Environment, Development and Sustainability (2023) 25:1017–1051
https://doi.org/10.1007/s10668-022-02118-8

REVIEW

Climate change vulnerability and adaptation of crop producers in sub-Saharan Africa: a review on concepts, approaches and methods

Sisay Belay Bedeke[1]

Received: 4 June 2021 / Accepted: 2 January 2022 / Published online: 14 January 2022

Abstract

Climate change severely affects sub-Saharan African economies in several ways: increased temperatures, erratic rainfall variability patterns, and recurrent droughts and floods. Such adverse climate change effects may result in a greater incidence of crop pests, loss of soil moisture content, rapid soil nutrient depletion and substantial decreases in crop productivity and yields. These effects in combination with lack of access to improved, high-yielding crop varieties, limited agricultural extension services and poor access to irrigation infrastructure could further threaten access to food, limit export earnings and markedly lower net crop revenue. Several definitions, assessment approaches and methods for the concepts related to "vulnerability" and "adaptation" exist due to complex nature of climate impact and strategies used to deal with them. Based on the context of such studies, this paper reviews climate change risks, people's vulnerability to such risks as well as synthesize different approaches, methods and models used to assess vulnerability and adaptation in the area of agriculture in sub-Saharan Africa. As climate change effects are complex and site-specific, the understanding of several concepts, approaches and methods provides detailed information on farmers' vulnerability and adaptation process. Such information would be useful to inform adaptation interventions and agricultural policies that build farmers' resilience.

Keywords Adaptation analysis approach · Climate change · Crop production · Sub-Saharan Africa · Vulnerability assessment methods

1 Introduction

Food production must double by 2050 to meet the rising demand from the world's growing population. Farmers worldwide will need to increase food production by enhancing productivity on existing agricultural land in a sustainable way (Neufeldt et al., 2013; Myers et al. 2017; Pereira, 2017). However, agricultural productivity in developing countries is

---

✉ Sisay Belay Bedeke
belaysisay@gmail.com

[1] Department of Rural Development and Agricultural Extension, College of Agriculture, Wolaita Sodo University, PO Box 138, Sodo, Ethiopia

not improving fast enough to keep up with food demand, and subsequently resulting in food crises (Mall et al., 2017). Low levels of productivity are due, in part, to rapid natural resource degradation, limited investment in irrigation development and weak institutional systems (Campbell et al., 2014; Gachene et al., 2014; Niang et al., 2014). Climate change adds to these phenomena by negatively affecting crop production (AGRA, 2014), land use (Falco, 2014) and livelihood systems (Descheemaeker et al., 2016). Such change refers to a statistically significant change in the mean state of the climate and in its variability, which persists for an extended period (typically decades or longer) (Niang et al., 2014).

Although climate change is a global environmental phenomenon, its adverse impacts vary across geographical areas (Fellmann, 2012; Fisher et al., 2015; Gachene et al., 2014; Kotir, 2011). Sub-Saharan Africa (SSA) is particularly vulnerable to negative climate change impacts due to the fact that the major part of its land surface covers the tropics which are warm to hot year-round (Pereira, 2017) and the population depends largely on climate-sensitive sectors such as agriculture for their livelihoods (Niang et al., 2014). Limited financial capital, lack of access to physical infrastructure such as roads and public health services, poor access to information on weather forecasts and a paucity of improved technologies are exacerbating the SSA's climate change vulnerability by reducing capacity to cope with climate risks (Falco, 2014; Fisher et al., 2015; Mall et al., 2017). Severe land degradation and widespread deforestation as a result of human pressure are leading to agro-biodiversity loss and ecosystem service depletion, and subsequently contributing to climate change vulnerability (Kates et al., 2012; Kotir, 2011; Pereira, 2017).

The SSA economy is mostly driven by agriculture, which forms the basis for reducing rural poverty and ensuring food security (Khan & Akhtar, 2015; Kotir, 2011). Although SSA's agriculture generates about 95% of total crop produces sold in the domestic market and up to 85% of total export value (AGRA, 2014), climate change adversely affects crop production (Gachene et al., 2014). Climate change projections predict significant increases in atmospheric carbon dioxide and water vapour along with temperatures (Mall et al., 2017). In SSA, average temperatures have increased by 0.5 °C over the past century (Kotir, 2011) and are expected to increase more than 2 °C by the end of 2100 (Niang et al., 2014), which could cause extreme heat stress and soil moisture loss and hence induce significant plant cell damage (Khan & Akhtar, 2015) (Fig. 1).

Changes in precipitation have also a negative impact on crop production in SSA. Shi and Tao (2014) in the dryland areas of SSA indicated that decreases in rainfall are leading to significant crop yield declines and subsequent rises in food prices in the local market. Seasonal rainfall patterns across SSA are expected to show high levels of spatial and temporal variability (Gachene et al., 2014; Serdeczny et al., 2017), which could adversely affect the length of plant growth period, the cropping calendar and crop water requirements (Pereira, 2017; Simelton et al., 2011). Such patterns in combination with extreme heat stress are expected to further increase the frequency and intensity of droughts (AGRA, 2014; Kotir, 2011). Climate models indicate that the rainfall intensity in SSA is estimated to rise substantially, which could increase flood risks (Falco, 2014). In East Africa, increases in frequency of floods in combination with severe droughts are likely to result in low yields and poor access to sufficient food (Adimassu et al., 2017; Fisher et al., 2015; Khan & Akhtar, 2015). This in turn could lead to low household labour productivity and income inequality while perpetuating impoverishment and malnutrition in SSA (Conway & Schipper, 2011; Myers et al. 2017).

Vulnerability refers to the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including extreme events such as flood and drought (IPCC, 2007). SSA is highly vulnerable to climate change not only because of its exposure

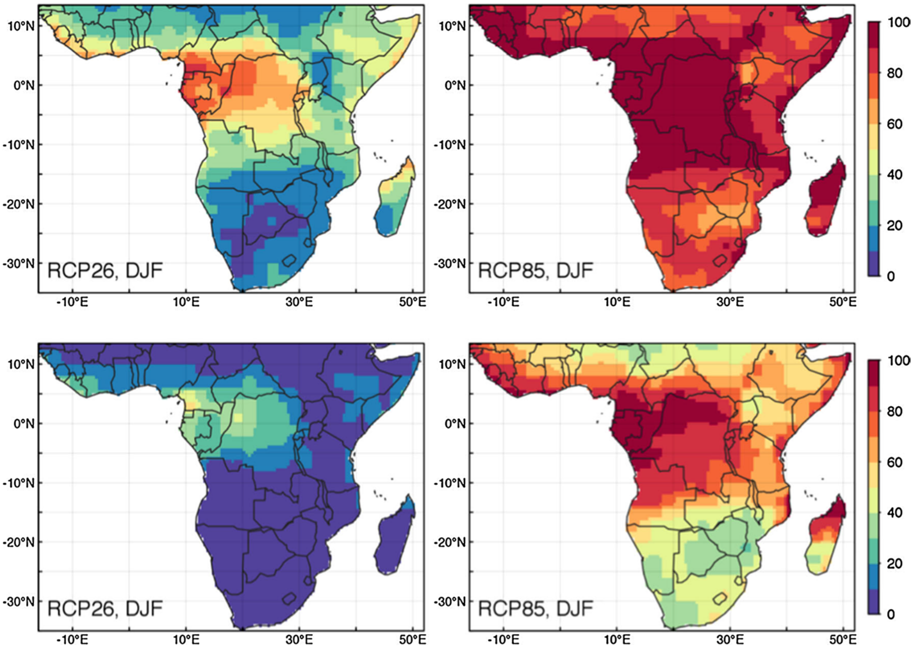

Fig. 1 Multi-model mean of the percentage of austral summer months in the time period 2071–2099 with temperatures greater than 3-sigma (top row) and 5-sigma (bottom row) for scenario RCP2.6 (left) and RCP8.5 (right) over sub-Saharan Africa

to extreme climate events but also due to poor capacity to adapt (CSA, 2016; Ferede et al., 2013). Key drivers of such vulnerability include limited income diversification, low access to irrigation, weak agricultural extension systems and poor access to improved technologies that influence farmers' livelihood (McSweeney et al., 2010; Echeverría & Tornton, 2016). In particular, farmers who are located in highly degraded areas and prone to droughts may be particularly vulnerable to climate change (Yirgu et al., 2013). Although climate change vulnerability may differ amongst different communities, strategic decisions to reduce such vulnerability often take at local level, making this scale appropriate for review (Antwi-Agyei et al., 2013; Hinkel, 2011; Preston et al., 2011). In Ethiopia, district is a strategic management unit in which federal financial and technological resources are allotted and local decisions are made. Thus, understanding multi-dimensional social and biophysical factors that drive vulnerability to climate change at the local level is of policy and practical interest (Panthi et al., 2015).

While mitigation is an important policy to deal with green-house gas (GHG) emissions (Cutter et al., 2009), adaptation is a key strategy to reduce climate change vulnerability (Niang et al., 2014). Farmers in SSA are developing and testing several strategies to adapt to climate change (Falco, 2014; Hisali et al., 2011; Kassie, Hengsdijk, et al., 2013; Kassie, Jaleta, et al., 2013). For example, farmers in dryland areas may adapt to frequent droughts by choosing drought-resistant and short-maturing crop varieties as well as modulating planting dates (Deressa et al., 2009; Descheemaeker et al., 2016). In Malawi, Simelton et al. (2013) showed that farmers delay seed sowing periods for three weeks to avoid early season dry spells that lead to soil moisture loss. Moreover, farmers may implement rainwater harvesting practices, mixed planting of trees with crops and soil moisture conservation practices to increase productivity while reducing harmful climate change effects (Reed et al., 2013; Vignola et al., 2015). Such adaptation strategies may vary with respect to climate change risks (Antwi-Agyei et al., 2016; Smit & Wandel, 2006). Strategies might also differ depending on location and the economic, political and institutional circumstances in which climate change stimuli are experienced and management decisions are made (Mimura et al., 2014; Pereira, 2017; Shiferaw et al., 2014). The IPCC (2007) made a case for more extensive adaptation by expressing the need for a deeper understanding of the drivers and processes of farmers' vulnerability. Moreover, understanding how farmers adapt to climate change is a key aspect in terms of national planning aimed at reducing vulnerability (Thornton & Herrero, 2014). Therefore, this study assesses farmers' climate change vulnerability and adaptation processes in SSA.

2 Climate change effects

2.1 Temperature trends

Climate change is one of the potent environmental factors affecting agricultural production and livelihood systems. The global average for air surface temperature shows a rising trend of 0.85 °C since 1950 (Mall et al., 2017). With this trend, the frequency of cold days, cold nights and frosts has decreased, whereas the frequency of hot days, hot nights and heat waves has increased (Kotir, 2011; Pereira, 2017). Africa is noted to be dry and hot with current trends showing more warmer spells than occurred 100 years ago (AGRA, 2014). Average temperatures in Africa are projected to rise substantially, particularly in arid and semi-arid regions (Khan & Akhtar, 2015). In the high-emission scenario with Representative Concentration Pathways (RCP)8.5, Africa's monthly summer temperatures reach 5 °C above the 1951–1980 baseline by 2100 (Niang et al., 2014). In the low-emission scenario with RCP2.6, African's summer temperatures increase until 2050 at about 1.5 °C above the 1951–1980 baseline (Serdeczny et al., 2017). Climate projections indicate that both the maximum and minimum temperatures over equatorial East Africa will rise and that there will be warmer days compared to the 1951. This warming will be more than one and half times the projected global mean temperature (Khan & Akhtar, 2015).

2.2 Precipitation patterns

Precipitation plays a significant role in shaping agriculture production and livelihood systems of communities in Africa. Although there has been an increase in precipitation intensity over the past two decades, overall rainfall has been decreasing in SSA, particularly in arid and semi-arid areas (Khan & Akhtar, 2015). For example, the average rainfall in western Sahel observed to have declined by 20–49% since the late 1960s (Kotir, 2011; Pereira, 2017). Seasonal and annual rainfall patterns are usually characterized by a high variability. Such variability is modulated by the influence of a large-scale atmospheric circulation that causes a serious hydrological imbalance (Khan & Akhtar, 2015). Under the high-emission scenario, a reduction in precipitation is likely in SSA, particularly in lowland areas by the end of the twenty-first century (Niang et al., 2014). As a result, seasonal water shortages along the river basins are expected. Climate models indicate an increasing precipitation in central Africa (Khan & Akhtar, 2015), declining rainfall in southern and western Africa (Kotir, 2011) and poorly specified outcome in eastern Africa (Conway & Schipper, 2011).

2.3 Extreme climate event

Drought poses one of the greatest natural hazards affecting one-third of communities in SSA. It accounts for 25% of all natural disasters on the continent that have occurred in 1960–2009 (Ayanlade et al., 2017; Shiferaw et al., 2014). Over the past four decades, droughts have mainly persisted in SSA, particularly in the Sahel region and southern Africa. Several East African countries, including Ethiopia and Kenya, have suffered severe droughts as a result of failed seasonal rainfall since 1950 (Khan & Akhtar, 2015). Climate projections indicate that SSA will experience prolonged droughts by the end of twenty-first century (Kotir, 2011). As a result, the area of highly drought prone, arid land is projected to increase by 60–90 million ha over SSA (Serdeczny et al., 2017). Moreover, flash floods are one of the greatest extreme hydrological events arising from tropical cyclones and severe storms. More heavy precipitation as a result of climate change is expected to cause dams and rivers to overflow and threaten riverside communities (AGRA, 2014; Kotir, 2011).

3 Climate change impacts on crop production

Increases in farmers' dependence on erratic seasonal rainfall and the high sensitivity of crops to extreme heat in SSA may indicate higher levels of exposure of agriculture to climate risks (Ayanlade et al., 2017; Shiferaw et al., 2014). Such risks may threaten agriculture by shortening the growing season, amplifying water shortages, increasing the incidence of diseases and weeds (Oppenheimer et al., 2014). In East Africa, maize yield per hectare has been declining over the past two decades because of extreme heat and frequent soil moisture loss (Ramirez-villegas & Thornton, 2015). The increase in heat conditions during growth phase of the maize leads to fewer and smaller plant organs, reduced light inception due to shortened crop life and altered carbon assimilation processes such as photosynthesis (Gachene et al., 2014; Serdeczny et al., 2017). Heat stress during flowering and grain filling stages of the maize may result in decreased grain count and weight (Lobell et al., 2011). Lack of soil moisture may lead to a shortening of crop germination stages, reductions in maize leaf area, and the closure of stomata to minimize water loss (Tesfaye et al., 2015).

