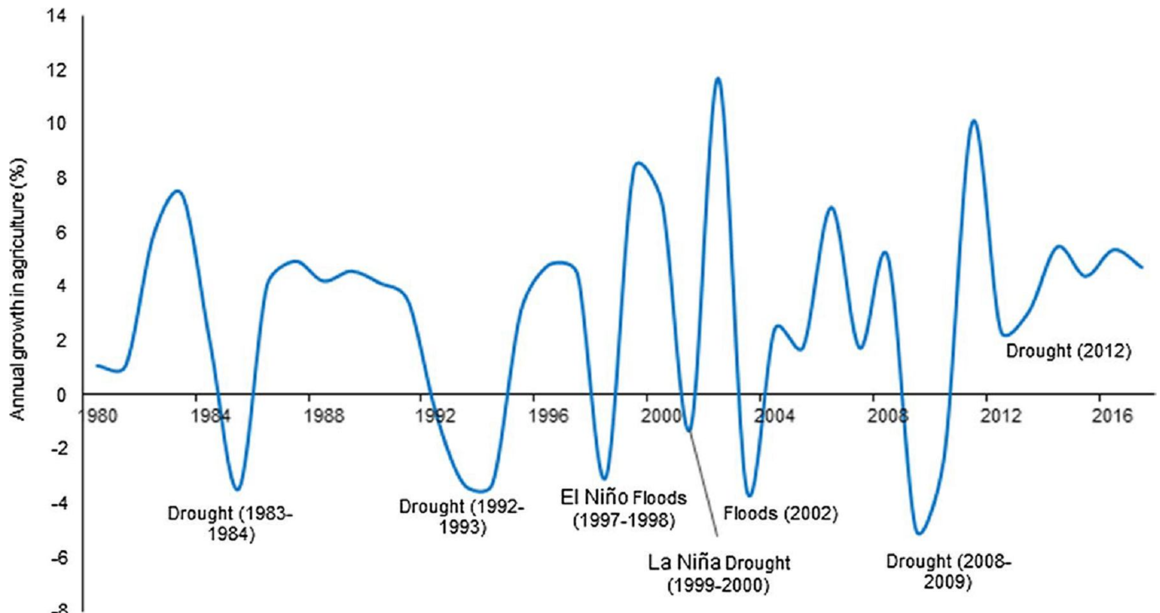

Fig. 3. Climate extreme events and agricultural growth trends in Kenya from 1980 to 2016. Source: [5]

Production trends of major crops produced in Kenya show high variability between 1980 and 2016 (Fig. 3) and crop yields in the agricultural sector over the same time (Fig. 3) are also provided. Based on the information of these graphs, drop in crop production appears to echo with drought conditions.

