VUNA

changing farming for
a changing climate

Transformational Adaptation to Climate Change:

Concepts, Examples, and Relevance for Agriculture in Eastern and Southern Africa

Research Report commissioned by Vuna | November 2016

Adam Smith International

UKaid
from the British people

Please cite this publication as follows:

Brooks, Nick. 2016. Transformational Adaptation to Climate Change: Concepts, Examples, and Relevance for Agriculture in Eastern and Southern Africa. Pretoria: Vuna. Online: http://www.vuna-africa.com

Project Team

Project Team Leader	Nick Brooks
Project Manager	Vimbai Chasi
Editor	Mark Essig

Date: November 2016 | **Lead Author:** Nick Brooks | **QA'd by:** David Rohrbach

Vuna is a DFID-funded regional Climate Smart Agriculture Programme. The British Government's Department for International Development (DFID) financed this work as part of the United Kingdom's aid programme. However, the views and recommendations contained in this report are those of the consultant, and DFID is not responsible for, or bound by the recommendations made.

UKaid
from the British people

TABLE OF CONTENTS

Acronyms iii

Executive Summary iv

1 Introduction 1

2 Incremental versus transformational adaptation 2

3 Transformational changes driven by considerations other than severe climate change 4

4 Transformational adaptation as a necessary response to climate change 5

5 Examples and case studies 9

5.1 Transformational change and adaptation in the distant past 10

5.2 Transformational change and adaptation in the recent past: The Sahel 12

5.2.1 Indigenous intensification of agriculture in northern Nigeria 13

5.2.2 Transformational adaptation to increased aridity by pastoralists in eastern Niger 15

5.2.3 Transformations in livelihoods and social structures in northern Mali in response to the drying of Lake Faguibine 15

6 Transformational adaptation in the agricultural sector in East and Southern Africa 16

6.1 Regional climate trends and projections 16

6.1.1 Observed trends and variations in climate 16

6.1.2 Projected changes in climate 17

6.2 Climate change impacts on agriculture in East and Southern Africa 18

6.3 Current approaches to adaptation and agricultural development 20
6.4 Possible transformational changes in climate and adaptation responses in East and Southern Africa 22
6.4.1 Temperature shifts outside the range of historical variability 22
6.4.2 Transitions from cropping to extensive livestock systems 22
6.4.3 Possible transitions to aridity: The Greater Kalahari region 23
6.4.4 Increasing marginality and increased frequency of crop failure 24
6.4.5 Loss of productive land to sea-level rise 25
6.4.6 Transformational adaptation through the exploitation of opportunities 25
6.5 Timing and extent of transformational change and adaptation in East and Southern Africa 26
6.6 Facilitating transformational adaptation 28
7 Conclusions 31
References 33

List of Figures

Figure 1: Illustration of the concept of the coping range, defined in this hypothetical example by a critical threshold in a notional climate variable, beyond which a system experiences disruption (i.e. is vulnerable). Climate change may increase the frequency at which the critical threshold is breached, while incremental adaptation measures may expand the coping range, shifting the critical threshold so that disruption is reduced. The system is 'resilient' within the coping range. The increase in resilience resulting from the adaptation measures can be measured as the amount by which the critical threshold changes. Reproduced from European Commission (2013). 6

Figure 2: Summer (June-October) Sahel rainfall anomalies over the region from 10°-20°N and 20°W-10°E for the period 1900-2013. Data from the NOAA NCDC Global Historical Climatology Network, graphic from Todd Mitchell, University of Washington. 13

List of Tables

Table 1: Possible transformational adaptations identified in the literature relating to the period centred on the Middle Holocene Climatic Transition (MHTC), from approximately 4500-3000 BCE. This table is based on the conclusions of reviews by Brooks (2006a, 2010), Clarke et al. (2016). 11

Table 2: Barriers to transformational adaptation as identified in the limited literature relating to this topic. 28

Acronyms

BCE	Before the common era
CSA	Climate Smart Agriculture
DFID	Department for International Development
ENSO	El Niño-Southern Oscillation phenomenon
FAO	Food and Agriculture Organization of the United Nations
IEG	The World Bank Independent Evaluation Group
IPCC	Intergovernmental Panel on Climate Change
MHTC	Middle Holocene Climatic Transition
NOAA NCDC	National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC)
OCED	Organisation for Economic Co-operation and Development
OND	October-December
PDSI	Palmer Drought Severity Index