Future climate change effects on maize outputs in SSA are expected to be negative (Fig. 2). In east Africa, upward temperature trends may well increase crop yields in highland areas, but it will lead to decrease in crop yields in lowland areas because of excessive heat (Tesfaye et al., 2015). Moreover, precipitation variability is expected to decrease water availability, reduce soil organic matter and threaten crop productivity. This could in turn adversely affect human capital assets such as the ability of working individuals, as it exacerbates food insecurity and accesses to household labour (Oppenheimer et al., 2014). It also negatively influences farmers' financial capital assets by driving up production costs (Reed et al., 2013), reducing net crop revenue (Bene et al., 2012) and inflating food prices in the local markets (Simelton et al., 2013).

Moreover, frequent drought and flood events have negatively affected people's livelihood by diminishing both farm and livestock production systems. Recurrent drought events alone have been accounted for 11.8% of agricultural GDP losses in eastern Africa over the

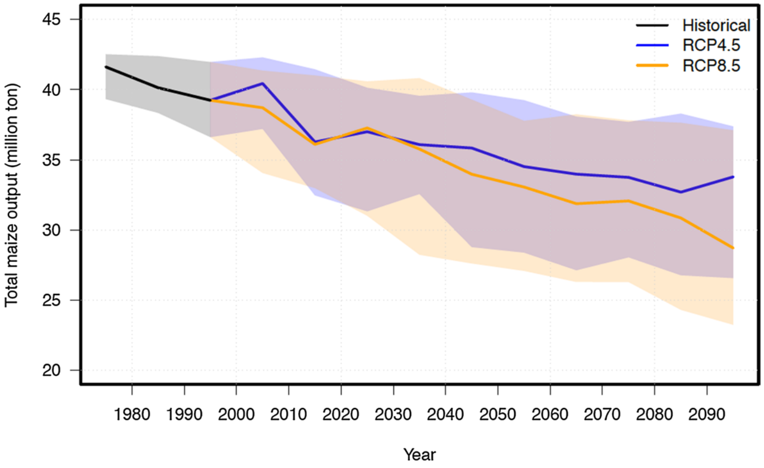

Fig. 2 Maize output projections at both intermediate (RCP4.5) and high (RCP8.5) emission pathways by the end of twenty-first century in SSA. Ramirez-villegas and Thornton (2015) *Source*: Adapted from

period 1999–2000 (Khan & Akhtar, 2015). Such losses have threatened Africa's development gains by markedly reducing its gross domestic product (GDP) (Shiferaw et al., 2014). Future extreme climate events are likely to influence the productivity of natural capital assets such as soil and forests on which people depend for their livelihoods. Increased soil erosion as a result of frequent floods is likely to result in substantial soil nutrient losses. These in turn might reduce crop productivity and yields and hence exacerbate food insecurity (Serdeczny et al., 2017). Floods are estimated to negatively affect social networks by disrupting pre-existing local self-support systems such as exchange of household labour, crop seed and farm equipment during crop failure (Pelling, 2011). It is expected that flood events will disrupt infrastructure such as roads, electricity, water supply systems, sanitation and health services, thus deepening people's susceptibility to climate risks (Oppenheimer et al., 2014). Erosion is predicted to cause a serious damage to terraces, micro-dams and roads. Climate projections show that recurrent flash floods in east Africa are likely to inflict substantial damage to terraces and plantations, which could result in frequent dislocation (Gachene et al., 2014; Serdeczny et al., 2017).

4 Climate change vulnerability

"Vulnerability" describes a central concept in a variety of research contexts. It has its roots in ecological fields linked to carrying capacity (Adger, 2006), but the term is now widely used in the social sciences, particularly in the poverty assessment (Füssel & Klein, 2006) and in socio-ecological research that examines the effect of climate change on livelihoods (Kok et al., 2016). Vulnerability to climate change is usually conceptualized with reference to a specific vulnerable situation. Such situation can be categorized into four major characteristics: (1) *vulnerable system*; (2) *hazard*; (3) *attributes of concern*; and (4) *temporal reference* (Füssel, 2007). The *vulnerable system* indicates a particular system, which is highly exposed to and negatively affected by climate change. A *hazard* is a potentially damaging climate change event that results in the loss of household property, disruption of livelihoods and degradation of agro-ecosystem services. For example, farmers operating in the arid areas are prone to droughts (a hazard) that results in poor productivity and production. *Attributes of concern* are features of the vulnerable system often threatened by a specific climate hazard. Examples of attributes of concern include public health, irrigation and crop production systems, all of which are highly sensitive to climate change. *The temporal reference* is the point in time when a vulnerable system and its attributes of concern are changed as result of climate change. The latter is especially relevant to assessing climate change vulnerability, which has a time horizon of several years, decades, or centuries (Füssel, 2007; Füssel & Klein, 2006).

Vulnerability to climate change can be described by *external* and *internal* dimensions (Brooks et al., 2005). The external dimensions of climate change vulnerability are biophysical conditions such as land degradation and desertification that affect specific farming and livelihood systems. In contrast, internal dimensions of climate change vulnerability are socio-economic factors such as financial constraints and poverty that reduce the capacity of a system to cope with a hazard. Each dimension is useful to assessing climate change vulnerability of agriculture. However, such dimensions may not be integrated into climate change vulnerability assessment as none of them complements others (Füssel, 2007). This is because of a failure to recognize other dimensions of climate change vulnerability such as *scale* and the *disciplinary domain* (Table 1). Scale describes the internal (in place) and external (beyond place) features of a particular vulnerable system to climate change (Downing & Patwardhan, 2005). For example, agricultural policies that promote landscape conservation practices can be regarded as i*nternal* for national-scale assessments and as *external* for local-scale assessments. This classification further depends on the knowledge domain that influences the choice of assessment approach to climate change vulnerability. Such an approach can be rooted either in physical sciences assessing biophysical vulnerability or in social sciences that explore socio-economic vulnerability to climate change (Füssel, 2007).

Vulnerability to climate change can also be understood through *outcome and contextual* factors.

4.1 Outcome vulnerability

Outcome vulnerability is a concept that considers vulnerability as the net climate change impacts on a specific system (either biophysical or social) after feasible adaptation are taken into account. Fellmann (2012) shows that outcome vulnerability is an end-point of analyses beginning with projection of future emission trends, moving on to the development

Table 1 Vulnerability dimensions classified according to scale and disciplinary domain. *Source*: Adapted from Füssel (2007)

Scale	Disciplinary domain	
	Socio-economic	Biophysical
Internal	Household income, size of social networks, access to information on climate change	Soil fertility level, land degradation rates, land cover change
External	National adaptation policies, international financial aid for agriculture, economic globalization	Severity of rainfall storms, frequency of drought, extent of sea level rise

of climate scenarios, and hence assessment of climate change effects and identification of adaption strategies. It typically focuses on biophysical features such as landscape conservation, soil nutrient management and soil moisture conservation as potential adaptation strategies to climate change. In SSA, Gachene et al., (2014) revealed that increased crop yields may be achieved by the combination of physical factors, including regular rainfall and improved soil fertility that enhance productivity. However, regarding the adaptive capacity, higher attention is given to biophysical components than socio-economic dimensions in which climate change effects occur (Kok et al., 2016; Nardo et al., 2014; O'Brien et al., 2007). As a result, the most vulnerable systems are those that are susceptible to potential climate hazard (Gallopín, 2006; Hinkel, 2011).

4.2 Contextual vulnerability

Contextual vulnerability refers to a situation in which specific production systems are unable to cope with and adapt to adverse climate change effects (Fellmann, 2012). This concept recognizes that climate change vulnerability is the starting point of socio-economic risks such as frequent conflicts and poverty and physical conditions, including soil nutrient loss and water scarcity (Cannon & Müller-Mahn, 2010; Eriksen & Kelly, 2007; Füssel, 2007). In Ghana, Antwi-Agyei et al. (2016) show that farmers' climate change vulnerability linked to limited access to sufficient food may not only be explained by poor soil fertility and low crop yields, but it is also influenced by untimely access to information on weather forecasts. Such a relationship shows that both outcome and contextual factors simultaneously contribute to climate change vulnerability in a specific production system and complement one another (O'Brien et al., 2007). This in turn provides wide-ranging information when one wants to assess climate change vulnerability and develop successful coping strategies that build resilience (Fellmann, 2012).

The IPCC's FAR is the first international scientific assessment in combining socio-economic dimensions with biophysical components of climate change vulnerability. According to the IPCC (2007), vulnerability is a function of exposure and sensitivity to climate change as well as the result of the adaptive capacity. Exposure to climate change is the degree and/or duration to which a system is subject to perturbation (Füssel, 2007). It shows the relationship between a system and the perturbation factors, rather than only the latter. The magnitude of this relationship depends on the sensitivity of a system that is subject to climate change (Gallopín, 2006). Sensitivity to climate change is the extent to which a system can absorb the impact of climate change without suffering long-term harm or other significant state changes. It shows the degree to which a system is affected, either adversely or beneficially, by climate change (IPCC, 2007). Smit and Wandel (2006) argued that sensitivity partly reflects the internal side of vulnerability to climate change and cannot be separated from exposure, i.e. the external side. Fellmann (2012) described sensitivity as the responsiveness of a system or the degree to which a specific agricultural system might be impacted in its actual form. As a result, both exposure and sensitivity indicate the potential impact that climate change can have on a vulnerable system (Fig. 3). However, a system that is highly exposed and sensitive to significant climate change events may not necessarily be vulnerable to changing conditions. Neither exposure nor sensitivity to climate change makes it possible to understand the capacity of a specific system to adapt to disturbance (Fellmann, 2012; Smit & Skinner, 2002; Smit & Wandel, 2006).

Adaptive capacity is a system's ability to respond to climate change, cope with its consequences and take advantage of beneficial opportunities (Cannon & Müller-Mahn,

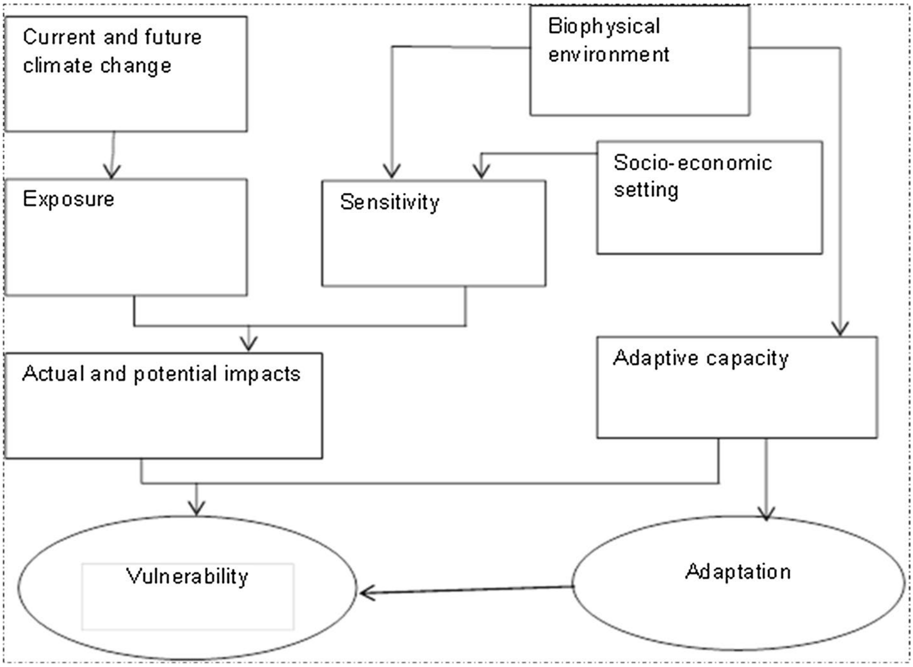

Fig. 3 Climate change vulnerability components. *Source*: adapted from Fellmann (2012)

2010; Füssel & Klein, 2006; Gallopín, 2006). It consists of risk management strategies such as the use of improved cattle breeds, increased access to micro-finance service and higher household income (Berman et al., 2012; Eakin & Luers, 2006). It also involves enhancing farm productivity by planting fodder trees that can provide shade for crops, maintain soil fertility and reduce frequent erosion. Cannon and Müller-Mahn (2010) showed us that it is not only the availability of strategies that reduce the vulnerability of a particular system to climate change, but also the ability of this system to cope with and adapt to changing conditions. This ability can be strengthened by increasing access to financial capital, developing strong policies and maintaining improved systems of governance that promote livelihood diversification and agro-ecosystem service conservation (Berman et al., 2012; Gentle & Maraseni, 2012). A system is vulnerable to a specific hazard if it is exposed and sensitive to this hazard, and if it has weak capacity to adapt to changing conditions (Fig. 3).

4.3 Classic approaches to vulnerability research

Vulnerability assessment approaches can differ according to the research domain ranging from physical sciences to social studies. Each approach provides means to understand a set of social and ecological factors contributing to climate change vulnerability in a particular system (Adger, 2006; Eriksen & Kelly, 2007). In the field of climate change, four assessment approaches exist: the *risk hazard*, *political economy of risks*, *sustainable livelihood* and *integrated assessment approaches* (Adger, 2006; Füssel, 2007; Turner et al., 2003).