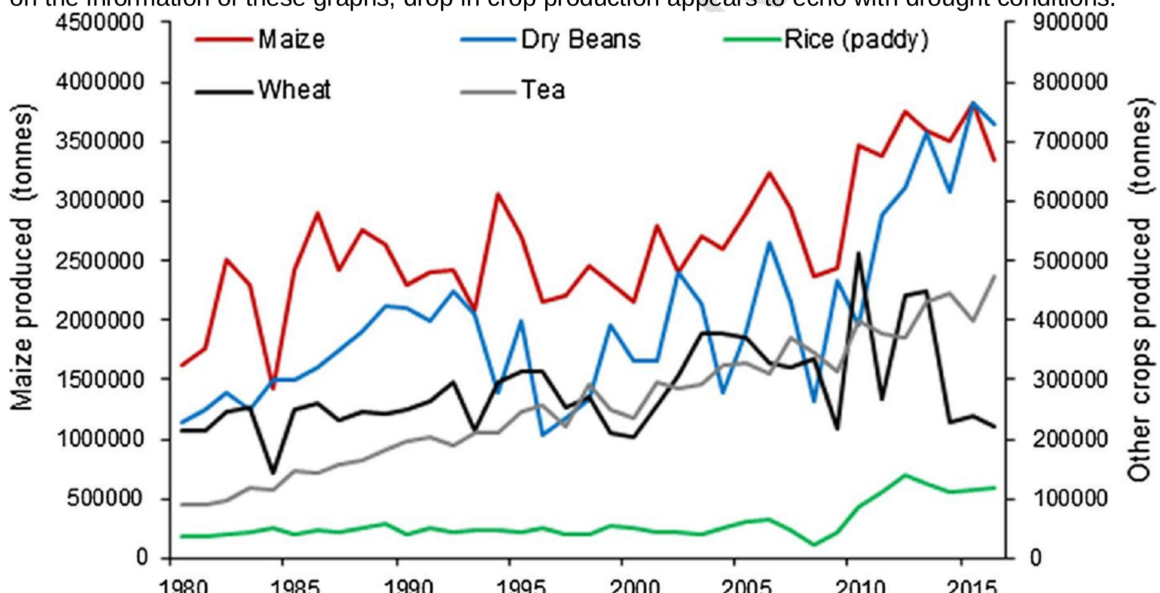

Fig 4. Production trends of various selected crops in Kenya over time. Adapted from FAOSTAT database

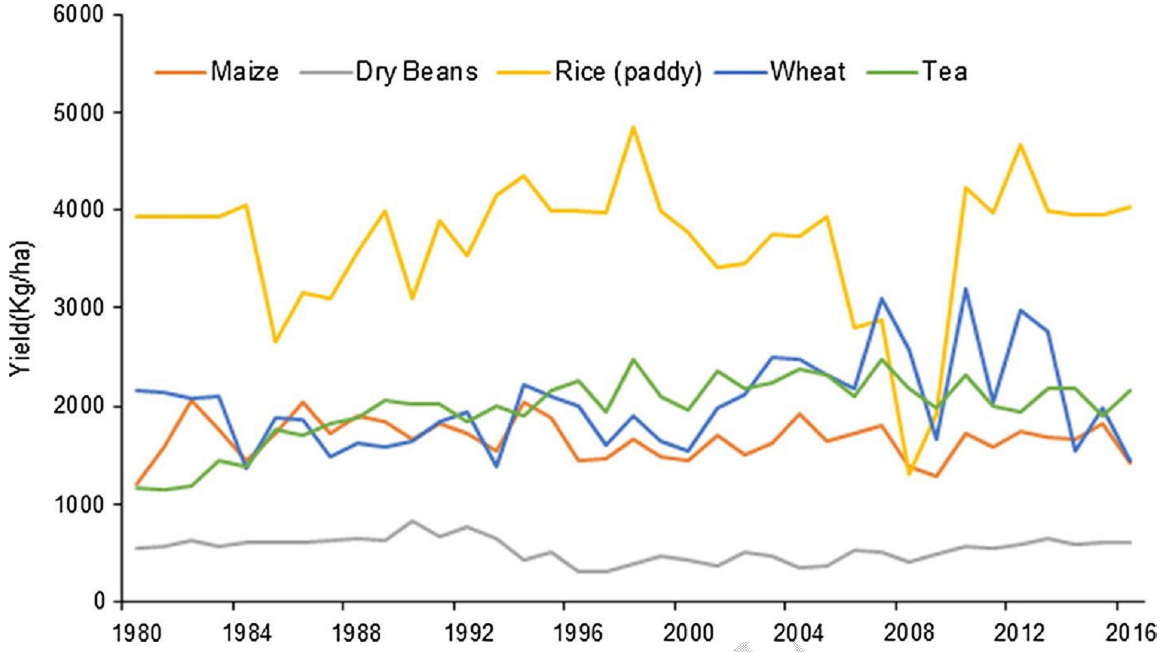

Fig 5. Yield of selected crops in Kenya. Adapted from FAOSTAT database

Other factors that affect agricultural productivity in Kenya that are related to climate change are pests and diseases, declining soil fertility, land cover changes, and inadequate climate change preparedness and responses well as over-reliance on rain-fed agriculture which is constantly affected by climate variations [54, 55].

