Climate and Development

ISSN: 1756-5529 (Print) 1756-5537 (Online) Journal homepage: https://www.tandfonline.com/loi/tcld20

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Climate and Development, 2017
Vol. 9, No. 5, 383–398, http://dx.doi.org/10.1080/17565529.2016.1167659

RESEARCH ARTICLE

Drivers of climate risk in African agriculture

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(*Received 4 December 2013; accepted 8 January 2016*)

Climate-related risks to African agriculture are highly contextual. Climatic conditions are changing in diverse agro-ecological environments throughout Africa, and populations are being affected by, and responding to, these changes. The paper describes how climate change risks in African agriculture are mediated by multiple factors, ranging from the availability of physical resources through policy contexts to the role of culture. Consequently, support to adaptation needs to be complemented with research that can generate contextual information to inform adaptation policies, strategies, and measures. Interventions need to go beyond just technical fixes such as the development of new crop varieties, and must be based on an understanding of how different factors interact in a complex manner to drive risks and results in specific contexts to diverse outcomes.

Keywords: Climate change; agriculture; Africa; hazards; impacts; vulnerability; adaptive capacity

1. Introduction

Around 80% of Africa's approximately one billion people are dependent on agriculture for their livelihoods. Despite increasing commercialization, African agriculture is largely smallholder based and non-irrigated, and is characterized by low levels of investment (Beintema & Stads, 2011). Crop and livestock systems are complemented by a range of food production and livelihood activities, including aquaculture, agro-forestry, and the harvesting of non-timber forest products and other wild fauna and flora (Inter-Academy Council, 2004). Smallholder agriculture and related activities are vital not only to livelihoods and food security, but also to wider national economic well-being. Nonetheless, food insecurity remains high in Africa, with some 23% of the population of the continent undernourished in 2006, compared with 13% of the global population (FAO, 2011). Fertilizer use and per-hectare crop yields are low in Africa (15,349 Hg/Ha compared with 35,664 Hg/Ha globally for cereals, and 88,101 Hg/Ha compared with 137,867 Hg/Ha for roots and tubers (FAO, 2011)), and increases in productivity are associated principally with land extension (Gockowski & Sonwa, 2011). Annual post-harvest crop losses in sub-Saharan Africa have been estimated at up to USD 4 billion per year, or 15% of production (World Bank, 2011).

In addition to low productivity and low levels of investment, agricultural production in much of Africa is constrained by climatic conditions, which in many parts of the continent are marginal and/or associated with high inter- and intra-annual variability and uncertainty (Agoumi, 2003; Dixon, Smith, & Guill, 2003). In this context, climate change poses a major challenge for African agriculture. Changes in variability will affect the length and success of growing seasons, and changes in rainfall coupled with increased mean and extreme temperatures will have implications for water resources on which agriculture depends. Recent studies have linked increased drought incidence in East Africa with climate change (e.g. Cook & Vizy, 2013; Lott, Christidis, & Stott, 2013), and drought is likely to become more common over much of the continent over the course of the twenty-first century (Niang et al., 2014). Other studies have indicated that temperature increases alone can have significant implications for crop yields (Battisti & Naylor, 2009;

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Lobell, Banziger, Magorokosho, & Vivek, 2011), and that existing cropping systems are likely to experience significant reductions in yields over the coming decades as a result of warming combined with other factors (Schlenker & Lobell, 2010). Burke, Lobell, and Guarino (2009) estimate that "the majority of African countries will have novel climates over at least half of their current crop area by 2050". In order to feed a population projected to double or even triple over the course of the twenty-first century (UNFPA, 2011), African agriculture needs to become more productive while also addressing the significant challenges posed by climate change.

Increased investments in capital and labour may offset many of the adverse impacts of climate change on African agriculture, at least up until around 2030 (Bezabih, Chambwera, & Stage, 2010). In the longer term, a wider array of adaptation strategies and measures will be required. Adaptation actions, therefore, need to address evolving risks to agricultural livelihoods and productivity – here seen as resulting from the interaction of climate hazards with underlying socially constructed vulnerabilities – over a range of timescales, from the immediate near-term to the medium and longer term. The diversity of farming systems in Africa means that regionally and locally tailored, rather than continent-wide, strategies are required to ensure food production and security for Africa's growing population in the face of climate change (InterAcademyCouncil, 2004). Adesina (2010) emphasizes the need to build on domestic policies aligned with local development realities. Agricultural development in Africa therefore needs to address the needs of smallholders, and to build on existing livelihoods (Collier & Dercon, 2009). Accordingly, adaptation needs to be built on an understanding of current, emerging, and potential future climate-related risks to livelihoods, as well as an appreciation of the need for near-term development and adaptation actions to be compatible with longer term adaptation needs (Brooks, Anderson, Ayers, Burton, & Tellam, 2011).

Research into the factors that drive risks to livelihoods and agricultural productivity, therefore, has a key role to play in adaptation, through the gathering and dissemination of data and information on (i) evolving climatic and environmental stresses, (ii) agricultural and livelihood outcomes associated with these evolving stresses, (iii) the factors that make people and livelihoods more or less vulnerable to climatic and environmental stresses, and (iv) the factors that constrain and enable adaptation to climatic and environmental change in various livelihood contexts. Such data and information can help to inform adaptation actions and policies, and need to be generated in cooperation with a diverse array of stakeholders who tell us what is happening "on the ground" in diverse risk and adaptation contexts. These include smallholders, pastoralists, and users of natural resources at large, whose perceptions of risk will inform risk assessments and adaptation initiatives. Local-level adaptations to changes in climatic conditions are already being documented in Africa (Grist, 2014), and these can provide useful lessons for further adaptation, building on existing adaptive capacity. Nonetheless, significant gaps exist in current research initiatives, including in geographical representation, and considerable challenges remain at the interface between research and the users of research products (Zoundi & Hitimana, 2011).

One way of addressing these gaps and challenges is through participatory action research (PAR), which enables (i) the generation of outputs that can feed into ongoing research programmes, (ii) the dissemination of research results at the local level outside of formal extension services contexts, and (iii) different stakeholders to work together and generate output that can inform the mainstreaming of adaptation into agricultural and development policy. Adaptation can then be built on a genuine contextual understanding of the factors that drive risk in specific contexts. For example, what are the societal factors that influence the underlying vulnerabilities of agricultural livelihoods and production to climate hazards, and to what extent can we attribute changes in agricultural losses associated with climate variations to changes in vulnerability versus changes in the nature of climate hazards? This paper aims to contribute to such an approach by examining the drivers of climate-related risk identified in six projects under the climate change and adaptation in Africa (CCAA) programme, from Central Africa, East Africa, North Africa, Southern Africa, and West Africa. The CCAA programme funded 41 research projects in 33 African countries, and addressed the need to strengthen the knowledge base of African scientists in ways that would benefit the most vulnerable (IDRC, 2012). For this paper, we are focusing on the six projects that were more relevant to agriculture.