4.3.1 Risk hazard approach

The risk hazard approach is useful to assessing the degree of risks caused by exposure to certain climate hazards that affect a specific vulnerable system (Füssel, 2007). This approach emerged in the late 1980s. It has been applied to assessing the impact of certain extreme climate events on ecological and human systems (Cannon & Müller-Mahn, 2010). It is mostly applied by engineers and economists who assess the sources, causes and effect of natural disasters such as earthquakes and landslides on the vulnerability of specific system to such events (Eakin & Luers, 2006; Füssel, 2007; Kok et al., 2016). A key aspect of the risk hazard approach is the distinction between two factors: (1) the "hazard", potentially damaging extreme climate events such as drought and flood (Smit & Wandel, 2006); and (2) the "risk", the probability of occurrence of such hazards on a specific vulnerable system and its damage levels (Füssel, 2007). In a semi-arid region of SSA, Kotir (2011) shows that climate change may result in more recurrent dry spells (hazard) by increasing the probability of occurrence of extreme heat that leads to water scarcity (risk). Shi and Tao (2014) make use of the risk hazard approach to assess the vulnerability of maize production system to climate change in SSA. The latter indicates that vulnerability of maize production system to climate change may not only be explained through exposure to extreme hot conditions, sporadic precipitation patterns and frequent droughts, but also influenced by levels of damage as result of such climate events. To this end, the risk hazard approach is a useful means for assessing climate change vulnerability linked to the nature and character of a specific hazard, its magnitude of impact and its damage levels (Cairns et al., 2013; Gachene et al., 2014). However, the risk hazard approach does not take into account the capacity of communities to deal with such risks. In fact, climate change vulnerability is not only the outcomes of the physical hazards, including built infrastructure, but also results of social and economic stresses on which such hazards occur. As a result, the risk hazard approach neglects socio-economic factors, including access to information on natural disaster early warning and availability of financial capital that shape the levels of damage by a hazard on a specific system (O'Brien et al., 2007).

4.3.2 Political economy of risk approach

The political economy of risk approach assesses climate change vulnerability by defining the state of people's ability to withstand any stresses placed on their livelihoods (Fellmann, 2012; Füssel, 2007). This approach emerged in the early 1990s. It largely focuses on the social and economic contexts in which the risks to a hazard can be explained and addressed (Füssel, 2007). Whilst its roots lay in development economics dealing with poverty reduction, food security and livelihood adaptation (Fellmann, 2012), this approach assesses the capacity of households to cope with and adapt to climate change (O'Brien et al., 2004). Antwi-Agyei et al. (2013) have characterized the nature of household vulnerability to climate variability: empirical evidence from two regions of Ghana using a political economy of risk approach. The study provided innovative methodological steps in relation to livelihood assessment to identify the vulnerability of households and communities to drought. Accordingly, vulnerability to climate change is an outcome of social and economic response capacities of a specific system to a variety of stresses. However, the political economy of risk approach does not focus on the system's exposure to external physical hazard such as forest fires and droughts (Cutter et al., 2009; Panthi et al., 2015).

Such a limitation results in an incomplete understanding of causes and sources of climate change vulnerability to inform coping strategies.

4.3.3 Sustainable livelihood approach (SLA)

SLA is useful to assess climate change vulnerability by providing detailed information on how households achieve their livelihood outcomes such as increased income and reduced poverty. These outcomes allow households to withstand social and environmental stresses (Antwi-Agyei et al., 2013; Scoones, 1998). Such stresses consist of seasonal rainfall fluctuation, poor soil fertility, frequent conflicts because of inadequate access to water and prolonged illness caused by disease epidemics, all of which contribute to climate change vulnerability. Climate change vulnerability within the context of SLA refers to the result of the susceptibility of a specific livelihood system to stresses and the system's ability to withstand shocks. In South Africa, Reid and Vogel (2006) applied SLA to assess a range of social and biophysical stresses linked to population pressure, land degradation and droughts that increase farmers' exposure to climate change risks whilst reducing their adaptive capacity. Improved access to livelihood capital stocks such as soil, land, water, forest and household income may help farmers develop adaptive capacity by reducing their susceptibility to climate change (Reed et al., 2013). In Ghana, Antwi-Agyei et al. (2016) used the SLA to identify social and physical factors, including plot size, access to microfinance service, educational levels and access to information on seasonal rainfall patterns that influence climate change vulnerability. They further indicated that the use of fertilizers and high-yielding crop varieties in combination with diversification of off-farm income sources helps farmers ensure livelihood security.

Of particular importance in SLA is the role of local institutions such as farmer organisations, women groups, and public as well as private agencies that mediate people's access to livelihood capital assets and strategies (Bene et al., 2012; Berman et al., 2012; Brooks et al., 2005). In a SLA, local institutions transform livelihood capital into potential strategies that help us to deal with changing conditions through fostering cooperation among communities affected by hazards (Reed et al., 2013). They influence key decisions towards livelihood adaptation to climate change by converting personal values of an individual into social norms, shared beliefs and common rules. For example, in a smallholder-managed irrigation system in Ethiopia, Bedeke and Beyene (2013) indicated that Water User Associations play a significant role to manage canals and regulate water allocation by enforcing shared rules that sustain their livelihoods. As a result, SLA recognises the involvement of communities and local institutions in assessing climate change vulnerability and developing coping strategies (Gentle & Maraseni, 2012; Reid & Faulkner, 2014; Smit & Wandel, 2006).

Despite the utility of SLA in assessing climate change vulnerability (Descheemaeker et al., 2016; Downing & Patwardhan, 2005; Gentle & Maraseni, 2012; Osbahr et al., 2008; Reed et al., 2013), the approach has been criticized for not taking into account temporal dimensions (Hinkel, 2011; Koch et al., 2007; Laube et al., 2012; Maleksaeidi & Karami, 2013). This is because climate change vulnerability is not only explained by the magnitude of extreme events, but also affected by the duration of occurrence of such events. Using the rainfall data of 1961–2011, Sutcliffe et al. (2016) analysed the effect of long-term past climate change events on maize producers' vulnerable to future droughts. First, they found that declined precipitation over the past two decades influences how maize production systems are sensitive to future climate change. Second, farmers' climate change vulnerability is the result of current ability to switch from rainfed agriculture to irrigation utilization based on their long-term past experiences in dealing with climate change. Although vulnerability of a specific household to climate change is always in a state of flux following dynamic social and environmental stresses (Antwi-Agyei et al., 2013), SLA only provides a snapshot of the assessment at a particular point in time. Thus, such an approach may not reflect the temporal variation with respect to past and future climate change that could destabilize the sustainability of livelihoods (Liverman, 1990; Smit & Skinner, 2002; Turner et al., 2003).

Moreover, SLA has been criticized for not addressing issues of equity in the distribution of livelihood assets, including landholding and water supply which influence capacity to withstand changing conditions (Adger et al., 2000; Crane et al., 2011; Eakin & Luers, 2006). This criticism is due to the failure of SLA to combine the role of power into accessing livelihood capital assets that influence the household decision-making capacity (Osbahr et al., 2008). In fact, social structure and priorities may generate the process of inclusion and exclusion, which result in unpredictable livelihood outcomes for some agents, which give rise to inequalities of power (Antwi-Agyei et al., 2013; Scoones, 1998). Pelling (2011) states that power plays a significant role in mediating the process of household income diversification and poverty reduction by regulating access to livelihood assets. Power relations influence for whom and where the impacts of changing conditions are felt and the scope for recovery. Hence, the inclusion of power in assessing how decision-making process developed could greatly enhance the use of SLA (Chhetri et al., 2012; Cuevas et al., 2015; Koch et al., 2007).

4.3.4 Integrated approach

The integrated approach is useful when one wants to combine the “internal” factors of a specific climate-vulnerable system together with its exposure to “external” hazards (Fellmann, 2012; Füssel, 2007). This approach emerged during the late 1990s. It has been widely used in fields ranging from environmental studies that deal with coupled human–environment (Bene et al., 2012; Eakin & Luers, 2006; Liverman, 1990) to socio-ecological research that addresses the relationship between ecosystem service, economic growth and societal development (Adger, 2006; Fellmann, 2012; O’Brien et al., 2004). In this approach, climate change vulnerability is a function of multi-dimensional interactions among different features of social and ecological systems. For example, in a specific rain-fed production system, farmers’ vulnerability to droughts is the result of erratic seasonal rainfall patterns, soil nutrient loss, substantial yield variability and low household income, all of which reduce their capacity to cope with changing conditions (Gachene et al., 2014). This means that combining multi-dimensional aspects of land use, food production and livelihood strategies into vulnerability assessments is critical for understanding how farmers are subjected to, and coping with ever-increasing climate change risks (Eakin & Luers, 2006).

Several studies have used an integrated approach to assess the climate change vulnerability of farming communities in developing world (Antwi-Agyei et al., 2013; Madhuri et al., 2014; Reed et al., 2013; Simane et al., 2014). By applying an integrated approach, Reed et al. (2013) described vulnerability to climate change as the result of the system’s susceptibility to a hazard and its ability to cope with such hazard. This shows that vulnerability to climate change has two components: (1) risk of exposure to different social and physical hazards and (2) ability of the population to cope with such hazards. Cannon and

Müller-Mahn (2010) indicated that farmers' vulnerability to climate change can be influenced by widespread crop disease/pest infestation, increased deforestation, a poor land tenure system and rampant corruption, all of which reduce their adaptive capacity. In Ghana, Antwi et al. (2015) used the integrated approach to assess the effect of biophysical factors and socio-economic stresses on climate change vulnerability. They suggested that such an approach is useful to identify context-specific physical processes such as soil fertility and irrigation infrastructure that interact with social conditions, including poverty and weak institutional system to exacerbate climate change vulnerability. Panthi et al. (2015) applied an integrated approach in Nepal to assess the climate change vulnerability of mixed crop-livestock producers by examining socio-economic factors such as household educational level, access to improved crop seeds, extent of family ties with social groups and local organizations, and the quality of both water supply and health services in combination with biophysical factors such as land size and soil fertility. Therefore, an integrated approach is useful to identify wide-ranging drivers of climate change vulnerability that provides detailed information to develop coping strategies (Füssel, 2007) and inform policies how to reduce hazards caused by changing conditions (Fellmann, 2012).

4.3.5 Vulnerability assessment methods

Vulnerability assessment methods are used to systematically integrate and examine interactions between humans and their physical and social surroundings. Several assessment methods have been developed to understand how communities are vulnerable to climate change and how they are coping with changing conditions. Most assessment methods allow researchers to identify climate-vulnerable locations, sectors and social groups and develop effective coping strategies that build resilience (Adger, 2006; Hinkel, 2011; Preston et al., 2011). Based on the characteristics of the vulnerable system, the type of stress and its effect on that system, three methods are widely applied to assess climate change vulnerability: *model-based*, *stakeholder-oriented* and *indicator methods* (Fellmann, 2012).

4.4 Model-based methods

Whilst providing a state-of-the-art understanding of global environmental systems (Fellmann, 2012; Füssel, 2007), model-based methods follow the concept of the risk hazard approach (Cannon & Müller-Mahn, 2010; Eakin & Luers, 2006). Such methods often use biophysical models to simulate the effect of future climate change on the natural environment. They include general circulation models predicting the nature and character of global temperatures and precipitation patterns (Cairns et al., 2013; Kassie, Hengsdijk, et al., 2013; Kassie, Jaleta, et al., 2013), crop models that simulate the relationship between climate, soils and crops in a specific location (Kotir, 2011; Lobell et al., 2011) and water scarcity models, which assess the effect of drought on water availability (Huang et al., 2017; Sullivan et al., 2002). In SSA, Gachene et al. (2014) used a model-based method to assess the sensitivity of crops to climate change risks. Using crop models, they predicted that agricultural yields will likely to decline by more than 10% by 2050 due to climate change. Increases in the inappropriate use of mineral fertilizers are expected to elevate nitrous oxide concentrations by more than 5–20% in the atmosphere. Moreover, increases in intra-seasonal rainfall variability are likely to result in poor soil nutrient, weed competition and diseases and/or pest infestation that could threaten crop productivity (Gachene et al., 2014). However, model-based methods only focus on a narrow set of physical variables such as moisture content, soil fertility and crop yields with limited attention to socio-economic factors, including access to improved sees, access to fertilizers and/or land size that influence production (Pelling, 2011).

Economic models estimating the effect of differential socio-economic risks on poverty are also useful to assess climate change vulnerability. In this model, vulnerability is defined as the likelihood that at a given time in the future, an individual will have a low level of welfare below some norm or bench mark. Although vulnerability assessment using economic models typically expresses welfare in terms of consumption, and the norm or bench mark as the poverty line, vulnerability encompasses multi-dimensional wellbeing (Hoddinott & Quisumbing, 2003). Moreover, vulnerability is a theoretical concept which cannot be measured by a few variables, but it can be quantified and predicted (Hinkel, 2011). Based on the type of hazard, the ability of a system to withstand this hazard and the temporal dimensions of the assessment, Hoddinott and Quisumbing (2003) identified three economic models: *vulnerability to expected poverty*, *vulnerability as low expected utility* and *vulnerability as uninsured exposure to risks*.

Vulnerability to expected poverty is the prospect of farmers to be poor if they are (not) being poor (Hoddinott & Quisumbing, 2003). According to this model, vulnerability to climate change is the outcome of expected poverty following limited household consumption. It analyses the probability that a given hazard keeps household consumption below a poverty line, which helps to discriminate poor from non-poor (Chaudhuri et al., 2002). Such a model allows us to understand how consumption losses cause vulnerability to expected poverty and what strategies are available and should be undertaken to withstand hazard risks. This model uses cross-sectional datasets gathered at a specific point in time in assessing household vulnerability to consumption losses. However, the use of such datasets neglects the temporal dimensions of vulnerability to expected poverty, i.e. its extension into future. This is because current consumption levels might not be a reliable indicator of future consumption levels and can provide incomplete information for designing strategies to reduce expected poverty (Hoddinott & Quisumbing, 2003).