Executive Summary

Increasingly, a distinction is being made between 'incremental' and 'transformational' adaptation. Incremental adaptation is defined in the latest IPCC report as consisting of "actions where the central aim is to maintain the essence and integrity of a system or process at a given site". In contrast, transformational adaptation "changes the fundamental attributes of a system in response to climate and its effects." Incremental adaptation typically involves using familiar strategies and measures to reduce losses or enhance benefits associated with climate variations and extremes, and overlaps with approaches that seek to increase the 'resilience' of existing systems and practices in the face of evolving climate hazards and risks. Transformational adaptation is predicated on the recognition that existing systems and practices may be inappropriate or unviable under emerging or anticipated conditions associated with climate change (although it might also involve radical changes to, or the replacement of, existing systems and practices with ones that confer greater benefits under existing conditions). Transformational adaptation will be necessary where climate change results in the crossing of critical thresholds or 'thresholds of viability', beyond which existing systems and practices cannot be sustained. These thresholds may be dynamic, and depend on the nature and extent of incremental adaptation; transformational adaptation will be required where further incremental adaptation is impossible or impractical (e.g. due to prohibitive costs), and where incremental approaches cannot keep pace with changes in climate due to the rapidity and/or magnitude of those changes.

Most current adaptation initiatives and actions are incremental in nature, and examples of recent or contemporary transformational adaptation are scarce. The most obvious such examples involve the actual or planned relocation of settlements and populations from low-lying coastal areas in small island states and North America, where adaptation *in situ* to rising sea-levels is impractical. The deliberate retreat landwards of coastal defences as part of 'managed realignment' programmes also represents a transformational approach to adaptation, contrasting with the incremental approach of building ever-higher and more robust sea defences. The Sahel region of Africa provides examples of transformational adaptation to climatic desiccation – transformational adaptation in response to transformational changes in climatic and environmental conditions. These include transitions from aquatic livelihoods to livelihoods based on livestock and forest products in the area formerly occupied by Lake Faguibine in Mali, whose dry bed is now occupied by forest; a shift from cattle to more drought-tolerant sheep and goats in northern Nigeria; out-migration from rural villages to urban centres and the establishment of businesses exploiting niche markets; and the autonomous adoption of new crops by farmers without external development project interventions.

These examples from the Sahel echo examples of transformational adaptation apparent in the archaeological record of the last period of global climatic reorganisation and disruption, between about 4500 and 3000 BCE, during which the present-day northern hemisphere arid belt underwent a transition from relatively humid conditions to desert. During this period, human populations in the northern hemisphere sub-tropics adapted to increased aridity and a decline in resource availability through a combination of increased mobility based on extensive grazing (where this enabled them to exploit more sparsely distributed pasture resources); increased sedentism in oasis areas (where aridity crossed thresholds beyond which pasture was unavailable outside these areas); transitions from farming to extensive livestock grazing and vice versa; shifts from cattle to sheep and goats; agricultural intensification in restricted areas where irrigation was possible; intensified use of river and lake environments; out-migration; and in-migration to environmental 'refugia' where resources where still available. These strategies, particularly in-migration to refugia and agricultural intensification, were associated with a variety of profound social changes, including increased social organisation based on more hierarchical and unequal societies; the emergence of elite groups; and changes in social relations within and between populations in specific locations. These changes in social relations are echoed in changes in gender relations and power relations between different ethnic and livelihoods groups associated with recent transformational adaptation in the Sahel.

Climate projections and studies of the potential impacts of climate change on agricultural systems in East and Southern Africa highlight the potential need for transformational adaptation in these regions in the 21st century. Transformational adaptation might be a necessary response to shifts in growing season temperatures outside the range of historical variability, shifts in agro-climatic zones, transitions to (hyper-) aridity (e.g. in the Greater Kalahari region), reductions in the availability of water including groundwater, the loss of agricultural land to sea-level rise and coastal erosion, and the intrusion of salt water in coastal aquifers due to a combination of sea level rise and lowered groundwater levels. Changes in rainfall, increased temperatures, intensified evapotranspiration and periodic drought might combine to increase the frequency of crop failures to such an extent that disaster response becomes impractical and prohibitively costly, requiring transformational adaptation responses.