2. Methodology and risk framework

The implications of climate change for human populations are often discussed in terms of "vulnerability", where vulnerability is defined as a function of the rate and magnitude of climatic variations, the exposure and sensitivity of exposed populations or systems, and their adaptive capacity (IPCC, 2007). However, such definitions can be problematic (Brooks, 2003), and recently there has been a shift towards an emphasis on risk as defined in the natural hazards literature that predates that on climate change vulnerability (IPCC, 2012, 2014; Wisner, Blaikie, Cannon, & Davis, 1994).

Adaptive capacity is the ability to adjust to changes and variations in climatic and environmental conditions in order to moderate potential damages, exploit opportunities, and cope with the consequences of such changes (IPCC, 2007). The capacity to adapt to trends and changes in climate over the medium to long term can be distinguished from the ability to cope with climate variations in the shorter term. The former implies permanent changes in behaviour and practices, whereas the latter might simply involve the deployment of existing strategies or temporary measures to address transient hazards and related risks. Adaptive capacity depends on a suite of often related factors including (i) knowledge, preparedness, and ability to act; (ii) the role of institutions (formal and informal, including social networks) in facilitating or constraining action/innovation; (iii) access to resources including natural resources, technology, and financial resources; (iv) mobility (closely related to access to resources); and (v) cultural factors, perceptions, and beliefs that affect the willingness to take (or not take) certain actions (Adger, Huq, Brown, Conway, & Hulme, 2003; Downing, Ringius, Hulme, & Waughray, 1997; Grist, 2014; Mubaya, Njuki, Liwenga, Mutsvangwa, & Mugabe, 2010; Reid & Vogel, 2006). There will be significant overlaps in the factors influencing adaptive capacity and those mediating vulnerability; for example, access to certain resources such as finance and information network will help people anticipate and recover from transient hazards in the short term, and also plan for and adapt to longer term changes in climate.

Here, we use a risk framework in which *risks* that climatic stresses will result in a population or system experiencing adverse outcomes or "impacts" (crop failure, reductions in household incomes, food insecurity, livelihood collapse, etc.) are viewed as resulting from the interaction of climate-related *hazards* (the physical manifestations of climate change and variability such as extreme climatic events and long-term trends) with the underlying *vulnerabilities* of exposed populations or socio-ecological systems. In this framework, vulnerability may be decomposed into the societal factors that make farmers, pastoralists, and those directly dependent on natural food resources more susceptible to harm when exposed to climate hazards, and the environmental factors than make landscapes, ecosystems, and other aspects of the "natural" or managed physical environment susceptible to harm as a result of exposure to the same hazards. These two aspects of vulnerability are described in terms of *social vulnerability* and *biophysical vulnerability*, respectively. When addressing risks associated with longer term changes in climatic conditions, vulnerability will also depend on the *adaptive capacity* of populations and socio-ecological systems (Brooks, 2003). In this framework, hazards, impacts, social vulnerability, biophysical vulnerability, and adaptive capacity may be viewed as the five key elements of risk.

Here, we present a synthesis of findings from across six projects (Table 1) undertaken as part of the CCAA programme, representing the five African regions identified above (Figure 1), and addressing a variety of agricultural and related livelihood contexts (the opening paper to this special issue sets out the process of generating the synthesis papers). PAR which was used within projects is a collaborative research approach involving iterations of action and reflection (German et al., 2012). After project completion, the authors of this article reflected on the results obtained in the six CCAA projects, using a common framework. Drawing on the results of these projects, we identify factors that map onto the five key elements of risk as defined above, in order to present an "anatomy of risk" for African agriculture in the locations considered. The identification of impacts helps us to understand the (potential) consequences of climate variability and change for agriculture and livelihoods, and the types of risks that must be addressed. The identification of hazards and social and biophysical vulnerabilities enables us to separate the drivers of these risks into those about which we can do little at the regional and local scales (hazards driven by macro-scale climatic processes), those that can be addressed through livelihood interventions (social vulnerability), and those that can be addressed through actions related to land and natural resource management (biophysical vulnerability). The identification of factors related to adaptive capacity in principle enables us to propose interventions to remove barriers to adaptation and to enhance people's ability to respond to climate change. It is recognized that some of the factors influencing social and biophysical vulnerability and adaptive capacity will be closely related, and that the boundaries between these elements will be blurred in many instances.

Results from different regions and projects are compared and contrasted where possible, in order to examine similarities and differences in the drivers and composition of climate-related risks in different contexts. However, different regional and project contexts illuminate different elements of risk, and discussion of these elements seeks to draw lessons as project results permit, rather than to compare and contrast findings evenly across all the regions addressed.

3. Elements of risk: findings of the CCAA projects

Here, we identify how the five elements of climate risk described above are manifest in the studies from the five regions examined. Manifestations of the elements of climate risk are summarized in Table 2 for each region and project.

3.1. *Hazards*

Situational analyses conducted by CCAA project researchers in diverse African agro-ecological environments (Benaouda, El Ouali, & Saloui, 2008; El Ouali, Benaouda, & Saloui, 2009; Lema & Majule, 2009; Majule et al., 2013; Mongi, Majule, & Lyimo, 2010) identify a number of hazards associated with climate change and variability,

Table 1. Summary of the six projects including location, timing/duration, title of project, key stakeholders, and methods used (PAR, risk mapping, scenario planning, vulnerability assessment, etc.).

#	Project title	Location	Methods	Purpose/objectives	Key stakeholders
1	Cofcca: Congo Basin and Climate change Adaptation	Central Africa (countries covered: Cameroon, Democratic Republic of Congo, and Central African Republic) Field Locations: Nkol-evodo & Yokadouma (Cameroon) Kisangani & Mambasa (DRC) Mbaiki and Bayanga (CAR)	Participatory Action Research (PAR) participatory diagnosis and visioning, conceptualization of change, and identification of specific strategies for climate change adaptation in the community	Pilot projects were part of Cofcca project. The main objective of the overall Cofcca project was to contribute to national processes of adaptation to climate change through the development of policy-oriented adaptation strategies that also ensure sustainable use of forest resources in the Congo Basin Forests.	Key stakeholders involved in the pilot projects are from Conservation Agencies, Agricultural states department, local NGO, and national and Research organization
2	Enhancing Adaptive Capacity of Pastoralists to Climate Change: Induced Vulnerability in Northern Kenya	East Africa (Countries covered: Kenya) Field Locations: Mandera and Turkana in Northern Kenya	PAR, Participatory diagnosis and visioning, indigenous knowledge systems, capacity building, climate modelling, risk mapping, scenario planning, Outcome mapping, Gender analysis	Develop the knowledge base to guide adaptation of pastoralist communities to climate change, and provide guidelines on the integration of climate change adaptation within the pastoral system into national development institutions and policies.	Key stakeholders – Pastoralists, Government policy makers, NGOs, CBOs, Universities, research institutions
3	Adaptation Mechanisms to Climate Changes of local communities of two contrasted ecosystems of Morocco: arid plain and High Atlas Mountain	North Africa (country covered: Morocco) Locations: 1. Arid plain area: RC of Lamzoudia, Chichaoua Province 2. Sub-humid Moutain area:RC of Tabant, Azilal Province.	• Agro-ecological and socio-economic characterization • GIS • Communal modelling • Climatic modelling • Gender analysis • Behaviour analysis towards risk • Multidisciplinary participative • Structured and semi-structured questionnaires • Venn diagrams and resources maps • Transects • Visualization tools • Decision tool making methodology • Multifactor's approaches • PAR • Participatory diagnosis and visioning, conceptualization of change, and identification of specific strategies for climate change adaptation in the community	To contribute to a better integration of ways and forms of adaptation of local populations to CC in a new rural development perspectives in Morocco. Project objectives: Study cases in two contrasting environments: to reinforce adaptive capacity of vulnerable populations to CC through the identification and the development of appropriate TIPO's according to local fragile ecosystems.	Key stakeholders: • Peasants (farmers) • Local NGOs (Associations and Cooperatives) • Rural communes • Caudate • Provincial rural affairs divisions • Extension centres • Provincial agricultural departments • Forestry • National meteorology Direction • Climate change service • Regional Agronomic research centres
4	Building adaptive capacity to cope with increasing	Southern Africa (Countries covered: Zambia and Zimbabwe)	PAR, Participatory diagnosis and visioning, indigenous knowledge systems, demonstration plots, capacity	Develop education, research, and extension competencies to be able to create strategies that facilitate	Key stakeholders – farmers, agricultural extension staff, University students,