In the Nile Basins of northern Ethiopia, Deressa (2010) assessed the vulnerability of farmers to climate extremes such as droughts, floods and hailstorms through the vulnerability to expected poverty model. The data were collected through a household survey of farmers over the period 2004–2005. Using this model, the latter author estimated the probability that a given shock or set of shocks will keep consumptions below a given minimum level (such as the consumption poverty line). Findings show that household vulnerability to poverty is substantially influenced by their minimum daily consumption requirement (poverty line). Results suggest that farmers in lowland locations (which are warm and semi-arid) are most vulnerable to consumption losses as a result of extreme climate events and socio-economic stresses, including shortage of ploughing oxen, diminishing land size, lack of access to micro-credit services and poor access to health facilities. Strategies such as sale of more livestock than usual, borrowing of food and/or cash, reduced meal size and seasonal migration that help households to cope with consumption falls are critical to reduce vulnerability to expected poverty. Hence, this model is useful to understand consumption dynamics caused by expected poverty and coping with such poverty (Chaudhuri et al., 2002).

Vulnerability to low expected utility indicates decreases in the utility of expected consumption expenditures compared to the utility of certain consumption expenditure levels at a specific point in time (Hoddinott & Quisumbing, 2003). This is because expected consumption loss caused by increased shocks contributes to the vulnerability of households to low expected utility by reducing welfare. So, it is desirable to have a measure of household welfare which takes into account both the utility of expected consumption and the risks households bear investing in such consumption. However, this model rarely combines the individual's risk preference linked to uncertain shocks into vulnerability assessment as he/she might be ill-informed about their preference (Chaudhuri et al., 2002).

Vulnerability as an uninsured exposure to risks indicates the extent to which a negative shock causes household welfare loss (Hoddinott & Quisumbing, 2003). Such shocks impose substantial reduction in household consumption and hence contribute to household vulnerability. This model assesses the vulnerability of a specific system to risks by calculating the amount and frequency of payments provided by insurance companies to withstand welfare loss. It is an *ex-post* (backward looking) assessment of the extent to which a negative shock causes a welfare loss rather than *an ex-ante* (forward looking) assessment of future poverty. This model uses *panel datasets* gathered over several time periods to analyze changes in household welfare due to negative shocks that influence their wellbeing. However, such datasets may not be readily available or accessible in developing countries due to poverty, lack of human capital and poor access to technological infrastructure. As a result, this model is not frequently used to assess household vulnerability to welfare losses caused by uninsured exposure to risks (Chaudhuri et al., 2002; Dercon et al., 2005).

4.5 Stakeholder-based methods

Stakeholder-based methods allow interactions with individuals and organizations in assessing climate change vulnerability (Eriksen & Kelly, 2007; Fellmann, 2012). Such methods can be used at several stages of assessments starting from identification of causes and sources of climate change vulnerability and developing coping strategies (Nardo et al., 2014). When sufficient data on the nature and character of climate change are not available at the local level, stakeholder-based methods offer an alternative source of information on household vulnerability to changing conditions (Singh & Nair, 2014). They foster our understanding on how households become vulnerable to social and biophysical risks that may be important to mitigate ever-increasing climate change events (Gentle & Maraseni, 2012). Such methods may help to involve farmers who are affected by climate change (in)directly and who have in-depth experience in dealing with changing conditions (Panthi et al., 2015). It thus helps us to translate causes and sources of farmers' climate change vulnerability into coping strategies that build livelihood resilience (Eriksen & Kelly, 2007).

One of the stakeholder-based methods widely used in assessing the vulnerability of farmers to climate change is the *climate vulnerability and capacity analysis* (Gentle & Maraseni, 2012; Wiggs, 2009). This method assesses the effect of multi-dimensional social and environmental stresses, including a decreasing soil organic matter content, prolonged drought, lack of access to drinking water and pasture, increased livestock deaths, limited access to irrigation, poor access to fertilizers and widespread deforestation on climate change vulnerability (Speranza et al., 2014). In so doing, this method characterizes household vulnerability to climate change by means of group interviews and discussions that help to produce results more acceptable by the stakeholders (Fellmann, 2012; Wiggs, 2009). Such techniques help when one wants to obtain detailed information about the individual's feelings, perceptions and experience in understanding and dealing with adverse climate change impact (Below et al., 2012).

Gentle and Maraseni (2012) applied the climate vulnerability and capacity analysis to assess the effect of climate change on the livelihood of local communities and their coping mechanisms in the remote mountainous of Nepal. Through the wellbeing lens, they predicted the duration, frequency and severity of climate change risks now and into the future. Focus group interviews and wealth ranking techniques were used to analyse the coping strategies of different wellbeing groups. Results show that irregular rainfall variability patterns and prolonged droughts have significantly challenged the livelihoods of a community that has experienced land degradation, food scarcity, lack of water supply services and increasing social inequality. Findings indicate that climate change is an additional burden to the poor people in the mountain communities that live in poverty. They suggested that adaptation should not be considered as an isolated strategy but rather as part of on-going development initiatives dealing with poverty, economic losses and environmental degradation.

However, results of the *climate vulnerability and capacity analysis* may not be generalizable to a large population as it deals with a limited number of participants (Singh & Nair, 2014). In the latter method, group discussions among households may be dominated by the power asymmetry and gender bias that predominate in the decision-making process and in turn exacerbate pre-existing inequality that in turn perpetuate poverty and climate change vulnerability (Gentle & Maraseni, 2012). However, this method may be useful for understanding how stakeholders identify social and physical factors that drive climate change vulnerability and how they develop coping strategies (Hinkel, 2011; Preston et al., 2011).

4.6 Indicator-based methods

Indicator-based methods are useful to assess climate change vulnerability through a set of proxy indicators. Such indicators are helpful when one wants to combine multi-dimensional biophysical and socio-economic attributes of a specific system into indices (Fellmann, 2012; Rottenburg et al., 2011). For example, the sustainability of a specific farm production system may be expressed by indicators linked to the state of system's productivity, size of yields and the level of net revenue that influence its capacity to withstand ongoing disturbance (Reed et al., 2013). Rottenburg et al. (2011) assess human development levels among nations using three indicators: life expectancy, educational attainment and gross domestic product (GDP) per capita that build resilience. Such indicators can also be used in combination with simulation models that predict possible future state of the vulnerable system at the national scale (Füssel & Klein, 2006; O'Brien et al., 2007; Rottenburg et al., 2011). However, collapsing simulation models into "simple" indicator function is, however, would mean that one disregards the more advanced knowledge available in the form of such models (Hinkel, 2011).

At the local scale, indicators are useful to assess and understand the nature of climate change vulnerability among individuals and households (Fellmann, 2012). Hinkel (2011) argued us that indicator-based methods are useful to identify the most vulnerable households, communities or sectors to climate change at the local scale where the underlying causes of vulnerability can be narrowly defined by few variables. Smit and Wandel (2006) describe that the main goal of an indicator-based method is not to rank the levels of vulnerability to climate change. Rather, the aim is to characterize the sources and drivers of climate change vulnerability, and so as to inform a specific policy aimed at developing coping strategies (Gallopín, 2006). With this in mind, indicator-based methods allow one to quantify social and biophysical drivers of climate change vulnerability using indices. Such methods are appropriate for local scales, where the complexity of social and biophysical factors contributing to climate change vulnerability can be manageable (O'Brien et al., 2007; Rottenburg et al., 2011). This in turn allows the comparison to be made between the climate change vulnerability of different households and communities. In so doing, indicators provide a means to understanding ways in which households and communities are subjected to, and unable to cope with ever-increasing climate change events (Cutter et al., 2009; Gallopín, 2006; Hinkel, 2011; Panthi et al., 2015).

However, the selection of indicators in assessing climate change vulnerability has been highly contested by several authors (Eriksen & Kelly, 2007; Fellmann, 2012; Füssel, 2010). This is because indicators are mostly selected and aggregated based on expert consultations. Although the latter is useful to identify several indicators, different experts may select and aggregate indicators differently, and as result, robust indices have not been developed (Hinkel, 2011). Kok et al. (2016) show that subjectivity biases involved in selecting and aggregating indicators through experts may distort the objectivity of indicators and hence influence the success of an index. Such biases occur due to the difference in professional background among experts and complex and context-specific nature of climate change vulnerability (Rottenburg et al., 2011). Aggregation of several indicators into a "single" index score depends on the extent to which indicators are developed with clear, spatial scale in mind because climate change vulnerability is a highly scale-specific phenomenon (Hinkel, 2011). Differences in scale may challenge the comparability of households through index scores (Füssel, 2010). This limitation leads to further difficulties in identifying households most vulnerable to climate change (Cutter et al., 2009; Hinkel, 2011; Panthi et al., 2015), and in developing strategies that help them to withstand shocks (Gallopín, 2006; Panthi et al., 2015).

Although indicators are useful to assess climate change impacts on a specific production system, they neglect the views of farmers negatively affected by climate change (Grothmann & Patt, 2005; Simelton et al. 2011; Woods et al., 2017). This is especially problematic when the effect of farmers' views towards climate change on their decisions to use any coping strategies varies significantly (Helgeson et al., 2012). Reducing climate change vulnerability may be influenced by how farmers find evidence of such change (Bandura, 2001; Linden, 2015) (Table 2).

This relationship calls for assessing climate change vulnerability from the perspective of farmers by recognizing their long-term knowledge on and experience with such change (Helgeson et al., 2012).

5 Climate change adaptation

Adaptation is a multi-faceted process that tries to fight adverse impacts caused by climate change. The climate change adaptation decisions that farmers take are unlikely to be considered separately from other agricultural development decisions (Eriksen & Kelly, 2007; Falco, 2014). This is because adaptation is not a discrete technical activity that should be undertaken only in response to climate change risks. Rather, it is a progressive strategy to deal with on-going environmental, economic and social processes (Kok et al., 2016; Mertz et al., 2009). For example, farmers' decisions to sustainably manage their crops, farm and livelihoods in drought-prone areas are not necessarily exclusive to climate change. Market risks, personal preference and changes in public policies may influence farmers' adaptation decisions to climate change (Smit & Skinner, 2002). In Malawi, Sutcliffe et al. (2016) showed that maize producers' adaptation decisions to erratic seasonal rainfall are substantially explained by access to information on weather forecasts over days or weeks. Such information has further relevance to the timing and frequency of agricultural operations

Table 2 A review of studies applying different approaches, methods and models on climate change vulnerability in Ethiopia

Context	Author	Approach	Method	Model
1. Vulnerability of maize-dependent smallholders to climate change in three districts of Ethiopia	Bedeke et al. (2018)	Integrated approach	Index-based and stakeholder-based method	Livelihood vulnerability index
2. Characterising the Nature of Household Vulnerability to Climate Variability: Empirical Evidence from Two Regions of Ghana	Antwi-Agyei et al. (2013)	Political-economy approach	Composite index approach	Livelihood vulnerability and capacity index
3. Perceived Stressors of Climate Vulnerability across Scales in the Savannah Zone of Ghana: A Participatory Approach	Antwi-Agyei et al. (2016)	Participatory approach	Stakeholder method	Participatory model
4. Small Scale Farmers' Vulnerability to Climatic Changes in Southern Benin: The Importance of Farmers' Perceptions of Existing Institutions	Boansi et al. (2017)	Integrated approach	Economic method	Econometric models
5. Agro-ecological-based smallholder farmer livelihoods' vulnerability to climate variability and change in Didesa Basin of Blue Nile River, northern Ethiopia	Chala et al. (2016)	Agro-ecology-based approach	Index-based methods	Livelihood vulnerability and adaptation index
6. Managing Vulnerability to Drought and Enhancing Livelihood Resilience in Sub-Saharan Africa: Technological, Institutional and Policy Options	Shiferaw et al. (2014)	Risk-hazard approach	Stakeholder-based method	

Table 2 (continued)

Context	Author	Approach	Method	Model
7. Vulnerability of African Maize Yield to Climate Change and Variability during 1961–2010	Shi and Tao (2014)	Risk-hazard approach	Biophysical methods	Crop and soil, climate models
8. Climate change vulnerability in Ethiopia: disaggregation of Tigray Region	Gebrehiwot and Van Der Veen (2013)	Political economy and sustainable livelihood approach	Index-based method	Factor analysis
9. Agro-ecosystem-specific climate vulnerability analysis: application of the livelihood vulnerability index to a tropical highland region of Est Africa	Simane et al. (2016)	Agro-ecology-based assessment approach	Index-based and stakeholder methods	Principal component analysis
10. Application of livelihood vulnerability index in assessing smallholder maize farming households' vulnerability to climate change in Brong-Ahafo region of Ghana	Adu et al. (2017)	Integrated approach	Composite index	Livelihood vulnerability index
11. An integrated risk and vulnerability assessment framework for climate change and malaria transmission in East Africa	Oyango et al. (2016)	Risk-hazard approach	Stakeholder-based method	Participatory model
12. Climate variability and households' vulnerability to food insecurity in Ethiopia: A Case Study of Boset District, East Shewa in Ethiopia	Moroda et al. (2018)	Integrated approach	Econometric method, Index method	Econometric models, process models

such as planting, weeding and harvesting practices. In fact, access to information on climate change risks promotes adoption of short-season maize cultivars, crop diversification and irrigation utilization. For long-run sustainability, the potential of such strategies may not be maintained when soils are depleted of plant nutrients as a result of lack of information on the frequency of flood and drought (Kassie et al., 2015). Changes in livelihood and land use systems may influence the adoption of soil and water conservation practices that reduce risks to climate threats (Adimassu et al., 2017). Hence, farmers' adaptation decisions and actions are usually made not in a "one-off manner", but through dynamic, on-going "trial-by-error" process (Pelling & High, 2005; Smit & Skinner, 2002; Smit & Wandel, 2006).

Adaptation in agriculture requires the involvement of key local stakeholders with different, yet often interrelated point of views on climate change (Mertz et al., 2009; Smit & Skinner, 2002). The latter includes individuals, groups or organisations that operate at the local level and have in-depth experience in dealing with climate change (Antwi et al., 2015). To successfully promote the adoption of climate change adaptation strategies such as the development of improved crop varieties, improved livestock breeds and irrigation utilization, it is necessary to recognize which players are involved and what roles they play (Gentle & Maraseni, 2012). Their knowledge on and experience with climate change risks is critical in taking adaptation decisions and actions. Indeed, local stakeholders can build a shared understanding of the sources, causes and effects of climate change and strategies to deal with these effects through continuous discussion with one another (Eriksen & Kelly, 2007; Fellmann, 2012). Such discussion helps them to analyse and identify priorities and pathways to develop adaptation strategies (Sutcliffe et al., 2016). For example, whilst it is the farmers' capacity to invest in water pumps that affect their decision to utilize irrigation, membership in water user associations is critical to regulate water supply and distribution systems (Bedeke & Beyene, 2013). Understanding stakeholders knowledge provides information on developing successful strategies to build household resilience (Singh & Nair, 2014; Sutcliffe et al., 2016).