Simulated impacts of climate change on agricultural production in Kenya suggest that between 2010 to 2050, there will be losses in yield of some crops such as maize, wheat, rice and groundnuts due to climate change [56, 57]. Whereas accurate prediction of crop yield remains difficult for a number of crop due to other anthropogenic influences, the yield of maize is expected to decline by almost 50% or an equivalent decrease by approximately 200 kg/ha for every rise in temperature by 1ºC above the optimum temperature [58]. This is mainly due to dependence of rain-fed water availability for maize production, which makes it apparent candidate to be affected by erratic weather events including droughts—a negative outcome of climate change.

5.2 Impacts on forest ecosystems

Climate change may affect forest ecosystems through alteration of the growth, mortality and reproduction of trees [59, 60]. There is also the climate change risks to global forest health which may accelerate tree mortality [61]. Climate change affects forest vegetation physiology, their relationships with pests, competitors and mutualism. Warmer temperatures change the timing of life cycle events (phenology), with earlier bud burst, leafing and flowering in trees, although there is much year-to-year and regional variation. It will affect forests also indirectly by increasing the risk of infestation [62]. Also climate change may affect nutrient cycling directly through its impact on temperature and precipitation [63]. The productivity and integrity of forest ecosystems is linked to the supply of nutrients and climate change can influence nutrient dynamics by altering the rate of litter decomposition.

Effects of climate change on forest ecosystems also alter the frequency and/or severity of natural disturbances in some forests, particularly fire and insect disturbances [64]. Climate change id driving disturbance regimes in several forests ecosystems. In case there is increases in disturbance there will be massive effects on forest ecosystem structures such as species richness, composition, their overall functioning [65]. There is evidence resulting in increased forest damage, erosion and landslides, with wetter soils and flooding over the last century.

In addition, forest growth including undergrowth will be affected by elevated levels of carbon dioxide. The combination of rising temperatures and higher CO_2 levels is expected to have several major effects on trees. This dynamic process is expected to cause dieback in some places and the disappearance of entire forests in others.

5.3 Impact on water resources

Climate change impacts the world's water in complex ways. Climate change will affect water resources through its impact on the quantity, variability, timing, form, and intensity of precipitation [66]. Climate change may threatens the quality of source water through increased runoff of pollutants and sediment, decreased water availability from drought and saltwater intrusion, as well as adversely affecting overall efforts to maintain water quality [67]. Extreme weather events are making water scarce, more unpredictable, more polluted or all three. Additional effects of global climate change that have important implications for water resources include increased evaporation rates, increased water temperatures, and decreased water quality in both inland and coastal areas [68].

Climate change is expected to affect water quality in both inland and coastal areas. Specifically, precipitation is expected to occur more frequently via high-intensity rainfall events, causing increased runoff and erosion [69]. More sediments and chemical runoff will therefore be transported into streams and groundwater systems, impairing water quality. Water quality may be further impaired if decreases in water supply cause nutrients and contaminants to become more concentrated. Rising air and water temperatures will also impact water quality by increasing primary production, organic matter decomposition, and nutrient cycling rates in lakes and streams, resulting in lower dissolved oxygen levels [70]. This suite of water quality effects will increase the number of water bodies in violation of today's water quality standards, worsen the quality of water bodies that are currently in violation, and ultimately increase the cost of meeting current water quality goals for both consumptive and environmental purposes.

Radical changes to the freshwater hydrology of coastal areas, caused by saltwater intrusion, would threaten many coastal regions' freshwater supplies [71]. Rising sea levels could also affect water availability in coastal areas indirectly by causing water tables in groundwater aquifers to rise, which could increase surface runoff at the expense of aquifer recharge [72].

Climate change projections on water resources indicate that Kenya, will suffer from water scarcity [73]. Climate change impacts on water availability are a consequence of the rising global temperatures which change the water cycle by influencing when, where and how much precipitation falls and evaporate, and such water is not always available when and where people need it. Furthermore, the impact of climate change on water would result in increased demand on a reduced resource. Climate change impacts in the water sector in Kenya have been manifested through severe flooding, droughts, rising water levels in lakes, water scarcity, invasion of alien species in water bodies such as water hyacinth in Lake Victoria and other water bodies.