vulnerability due to climatic change	Locations: Lupane and Lower Gweru (Zimbabwe), Monze, Sinazongwe (Zambia)	building, crop simulation modelling, risk mapping, scenario planning	rural communities to increase their adaptive capacity to cope with risks and opportunities associated with climate change and variability	University staff, national research organizations
5 InfoClim (*Platform* for Helping Vulnerable Communities Adapt to Climate Change)	West Africa (Country covered: Senegal) Locations: Thies Region (Senegal) in 4 communities: 3 rural and 1 urban (see map)	Assess communities' perception of climate change impacts (focus groups) Climate information analysis (agro-climatic parameters; start and end dates of the rainy season; statistical downscaling of the forecast) Document the process (PAR) Elaborate system to collect, process, share, and disseminate information (information system, i.e. Observatory)	Help vulnerable populations gain access to science-based information in order to strengthen their climate change adaptation strategies Validation of the data/information; promote the integration of information into the local development plans	NATIONAL LEVEL STAKEHOLDERS: National Scientific and Technical Committee with the role to facilitate collection exchange and dissemination of scientific information and practical knowledge (including local knowledge among and between communities) PROVINCIAL LEVEL STAKEHOLDERS: Regional Climate Change Committee with the role to ensure the functionality of the Observatory and the Local Climate Change Committee; advise and direct users to the appropriate technical services; facilitate collection, process, LOCAL LEVEL STAKEHOLDERS: Local Climate Change Committee with the role to Identify difficulties and information needs within the community; Transmit the needs to the Provincial Committee; and get their feed back; Disseminate/share the information within the community.
6 Strengthening Local Agriculture Innovation Systems to Adapt to Climate Change	East and southern Africa (Tanzania and Malawi)	– PAR activities through learning and training. – Documentation and sharing of information. – Situation analysis on climate issues and livelihoods – Training and application of situation analysis • Multidisciplinary participative • Structured and semi-structured questionnaires	The purpose of the project was to strengthen the capacity of individuals, organizations, and systems within the agricultural innovation systems in less favoured areas (semi-arid in Tanzania and Malawi) and more favoured areas of Tanzania and Malawi to adapt to the challenges and opportunities arising from CC & V. Dissemination and share the information at National and local levels through National Consultation Groups and Districts	Individuals, organizations, and systems within the agricultural innovation systems