Adaptation is a critical strategy to deal with climate change caused by global warming. Even if we mitigate the anthropogenic GHGs from the atmosphere by reducing their "sources" such as fossil fuels and transport as well as enhancing their "sinks", including forest and soil, world temperatures are expected to increase over the next century due to past emissions (Kotir, 2011; Lobell et al., 2011). It is not only useful to reduce exposure to risks of significant climate change, but also to cope with unavoidable damage. The United Nation through its Sustainable Development Goal (SDG) under 13 urges all nations to take actions to combat climate change by promoting the use of adaptation strategies (Tosun & Leininger, 2017). Under this goal, the adoption of adaptation strategies to climate change is regarded as a necessary complement to mitigation strategies. Such strategies include the use of multiple crop cultivars and utilizing complementarity of trees, crops and livestock that conserve soil nutrients, improve crop yields and reduce carbon dioxide and methane from the atmosphere (Descheemaeker et al., 2016; Eriksen & Kelly, 2007; Smit & Skinner, 2002; Smit & Wandel, 2006).

5.1 Characteristics of adaptation

There are huge varieties of strategies and practices that could be undertaken to combat climate change impact in SSA (Falco, 2014; Gbetibouo, 2009; Kotir, 2011). Such strategies vary from investment in technological innovations to agronomic and natural resource management practices (Mertz et al., 2009; Pelling, 2011). Technological development is principally the responsibility of public and private agencies that promote adaptation through, for example, crop development to increase their tolerance. The development of improved crop types, cultivars and hybrids through breeding and genetic modification has the potential to adapt to extreme heat waves, erratic rainfall patterns and droughts (Adimassu et al., 2014; Sutcliffe et al., 2016). There already exists several crops and varieties to deal with changing conditions in SSA (Adger et al., 2007; Below et al., 2012; Biagini et al., 2014), yet farmers should make choices on climate information sources when selecting such varieties (Asfaw et al., 2013; Boansi et al., 2017; Shiferaw et al., 2014). The latter includes the development of information system, which is capable to forecast weather conditions and timing of agricultural operations. Such information further enhances farmers' adaptive capacity with respect to farm production, land use and water supply systems (Boansi et al., 2017; Falco, 2014). Combining plant types, cultivars and hybrids together with improved livestock breeds has the potential to reduce climate change impacts (Wainaina et al., 2016). Contour terracing, construction of river diversions and water storage ponds reduce climate risks through decreasing runoff and erosion, improve the retention of nutrients and improve water uptakes by plants (Asfaw et al., 2013; Ndiritu et al., 2014). Moreover, promotion of conservation tillage through the use of crop residue may improve productivity by increasing soil moisture retention (Falco, 2014).

Climate change adaptation strategies can be classified in terms of their efficacy, purposefulness, duration and the scale at which they are implemented (Below et al., 2012; Boansi et al., 2017; Cairns et al., 2013; Eakin et al., 2014).

5.1.1 Efficacy

Based on efficacy, Grothmann and Patt (2005) identified three components of climate change adaptation: adaptation efficacy, self-efficacy and adaptation cost. *Adaptation efficacy* indicates an individual's beliefs in the capacity of current strategies to deal with future climate change risks. *Self-efficacy* refers to the individual's capacity to implement adaptation strategies on his or her own initiative. *Adaptation costs* are the financial costs needed to implement adaptation strategies. Adaptation efficacy is positively correlated with self-efficacy in the context of climate change, as individual's improved adaptation efficacy may lead to strong self-efficacy (Bandura, 2001; Linden, 2015). To illustrate, farmers who have improved capacity to obtain information on weather change are likely to develop their ability to use improved crop varieties that tolerate droughts. Increased adaptation costs may also lead to maladaptive strategies that exacerbate already existing social and environmental risks. Such strategies often reflect avoidance reactions such as threat denial, wishful thinking and fatalism to changing climate conditions (Kates et al., 2012; Monirul et al., 2014; Kassie, 2014; Ayal & Filho, 2017).

5.1.2 Purpose

Based on their purpose, climate change adaptation can be categorized as autonomous or planned. Autonomous adaptation strategies involve dealing with specific environmental and/or socio-economic risks in particular areas over a short period of time (Falco, 2014; Gbetibouo, 2009). For example, in the dryland areas, a farmer may decide to use improved crop varieties to help him/her cope with drought stress. Such strategies are triggered by market and welfare changes and carried out through individuals or private actors rather than public agencies (Hisali et al., 2011; Kates et al., 2012). Smit and Skinner (2002) described autonomous adaptation strategies as those practices that are undertaken by farmers without any pre-determined plan. Such strategies include changes in cropping dates, crop rotation and mixed crop-livestock production, among others. In contrast, planned adaptation strategies are the result of proposed policy decisions on the parts of public agencies. Such strategies are useful for dealing with likely impacts of climate change on a specific production system (Below et al., 2012; Boansi et al., 2017). Examples of planned adaptation strategies include investment in crop insurance schemes, improvement of disaster preparedness and forecast systems and development of irrigation infrastructure (Osbahr et al., 2008; Pelling, 2011). Hence, autonomous and planned adaptations mainly correspond with private and public forms of adaptation forms, respectively (Adger et al., 2007). The first category can complement the second, especially in areas where farmers and public agencies jointly implement adaptation strategies. For example, the use of irrigation water can be an autonomous practice for farmers affected by frequent droughts and dry spell events, but this practice can also be a planned strategy undertaken and/or sponsored by public and/or private agencies that regulate maintenance and water distribution (Kotir, 2011). As a result, private and public adaptation options are not necessarily independent of one another and are often have interdependent roles in adaptation process (Biagini et al., 2014; Eakin et al., 2014; Fellmann, 2012).

5.1.3 Duration

Adaptation to climate change can be categorized as reactive and proactive strategies based on the duration of climate risk occurrence (Smit & Skinner, 2002). On the one hand, reactive adaptation strategies are *expost* measures, which can be undertaken as climate change risks are felt by farmers in a specific area. Such strategies include the selling of livestock, purchasing of feed, reducing household food consumption and migration from rural to urban areas in search of works (Smit & Wandel, 2006). On the other hand, proactive adaptation strategies are *ex-ante* adjustments in farm operations and/or livelihood systems to expected climate change risks. The latter strategies include livelihood diversification, use of drought-resistant crop varieties and rainwater harvesting practices (Biagini et al., 2014). However, proactive climate change adaptation strategies can be reactive and vice versa (Smit & Skinner, 2002). For example, a farmer who is susceptible to recent drought that adversely affects his/her yields and expects that such an effect continues to increase in future, may use drought-resistant crop varieties to on-going climate change risks (Nhemachena et al., 2014). Consequently, the demarcation line of reactive and proactive adaptation strategies may be blurred (Adger et al., 2007).

5.1.4 Scale

Climate change adaptation strategies can also be categorized in terms of a specific scale at which they are undertaken (Adger et al., 2007; AGRA, 2014; Biagini et al., 2014). Such strategies range from climate change adaptation strategies implemented at the national scale to the local scale. Some of the national-scale adaptation strategies to climate change include changes in agricultural policies, investment in climate-resilient development interventions and promotion of sustainable water supply systems (Descheemaeker et al., 2016). Local-scale adaptation strategies are a range of crop, farm and livelihood management practices undertaken by farmers alone or in collaboration with private and/or public agencies. In Tanzania, Below et al. (2012) identified several (types of) local-scale adaptation strategies, including the use of improved crop cultivars, terracing, irrigation water utilization and changes in the timing of operations. Such strategies may help farmers substantially reduce exposure to significant climate change events whilst increasing their adaptive capacity (Biagini et al., 2014; Pelling, 2011; Smit & Skinner, 2002).

5.2 Approaches to the analysis of adaptation

Analyses of adaptation in the climate science emerged simultaneously with the growing awareness of climate change itself. Adaptation to climatic change can be analysed through four approaches: *climate impact assessment*, *potential adaptation analysis*, *adaptive capacity assessment* and *actual adaptation analysis* (Pelling, 2011; Smit & Wandel, 2006).

The impact assessment approach analysis the extent to which modelled impacts of climate change scenarios could be mitigated by adaptation (Smit & Skinner, 2002; Smit & Wandel, 2006). Such an approach compares the effect of adaptation on a specific system relative to the estimated climate change impacts on this system under a particular emission scenario (Smit & Skinner, 2002; Smit & Wandel, 2006). It is in line with the UNFCCC's Article 2.1, which commits all countries to mitigate "dangerous" anthropogenic GHG emissions by reducing their causes and sources (IPCC, 2007). Here, adaptation refers to the degree to which countries' can moderate or reduce negative climate change impacts, or realize positive effects, to avoid the danger. Such analysis can be undertaken at the global- and regional-scale where models can be used to estimate climate change impacts with(out) adaptation under specific emission scenarios (Cairns et al., 2013; Eakin et al., 2014). Hence, the term "impact assessment" describes an estimated net result of climate change impacts after adaptation and/or mitigation strategies are taken place. Although vulnerability to climate change depends on present adaptation, this approach rarely identifies adaptation strategies nor does it examines an adaptation process that strengthens people's capacity to deal with ever-increasing climate events (Falco, 2014).

The potential adaptation analysis approach evaluates the expected impact of adaptation strategies on a specific system subjected to climate change risks. Given that increases in adaptation costs and low net revenues are often regarded as a constraint to the adoption of adaptation strategies (Kates et al., 2012; Kotir, 2011), this approach identifies potential sets of strategies to deal with ever-increasing climate change events (Smit & Wandel, 2006). This approach addresses the UNFCCC's report Article 4.1, which commits member countries to "formulate and implement measures to provide adequate and potential adaptation strategies" (IPCC, 2007). Whilst helping when one wants to examine the relative merit, effectiveness and utility of adaptation, this approach identifies potential strategies that could reduce adverse climate change impacts and enhance people's adaptive capacity. Such strategies are distinct in nature and they can be subjected to economic evolution using cost–benefit and cost-effectiveness analyses through which adaptations are evaluated (Smit & Skinner, 2002). The evaluation of climate change adaptation needs to be considered as part of an ongoing assessment of vulnerability in the context of multiple risks. Although the focus of this approach is to identify and promote potential adaptation strategies, it rarely explores the processes in which they are implemented, either in light of climatic change or as part of the development policy and decision-making process (Füssel, 2007; Smit & Wandel, 2006).

The adaptive capacity assessment approach examines the relative ability of specific households, groups, communities and sectors to cope with changing climate conditions using indicators (Füssel & Klein, 2006; Hinkel, 2011; O'Brien et al., 2007). These indicators combine and quantify multi-dimensional socio-economic and physical factors that influence adaptive capacity into a specific index. This in turn allows when one wants to compare the extent of the available adaptive capacity among households. In so doing, this approach promotes the targeting of scarce economic and physical resources to cope with, recover from and adapt to changing conditions (Adger et al., 2005; Reed et al., 2013). This approach is in line with the UNFCCC's Article 4.4 that commits parties in developed countries to "assist developing countries that are particularly vulnerable to climate change" (IPCC, 2007). Adaptation efforts should be directed towards households with the highest levels of exposure to significant climate change events and with the least adaptive capacity (Callo-concha, 2016). Although this approach analyses sources and causes of adaptive capacity and hence vulnerability in a specific system, it does not explore climate change adaptation barriers and drivers that shape the adaptation decision-making process (Smit & Wandel, 2006) (Table 3).

The actual adaptation approach is the analysis of adaptation process that enhances the capacity of a specific community or household to deal with climate change. This includes the identification of the existing adaptation strategies tailored to the needs of the particular community (Osbahr et al., 2008). Here, the purpose of the such identification is neither to score the efficacy of each adaptation strategy (Eakin & Luers, 2006) nor to quantify the magnitude of future climate change impacts (Falco, 2014). Rather, the goal is to understand how climate change adversely affects a particular system as well as how this system adapts to changing conditions (Below et al., 2012; Fisher et al., 2015; Hisali et al., 2011). Eakin and Luers (2006) describe actual adaptation analysis as a "bottom-up approach" examining adaptation process at the local scale, opposing to a "top-down approach" that analysis adaptation process at the national scale. In SSA, there exist several examples of actual adaptation strategies, such as conservation agriculture through crop rotation and use of animal manures (Osbahr et al., 2008), investment in irrigation infrastructure (Falco et al., 2012), use of organic and inorganic fertilizers (Kassie, 2014), household livelihood diversification (Eakin & Luers, 2006) and mixed leguminous tree-crop planting (Reid & Faulkner, 2014). Each strategy helps farmers to reduce adverse climate change effects as well as strengthen their adaptive capacity by increasing productivity and building resilience (Gallopín, 2006; Mertz et al., 2009; Pelling, 2011).