Transformational adaptation in East and Southern Africa might involve the substitution of existing crops and cropping systems with new ones, perhaps based on current analogues – other locations or countries that currently experience climatic conditions expected to pertain in the future at the location at which adaptation is required. In some locations crop systems might be replaced with extensive livestock management. Agriculture might be relocated within countries, to areas where future conditions move into the range currently experienced at the original location. This is likely to be possible in many countries in East and Southern Africa, although Namibia and Somalia may be exceptions. Transformational adaptation might also involve the exploitation of opportunities, including the expansion of growing areas and the lengthening of growing seasons at higher altitudes, and reduced disease burdens in currently humid areas that move to drier climatic regimes.

> **A number of barriers will need to be overcome to facilitate transformational adaptation, including psychological barriers that make it difficult for people to imagine the possible nature and impacts of climate change.**

While there is significant uncertainty regarding the extent and timing of necessary transformational adaptation across East and Southern Africa, recent research using climate projections and crop models suggest that trans-formational adaptation will be required by the 2020s or 2030s for a small percentage of current production or banana, cassava, beans, groundnuts, pearl millet sorghum and yam. In these areas, transformational responses should be in development now or in the very near future. The same study proposes that transformational adaptation will be required by the middle of the 21st century over more than 30% of the current maize and banana growing areas, and over some 60% of the current bean growing area in East Africa after the 2050s. In most areas, transformational adaptation is likely to involve a mix of substitute crops, although in some locations suitable substitute crops are limited to low-productivity subsistence crops such as pearl millet, and in certain areas, the potential for crop substitution may be very limited.

Transformational adaptation will require the creation of enabling environments through institutional capacity building and the raising of awareness of climate change risks and available responses among key stakeholders and society at large. The mainstreaming of climate change adaptation into institutional decision-making will be vital to support transformational adaptation; this will involve improving institutional knowledge, coordination and financing, as well as the development of mainstreaming processes and mechanisms such as those for climate risk screening and assessment. Participatory processes will be required to involve stakeholders and beneficiaries of adaptation-related interventions in adaptation decision-making, in order to ensure stakeholder buy-in and local ownership of transformational (and other forms of) adaptation. A key challenge will be the alignment of expert assessments of risks and thresholds with local stakeholder/beneficiary assessment and prioritisation of adaptation options. A number of barriers will need to be overcome to facilitate transformational adaptation, including psychological barriers that make it difficult for people to imagine the possible nature and impacts of climate change. This might be addressed using analogues of future impacts based on past extreme events or conditions at other locations.

Anticipatory approaches that move from incremental approaches to transformational adaptation via a phase of preparation and capacity building will be needed to deliver successful transformational adaptation. These will include risk assessments that use model-based and other studies to identify areas where transformational adaptation may be required; these areas can then be targeted for the monitoring of trends in climatic conditions and agricultural performance, to further clarify the extent to which transformational adaptation is desirable. Transformational adaptation can also be promoted through policy changes that consider existing social and economic trends, for example, to pre-empt climatically triggered transformational responses that are likely to be disruptive if they are pursued only after climatic conditions have crossed critical thresholds.

Transformational adaptation might be promoted within existing 'climate smart agriculture' (CSA) initiatives. While current CSA discourses and activities exhibit little sign of grappling with the potential need for transformational adaptation, the piloting of potential transformational adaptation measures within existing CSA frameworks focusing on diversification represents a promising entry point for linking transformational adaptation with CSA. The demonstration of transformational adaptation options through such pilots will be an essential component of any preparatory phase designed to facilitate future transformation. Where transformational adaptation options can be demonstrated to be viable under both current and anticipated future climatic conditions they can represent 'low-regret' or 'win-win' adaptation options.

> Adaptation seeks to secure development gains in the face of climate change that might otherwise undermine or reverse these gains.

1 Introduction

The latest report by the Intergovernmental Panel on Climate Change defines adaptation as "The process of adjustment to actual or expected climate and its effects" in both "human" and "natural" systems (IPCC 2014: 1758). In the former, "adaptation seeks to moderate or avoid harm or exploit beneficial opportunities." With respect to the latter, "human intervention may facilitate adjustment to expected climate and its effects."

The principal purpose of development interventions that focus on adaptation or resilience building is to promote and facilitate such adjustment to experienced or anticipated changes in climate. The intended results of this adjustment are reductions in the likelihood and/or magnitude of climate-related losses, damages and disruptions, either in absolute terms or against a projected baseline. Adaptation ultimately seeks to secure and deliver development gains such as poverty reduction, improved food security, better health and education outcomes, and (faster) economic growth, in the face of climate change that might otherwise slow, undermine or reverse these gains.