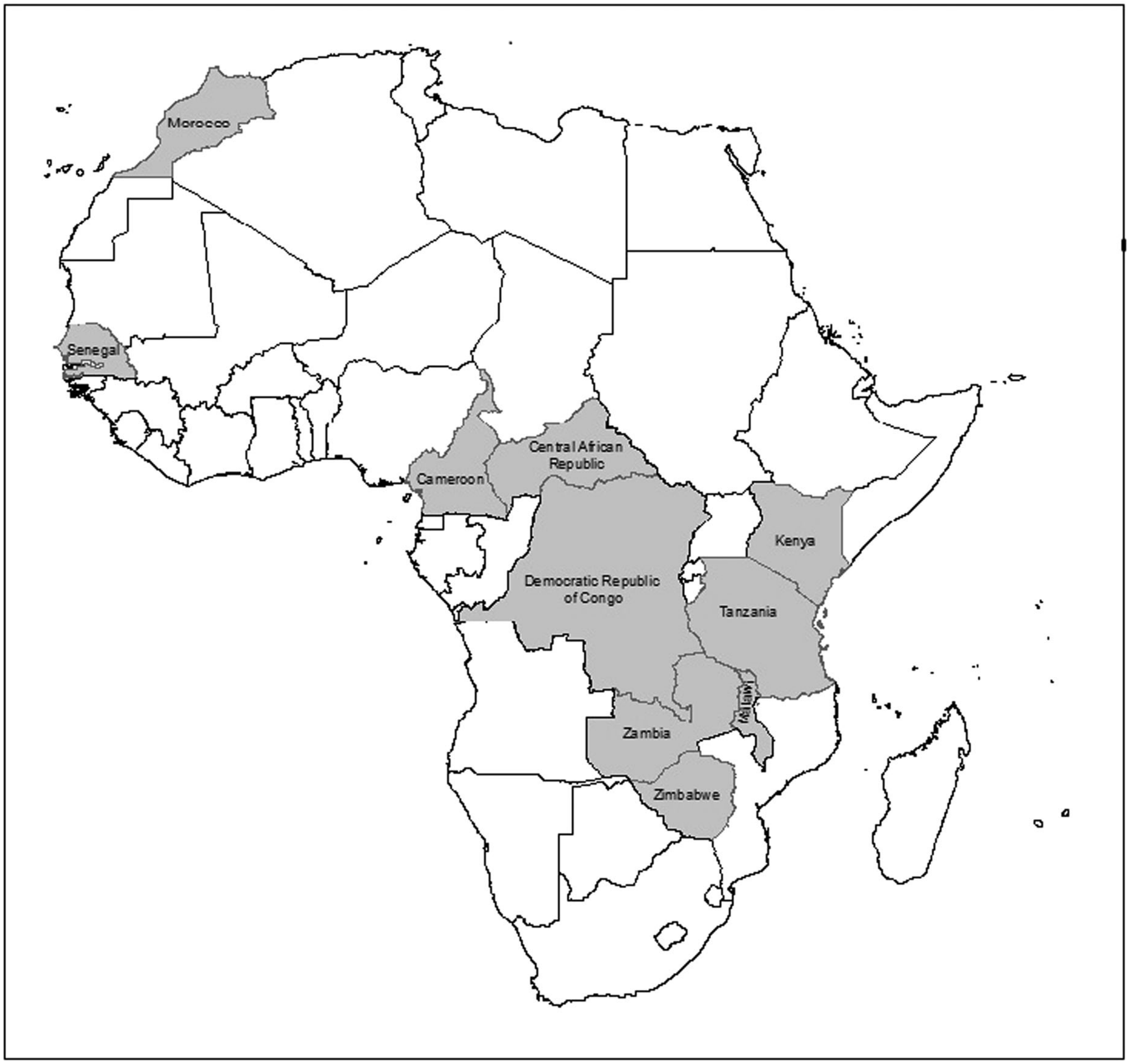

Figure 1. Map showing countries covered by the six projects.
Note: The boundaries, colors, denominations, and other information shown on this map do not imply any judgment concerning the legal status of any territory or the endorsement or acceptance of such boundaries. The aim of the map is to show the distribution of the projects across the continent.

manifest principally through changes in temperature and precipitation.

Increases in minimum and maximum temperatures are apparent in meteorological observations and accounts from participants in CCAA projects in Malawi, Tanzania, Zambia, and Zimbabwe (Kalanda-Joshua, Ngongondo, Chipeta, & Mpembeka, 2011; Lema & Majule, 2009; Mongi et al., 2010; Mubaya et al., 2010). El Mzouri, Chriyaa, and Saloui (2010) also find increased variability in temperature at the CCAA sites in Morocco. In the Congo Basin, heat waves during the dry season were also highlighted (Bele, Mulotwa, Bokoto de Semboli, Sonwa, & Tiani, 2010, 2013a, 2013b). Generally, temperature has increased throughout the continent in the past 30 years, with warming being greatest over the interior and semi-arid margins of the continent (El Ouali et al., 2009).

Increasingly variable and unpredictable rainfall within and between years was widely reported, including significant reductions in the duration of rainy seasons, with the onset of rainfall occurring later and rainfall finishing earlier, and rainfall concentrated in a smaller number of days in many locations (Benaouda et al., 2008; Lema & Majule, 2009; Majule et al., 2013). In the Congo Basin respondents highlighted heavy rainfall, drought episodes and instances of only occasional rainfall during the rainy season, low rainfall throughout the year, heavy rainfall,

Table 2. Summary of the five elements of risk for each CCAA project.

Hazards	Impacts	Social vulnerability	Biophysical vulnerability	Opportunities for adaptation
Heavy rainfall (1)	weak agricultural productivity, crop failure and losses (1,3,4,6)	remoteness of populations from urban centres (1)	Intercropping is generally considered to be more resilient than mono-cropping (1)	Livelihood Diversification and innovation within and beyond agricultural systems (1,2,3,4,5)
Heavy rainfall for a short period (6)	Decrease in animal performances and number (3)	Poor transport network Limited access to markets (2)	Continuous change in the cropping system as varieties, species, and farming practices try to adapt (3)	Diversification – from pastoralism to agro-pastoralism, increase in permanent settlement from nomadism lifestyle, increase in Remittances from the diaspora, increase in Women-headed households, increase in ownership of smaller livestock (goats and sheep) (2)
Stone rains which destroy annual crops (6)	Crop pest infestations (1,4)	Limited access to information (2)	Increase in loss of biodiversity and deforestation (3)	Crop and farming diversification; Expansion of new cash crops using excessive water during summer time; Increased intercropping using more than two species (woody and herbaceous) ; Activity and income diversification (3)
Irregular rainfall (3)	Etiolating (rapid elongation) of rain-fed rice, peanuts, and corn (1)	Sense of hopelessness (2)	Decline in vegetation cover (5)	Crop diversification and growing of short-season varieties in years that are predicted to be below normal and medium season varieties in years that are predicted to be above normal (4)
Erratic rainfall (5)	withdrawal of wild game during pockets of severe drought (1)	Increased jobless population and poverty (3)	Reduced vegetation for grazing (2)	More producers pool together to exploit land (5)
Occasional rainfall during dry season (1)	loss of flowers of cocoa, branches of multipurpose trees (1)	Increased female and child vulnerability (3)	Frequency in the occurrence of drought (2)	Improved deep tillage practices using deep tillage implements; Used early maturing crop varieties of annual and tree crops; Improved application of organic fertilizers, particularly compost manures and animal farmyard manure; Improved and engaged local agricultural innovation systems; (6)
Low rainfall during the year (1,3)	fewer edible caterpillars, mushrooms, and fish (1)	Changes in gender roles (2)	Increase in soil degradation and losses (3,4,5,6)	Change of crop types and varieties; more livestock rearing such as poultry and livestock; crafting as alternative activity (woody and non-woody items) (5)
Droughts (2,4,5)	increased animal, livestock, and human morbidity (1,2)	Differentiation of vulnerability by gender (1,4)	Increase in soil desertification as result of non-adopted agricultural practices and overgrazing (3)	Herd sizes reduction in animal husbandry transformations (3)
Severe Frequent drought (3)	increased bushfires (1,6)	Food insecurity (2,4,6)	Increase in the occurrence of flash floods (2)	Abandon of some traditional practices (5,6)
Early and late season droughts (3)	Migration (2)	Introduction of new cops (6)	Increased water loss and decreased water use efficiency (3)	More people drop rain-fed agriculture to turn to gardening (5)
Punctual droughts during rainy season (1,4)	Abandon of agricultural activities in some areas (5)	Increase in conflicts (2)	Increase in water salinity as deep water is over exploited (3)	Increased access to deep water tables (3)
High temperatures (6)	Increase in livestock theft (2)	Increase in conflict around water, grazing land, and land tenure (3)	Sedimentation (4)	Improvement of irrigation systems and water management (5)
Heat waves during dry season (1,3)	Decrease in the snowbelt (3)	Increase in conflict between crops and livestock keepers (6)	Poor infrastructures (2)	Increased state investments in water catchment and harvesting; New policies and investment for water economy and water use efficiency (3)
Strong winds (1)	Soil degradation and loss (3,6)	Disintegration of local institutions and organizations (3)		Migration from rural to urban or other areas (2,3,4,5,6)
Excessive wind in semi-arid areas (6)	Soil erosion or formation of hard pans (6)	Weak extension services Unfavourable government policies hindering the survival of pastoralism system (2)		
Floods (4,6)	Decrease in the water table (3,5)	poor performance of national institutions and international aid agencies as drivers of vulnerability (1,3)		
Occasional heavy flooding storms (3)	Disappearance of long-term growing crop such as maize and sorghum (6)	xx		

1: Project 1 (Cofcca: Congo Basin Forest and Climate Change) [Central Africa].
2: Project 2 (Enhancing Adaptive Capacity of Pastoralists to Climate Change: Induced Vulnerability in Northern Kenya) [East Africa].
3: Project 3: Adaptation Mechanisms to Climate Changes of local communities of two contrasted ecosystems of Morocco: arid plain and High Atlas Mountain [North Africa].
4: Project 4: Building adaptive capacity to cope with increasing vulnerability due to climatic change [Southern Africa].
5: Project 5: InfoClim (Platform for Helping Vulnerable Communities Adapt to Climate Change) [West Africa].
6: Project 6. Strengthening Local Agriculture Innovation Systems to Adapt to Climate Change in Tanzania and Malawi [Cross-Regional: East and Southern Africa].

and strong winds as hazards affecting their livelihoods (Bele et al., 2010, 2013b).