Most of the lakes in the Rift Valley in Kenya have been experiencing rise in water levels including Lake Victoria, Lake Nakuru, Lake Baringo, Lake Bogoria and Lake Turkana [74]. The rise has been attributed to climate change impacts such as severe rainfall, flooding and land-use degradation. The rise in water levels in these lakes have affected businesses, schools, and homes, led to pollution of fresh water while bringing crocodiles and hippos dangerously close to homesteads. Scientists and officials are concerned that the freshwater Lake Baringo and alkaline Lake Bogoria could merge which would cause cross-contamination and threaten aquatic species [74].

5.4 Impacts on quality of human, animal and plants life

In addition to impacts on the economy, climate change is likely to affect people's quality of human, animal and plants life [75]. For instance, as ecosystems shift, some plants and animals may be lost as species endemic to a specific location find it hard to move to new locations. Some scientists warn that there could be massive losses of species associated with even relatively modest warming. The Intergovernmental Panel on Climate Change (IPCC) argues that 20–30 percent of species are likely to be at risk of extinction if warming exceeds 1.5–2.5°C (2.7–4.5°F) [76]. The shifting of ecosystems also may bring disease, as some vector-borne pathogens may move into new territory causing health risk to human an animal life (IPCC 2007).

Heat stress might increase as a result of more intense or more frequent heat waves. It is difficult to place a value on the damages resulting from such changes. Valuing the loss of human and other species of animals is quite difficult. One strategy to value endangered species is to determine what it would cost to protect them. The same strategy could be used to value desired species in the face of climate change. The protection cost would then be the damages resulting from climate change. Similar strategies could be used to value the potential loss of life from disease or heat stress. The cost of the public health response needed to address these problems could be a measure of the damages.

6. CONCLUSIONS

In this review paper, the nexus of climate change and land-use are explored. First the paper describe land-use and their influence on climate change such as agricultural expansion, urbanization, activities, large scale settlements, deforestation, manufacturing and industrial activities. The paper then looks at the impacts of climate change on land including: primary effects such as changes in land surface air temperature, GHG emissions, occurrence of extreme events, forest cover change, water resources, drought and desertification. The paper also looks at the indirect effects such as food production, and socio-economic impacts on the population. On one hand, it examines the relationship between climate change and the components of the land nexus independently, and on the other hand, it provides an overview of how interconnected the components of the land nexus are, and how when climate change impacts one of them, the others can also directly or indirectly suffer the consequences. Initiatives supporting these measures draw on leading policy developments such as the Paris Agreement and concomitant available financing to take action but often lack the recognition of the negative externalities and conflict implications of adaptation and mitigation measures.

8. RECOMMENDATIONS

The nexus approach that allows for the inter-linkages, trade-offs, and synergies existing between climate and land resources suggest the need for developing mitigation and adaptation strategies toward climate change in a comprehensive manner. This is a very complex system, and therefore calls for a trans-disciplinary team which is a diverse group of professionals and experts from the sectors of climate change, water resource management, natural resource management, biodiversity and ecosystem conservation, sustainable agricultural production, environmental protection, economics, sociology, and local communities, working together across their disciplines to tackle the issues relating to climate change and the land nexus.

Most African governments have initiated governance systems for adaptation, such as disaster risk management, modifications of technologies and infrastructure, ecosystem-based approaches and livelihood diversification strategies. Similarly, the IPCC special report of 2018 identifies a range of adaptation options to reduce risks to livelihood, water and economic growth, among these are efficient irrigation, disaster risk management, risk spreading and sharing and community adaptation. The 5th Assessment Report of the IPCC therefore recommends the need for collaborative and participatory research, and improved communication systems on climate change and flexibility of livelihood options could be potential mechanisms to improve adaptive capacities for climate change.

Drastic measures should be taken to seize and maximize on viable adaptation and mitigation strategies in order to strengthen the agricultural sector and increase food production and access for the growing population. The Kenyan government can play a vital role by promoting appropriate farm-level adaptation measures, providing timely early warning information on seasonal climate forecasts, development of supportive policies and investments geared towards uptake of climate-smart agriculture in order to improve crop production and achieve food security, while contributing to reduction in challenges posed by climate change.