Typically, such interventions aim to 'climate proof' existing systems, enabling them to continue to function despite the intensification of climate hazards[1] (Chung Tiam Fook 2015). The stated aim of many 'adaptation' interventions, particularly those associated with development finance, is to enable systems to function better (e.g. become more productive), despite worsening climate hazards. Underlying these interventions, and arguably the emerging landscape of international adaptation finance and most development policy, is the implicit assumption that existing systems and activities can be maintained under future climatic conditions, and that adaptation will involve incremental changes to these systems to make them more 'resilient' in the face of climate change (Brooks et al. 2009; Kates et al. 2012; Wise et al. 2014). Citing evidence including a national study of adaptation in the United States (NRC 2010), a survey of adaptations in the health sector (Lesnikowski et al. 2011), and a more general review (Berrang-Ford et al. 2011), Kates et al. (2012) report that "Adaptation to human-induced change in climate has largely been envisioned as increments of these adaptations [to climate and its natural variations] intended to avoid disruptions of systems at their current locations." More recent studies reinforce this conclusion (Wise et al. 2014; Chung Tiam Fook 2015).

Lacking from most adaptation and development planning is any acknowledgement of the limits to adaptation (Adger et al. 2009; Morgan 2011; Dow et al. 2013), and of the possibility that climate change may result in the crossing of critical climatic or environmental thresholds, beyond which existing systems and activities are simply unviable (Brooks et al. 2011; IEG 2012). Where this occurs, 'transformational' approaches will be required, in which existing systems and activities are abandoned or replaced with something fundamentally different (Brooks et al. 2011; IEG 2012; Kates et al. 2012; Chung Tiam Fook 2014).

This discussion paper seeks to understand the relationship between incremental adaptation, transformational adaptation, and resilience, with a focus on transformational adaptation to changes in climatic and environmental conditions that result in conditions under which existing systems and practices are likely to be unviable. The paper presents some examples of transformational adaptation from the distant and recent past, and discusses the relevance of transformational adaptation for agriculture in East and Southern Africa, with particular attention to the linkages (or otherwise) between transformational adaptation and Climate Smart Agriculture.

1 Climate hazards are the physical manifestations of climate variability and change, and include extremes and long-term trends. They can be transient, persistent, slow-onset or rapid-onset, recurrent or isolated (e.g. a single glacial lake outburst, or a single erosion event that results in the loss of a specific area of land).

2 Incremental versus transformational adaptation

The need to complement incremental approaches to adaptation with transformational ones is recognized in the latest IPCC definition of adaptation (IPCC 2014: 1758), which includes the following definitions of incremental and transformational adaptation:

“

Incremental adaptation

Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.

“

Transformational adaptation

Adaptation that changes the fundamental attributes of a system in response to climate and its effects.”

Incremental adaptation as defined here links naturally to the concept of resilience defined by (Walker et al. 2004) as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks.” In other words, incremental adaptation allows systems or processes to continue to function in more-or-less the same way in the face of climate change – is its purpose is to make these systems and processes more resilient to climate hazards and to climate change at large.

We can view transformational adaptation as defined by the IPCC as adaptation that goes beyond resilience building, i.e. as adaptation that changes the function, structure, identity and feedbacks (the “fundamental attributes”) that characterise a system or process. This might involve replacing existing systems and processes with new systems and processes. An example might be replacing a production system based on sedentary agriculture with one based on mobile pastoralism.

The IPCC (2014) definitions of incremental and transformational adaptation are consistent with other conceptualisations of adaptation. For example, Chung Tiam Fook (2015: 2) defines incremental adaptation as “adjustments made to manage proximate climate risks and impacts while retaining the function and resilience of existing structures and policy objectives”. Kates et al. (2012: 7156) describe incremental adaptation as consisting of “extensions of [familiar] actions and behaviours that already reduce the losses or enhance the benefits of natural variations in climate and extreme events,” in other words “doing slightly more of what is already being done.” Chung Tiam Fook (2015: 2) points out that “incremental approaches may not address the historical and structural conditions driving climate risk and vulnerability…, or sufficiently challenge the societal regimes that allow these conditions to persist, thereby impeding long-term resilience and sustainability.” These might be the (economic and political) conditions that drive fossil fuel emissions in the first place, or they might be the political, economic, social and cultural conditions that result in certain groups, or whole societies, increasing their vulnerability or sensitivity to the climate hazards to which they are (or will be) exposed (Wisner et al. 2003). By allowing the conditions that drive risk and vulnerability to persist, incremental approaches may even be *maladaptive*, entrenching unsustainable systems and behaviours, locking in dependence on these systems and behaviours, and increasing the risk of catastrophic collapse when thresholds are crossed beyond which incremental approaches fail (Kates et al. 2012).