Trends towards aridity and more frequent drought are evident in multiple locations (Benaouda et al., 2008; Lema & Majule, 2009; Majule et al., 2013; Mongi et al., 2010). At the CCAA study sites in Morocco, surface water resources have declined significantly over the past 50 years, primarily due to reduced snowfall over the Atlas mountains and a subsequent reduction in spring meltwater (Benaouda et al., 2008). In the rural commune of Lamzoudia, over 94% of farmers reported that drought is the principal climate hazard of concern. Over 60% of surveyed farmers felt that the 1980s (and 1981 in particular) had been extremely dry. Subsequent droughts in the 1990s and 2000s convinced them of a downward trend in rainfall. These observations are consistent with projections for Morocco and the Maghreb as a whole, which indicate warming above the average for the African continent, and the largest percentage rainfall reductions in Africa (Christensen et al., 2007).

A CCAA project examining livelihood strategies in northern Kenya found that drought frequency had increased, with droughts now occurring at least once every five years, rather than once every 10 years as in the past. In all, 82% of respondents in the Turkana region noted that drought severity and frequency had increased, with drought becoming an almost regular and permanent phenomenon. These findings are consistent with results reported by Funk et al. (2008), Williams and Funk (2010), Cook and Vizy (2013), and Lott et al. (2013) that suggest drying and more frequent drought in the region, contrary to projections based on model averages described by the IPCC (Christensen et al., 2007). East African climate variability, associated with both droughts and extreme precipitation hazards such as flooding, is linked with El Niño and La Niña (Kyomuhendo & Muhanguzi, 2008), the future behaviour of which is uncertain (Meehl et al., 2007).

The prevalence of drought in the Sahel (Brooks, 2004) is underlined by meteorological data from the CCAA project site of Thies in Senegal, where the average annual rainfall for the period 1920–1967 was 660 mm, whereas that for the period 1968–1999 was 440 mm. During the latter period, annual rainfall fell below 300 mm in 1968, 1972, 1973, 1977, and 1983. In Tanzania, rainy seasons exhibited two distinct rainfall peaks prior to the 1950s, since when the second peak has decreased in duration and been associated with very little rain (Lema & Majule, 2009).

3.2. *Impacts*

The CCAA projects identified a wide range of impacts associated with the climate hazards described above, involving impacts on water resources, soils, crops, and livestock.

Reductions in spring meltwater from Mount Kilimanjaro have adversely impacted water resources in the Pangani River in Tanzania, while lower rainfall has resulted in a decline in groundwater and a drying of wetlands in Eastern Africa (Majule, 2008). In south-eastern Africa, intensified climate extremes have been associated with floods, landslides and soil erosion, and loss of property. In Morocco, reduced meltwater and drought have contributed to a decline in surface and groundwater levels in the Tensit al Haouz basin, in which groundwater declines of more than 20 m over the past 15 years have been reported at the CCAA study site of Lamzoudia (El Mzouri et al., 2010). Desertification has intensified in the Moroccan study areas as water resources have declined, resulting in the loss of productive land.

The above factors have impacted agricultural production in the locations assessed by the CCAA projects. At Lamzoudia (Morocco), declining water resources and land degradation have been associated with a reduction in irrigated areas, shorter growing seasons for some crops, and declines in the yields and cropped area of soft wheat (El Mzouri et al., 2010). CCAA projects in southern and south-eastern Africa conclude that erratic rains and increasing temperatures are associated with declines in soil fertility and crop yield, stunting of crops, and the destruction of mature crops in the field and of stored crops (Lema & Majule, 2009; Mubaya et al., 2010; Mugabe et al., 2010). Prolonged and frequent droughts as well as higher temperatures are associated with the drying of agricultural soils, impeding timely seed germination and crop establishment.

In the Congo Basin of Central Africa, farmers identified negative impacts on their livelihood activities including weak agricultural productivity and crop pest infestations such as cassava tuber rot; etiolating (rapid elongation) of rain-fed rice, peanuts, and corn; withdrawal of wild game during pockets of severe drought; loss of branches of multipurpose trees; failure of cocoa flowers; fewer edible caterpillars and mushrooms; decreased fish stocks; increased animal morbidity; and increased bushfires (Bele et al., 2010; Bele, Tiani, Somorin, & Sonwa, 2013b). Other studies in this region have associated prolonged rainy seasons with negative impacts on crop production leading to shortages in local markets (Yengoh, Tchuinte, Armah, & Odoi, 2010). However, farmers have also identified opportunities associated with changes in climatic conditions, including opportunities for the rapid growth of some plants such as plantain, cocoyam, and cassava during wet anomalies in the dry season (Bele, Sonwa, & Tiani, 2013a, 2013b). The occurrence of droughts provides an opportunity to produce off-season corn in drying watercourses and swamps, and to shift from one to two cycles of annual production.

Climate-related impacts on livestock systems were identified by various CCAA studies. In south-eastern Africa, CCAA projects highlighted reductions in livestock productivity, increases in livestock diseases such as East Coast Fever, the loss of livestock due to floods, and an increased incidence of vector-borne diseases. These impacts in turn have been associated with increasing periods of hunger, as well as an increased dependency on natural resources for food security as crops fail. In Morocco, reduced water and pasture have been associated with a decline in the size of grazing animals (El Mzouri et al., 2010). In semi-arid areas of Tanzania, reductions in pasture availability were reported by 60 % of respondents, and increased pests and livestock diseases by 40% of respondents (Majule et al., 2013).

A CCAA study in Turkana and Mandera in northern Kenya found that reduced pasture availability for livestock as a result of drought was reported by 60% of respondents. In all, 40% of respondents in semi-arid areas also reported increases in pests and diseases. As droughts have increased, the return period of famine in Kenya has reduced from 20 years (1964–1984), to 12 years (1984–1996), to two years (2004–2006), and to yearly (2007/2008/2009) (GOK, 2010), a trend reflected in oral testimony from a male Turkana pastoralist during the project inception workshop, who stated:

> In the past … we had droughts once in 10 years. But these days … droughts are frequently occurring every year, our animals are dying from diseases we don't know how to cure, there is less pasture and water is scarce … .

In Mandera, and to a lesser extent in Turkana, pastoralists are moving from nomadism to semi-permanent settlement, in which men move in search of water and pasture while most of the household is sedentary.