6 Conclusions

Our review showed that climate change in SSA is often felt through increased temperatures, more erratic precipitation patterns and more frequent extreme events such as drought and flood. Such events largely affect communities that are particularly susceptible to changing conditions and have limited adaptive capacity due to poverty, financial constraint and malnutrition. Farmers' climate change vulnerability is influenced by multiple social, economic and biophysical factors. Such multi-dimensional factors' that contribute to a particular system's vulnerability to a specific hazard can be present at a varying extent. Vulnerability is a function of exposure and sensitivity to climate change as well as the result of the adaptive capacity. Exposure to climate change is the degree to which a specific system is subjected to perturbation. Sensitivity to climate change is the extent to which a system is either adversely or beneficially affected by climate change. In contrast, adaptive capacity is a system's ability to respond to climate change, cope with its consequences and take advantages

Table 3 Review of studies applying different approaches and methods on climate change adaptation in Ethiopia

Context	Author	Approach	Method used
1. Ex-ante adaptation strategies for climate challenges in sub-Saharan Africa: Macro- and micro-perspectives	Rahut et al. (2021)	Actual and potential adaptation assessment	Econometric and statistical methods
2. Determinant factors of climate change adaptation by pastoral/agro-pastoral communities and smallholder farmers in sub-Saharan Africa	Menghistu et al. (2020)	Actual adaptation assessment	Econometric methods
3. Adaptation and resilience to climate change and variability in northeastern Ghana	Tambo (2016)	Actual adaptation assessment approach	Econometric methods
4. Climate Change in Sub-Saharan Africa: A menace to Agricultural productivity and Ecological protection	Ibe and Amikuzuno (2019)	Actual adaptation assessment approach	Participatory methods
5. Adaptation to climate change and other stressors among commercial and small-scale South African farmers	Wilk et al. (2013)	Actual adaptation assessment approach	Econometric model
6. Agro-ecology matters: impacts of climate change on agriculture and its implications for food security in Ethiopia	Ferede et al. (2013)	Impact assessment and potential adaptation assessment approach	Comparative method
7. Comparative analysis of maize-based livelihoods in drought-prone regions of Eastern Africa (Ethiopia): adaptation lessons for climate change	Erenstein et al. (2011)	Adaptive capacity assessment	Comparative methods
8. Determinants of farmers' choice of adaptation methods to climate change in Nile Basin of Ethiopia	Deressa et al. (2009)	Adaptive capacity assessment approach	Econometric method
9. Estimating the impact of climate change on agriculture in Low-income Countries: household-level evidence from the Nile Basin, Ethiopia	Falco et al. (2012)	Impact assessment approach	Statistical method
10 Farmers' adaptation to climate change in Chivi District of Zimbabwe	Mudzonga (2012)	Adaptive capacity assessment approach	Econometric methods
11. Farmers' decisions to adapt to climate change under various property rights: a case study of maize farming in northern Benin	Yegbemey et al. (2014)	Actual and potential adaptation assessment approach	Econometric method

Table 3 (continued)

Context	Author	Approach	Method used
12. Farmers' strategies to perceived trends of rainfall and crop productivity in the Central Rift Valley of Ethiopia	Adimassu et al. (2014)	actual adaptation assessment approach	Participatory and econometric methods
13. Rural organizations and adaptation to climate change and variability in rural Kenya	Washington-ottombre and Pijanowski (2013)	Institutional adaptation analysis approach	Participatory method
14. The influence of climate variability and climate change on the agricultural sector in East and Central Africa: Sensitizing adaptation strategic plan to climate change	Van de Steege (2019)	Adaptive capacity assessment approach	Stakeholder analysis method
15. The perception of and adaptation to climate change in Ghana by small scale and commercial farmers	Yaro (2013)	Actual and potential assessment approach	Econometric method
16. Tradeoffs and complementarities in the adoption of improved seeds, fertilizers and natural resource management technologies in Kenya	Wainaina et al. (2016)	Actual adaptation assessment approach	Econometric method

of beneficial opportunities. By analysing the complex processes that make communities vulnerable to past and current climate hazard events, it is possible to build our understanding of how they cope with these processes and prepare for future risks. Assessment of vulnerability to climate change is the first step in developing successful coping strategies that build people's resilience.

Farmers' perceptions of climate change often describe their long-term knowledge and experience with extreme climate events that affect their livelihoods. This means that farmers' perceptions are linked with how they respond to climate change risks that affect adaptation decisions. Responding to climate change requires three basic steps: (1) noticing shifts in one's external environment; (2) evaluating whether these shifts need actions; and (3) undertaking actions. However, even when farmers find evidence that global climate change is occurring, this does not necessarily translate into high-risk appraisal at the local level. Although farmers perceive climate change in terms of increased temperatures and declined rainfall, they may believe that global climate change impacts are occurring elsewhere, far in future, or both. Understanding farmers' perceptions of climate change provides information on how to develop adaptation strategies.

Adaptation is a multi-faceted process that tries to combat adverse climate change impacts. There are various actors and scales involved in adaptation processes. Some adaptations are undertaken by individuals in response to the climate change, often triggered by a specific extreme event. Others are undertaken by public agencies on behalf of society. Adaptation strategies can occur at the national scales through changes in physical infrastructure and planning systems. These strategies are also part of socio-economic, cultural and political processes, within which agricultural production decisions are made on an ongoing, "incremental" fashion. As a result, adaptation can be viewed as a range of social and ecological adjustments to actual and expected climate stimuli and their effects. As a result, integrating different methods and approaches to address climate change vulnerability and adaptation is essential to generate context-specific information on agriculture. Such information would be useful to inform adaptation interventions and agricultural policies that build farmers' resilience.

References

Adger, W. N., Arnell, N. W., & Tompkins, E. L. (2005). Successful adaptation to climate change across scales *15*, 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005.

Adger, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., & Takahashi, K. (2007). *Assessment of adaptation practices, options, constraints and capacity*. *climate Change 2007: Working group III: Mitigation of climate change*. https://doi.org/10.1017/CBO9781107415324.004.

Adger, N. W., Adger, W. N., & Adgar, W. N. (2000). Social and ecological resilience: Are they related? *Progress in Human Geography, 3*(3), 347–364. https://doi.org/10.1191/030913200701540465

Adger, W. N. (2006). Vulnerability. *Global Environmental Change, 16*(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Adimassu, Z., Kessler, A., & Stroosnijder, L. (2014). Farmers' strategies to perceived trends of rainfall and crop productivity in the central rift valley of Ethiopia. *Environmental Development, 11*, 123–140. https://doi.org/10.1016/j.envdev.2014.04.004

Adimassu, Z., Langan, S., Johnston, R., Mekuria, W., & Amede, T. (2017). Impacts of soil and water conservation practices on crop yield, run-off, soil loss and nutrient loss in Ethiopia : Review and synthesis. *Environmental Management, 59*, 87–101. https://doi.org/10.1007/s00267-016-0776-1

Adu, D. T., Kuwornu, J. K. M., & Anim-somuah, H. (2017). Kasetsart Journal of Social Sciences Application of Livelihood Vulnerability Index in assessing smallholder maize farming households' vulnerability to climate change in Brong-Ahafo region of Ghana. *Kasetsart Journal of Social Sciences, 4210*(14), 1–11. https://doi.org/10.1016/j.kjss.2017.06.009

AGRA. (2014). *African agriculture status report: Climate chnage and smallholder agriculture in sub-Saharan Africa. Aliance for a green revolution in Africa (AGRA)*. Nirobi, Kenya. https://ccafs.cgiar.org.

Antwi, E. K., Boakye-Danquah, J., Owusu, A. B., Loh, S. K., Mensah, R., Boafo, Y. A., & Apronti, P. T. (2015). Community vulnerability assessment index for flood prone Savannah agro-ecological zone: A case study of Wa West District, Ghana. *Weather and Climate Extremes, 10*, 56–69. https://doi.org/10.1016/j.wace.2015.10.008

Antwi-Agyei, P., Dougill, A. J., Fraser, E. D. G., & Stringer, L. C. (2013). Characterising the nature of household vulnerability to climate variability: Empirical evidence from two regions of Ghana. *Environment, Development and Sustainability, 15*(4), 903–926. https://doi.org/10.1007/s10668-012-9418-9

Antwi-Agyei, P., Quinn, C. H., Adiku, S. G. K., Codjoe, S. N. A., Dougill, A. J., Lamboll, R., & Dovie, D. B. K. (2016). Perceived stressors of climate vulnerability across scales in the Savannah zone of Ghana: A participatory approach. *Regional Environmental Change*. https://doi.org/10.1007/s10113-016-0993-4

Asfaw, S., Mccarty, N., Lipper, L., & Arslan, A. (2013). 144- Adaptation to climate change and food security. In *4th International conference of the African asssociation of agricultural economics*. Hammamet Tunisia.

Ayal, D. Y., & Filho, W. L. (2017). Farmers' perceptions of climate variability and its adverse impacts on crop and livestock production in Ethiopia. *Journal of Arid Environments, 140*, 20–28. https://doi.org/10.1016/j.jaridenv.2017.01.007

Ayanlade, A., Radeny, M., & Morton, J. F. (2017). Comparing smallholder farmers' perception of climate change with meteorological data: A case study from Southwestern Nigeria. *Weather and Climate Extremes,* 15 (December 2016): 24–33. https://doi.org/10.1016/j.wace.2016.12.001.

Bandura, A. (2001). Socio-congtive theory: An agentic perspective. *Annual Review of Pschology, 52*, 1–26. www.arjournals.annualreviews.org.

Baudoin, M., Sanchez, A. C., & Fandohan, B. (2013). Small scale farmers' vulnerability to climatic changes in Southern Benin: The importance of farmers' perceptions of existing institutions. *Mitig Adapt Strateg Glob Change*. https://doi.org/10.1007/s11027-013-9468-9

Bedeke, S. B., & Beyene, F. (2013). Small-scale irrigation and household income linkage: Evidence from Deder District, Ethiopia. *African Journal of Agricultural Research, 8*(34), 4441–4451. https://doi.org/10.5897/AJAR12.1793

Bedeke, S., Vanhove, W., Wordofa, M., Natarajan, K., & Van Damme, P. (2018). Vulnerability to climate change among maize-dependent smallholders in three districts of Ethiopia. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-018-0215-y

Below, T. B., Mutabazi, K. D., Kirschke, D., Franke, C., Sieber, S., Siebert, R., & Tscherning, K. (2012). Can farmers' adaptation to climate change be explained by socio-economic household-level variables? *Global Environmental Change, 22*(1), 223–235. https://doi.org/10.1016/j.gloenvcha.2011.11.012

Below, T. B., Schmid, J. C., & Sieber, S. (2014). Farmers' knowledge and perception of climatic risks and options for climate change adaptation: A case study from two Tanzanian villages. *Regional Environmental Change, 15*(7), 1169–1180. https://doi.org/10.1007/s10113-014-0620-1

Bene, C., Godfrey-Wood, R., Newsham, A., & Davies, M. (2012). *Resilience: New Utopia or New Tyranny? Reflection about the Potentials and Limits of the Concept of Resilience in Relation to Vulnerability Reduction Programmes*. *IDS Working Paper*. Vol. 2012. https://doi.org/10.1111/j.2040-0209.2012.00405.x.

Berman, R., Quinn, C., & Paavola, J. (2012). The role of institutions in the transformation of coping capacity to sustainable adaptive capacity. *Environmental Development, 2*(1), 86–100. https://doi.org/10.1016/j.envdev.2012.03.017

Biagini, B., Bierbaum, R., Stults, M., Dobardzic, S., & Mcneeley, S. M. (2014). A typology of adaptation actions: A global look at climate adaptation actions financed through the global environment facility. *Global Environmental Change* 25 (November 2013): 97–108. https://doi.org/10.1016/j.gloenvcha.2014.01.003.

Boansi, D., Tambo, J. A., & Müller, M. (2017). Analysis of farmers' adaptation to weather extremes in West African Sudan Savanna. *Weather and Climate Extremes, 16*(March), 1–13. https://doi.org/10.1016/j.wace.2017.03.001

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., & Yanda, P. (2007). *Africa. Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*. https://doi.org/10.2134/jeq2008.0015br.

Brooks, N., Neil Adger, W., & Mick Kelly, P. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change, 15*(2), 151–163. https://doi.org/10.1016/j.gloenvcha.2004.12.006

Bryan, E., Deressa, T. T., Gbetibouo, G. A., & Ringler, C. (2009). Adaptation to climate change in Ethiopia and South Africa: Options and constraints. *Environmental Science and Policy, 12*(4), 413–426. https://doi.org/10.1016/j.envsci.2008.11.002

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C., & Prasanna, B. M. (2013). Adapting Maize Production to Climate Change in Sub-Saharan Africa. *Food Security, 5*(3), 345–60. https://doi.org/10.1007/s12571-013-0256-x

Callo-concha, D. (2016). West African farmers' climate change adaptation: From technological change towards transforming institutions. In W. Leal Fi (Ed.), *Implementing climate change adaptation in cities and communities*. Bonn: Climate Change Management. https://doi.org/10.1007/978-3-319-28591-7.

Campbell, B. M., Thornton, P., Zougmoré, R., van Asten, P., & Lipper, L. (2014). Sustainable intensification: What is its role in climate smart agriculture? *Current Opinion in Environmental Sustainability, 8*, 39–43. https://doi.org/10.1016/j.cosust.2014.07.002

Cannon, T., & Müller-Mahn, D. (2010). Vulnerability, resilience and development discourses in context of climate change. *Natural Hazards, 55*(3), 621–635. https://doi.org/10.1007/s11069-010-9499-4

Dechassa, C., Simane, B., Alamirew, B., & Azadi, H. (2016). Agro-ecological based small- holder farmer ' s livelihoods vulnerability to climate variability and change in Didesa Sub Basin of Blue Nile River, Ethiopia. *Academia Journal of Agricultural Research, 4*(5), 230–240. https://doi.org/10.15413/ajar.2016.0150.

Chaudhuri, S., Jalan, J., & Suryahadi, A. (2002). Assessing household vulnerability to poverty from cross-sectional data: A methodology and estimates from Indonesia. *World* 0102–52 (April): 1–36.

Chhetri, N., Chaudhary, P., Tiwari, P. R., & Yadaw, R. B. (2012). Institutional and technological innovation: Understanding agricultural adaptation to climate change in Nepal. *Applied Geography, 33*(1), 142–150. https://doi.org/10.1016/j.apgeog.2011.10.006

Climate change and livelihoods in Northwest Bangladesh: Vulnerability and adaptation among extremely poor people University of Sussex. n.d.

Conway, D., & E. Lisa F Schipper. (2011). Adaptation to climate change in Africa: Challenges and opportunities identified from Ethiopia. *Global Environmental Change, 21*(1), 227–237. https://doi.org/10.1016/j.gloenvcha.2010.07.013

Crane, T. A., Roncoli, C., & Hoogenboom, G. (2011). Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. *NJAS—Wageningen Journal of Life Sciences, 57*(3–4), 179–185. https://doi.org/10.1016/j.njas.2010.11.002

CSA. (2016). Report on area and production of major crops. The Federal Democratic Republic of Ethiopia Central Statistical Agency. *Statistical Bulletin*. Vol. 584. Addis Ababa. http://www.csa.gov.et/.