In contrast, “transformational adaptation seeks deeper, long-term societal change in policies, values, paradigms and institutions that influence environmental change and sustainable development outcomes” (Chung Tiam Fook 2015: 2). Central to such change will be a shift away from an “intervention first” approach, in which development goals are established and the environment and climate change are then considered as external factors to be addressed through incremental approaches, to a “context first” approach, in which development decisions are made based on considerations of what will work under the range of climatic and environmental conditions that are likely or plausible over the timescales that are relevant to development planning and the systems addressed by this planning (Brooks et al. 2009). This will require a psychological shift away from world views that view human systems as separate from ‘nature’ and the environment at large, to one in which human systems are seen as being embedded within a dynamic natural environment (Heyd and Brooks 2009), albeit one that is now very heavily shaped by human activities and climate change (Waters et al. 2016).

3 Transformational changes driven by considerations other than severe climate change

Deliberate transformation of current systems or activities might be pursued even where systems are not currently affected by climate change, to make them more efficient or productive, to make them more sustainable under existing conditions, to increase their resilience in the face of current climate variability and possible future climate change, or to reduce climate change risks elsewhere through greenhouse gas mitigation. Examples of such transformation might include transitions from conventional to renewable energy, to more efficient energy systems based on different technologies or fuel sources, or from agriculture to the management of ecosystem services. Such transformations would only count as transformational adaptation as defined by the IPCC if it was demonstrably "in response to climate and its effects" (IPCC 2014: 1758).

Transformation might also be pursued where climate change makes a system or activity less efficient or productive, even if it does not threaten that system or activity's fundamental viability. Where this occurs, stakeholders might decide to move to a system or activity that is more productive under the changed climatic conditions, and that is likely to be more resilient in the future as climate change continues. Arguably, a shift from one crop to a different crop that is more drought tolerant might represent such a transformational adaptation. In this hypothetical context of 'desirable but not imperative' change, such a transition might be chosen over an alternative that involved continuing with the existing crop through incremental adaptation measures such as (increased) irrigation and increased investment in labour, forecasts and insurance.

Climate change might have little or no direct impact on an existing system or activity, but it may make an alternative more attractive. An example might be a shift away from crops for local consumption and sale to the production of crops that can be sold on international markets, made more attractive by increased prices of those crops on those markets. Such price changes might be the result of changing consumption patterns, or of scarcity resulting from adverse climate change impacts on the production of those crops in other growing regions. For example, the price of cotton on the international market rose sharply, by over 100%, following the devastating floods in Pakistan, a major cotton producer, in 2010 (Thorpe and Fennell 2012). Climate change is likely to result in more frequent such disasters (Coumou and Rahmstorf 2012), associated with temporary spikes in commodity prices, and perhaps contributing to longer-term increases in prices (Hertl et al. 2010).

The above examples represent voluntary transformations pursued to exploit opportunities or to make systems more sustainable, resilient, productive or efficient. They are based on choices to move away from systems and activities that are less sustainable, resilient, productive or efficient, but that are not fundamentally threatened by climate change. They may or may not be driven or informed by considerations of climate change.

4 Transformational adaptation as a necessary response to climate change

Transformational adaptation might be driven by changes in climatic or environmental conditions that result in existing systems and activities becoming unviable, giving people and systems no choice other than to adapt by fundamentally changing their behaviour or the nature of the systems on which they depend. The World Bank Independent Evaluation Group discusses adaptation to what it refers to as "transformational [climatic or environmental] changes", which it defines as "A dramatic state of change, after which current activities may no longer be feasible" (IEG 2012: 13). The same report discusses how "Gradual, long-term changes [in climate/environment] will have transformational impacts – those that result not just in a worsening of existing conditions but in a wholly new situation" (IEG 2012: 2). Brooks et al. (2011: 9) also discuss the need for "transformational change [adaptation] to address [the] more challenging manifestations of climate change" including "qualitative changes in climatic conditions, the emergence of new and unfamiliar risks, and impacts that cannot be addressed through very generalised actions such as livelihood diversification, seasonal forecasts, weather-based insurance, and better management of natural resources [often framed in terms of measures such as soil and water conservation]." A qualitative change in climatic conditions would be one in which a historical set of climatic conditions was replaced by an entirely new set of conditions, for example, a transition from a monsoonal rainfall regime to a regime of hyper-aridity such as occurred in the Sahara some five millennia ago (deMenocal et al. 2000). New and unfamiliar risks might include the emergence of tropical storms in regions where they have not been experienced previously, such as occurred in 2004, when the first ever recorded tropical storm in the South Atlantic made landfall in Brazil (Filho et al. 2010).