CCAA projects in both East and West Africa found evidence that climate change was challenging traditional knowledge based on predictable seasonality. A high proportion of survey respondents in northern Kenya had come to depend on the use of indigenous knowledge and local "diviners" for early warning information on weather and seasons due to the lack of access to modern meteorological information. When asked if the indigenous sources of knowledge on weather and seasons were working well for them, 43% of the respondents noted that reliability of weather and seasonal information from such indigenous systems is reduced as climatic conditions change and the occurrence of predictive, natural environmental indicators becomes less frequent. In Thies in Senegal, traditional knowledge and practices resulting from the accumulation of observations, innovations, and forms of adaptation that guided farmers' technological and economic choices appear to be less successful. Sowing, cultivation techniques, and tillage dates based on past experience seem increasingly inappropriate to new climate conditions. These conclusions echo those of Galvin, Thornton, Boone, and Sunderland (2004), who states that while East African pastoralists have been able to track climate variability very well in the past, their existing strategies, based on centuries of exposure to intra- and inter-annual climate variability, are no longer working, although this is partly because they are no longer able to implement them.

3.3. *Social vulnerability*

While factors such as poverty, low livelihood diversity, and geographical isolation mean that vulnerability to climate change and variability is high in many African populations, vulnerability varies considerably within and between populations (Brooks, 2003; Downing & Patwardhan, 2003). Climate change is particularly likely to affect resource-poor households who are unable to invest in or take advantage of alternative income sources or new agricultural strategies, and who are less able to recover following droughts, floods, diseases, or other shocks (USAID, 2010). Policies can also influence vulnerability; for example, policies promoting the expansion of agriculture into temporarily productive but historically marginal lands have been proposed as a major driver of vulnerability which, when combined with drought hazards, can result in famine (Brooks, Brown, & Grist, 2009; Heyd & Brooks, 2009).

Vulnerability in northern Kenya was found to be influenced by age, gender of the household head, disability, and factors that constrain mobility and/or access to pasture, foster conflicts and insecurity, encourage concentration of populations in the rangelands, constrain market access, promote unfair trade, and weaken veterinary service delivery. Men's vulnerability was associated with animal losses during droughts or floods, which makes it difficult for them to support their families and results in loss of social status, as wealth is defined by the number of animals one owns. In Turkana, it was noted that female-headed households lacked labour for herding and accessing better pastures, which tend to be located in conflict-prone areas. Heightened risks and climate impacts were observed to marginalize women from strategic decision-making such as investments, spreading risks, and planting decisions, even where female-headed households are a significant proportion of the population. Put simply, women's views are more likely to be ignored during these periods characterized by intensified climate-related stresses.

Conflict was cited as a reason for moving by 21.9% and 4.5% of respondents in Turkana and Mandera, respectively. In both areas it was observed that families that included educated female members were able to survive better during the 1999/2000 drought than those that did not. This result reflects the conclusions of other studies at much larger scales (e.g. Brooks, Adger, & Kelly, 2005). The proportion of women who could read and write was 7.9% of the 922 respondents in Turkana and 6.1% of the 423 in Mandera.

Structural issues characterizing vulnerability in northern Kenya included access to markets for livestock and crop produce, access to health centres, and access to roads used by motorized transport. In Mandera, 57% of respondents walked for over 6 hours to access the nearest livestock or produce market; 53% of respondents identified lack of access to market infrastructure, including livestock auction yards, as a constraint on the sale of livestock during droughts, an important coping strategy. In all, 83.6% of respondents cited lack of road and communications infrastructure as constraining their access to weather and seasonal forecast information. Three percent hardly received any information on weather or seasons and 1% of the respondents received no radio-transmitted weather information.

The Southern Africa (Zimbabwean, Zambian, and Malawian) experience demonstrates that existing agricultural extension agencies, though present, are not sufficiently well equipped or organized to provide farmers with the assistance they require. Poor transport networks represent a major problem hindering the delivery of information by extension workers to farmers. In West Africa (Senegal) accessing and understanding information on climate change and technical alternatives to address it are one of the challenges facing farmers. Information (meteorological, agricultural advisory services, national agricultural agencies, etc.) are produced by different stakeholders, but at the individual level, access to these sources of information is very limited. The findings of projects in Central Africa highlighted remoteness of populations from urban centres and the poor performance of national institutions and international aid agencies as drivers of vulnerability, and also emphasized the differentiation of vulnerability by gender (Bele et al., 2010, 2013a, 2013b; Brown, 2011; Brown, Nkem, Sonwa, & Bele, 2010; Nkem et al., 2013; Sonwa, Somorin, Jum, Bele, & Nkem, 2012).

3.4. *Biophysical vulnerability*

CCAA project results from Morocco in particular are used here to illustrate how biophysical vulnerability can be amplified by human activities, including responses to climatic and environmental change. Frequent droughts and the overexploitation of groundwater have been identified as factors in the abandonment of certain areas and movement to new locations such as Lamzoudia in the lowland area of the Tensit al Haouz basin. This has led to the introduction of new, market-oriented, cropping systems based on alfalfa, legumes, and watermelons, which are high consumers of water, land, and labour. This is a result of agricultural policies adopted since 1980s that encourages shifting from subsistence to commercial farming. Indeed, we observe less rain-fed barley, durum wheat and more high water-consuming crops such as watermelon and vegetable crops and rain-fed soft wheat (El Mzouri et al., 2010). Accelerated low soil fertility has been taking place as a result of high organic matter decomposition and export by over-grazing. Also, non-adapted crop irrigation increased soil salinity, making soils more vulnerable (El Mzouri et al., 2010). This is part of a longer term, policy-driven to move from subsistence to commercial farming since the 1980s, with a shift from barley, durum wheat, and some limited irrigated vegetable production to greater emphasis on soft wheat, which now comprises some 70% of the cultivated area (El Mzouri et al., 2010). These changes have resulted in greater groundwater abstraction and a more than two-fold expansion of the cultivated area which, along with changes in rainfall and runoff, have contributed to the depth of the water table increasing from around 20 m in the mid-1990s to over 70 m in recent years (El Mzouri et al., 2010). Overexploitation of groundwater has also resulted in salinization, with negative impacts on crop performance and drinking water supplies for humans and livestock. Since 2000, increased exploitation of water and land has led to a decline in vegetation cover, the disappearance of some species, and adverse impacts on pastoral systems.

In highland areas irrigated crop land is also expanding, along with the cultivation of high water consumption crops and practices. Water demand is increasing as supply is declining due to lower precipitation, and water quality is increasingly compromised, particularly during dry years, because of the heavy use of fertilizers and a lack of systems to manage wastewater effectively (El Mzouri et al., 2010). Forest and grazing land were the dominant land types in the 1950s and 1960s, and these landscapes have experienced pressure from natural resource exploitation and drought as well as the expansion of agriculture, with many species disappearing as a result (El Mzouri et al., 2010). This situation reflects that elsewhere in Africa, for example in Tanzania and Kenya, where agricultural expansion and demand for timber have reduced forest cover in mountainous areas (Muganyizi, 2008 and Maitima et al., 2009).