Cuevas, S. C., Peterson, A., & Tiffany, M. (2015). *An analytical framework for investigating complex institutions in climate change adaptation: The institutional environment matrix*. Edited by W. Leal Filho (Ed.). St. Lucia, Australia. https://doi.org/10.1007/978-3-642-38670-1.

Cutter, S. L., Emrich, C. T., Webb, J. J., & Morath, D. (2009). Social vulnerability to climate the literature social vulnerability to climate literature. *Final Report to Oxfam*. Southern Carolina. https://www.oxfamamerica.org/.

Dercon, S., Hoddinott, J., & Woldehanna, T. (2005). Shocks and consumption in 15 Ethiopian villages, 1999–2004. *Journal of African Economies, 14*(4), 559–585. https://doi.org/10.1093/jae/eji022

Deressa, T. T. (2010). Assessment of the vulnerability of Ethiopian agriculture to climate change and farmers' adaptation strategies. https://doi.org/10.13140/RG.2.1.1090.2889.

Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T., & Yesuf, M. (2009). Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change, 19*(2), 248–255. https://doi.org/10.1016/j.gloenvcha.2009.01.002

Descheemaeker, K., Oosting, S. J., Tui, S.-K., Masikati, P., Falconnier, G. N., & Giller, K. E. (2016). Climate change adaptation and mitigation in smallholder crop-livestock systems in sub-Saharan Africa: A call for integrated impact assessments. *Regional Environmental Change*. https://doi.org/10.1007/s10113-016-0957-8

Di Falco, S., Yesuf, M., Kohlin, G., & Ringler, C. (2012). Estimating the impact of climate change on agriculture in low-income countries: Household level evidence from the Nile Basin, Ethiopia. *Environmental and Resource Economics, 52*(4), 457–478. https://doi.org/10.1007/s10640-011-9538-y

Downing, T. E., & Patwardhan, A. (2005). Assessing vulnerbility for climate adaptation. *Adaptation Policy Frameworks for Climate Change*. https://doi.org/10.1007/978-94-007-1770-1_2

Eakin, H., Tucker, C. M., Castellanos, E., Diaz-porras Juan, R., & Barrera Helda, F. (2014). Adaptation in a multi-stressor environment: Perceptions and responses to climatic and economic risks by coffee growers in mesoamerica, 123–139. https://doi.org/10.1007/s10668-013-9466-9.

Eakin, H., & Luers, A. L. (2006). Assessing the vulnerability of social-environmental systems. *Annual Review of Environmental Resources, 31*, 365–394. https://doi.org/10.1146/annurev.energy.30.050504.144352

Echeverría, D., & Anika, T. (2011). Review of current and planned adaptation action: Southern Africa and planned adaptation action: Southern Africa. 8. http://www.idrc.ca/cariaa.

Echeverría, D., & Tornton, A. (2016). Review of current and planned adaptation action. *Collaborative Adaptation Research Initiatives in Africa and Aisa* (CARIAA) Working Paper No. 08. Pretoria, South Africa.

Edward, P. (2006). Examining inequality: Who really benefits from global growth? *World Development, 34*(10), 1667–1695. https://doi.org/10.1016/j.worlddev.2006.02.006

Erenstein, O., Kassie, G. T., & Mwangi, W. (2011). Comparative analysis of maize based livelihoods in drought prone regions of Eastern Africa: Adaptation lessons for climate change. In *Increasing agricultural productivity & enhancing food security in Africa*, 1–13. http://addis2011.ifpri.info/files/2011/10/Paper_4C_Olaf-Ernestein.pdf.

Eriksen, S. H., & Kelly, P. M. (2007). Developing credible vulnerability indicators for climate adaptation policy assessment. *Mitigation and Adaptation Strategies for Global Change, 12*(4), 495–524. https://doi.org/10.1007/s11027-006-3460-6

Falco, S. (2014). Adaptation to climate change in sub-Saharan agriculture: Assessing the evidence and rethinking the drivers. *European Review of Agricultural Economics, 41*(3), 405–430. https://doi.org/10.1093/erae/jbu014

Fellmann, T. (2012). The assessment of climate change-related vulnerability in the agricultural sector: Reviewing conceptual frameworks. *Building Resilience for Adaptation to Climate Change in the Agricultural Sector*, no. i: 37–62.

Ferede, T., & Ayenew, M., Hanjira, A. B. (2013). Agroecology matters: Impacts of climate change on agriculture and its implications for food security in Ethiopia. *Global Food Security: …*. http://www.oecd.org/env/cc/TADELE_AGROECOLOGY MATTERS (revised).pdf.

Fisher, M., Abate, T., Lunduka, R. W., Asnake, W., Alemayehu, Y., & Madulu, R. B. (2015). Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in Eastern and Southern Africa. *Climatic Change, 133*(2), 283–299. https://doi.org/10.1007/s10584-015-1459-2

Füssel, H. M. (2010). How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: A comprehensive indicator-based assessment. *Global Environmental Change*. Vol. 20. Standford. https://doi.org/10.1016/j.gloenvcha.2010.07.009.

Füssel, H. M. (2007). Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environmental Change, 17*(2), 155–167. https://doi.org/10.1016/j.gloenvcha.2006.05.002

Füssel, H. M., & Klein, R. J. T. (2006). Climate change vulnerability assessments: An evolution of conceptual thinking. *Climatic Change, 75*(3), 301. https://doi.org/10.1007/s10584-006-0329-3

Gachene, C. K. K., Karuma, A. N., & Baaru, M. W. (2014). Sustainable intensification to advance food security and enhance climate resilience in Africa. *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa*. https://doi.org/10.1007/978-3-319-09360-4

Gallopín, G. C. (2006). Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change, 16*(3), 293–303. https://doi.org/10.1016/j.gloenvcha.2006.02.004

Gbetibouo, G. A. (2009). Understanding farmers' perceptions and adaptations to climate change and variability: The case of the Limpopo Basin, South Africa. *IFPRI Discussion Paper 00849*, no. February: 52. https://doi.org/10.1068/a312017.

Gebrehiwot, T., & van der Veen, A. (2013). Farm level adaptation to climate change: The case of farmers in the Ethiopian highlands. *Environmental Management, 52*(1), 29–44. https://doi.org/10.1007/s00267-013-0039-3

Gentle, P., & Maraseni, T. N. (2012). Climate change, poverty and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environmental Science and Policy, 21*, 24–34. https://doi.org/10.1016/j.envsci.2012.03.007

Grothmann, T., & Patt, A. (2005). Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Global Environmental Change, 15*(3), 199–213. https://doi.org/10.1016/j.gloenvcha.2005.01.002

Habtemariam, L. T., Gandorfer, M., Kassa, G. A., & Heissenhuber, A. (2016). Factors Influencing Smallholder Farmers' Climate Change Perceptions: A Study from Farmers in Ethiopia. *Environmental Management*. https://doi.org/10.1007/s00267-016-0708-0

Helgeson, J., Van Der Linden, S., & Chabay, I. (2012). Learning for sustainability in times of accelerating change. *In Aadaptation Process*. https://doi.org/10.3920/978-90-8686-757-8

Hinkel, J. (2011). Indicators of vulnerability and adaptive capacity: Towards a clarification of the science—policy interface. *Global Environmental Change, 21*, 198–208. https://doi.org/10.1016/j.gloenvcha.2010.08.002

Hisali, E., Birungi, P., & Buyinza, F. (2011). Adaptation to climate change in Uganda: Evidence from micro level data. *Global Environmental Change, 21*(4), 1245–1261. https://doi.org/10.1016/j.gloenvcha.2011.07.005

Hoddinott, J., & Quisumbing, A. (2003). Methods for microeconometric risk and vulnerability assessments. *Food Policy, 0324*, 134. https://doi.org/10.2139/ssrn.1281055

Huang, S., Feng, Q., Lu, Z., Wen, X., Deo, R. C. (2017). Trend analysis of water poverty index for assessment of water stress and water management polices: A case study in the Hexi Corridor, China. *Sustainability (Switzerland) 9*(5). https://doi.org/10.3390/su9050756.

IAASTD. (2009). International assessment of agricultural knowledge, science, and technology for development (Project), & McIntyre, B. D. (Eds.). Synthesis report: A synthesis of the global and sub-global IAASTD reports. Washington, DC: Island Press. *Science And Technology*. Washington DC. https://www.globalagriculture.org/report-topics/about-the-iaastd-report.html.

Ibe, G. O., & Amikuzuno, J. (2019). Climate change in sub-Saharan Africa: A Menace to agricultural productivity and ecological protection. *Journal of Applied Sciences and Environmental Management, 23*(2), 329. https://doi.org/10.4314/jasem.v23i2.20

IPCC. (2001). CLIMATE C HANGE 2001: Impacts, adaptation and vulnerability. *Working Group II Impacts Adaptation and Vulnerability*. https://doi.org/10.1002/joc.775

IPCC. (2007). Summary for policymakers. In: M. L. Parry, O. F. Canziani, J. Palutikof, P. van Der Linden, & C. Hanson(Eds.), Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Pan." Edited by C. (Eds.) In: Palutikof, J., van der Linden, P., Hanson. *New York Cambridge University Press*. https://doi.org/10.1038/446727a.

Kassie, B. T. (2014). Climate variability and change in Ethiopia: Exploring impacts and adaptation options for cereal production.

Kassie, B. T., Asseng, S., Rotter, R. P., Hengsdijk, H., Ruane, A. C., & Van Ittersum, M. K. (2015). Exploring climate change impacts and adaptation options for maize production in the Central Rift Valley of Ethiopia using different climate change scenarios and crop models. *Climatic Change, 129*(1–2), 145–158. https://doi.org/10.1007/s10584-014-1322-x

Kassie, B. T., Hengsdijk, H., Rötter, R., Kahiluoto, H., Asseng, S., & Van Ittersum, M. (2013). Adapting to climate variability and change: Experiences from cereal-based farming in the Central Rift and Kobo Valleys, Ethiopia. *Environmental Management, 52*(5), 1115–1131. https://doi.org/10.1007/s00267-013-0145-2

Kassie, M., Jaleta, M., Shiferaw, B., Mmbando, F., & Mekuria, M. (2013). Adoption of interrelated sustainable agricultural practices in smallholder systems: Evidence from rural Tanzania. *Technological Forecasting & Social Change, 80*(3), 525–540. https://doi.org/10.1016/j.techfore.2012.08.007

Kates, R. W., Travis, W. R., & Wilbanks, T. J. (2012). Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences, 109*(19), 7156–7161. https://doi.org/10.1073/pnas.1115521109

Khan, A., & Akhtar, S. (2015). *Agricultural adaptation and climate change policy for crop production in Africa*. *Crop production and global environmental issues*. Crop Production and Global Environmental Issues. https://doi.org/10.1007/978-3-319-23162-4.

Koch, C. I., Vogel, C., & Patel, Z. (2007). Institutional dynamics and climate change adaptation in South Africa. *Mitigation and Adaptation Strategies for Global Change, 12*, 1323–1339. https://doi.org/10.1007/s11027-006-9054-5

Kok, M., Lüdeke, M., Lucas, P., Sterzel, T., Walther, C., Janssen, P., Sietz, D., & de Soysa, I. (2015). A new method for analysing socio-ecological patterns of vulnerability. *Regional Environmental Change, 16*(1), 229–243. https://doi.org/10.1007/s10113-014-0746-1

Kok, M., Lüdeke, M., Lucas, P., Sterzel, T., Walther, C., Janssen, P., Sietz, D., & de Soysa, I. (2016). A new method for analysing socio-ecological patterns of vulnerability. *Regional Environmental Change, 16*(1), 229–243. https://doi.org/10.1007/s10113-014-0746-1

Kotir, J. H. (2011). Climate change and variability in sub-Saharan Africa: A review of current and future trends and impacts on agriculture and food securityhttps://doi.org/10.1007/s10668-010-9278-0.

Laube, W., Schraven, B., & Awo, M. (2012). Smallholder adaptation to climate change: Dynamics and limits in Northern Ghana. *Climatic Change, 111*(3), 753–774. https://doi.org/10.1007/s10584-011-0199-1

Liverman, D. M. (1990). Vulnerability to global environmental change. In *Understanding global environmental change: The contributions of risk analysis and management*, 27–44. https://dianaliverman.files.wordpress.com/2014/12/liverman-1990-vulnerability-to-gec-in-kasperson-et-al.pdf.

Lobell, B., Bänziger, M., Magorokosho, C., & Vivek, and B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change, 1*(1), 42–45. https://doi.org/10.1038/nclimate1043

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation need for food security in 2030. *Science, 319*(February), 607–610. https://doi.org/10.1126/science.1152339

Madhuri, H. R., & Tewari, and Pradip K Bhowmick. (2014). Livelihood vulnerability index analysis: An approach to study vulnerability in the context of Bihar. *Journal of Disaster Risk, 6*(1), 1–13. https://doi.org/10.4102/jamba.v6i1.127

Maleksaeidi, H., & Karami, E. (2013). Social-ecological resilience and sustainable agriculture under water scarcity. *Agroecology and Sustainable Food Systems, 37*(3), 262–290. https://doi.org/10.1080/10440046.2012.746767

Mall, R. K., Gupta, A., & Sonkar, G. (2017). *Effect of climate change on agricultural crops*. *Current developments in biotechnology and bioengineering*. Elsevier B.V. https://doi.org/10.1016/B978-0-444-63661-4.00002-5.

McSweeney, C., New, M., & Lizcano, G. (2010). UNDP climate change country profiles: Ethiopia. http://country-profiles.geog.ox.ac.uk.