Kenya like many other developing countries lacks adequate participatory farmer-led extension activities to drive successful uptake of locally feasible adaptation strategies towards climate change adaptation. There is therefore need to strengthen community-based approaches and recognize adaptation strategies that are informed by indigenous, local knowledge and scientific research in order to help the farmers to cope with climate change.

To achieve the land nexus in a changing climate, sufficient attention must be given to both national and international organizations/institutions in SSA. They must be able to integrate the outcomes land nexus generated from the multidisciplinary teams into adaptation and mitigation plans toward climate change. Considering the novelty of the land nexus approach in the policymaking process of SSA region, efforts must be taken to deepen the knowledge hub of the stakeholders which will help to foster the ease of interactions between them. Finally, governments and private institutions must be ready to invest or provide institutional support to attract investments for promoting the land-climate nexus.

REFERENCES

1. Abbass K, Qasim MZ, Song H, Murshed M, Mahmood H, Younis I. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research* 2022,**29**:42539-42559.
2. Bedeke SB. Climate change vulnerability and adaptation of crop producers in sub-Saharan Africa: A review on concepts, approaches and methods. *Environment, Development and Sustainability* 2023,**25**:1017-1051.
3. Sun Q, Zhang X, Zwiers F, Westra S, Alexander LV. A global, continental, and regional analysis of changes in extreme precipitation. *Journal of Climate* 2021,**34**:243-258.
4. Africa S-S. Climate Change, Food Systems, and Nutrition. 2023.
5. Kogo BK, Kumar L, Koech R. Climate change and variability in Kenya: a review of impacts on agriculture and food security. *Environment, Development and Sustainability* 2021,**23**:23-43.
6. Volenzo TE, Odiyo JO, Obiri J. Greenhouse gas emissions as sustainability indicators in agricultural sectors' adaptation to climate change: Policy implications. *Jàmbá: Journal of Disaster Risk Studies* 2019,**11**:1-9.
7. Sagero PO. Assessment of past and future climate change as projected by regional climate models and likely impacts over Kenya: PhD Thesis]. School of Pure and Applied Science, Kenyatta University; 2019.
8. Muthike DM. Developmemt Of Climate Change Vulnerability Maps And A Poverty Model Using Kenya As A Case Study: UoN; 2019.
9. Mwangi HM, Julich S, Patil SD, McDonald MA, Feger K-H. Relative contribution of land use change and climate variability on discharge of upper Mara River, Kenya. *Journal of Hydrology: Regional Studies* 2016,**5**:244-260.
10. Guzha A, Rufino MC, Okoth S, Jacobs S, Nóbrega R. Impacts of land use and land cover change on surface runoff, discharge and low flows: Evidence from East Africa. *Journal of Hydrology: Regional Studies* 2018,**15**:49-67.
11. Adizovna ED, Farrukhovna QL. Land resources management issues. *European International Journal of Multidisciplinary Research and Management Studies* 2022,**2**:138-141.
12. Odongo VO, van Oel PR, van der Tol C, Su Z. Impact of land use and land cover transitions and climate on evapotranspiration in the Lake Naivasha Basin, Kenya. *Science of the total environment* 2019,**682**:19-30.
13. Pecl GT, Araújo MB, Bell JD, Blanchard J, Bonebrake TC, Chen I-C*, et al.* Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science* 2017,**355**:eaai9214.
14. Ochieng J, Kirimi L, Mathenge M. Effects of climate variability and change on agricultural production: The case of small scale farmers in Kenya. *NJAS-Wageningen journal of life sciences* 2016,**77**:71-78.
15. Jia S, Yang C, Wang M, Failler P. Heterogeneous impact of land-use on climate change: study from a spatial perspective. *Frontiers in Environmental Science* 2022:510.
16. Scheffran J, Brzoska M, Brauch HG, Link PM, Schilling J. *Climate change, human security and violent conflict: challenges for societal stability*: Springer Science & Business Media; 2012.
17. Sang CC, Olago DO, Nyumba TO, Marchant R, Thorn JP. Assessing the Underlying Drivers of Change over Two Decades of Land Use and Land Cover Dynamics along the Standard Gauge Railway Corridor, Kenya. *Sustainability* 2022,**14**:6158.
18. Langat PK, Kumar L, Koech R, Ghosh MK. Monitoring of land use/land-cover dynamics using remote sensing: A case of Tana River Basin, Kenya. *Geocarto International* 2021,**36**:1470-1488.
19. Lynch J, Cain M, Frame D, Pierrehumbert R. Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO2-emitting sectors. *Frontiers in sustainable food systems* 2021:300.
20. Ivanovich CC, Sun T, Gordon DR, Ocko IB. Future warming from global food consumption. *Nature Climate Change* 2023:1-6.
21. Musafiri CM, Macharia JM, Ng'etich OK, Kiboi MN, Okeyo J, Shisanya CA*, et al.* Farming systems' typologies analysis to inform agricultural greenhouse gas emissions potential from smallholder rain-fed farms in Kenya. *Scientific African* 2020,**8**:e00458.