The IEG (2012) provides the following examples of transformational climatic and environmental changes:

- Sea-level rise;
- The disappearance of glaciers and mountain snowpacks that will result in winter floods and summer droughts in the watersheds below;
- Salinisation of freshwater supplies in coastal regions and low-lying islands;
- Shifting of climatic zones polewards and to higher elevations, "displacing the traditional belts of grain, coffee, and other crops" (IEG 2012: 3);
- Large shifts in agroclimatic regimes;
- Loss of biodiversity-rich ecosystems that cannot migrate as climatic zones shift.

Kates et al. (2012: 7158) describe "two conditions [that] set the stage for transformational adaptation to *climate change impacts* [emphasis added]":

1. "Large vulnerability in certain regions, populations or resource systems," which might be the result of physical location (e.g. low-lying areas), socio-economic factors (e.g. poverty), or the fact that systems are already operating close to their limits (e.g. agricultural systems in already water-stressed regions). Where vulnerability is already high, even small changes in climate might mean that current systems and activities become unviable.

2. "Severe climate change that threatens to overwhelm even robust human-environment systems." According to Kates et al. (2012: 7158), large/severe changes in climate might involve changes beyond the range of current projections, the amplification of global changes in local "hot spots", and "tipping points that cause rapid climate change impacts in certain regions or globally."

Whether we are dealing with small changes in climate in a context of high vulnerability, or with large changes in climate that result in a 'new situation', and whether we are concerned with rapid or long-term climatic and environmental changes, transformational adaptation will be required where these changes result in the crossing of thresholds beyond which existing systems and activities cannot be sustained. These thresholds are unlikely to be fixed, and will depend on the resilience or vulnerability of the systems and activities exposed to the changes in question. A less vulnerable or more resilient system should be able to accommodate a higher rate and magnitude of climatic or environmental change or variation than a more vulnerable or less resilient one. Interventions to reduce vulnerability or increase resilience therefore may change the value or location of a viability threshold (e.g. in a specific climatic variable or set of variables). However, this depends on how vulnerability and resilience are framed: such interventions might focus on enabling people to recover more quickly from a shock rather than on preventing the shock by enabling a system to accommodate a greater amount of change or variation.

Viability thresholds can be understood through the concept of the 'coping range', the range of conditions that a system can accommodate without significant or lasting disruption, bounded by critical thresholds beyond which the system is compromised (Figure 1). Resilience is sometimes defined as the amount of disturbance (e.g. measured in terms of departure from average conditions) a system can accommodate and "still retain essentially the same function, structure, identity and feedbacks" (Walker et al. 2004). This provides a quantitative measure of climate resilience for a given system, as the amount of change in one or more climate-related variables that can occur before a system suffers problematic disruption. The term 'problematic' is subjective, and might relate to acceptable losses in agricultural yield over a given period, the duration of disruption to transport infrastructure, the amount of time and money required for recovery after a shock, or some other measure of the 'impact' of a disruption. These measures might be combined with measures of the frequency of disturbance; an impact of a certain magnitude might be 'acceptable' if it happens once every ten years, but not if it happens every three years. As long as a system is able to recover between shocks it might be said to be resilient. However, from the perspective of those dependent on that system, a practical definition of resilience is more likely to involve a measure of the extent to which the system provides sufficient, and sufficiently consistent, resources or services for that dependency to be viable.