Menghistu, H. T., Abraha, A. Z., Tesfay, G., & Mawcha, G. T. (2020). Determinant factors of climate change adaptation by pastoral/agro-pastoral communities and smallholder farmers in sub-Saharan Africa: A systematic review. *International Journal of Climate Change Strategies and Management, 12*(3), 305–321. https://doi.org/10.1108/IJCCSM-07-2019-0049

Mertz, O., Mbow, C., Reenberg, A., & Diouf, A. (2009). Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environmental Management, 43*(5), 804–816. https://doi.org/10.1007/s00267-008-9197-0

Monirul, I. M., Sallu, S., Hubacek, K., & Paavola, J. (2014). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change, 14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Moroda, G. (2018). *Climate variability and households' vulnerability to food insecurity in Ethiopia: A case study of Boset district, East Shewa in Ethiopia*. Ethiopia: Doctoral Dissertation, Addis Ababa University.

Mudzonga, E. (2012). Farmers' adaptation to climate change in Chivi District of Zimbabwe, 1–30. http://trapca.org/working-papers/Evengelista_adaptationtoclimatechangerevised.pdf.

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2014). Spatial climate change vulnerability assessments: A review of data, methods, and issues. https://doi.org/10.13140/2.1.1888.0002.

NCEA. (2015). Climate change profile: Ethiopia. Netherlands Commision for Environmental Assesment (NCEA). Dutch Sustainability Unit. http://dsu.eia.nl/publications/advisory-reports/7196.

Ndiritu, S. W., Kassie, M., & Shiferaw, B. (2014). Are there systematic gender differences in the adoption of sustainable agricultural intensification practices? Evidence from Kenya. *Food Policy, 49*(P1), 117–127. https://doi.org/10.1016/j.foodpol.2014.06.010

Neufeldt, H., Jahn, M., Campbell, B. M., Beddington, J. R., Declerck, F., De Pinto, A., Gulledge, J., et al. (2013). Beyond climate-smart agriculture : Toward safe operating spaces for global food systems. *Agriculture & Food Security, 2*, 1–6.

Nhemachena, C., Hassan, R., & Chakwizira, J. (2014). Analysis of determinants of farm-level adaptation measures to climate change in Southern Africa 6(5), 232–241. https://doi.org/10.5897/JDAE12.0441.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2014). Africa. In: Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D.

Niles, M. T., & Mueller, N. D. (2016). Farmer perceptions of climate change: Associations with observed temperature and precipitation trends, irrigation, and climate beliefs. *Global Environmental Change, 39*, 133–142. https://doi.org/10.1016/j.gloenvcha.2016.05.002

O'Brien, K., Eriksen, S., Nygaard, L. P., & a N E Schjolden. (2007). Why different interpretations of vulnerability matter in climate change discourses. *Climate Policy, 7*(1), 73–88. https://doi.org/10.1080/14693062.2007.9685639

O’Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., et al. (2004). Mapping vulnerability to multiple stressors: Climate change and globalization in India. *Global Environmental Change, 14*(4), 303–313. https://doi.org/10.1016/j.gloenvcha.2004.01.001

Onyango, E. A., Sahin, O., Awiti, A., Chu, C., & Mackey, B. (2016). An integrated risk and vulnerability assessment framework for climate change and malaria transmission in East Africa. *Malaria Journal, 15*(1), 1–12. https://doi.org/10.1186/s12936-016-1600-3

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O’Neill, B., & Takahashi, K. (2014). Emergent risks and key vulnerabilities. *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1039–1099. https://doi.org/10.1017/CBO9781107415379.

Osbahr, H., Chasca Twyman, W., Adger, N., & Thomas, D. S. G. (2008). Effective livelihood adaptation to climate change disturbance: Scale dimensions of practice in Mozambique. *Geoforum, 39*(6), 1951–1964. https://doi.org/10.1016/j.geoforum.2008.07.010

Panthi, J., Aryal, S., Dahal, P., Bhandari, P., Krakauer, N. Y., & Pandey, V. P. (2015). Livelihood vulnerability approach to assessing climate change impacts on mixed agro-livestock smallholders around the Gandaki River Basin in Nepal. *Regional Environmental Change*. https://doi.org/10.1007/s10113-015-0833-y

Pelling, M. (2011). *Aadaptation to climate change: From resiliance to trasformation*. Routledge.

Pelling, M., & High, C. (2005). Understanding adaptation: What can social capital offer assessments of adaptive capacity? *Global Environmental Change, 15*(4), 308–319. https://doi.org/10.1016/j.gloenvcha.2005.02.001

Pereira, L. (2017). *Oxford research encyclopedia of environmental science climate change impacts on agriculture across Africa*. https://doi.org/10.1093/acrefore/9780199389414.013.292.

Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science, 6*(2), 177–202. https://doi.org/10.1007/s11625-011-0129-1

Rahut, D. B., Aryal, J. P., and Marenya, P. (2021). Ex-ante adaptation strategies for climate challenges in sub-Saharan Africa: Macro and micro perspectives. *Environmental Challenges* 3 (December 2020): 100035. https://doi.org/10.1016/j.envc.2021.100035.

Ramirez-villegas, J., Thornton, P. K. (2015). Climate change impacts on African crop production. 119. Cophenhagen, Denmark.

Reed, M. S., Podesta, G., Fazey, I., Geeson, N., Hessel, R., Hubacek, K., Letson, D., et al. (2013). Combining analytical frameworks to assess livelihood vulnerability to climate change and analyse adaptation options. *Ecological Economics, 94*, 66–77. https://doi.org/10.1016/j.ecolecon.2013.07.007

Reid, H., & Faulkner, L. (2014). Assessing how participatory/community-based natural resource management initiatives contribute to climate change adaptation in Ethiopia. *Handbook of Climate Change Adaptation*. https://doi.org/10.1007/978-3-642-40455-9

Reid, P., & Vogel, C. (2006). Living and responding to multiple stressors in South Africa-glimpses from KwaZulu-Natal. *Global Environmental Change, 16*(2), 195–206. https://doi.org/10.1016/j.gloenvcha.2006.01.003

Rottenburg, R., Merry, S. E., Park, S.-J., Mugler, J., Sterzel, T., Orlowsky, B., & Hannah, F. (2011). Climate change vulnerability indicators–from noise to signal. In: R. Rottenburg, S. E. Merry, S. J. Park, & J. Mugler (Eds.), *The making of governmental knowledge through quantification.* Cambridge: Cambridge University Press, UK.

Scoones, I. (1998). Sustainable rural livelihoods a framework for analysis. 72. *IDS Working Paper 72*. https://doi.org/10.1057/palgrave.development.1110037.

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., & Reinhardt, J. (2017). Climate change impacts in sub-Saharan Africa: From physical changes to their social repercussions. *Regional Environmental Change, 17*(6), 1585–1600. https://doi.org/10.1007/s10113-015-0910-2

Shi, W., & Tao, F. (2014). Vulnerability of African maize yield to climate change and variability during 1961–2010. *Food Security, 6*(4), 471–481. https://doi.org/10.1007/s12571-014-0370-4

Shiferaw, B., Tesfaye, K., Kassie, M., Tsedeke Abate, B. M., & Prasanna, and Abebe Menkir. (2014). Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: technological, institutional and policy options. *Weather and Climate Extremes, 3*, 67–79. https://doi.org/10.1016/j.wace.2014.04.004

Simane, B., Zaitchik, B. F., & Foltz, J. D. (2016). Agro-ecosystem specific climate vulnerability analysis: Application of the livelihood vulnerability index to a tropical highland region. *Mitigation and Adaptation Strategies for Global Change, 21*(1), 39–65. https://doi.org/10.1007/s11027-014-9568-1

Simbizi, M. C., Dushimyimana, R. M., & Bennett, and Jaap Zevenbergen. (2014). Land tenure security: Revisiting and refining the concept for sub-Saharan Africa's rural poor. *Land Use Policy, 36*, 231–238. https://doi.org/10.1016/j.landusepol.2013.08.006

Simelton, E., Quinn, C. H., Antwi, P., Batisani, N., Dougill, A. J., Dyer, J., Fraser, E. D. G., et al. (2011). African Farmers' perceptions of erratic rainfall October 2011 Centre for climate change economics and polic. *73*, 1–36.

Simelton, E., Quinn, C. H., Batisani, N., Dougill, A. J., Dyer, J. C., Fraser, E. D. G., Mkwambisi, D., Sallu, S., & Stringer, L. C. (2013). Is rainfall really changing? Farmers' perceptions, meteorological data, and policy implications. *Climate and Development, 5*(2), 123–138. https://doi.org/10.1080/17565529.2012.751893

Singh, P. K., & Nair, A. (2014). Livelihood vulnerability assessment to climate variability and change using fuzzy cognitive mapping approach. *Climatic Change, 127*(3–4), 475–491. https://doi.org/10.1007/s10584-014-1275-0

Small, L.-A. (2011). The sustainable rural livelihoods approach: A critical review the sustainable rural livelihoods approach: A critical review. *Canadian Journal of Development Studies* 5189 (June 2012): 37–41. https://doi.org/10.1080/02255189.2007.9669186.

Smit, B., & Skinner, M. W. (2002). Adaptation option in agriculture to climate chnage: A typology. *Mitigation and Adaptation Strategies for Global Change, 7*, 85–114.

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change, 16*(3), 282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

Speranza, I., Wiesmann, U., & Rist, S. (2014). An indicator framework for assessing livelihood resilience in the context of social-ecological dynamics. *Global Environmental Change, 28*(1), 109–119. https://doi.org/10.1016/j.gloenvcha.2014.06.005

Sullivan, C. A., Meigh, J. R., & Fediw, T. S. (2002). Derivation and testing of the water poverty index phase 1. *Center for Ecology and Hydrology CEH. Natural …* 1 (May): 53. http://www.soas.ac.uk/water/publications/papers/file38386.pdf.

Sutcliffe, C., Dougill, A. J., & Quinn, C. H. (2016). Evidence and perceptions of rainfall change in Malawi: Do maize cultivar choices enhance climate change adaptation in sub-Saharan Africa? *Regional Environmental Change, 16*(4), 1215–1224. https://doi.org/10.1007/s10113-015-0842-x

Tambo, J. A. (2016). Adaptation and resilience to climate change and variability in northeastern Ghana. *International Journal of Disaster Risk Reduction, 17,* 85–94. https://doi.org/10.1016/j.ijdrr.2016.04.005

Tesfaye, K. G., Cairns, S., Shiferaw, J., Prasanna, B., Sonder, B., Boote, K., Makumbi, K., & Richard, D. R. (2015). Maize systems under climate change in sub-Saharan Africa potential impacts on production and food security. *International Journal of Climate Change Strategies and Management, 7*(3), 247–271. https://doi.org/10.1108/IJCCSM-01-2014-0005.

Thornton, K., & Herrero, M. (2014). Climate change adaptation in mixed crop-livestock systems in developing countries. *Nairobi, Kenya.* https://doi.org/10.1002/jssc.201300750.This

Tosun, J., & Leininger, J. (2017). Governing the interlinkages between the sustainable development goals: Approaches to attain policy integration. *Global Challenges, 1700036*(1), 1–12. https://doi.org/10.1002/gch2.201700036

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., et al. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1231335100

Van de Steege. (2009). The influence of climate variability and climate change on the agricultural sector in East and Central Africa: Sensitizing adaptation strategic plan to climate change. Research report 22. ILRI (International Livestock Research Institute), Nairobi, Kenya. https://doi.org/10.13140/RG.2.1.4115.0484

Van Der Linden, S. (2015). The social-psychological determinants of climate change risk perceptions: Towards a comprehensive model. *Journal of Environmental Psychology, 41*, 112–124. https://doi.org/10.1016/j.jenvp.2014.11.012

Vignola, R., Alice, C., Bautista-solis, P., Avelino, J., Rapidel, B., Donatti, C., & Martinez, R. (2015). Ecosystem-based adaptation for smallholder farmers: Definitions, opportunities and constraints. *Agriculture, Ecosystems and Environment, 211,* 126–132. https://doi.org/10.1016/j.agee.2015.05.013.

Wainaina, P., Tongruksawattana, S., & Qaim, M. (2016). Tradeoffs and complementarities in the adoption of improved seeds, fertilizer, and natural resource management technologies in Kenya. *Agricultural Economics (united Kingdom), 47*(3), 351–362. https://doi.org/10.1111/agec.12235

Washington-ottombre, C., & Pijanowski, C. (2013). Rural organizations and adaptation to climate change and variability in rural Kenya. *Regional Environmental Change,13,* 537–550. https://doi.org/10.1007/s10113-012-0343-0

Wiggs, M. (2009). Climate change and environmental degradation risk and adaptation assessment. www.tearfund.org/tilz.

Wilk, J., Andersson, L., & Warburton, M. (2013). Adaptation to climate change and other stressors among commercial and small-scale South African farmers. *Regional Environmental Change, 13,* 273–286. https://doi.org/10.1007/s10113-012-0323-4

Woods, B. A., Nielsen, H. Ø., Pedersen, A. B., & Kristofersson, D. (2017). Farmers' perceptions of climate change and their likely responses in Danish agriculture. *Land Use Policy, 65*(April), 109–120. https://doi.org/10.1016/j.landusepol.2017.04.007

World Bank. (2008). Ethiopia—a country study on the economic impacts of climate change. https://openknowledge.worldbank.org/bitstream/handle/10986/8030/469460ESW0P1101B01PUBLIC1010P110947.pdf?sequence=1&isAllowed=y.

World Bank. (2011). Ethiopia: Climate risk factsheet. The World Bank, Washington D.C., USA.

Yaro, J. A. (2013). The perception of and adaptation to climate change in Ghana by small-scale and commercial farmers. *Climate and Development*, 1259–1272. https://doi.org/10.1007/s10113-013-0443-5

Yegbemey, RN., Yabi, JA., Tovignan, SD., Gantoli, G., Haroll Kokoye, SE. (2013). Farmers' decisions to adapt to climate change under various property rights: A case study of maize farming in northern Benin. *Land Use Policy, 34*, 168–175. https://doi.org/10.1016/j.landusepol.2013.03.001

Yirgu, L., Nicol, A., & Srinivasan, S. (2013). Warming to change? Climate policy and agricultural development in Ethiopia. 71. www.future-agricultures.org.