22. FAO. Global Forest Resources Assessment 2020: Main report. Rome. https://doi.org/10.4060/ca9825en. 2020.
23. Güneralp B, Reba M, Hales BU, Wentz EA, Seto KC. Trends in urban land expansion, density, and land transitions from 1970 to 2010: A global synthesis. *Environmental Research Letters* 2020,**15**:044015.
24. Derkenbaeva E, Vega SH, Hofstede GJ, Van Leeuwen E. Positive energy districts: Mainstreaming energy transition in urban areas. *Renewable and Sustainable Energy Reviews* 2022,**153**:111782.
25. Ribeiro HV, Rybski D, Kropp JP. Effects of changing population or density on urban carbon dioxide emissions. *Nature communications* 2019,**10**:3204.
26. Wang Z-H. Reconceptualizing urban heat island: Beyond the urban-rural dichotomy. *Sustainable Cities and Society* 2022,**77**:103581.
27. Nyairo R, Onkangi R, Ojwala M. Contextualizing Resilience Amidst Rapid Urbanization in Kenya through Rural-Urban Linkages. *Climate Vulnerability and Resilience in the Global South: Human Adaptations for Sustainable Futures* 2021:55-73.
28. Ochola EM, Fakharizadehshirazi E, Adimo AO, Mukundi JB, Wesonga JM, Sodoudi S. Inter-local climate zone differentiation of land surface temperatures for Management of Urban Heat in Nairobi City, Kenya. *Urban Climate* 2020,**31**:100540.
29. Matsaba EO. Modelling of Urban Heat Island and Quantification of Amelioration Effects of Plant Species on Microclimate and Human Thermal Comfort in Nairobi City, Kenya: JKUAT-COETEC; 2021.
30. Mutua MM. Planning Implications of Urban Heat Island Effect in Mombasa: University of Nairobi; 2022.
31. Simwanda M, Ranagalage M, Estoque RC, Murayama Y. Spatial analysis of surface urban heat islands in four rapidly growing African cities. *Remote Sensing* 2019,**11**:1645.
32. Corbane C, Pesaresi M, Kemper T, Politis P, Florczyk AJ, Syrris V*, et al.* Automated global delineation of human settlements from 40 years of Landsat satellite data archives. *Big Earth Data* 2019,**3**:140-169.
33. Greiner C. Land-use change, territorial restructuring, and economies of anticipation in dryland Kenya. *Journal of Eastern African Studies* 2016,**10**:530-547.
34. Bassett E. Reform and resistance: The political economy of land and planning reform in Kenya. *Urban Studies* 2020,**57**:1164-1183.
35. Boone C, Lukalo F, Joireman SF. Promised land: settlement schemes in Kenya, 1962 to 2016. *Political Geography* 2021,**89**:102393.
36. Manji A. *The struggle for land and justice in Kenya*: Boydell & Brewer; 2020.
37. Kweyu R, Thenya T, Kiemo K, Emborg J. The nexus between land cover changes, politics and conflict in Eastern Mau forest complex, Kenya. *Applied Geography* 2020,**114**:102115.
38. Burgess R, Hansen M, Olken BA, Potapov P, Sieber S. The political economy of deforestation in the tropics. *The Quarterly journal of economics* 2012,**127**:1707-1754.
39. Buchadas A, Baumann M, Meyfroidt P, Kuemmerle T. Uncovering major types of deforestation frontiers across the world's tropical dry woodlands. *Nature Sustainability* 2022,**5**:619-627.
40. Njora B, Yilmaz H. analysis of the effects of deforestation on the environment and agriculture in Kenya. *International Journal of Water Management and Diplomacy* 2022,**1**:91-110.
41. Nyamari N, Cabral P. Impact of land cover changes on carbon stock trends in Kenya for spatial implementation of REDD+ policy. *Applied Geography* 2021,**133**:102479.
42. Marie Mireille N, M. Mwangi H, K. Mwangi J, Mwangi Gathenya J. Analysis of land use change and its impact on the hydrology of Kakia and Esamburmbur sub-watersheds of Narok county, Kenya. *Hydrology* 2019,**6**:86.
43. Ototo G, Vlosky RP. Overview of the forest sector in Kenya. *Forest Products Journal* 2018,**68**:6-14.
44. Nesha MK, Herold M, De Sy V, Duchelle AE, Martius C, Branthomme A*, et al.* An assessment of data sources, data quality and changes in national forest monitoring capacities in the Global Forest Resources Assessment 2005–2020. *Environmental Research Letters* 2021,**16**:054029.
45. Makanji D, Oeba V. The role of the Kenyan private forestry sector in response to climate change mitigation and adaptation. *International Forestry Review* 2019,**21**:102-111.
46. Celik S. The effects of climate change on human behaviors. *Environment, climate, plant and vegetation growth* 2020:577-589.