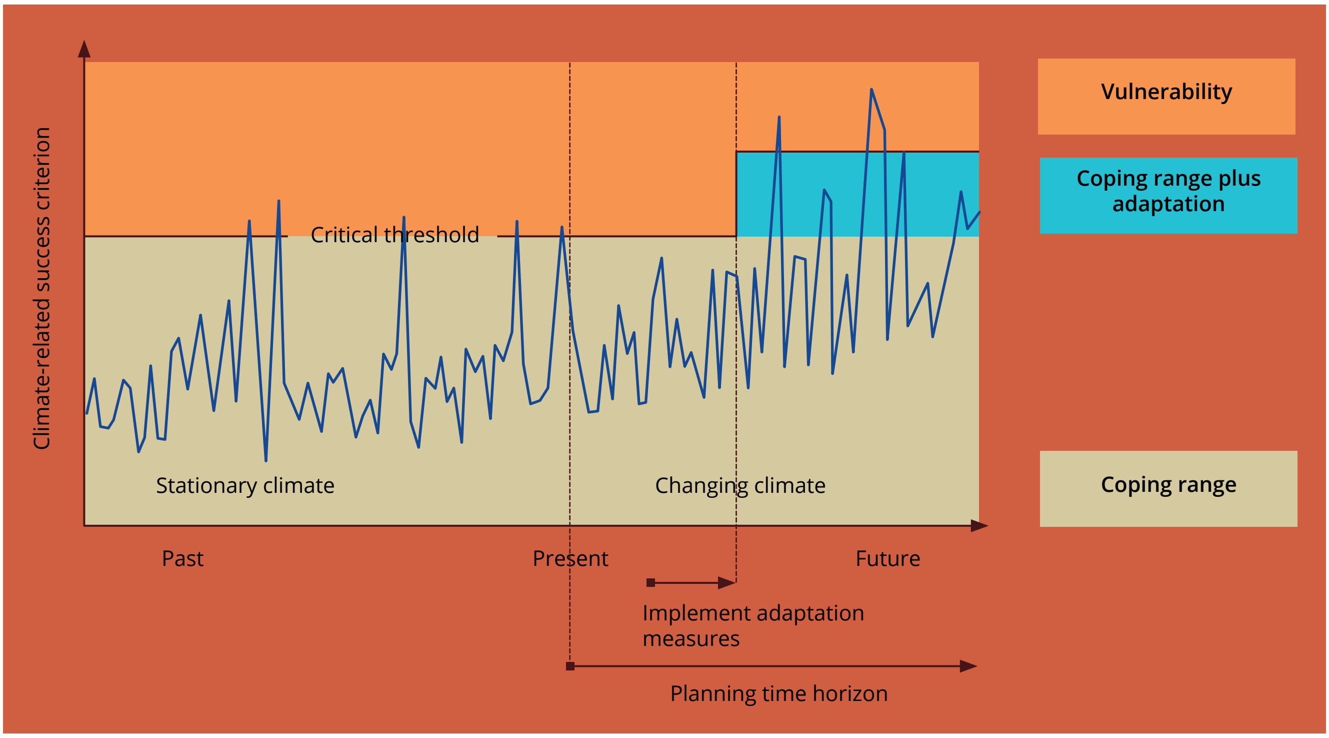


Figure 1: Illustration of the concept of the coping range, defined in this hypothetical example by a critical threshold in a notional climate variable, beyond which a system experiences disruption (i.e. is vulnerable). Climate change may increase the frequency at which the critical threshold is breached, while incremental adaptation measures may expand the coping range, shifting the critical threshold so that disruption is reduced. The system is 'resilient' within the coping range. The increase in resilience resulting from the adaptation measures can be measured as the amount by which the critical threshold changes. Reproduced from European Commission (2013).

Past adaptation might mean that the coping range of a system coincides approximately with the range of historical climate variation. This coping range may be exceeded periodically, but if this occurs sufficiently infrequently the system may be able to recover (Figure 1). Climate change may result in the coping range being exceeded more frequently (Figure 1), or even in conditions shifting permanently outside the coping range. Incremental adaptation might enable a system to expand its coping range (i.e. to reduce its vulnerability or increase its resilience), as illustrated in Figure 1. However, there might be a limit to the extent by which incremental measures can extend the coping range or 'push back' a critical threshold. Where a critical threshold is exceeded periodically, the viability of a system will depend on whether there is sufficient time between disruptions for it to recover. As argued above, if disturbances are of sufficient magnitude *and* frequency, the point at which a system ceases to become useful to human populations that depend on it may be reached significantly before the system itself collapses. In other words, there may be 'absolute' and 'pragmatic' definitions of viability or resilience thresholds. The 'practical' definitions might even be different for different actors.

The following questions need to be asked when considering whether incremental approaches to adaptation are likely to be sufficient:

1. What is the range of climatic conditions under which a current system/activity is viable (i.e. the coping range), and what are the thresholds that define the limits of this range?

3. How likely is it that climate change will result in these thresholds being exceeded on a permanent or periodic basis?

4. Where the coping range is likely to be exceeded periodically, will disruptions be sufficiently frequent and severe to make the system/activity non-viable (e.g. can these disruptions be absorbed by the system, and will recovery be sufficiently rapid between disruptions)?