Heavy grazing, deforestation, and the expansion of agriculture have resulted in soil degradation in the study areas in Morocco, where stony alluvial soils dominate. Decreases in organic matter have been observed in these soils and this is thought to be due to the removal of plant cover, including below-ground plant matter in dry years. According to the local populations, the resulting bare soils have been subject to water and wind erosion associated with heavy rains and strong winds that have prevailed during the last 30–40 years. Flooding, severe drought, and increased land salinity resulting from irrigation have amplified the vulnerability of these soils (El Mzouri et al., 2010).

Results from Central Africa highlight the biophysical vulnerability of different cropping systems. Intercropping is generally considered to be more resilient than mono-cropping, due to better utilization of solar radiation; greater efficiency in the use of soil and applied fertilizers; fewer problems with weeds, pest, and disease control; as well as enabling better use of manual labour (Sanchez, 1976; cited in Gockowski et al., 2004). Where mono-cropping performs well, this is generally due to high investment in inputs.

A variety of processes have been identified as contributing to the vulnerability of agricultural soils in parts of eastern and southern Africa. Vertisols tend to crack and become dry as temperatures increase following flooding, making them difficult to cultivate and prone to erosion (Mugabe, Nyamangara, Mushiri, Nyamudeza, & Kamba, 2002). In high-potential areas of the Kenyan, Tanzanian, and Malawian highlands, local populations report that bare soils have been exposed to water and wind erosion associated with an increased prevalence of torrential rains and strong winds over the last 30–40 years. A resulting increase in rates of organic matter decomposition leads to reduced soil fertility. Poor management of crop irrigation results in increased soil salinity, making soils more vulnerable to floods and droughts (El Mzouri et al., 2010). In West Africa, decline in vegetation, soil depletion (exposure to wind and water erosions), as well as high vulnerability of vegetable crops used to grow in cold season (e.g. potato) were also identified as biophysical vulnerability. These findings emphasize the non-linear nature of vulnerability, in which increased biophysical vulnerability of soils resulting from human activity is exacerbated by processes related to climate variability and change, making them even more susceptible to degradation and erosion.

3.5. *Adaptive capacity*

Most farmers in the CCAA study areas (and throughout Africa) have knowledge of strategies for coping with current climate variability and extremes, which enhance their capacity to modify their agricultural practices. These strategies include planting of drought-tolerant crops that suit the local climate, and improved water conservation technologies and techniques such as irrigation scheduling, the use of dynamic crop calendars, and the construction of water reservoirs. Livestock systems benefit from improved feeding systems, for example, the feeding of sheep on straw, cactus, and Atriplex in the dry areas of Morocco. Livestock and crop diversification is also evident in this context, along with granaries that protect harvests for use in the following year. Pastoralists and other users of natural resources will often have a detailed knowledge of their environment that enables them to anticipate and respond to changes in environmental conditions and the availability of resources such as surface water and pasture. Pastoralist adaptation strategies include mobility, herd splitting, redistribution of surplus livestock within society, and diversification of livestock (Omolo, 2010; Ouma, 2011). In northern Kenya, livestock keeping remains the primary livelihood activity (at 78% of respondents), but is complemented by crop farming along rivers, selling firewood, burning and selling charcoal, selling livestock products such as milk, and involvement in small businesses. Diversification in northern Kenya also exhibits gender differentiation, with women involved in commercial mat and basket weaving (mainly in Turkana) and growing numbers of women running small shops in Mandera, while men engage in carpentry and masonry, and in labour that is often casual and involves migration to towns. In Morocco, a growth in mountain tourism and handicrafts has occurred alongside an intensification of livestock husbandry as people diversify away from growing crops. Diversification is also taking place within livestock systems. For example, in East Africa, particularly in Tanzania, pastoralists maintain large cattle herds in rural areas, but increasingly are being encouraged to reduce livestock numbers and to keep "improved" breeds. In Morocco, there is a shift away from traditional breeds of sheep towards breeds that are raised more intensively, such as the D'man. In Central Africa, the diversity of cultural systems and plant and animal species represents a pool of resources on which local communities can draw for livelihood diversification and innovation (Gockowski et al., 2004).

Empirical or "traditional" knowledge built up over generations plays a key role in short-term adjustments and adaptations to evolving climatic conditions. Such knowledge includes an array of indigenous indicators based on environmental and cultural beliefs (Kalanda-Joshua et al., 2011). Though farmers share indigenous knowledge of climate predictions informally, it was noted in Zimbabwe and Zambia that there were no community-based institutions/platforms to share and compare farmers' predictions of the coming season. Such arrangements exist in Kenya where communities in Mandera and Turkana have formed various self-help groups and community-based organizations (CBOs) to help them cope and adapt to climate variability and change.

Traditional knowledge is increasingly complemented by technology, in the form of communications (which facilitate the rapid transmission of information about environmental conditions, for example, through the use of mobile phones by pastoralists to share information about rainfall) and short-term and seasonal weather forecasts. However, the poor coverage and sometimes limited usefulness of services such as forecasts mean that many people depend principally or exclusively on indigenous knowledge systems. As discussed above, in some instances these systems are breaking down as a result of climate change, meaning that lack of access to weather information acts as a constraint on adaptation.

Agricultural extension services in principle can play a role in disseminating information on climate-related risks and supporting adaptation (Ziervogel et al., 2008). Most sub-Saharan countries have such extension services and systems which take best practices to the farmers. Education, community development projects, and access to subsidized credit can also play a role in helping farmers improve their practices. These institutional factors play a role in facilitating the delivery of weather information and the adoption of appropriate adaptation strategies in Zimbabwe, Zambia, Kenya, and elsewhere (Sterm &

Easterling, 1999). The Zimbabwean, Zambian, and Malawian experiences demonstrate that existing agricultural extension, though present, is not well equipped or organized to assist farmers address the challenges they face now, let alone those they are likely to face in the future as climate change intensifies. For example, in Zimbabwe the ratio of extension workers to farmers is 1:600, compared with the recommended minimum ratio of 1:400. Poor transport networks and a lack of familiarity of extension workers with seasonal climate forecasts (meaning that forecasts are often not passed on to farmers) also represent barriers to adaptation.

Adaptive capacity also depends on financial resources, for example, to buy expensive short-season hybrid crops suitable for drier conditions. The construction of infiltration pits requires large initial labour investments that may not be feasible for more resource-poor farmers. The subsistence character of much African agriculture means that agriculture is often not undertaken as a business, but rather has to be supported by other enterprises that generate funds for purchasing farm inputs. In Kenya, Morocco, Zimbabwe, and Zambia, most farmers maintain gardens where they produce vegetables for both subsistence and sale, with income used to purchase grain in dry years as a coping strategy. In principle, such income can also be used to support adaptation, although the surplus that is available for sale is often small.