47. Imran, Benkeblia N, Amanullah, Al‐Tawaha ARMS. Climate Change and Agriculture: State of the Art, Challenges, and Perspectives. *Climate Change and Agriculture: Perspectives, Sustainability and Resilience* 2022:1-27.
48. Pörtner H-O, Roberts DC, Adams H, Adler C, Aldunce P, Ali E*, et al. Climate change 2022: Impacts, adaptation and vulnerability*: IPCC Geneva, Switzerland:; 2022.
49. Fatima Z, Naz S, Iqbal P, Khan A, Ullah H, Abbas G*, et al.* Field crops and climate change. *Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective* 2022:83-94.
50. Eichsteller M, Njagi T, Nyukuri E. The role of agriculture in poverty escapes in Kenya–Developing a capabilities approach in the context of climate change. *World Development* 2022,**149**:105705.
51. Faling M. Framing agriculture and climate in Kenyan policies: a longitudinal perspective. *Environmental Science & Policy* 2020,**106**:228-239.
52. Haile GG, Tang Q, Sun S, Huang Z, Zhang X, Liu X. Droughts in East Africa: Causes, impacts and resilience. *Earth-science reviews* 2019,**193**:146-161.
53. Otieno C. Model ensembles for Predictive drought severity and drought Effects monitoring using remote sensing & Socio-economic data: University of Nairobi; 2020.
54. Kogo BK, Kumar L, Koech R, Hasan K. Climatic and non-climatic risks in rainfed crop production systems: insights from maize farmers of western Kenya. *Climate and Development* 2021,**13**:869-878.
55. Alexandridis N, Feit B, Kihara J, Luttermoser T, May W, Midega C*, et al.* Climate change and ecological intensification of agriculture in sub-Saharan Africa–A systems approach to predict maize yield under push-pull technology. *Agriculture, Ecosystems & Environment* 2023,**352**:108511.
56. Mumo L, Yu J, Ojara M, Lukorito C, Kerandi N. Assessing changes in climate suitability and yields of maize and sorghum crops over Kenya in the twenty-first century. *Theoretical and Applied Climatology* 2021,**146**:381-394.
57. Yengoh GT, Ardö J. Climate change and the future heat stress challenges among smallholder farmers in East Africa. *Atmosphere* 2020,**11**:753.
58. Mulungu K, Ng'ombe JN. Climate change impacts on sustainable maize production in Sub-Saharan Africa: A review. *Maize Prod. Use* 2019:47-58.
59. D'Orangeville L, St-Laurent M-H, Boisvert-Marsh L, Zhang X, Bastille-Rousseau G, Itter M. Current Symptoms of Climate Change in Boreal Forest Trees and Wildlife. In: *Boreal Forests in the Face of Climate Change: Sustainable Management*: Springer; 2023. pp. 747-771.
60. Kramer RD, Ishii HR, Carter KR, Miyazaki Y, Cavaleri MA, Araki MG*, et al.* Predicting effects of climate change on productivity and persistence of forest trees. *Ecological Research* 2020,**35**:562-574.
61. Hartmann H, Bastos A, Das AJ, Esquivel-Muelbert A, Hammond WM, Martínez-Vilalta J*, et al.* Climate change risks to global forest health: emergence of unexpected events of elevated tree mortality worldwide. *Annual Review of Plant Biology* 2022,**73**:673-702.
62. Boisvert‐Marsh L, Périé C, de Blois S. Divergent responses to climate change and disturbance drive recruitment patterns underlying latitudinal shifts of tree species. *Journal of Ecology* 2019,**107**:1956-1969.
63. González de Andrés E. Interactions between climate and nutrient cycles on forest response to global change: The role of mixed forests. *Forests* 2019,**10**:609.
64. Gebeyehu MN, Hirpo FH. Review on effect of climate change on forest ecosystem. *International Journal of Environmental Sciences & Natural Resources* 2019,**17**:126-129.
65. Ganault P, Nahmani J, Hättenschwiler S, Gillespie LM, David J-F, Henneron L*, et al.* Relative importance of tree species richness, tree functional type, and microenvironment for soil macrofauna communities in European forests. *Oecologia* 2021,**196**:455-468.
66. Raju KS, Kumar DN. Impact of climate change on water resources. *Springer, Singapore.* 2018.
67. Brief U-WP. Climate change and water. In: UN Water: Geneva, Switzerland; 2019.
68. Melese SM. Effect of climate change on water resources. *Journal of Water Resources and Ocean Science* 2016,**5**:14-21.
69. Puntenney-Desmond KC, Bladon KD, Silins U. Runoff and sediment production from harvested hillslopes and the riparian area during high intensity rainfall events. *Journal of Hydrology* 2020,**582**:124452.

70. Paul MJ, Coffey R, Stamp J, Johnson T. A review of water quality responses to air temperature and precipitation changes 1: Flow, water temperature, saltwater intrusion. *JAWRA Journal of the American Water Resources Association* 2019,**55**:824-843.
71. Dessu SB, Price RM, Troxler TG, Kominoski JS. Effects of sea-level rise and freshwater management on long-term water levels and water quality in the Florida Coastal Everglades. *Journal of Environmental Management* 2018,**211**:164-176.
72. Bosserelle AL, Morgan LK, Hughes MW. Groundwater Rise and Associated Flooding in Coastal Settlements Due To Sea‐Level Rise: A Review of Processes and Methods. *Earth's Future* 2022,**10**:e2021EF002580.
73. Mulwa F, Li Z, Fangninou FF. Water scarcity in Kenya: current status, challenges and future solutions. *Open Access Library Journal* 2021,**8**:1-15.
74. Herrnegger M, Stecher G, Schwatke C, Olang L. Hydroclimatic analysis of rising water levels in the Great rift Valley Lakes of Kenya. *Journal of Hydrology: Regional Studies* 2021,**36**:100857.
75. Swinburn BA, Kraak VI, Allender S, Atkins VJ, Baker PI, Bogard JR*, et al.* The global syndemic of obesity, undernutrition, and climate change: the Lancet Commission report. *The lancet* 2019,**393**:791-846.
76. Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R*, et al. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*: Ipcc; 2014.