Just as mobility represents a key strategy for "coping" with climate variability for pastoralists, so changes in patterns of mobility may be necessary if pastoralists are to adapt to climate change. As well as increasing vulnerability by restricting mobility and undermining livelihoods through loss of livestock, livestock raids and conflicts over resources also limit the adaptive capacity of pastoralists by narrowing mobility options.

Cultural factors play a key role in mediating farmers' adaptation strategies. In Southern Africa (Zambia and Zimbabwe), farmers might not adopt certain proven agricultural practices because of beliefs, for example, that adding fertilizers will reduce the fertility of their soils or vertisols. Smallholder farmers on the Chisumbanje vertisols in semi-arid Zimbabwe will not use fertilizers in their fields even if these are given freely through agricultural input schemes (Mugabe et al., 2002), despite research results showing that fertilizers will increase maize yields on the vertisols (Nyamudeza, 1998). Farmers are also reluctant to use fertilizers in case drought results in the input being wasted. In Central Africa (Congo Basin), conservation of biodiversity is generally perceived as a barrier to the adoption of certain adaptation measures and thus as an obstacle to poverty reduction. Conservation can result in the denial of access to forest habitat that is suitable for agriculture and that also provides forest products that play an important role in livelihoods (Nasi et al., 2008).

Institutions play vital roles in the success and failure of adaptation and changes in the adaptive capacity of individual households (Reid & Vogel, 2006). Institutional norms and practices can create incentives and disincentives. In Ghana, it was observed that migrant farmers were unwilling to invest in more sustainable forms of agriculture. Adger (2003) explains that adaptation is a dynamic social process, thus the ability of societies to adapt is determined, in part, by the ability to act collectively. Research findings from Kenya reveal that farmers have formed various self-help groups and CBOs to help them cope with and adapt to climate variability and change. In the Congo Basin, the importance of farmers' associations and local NGOs was highlighted in this context, while farmers in Central Africa attempt to cope with change by diversifying their livelihoods, modifying their consumption patterns, and exploiting networks across communities. Such "autonomous" initiatives might be assisted and enhanced with effective institutional support. Currently, adaptation in this region is constrained by a lack of infrastructure and, in some areas, by conflict or post-conflict situations, which inhibit communications, learning, and innovation.

Of course adaptive capacity and vulnerability are closely related, and the building and deployment of the former, for example through collective action, should serve to reduce the latter.

4. Discussion and conclusions

The findings of the CCAA programme indicate that climatic conditions are changing in diverse agro-ecological environments throughout Africa, and that African populations are being affected by, and responding to, these changes. In some cases people appear to be adapting to climate change, while in others changes are driven more by policy or commercial imperatives.

In all of the six research projects, adaptive capacity involved a change or a diversification of livelihood practices. The framework that we presented in this article can guide a reflection among stakeholders about how to allow these changes to reduce biophysical and social vulnerability in the long run.

Agricultural risks and food security outcomes are associated with changes in climatic conditions themselves, with a host of factors that mediate the vulnerability of physical systems (e.g. geomorphological and hydrological systems) and social systems (e.g. households, communities, and local institutions) to climate hazards, and with other factors that facilitate or constrain adaptation.

Drivers of risk interact in complex ways. For example, in Morocco it appears that the concentration of commercial agriculture in Lamzoudia was, at least in part, a response or adaptation to worsening climatic conditions elsewhere. However, this has resulted in an intensification of pressure on water and soils, increasing biophysical vulnerability to further climatic deterioration. This in turn has the potential to increase social vulnerability by undermining livelihoods that depend on natural resources, and the reduction in available productive land may constrain adaptive capacity by reducing options for agricultural and pastoral diversification. So, vulnerability is observed to increase while adaptive capacity is being constrained, as hazards (principally droughts) are intensifying. Drivers of all the components of risk are thus intensifying, increasing the likelihood of adverse outcomes.

The Moroccan case study illustrates that while production systems may be responding to climate change, there are questions about the sustainability of some of these responses. It also illustrates the costs and risks of institutional adaptation, as local institutions responsible for water management restructure water allocations to manage increasing demand. While changes to allocation regimes aim to limit the impacts of water scarcity, conflicts over water resources are increasing, as radical solutions are adopted by users, including the digging of new wells, the installation of pumps, and the extension of irrigation to mountain slope areas.

The CCAA project findings reveal livelihood diversification and the growth of non-agricultural income-generating activities as responses to climate and other changes in diverse contexts.

CCAA research results from the Congo Basin illustrate that, at least in some contexts, climate change generates opportunities as well as risks. Where climate change is not associated with absolute declines in potential productivity in food producing systems, whether changes represent risks or opportunities may depend on how people respond to them. In contrast, in areas such as semi-arid East Africa, it is difficult to see how an intensification of drought could be seen as an opportunity, except to stimulate attempts to transition to more resilient agricultural and social systems. Also, a new option would be to take out weather-indexed insurance, which pays policy holders in response to “trigger events” such as frequent droughts and abnormal rainfall to help pastoralists better manage the risks they incur. This is so as it can take family herders in semi-arid climate change hotspots in East Africa up to a decade to restock after a drought has killed many of their animals, and in worse cases, some are never able to recover their livestock livelihoods.

CCAA research concludes with a number of precepts of the climate-related risks that research-for-development communities should bear foremost in mind to make a bigger difference. Attend to context is one prominent precept as silver bullets would not work. Every option enhancing adaptive capacity, diversification, or risk management in the given regions and circumstances may not necessarily work in others. The context is decisive: local circumstances determine what works and what does not. The findings from this synthesis of CCAA research thus emphasize the highly contextual nature of climate-related risks, outcomes, and adaptation in African contexts. It highlights the role of multiple factors, ranging from the availability of physical resources through policy contexts, to the role of culture, in mediating climate change risks and opportunities. Consequently, adaptation support needs to be complemented by research that can generate contextual information to inform adaptation policies, strategies, and measures. Interventions need to go beyond technical fixes, such as the development of new crops, and must be based on an understanding of how different factors can and do interact in a complex manner to drive risk and to result in adverse outcomes in specific contexts.

PAR approaches have the potential to generate contextual knowledge, as well as to allow stakeholders to share, discuss, and act on it. PAR-like approaches, using reflection frameworks such as the one presented here, can be used in adaptation planning at the community level, and also to design policies and programmes that will support sustainable adaptation by the most vulnerable.

Acknowledgements

The authors thanks Nathalie Beaulieu for her support during the reviewing process of this paper. The two anonymous reviewers are thanked for their advices on how to improve the quality of this paper. Special thanks go to all the farmers and stakeholders involved in each of the six projects for their time and interest on our research. The first author (DJS) is working with CIFOR within the CGIAR Research Program on Forests, Trees and Agroforestry (CRP-FTA).

Funding

The six projects from which this paper is written were financed by CCAA (Climate Change Adaptation in Africa) program funded by International Development Research Centre (IDRC) and the Department for International Development (DFID).

Disclosure statement

No potential conflict of interest was reported by the authors.

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