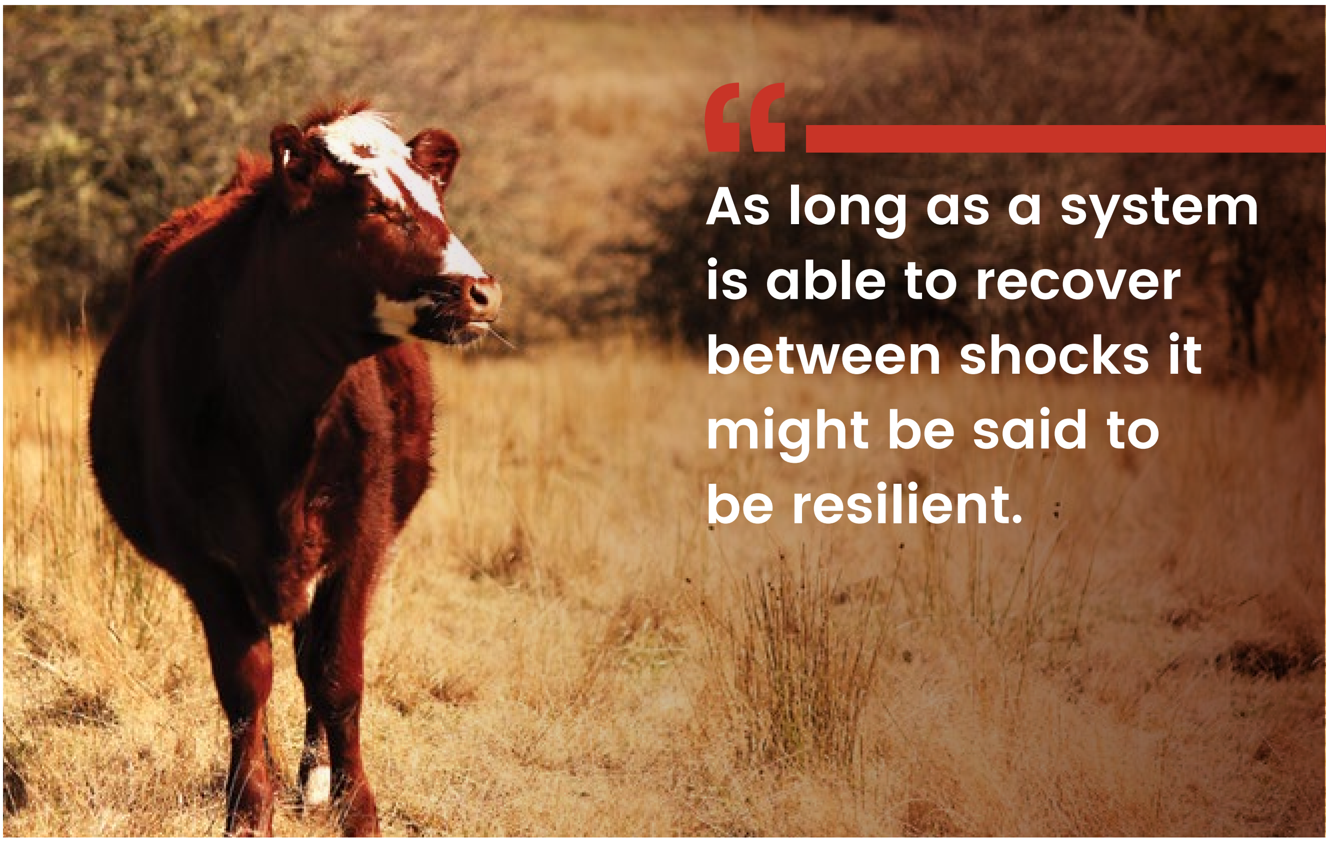
5. How far can the coping range be expanded through incremental adaptation, including vulnerability reduction and resilience building?

6. Will any such expansion of the coping range be of sufficient magnitude and rapidity to keep pace with likely or plausible changes in climatic conditions, and if so, for how long?

7. How long will incremental adaptation be cost effective compared with more transformational approaches, and at what point is there an economic case for transformational adaptation?

8. What are the risks of catastrophic failure associated with incremental approaches, for example due to very rapid changes or variations in climate outside of the (expanded) coping range? How do these change the assessment of cost-effectiveness?

Incremental adaptation may allow a system to reduce its vulnerability or increase its resilience to an extent that its coping range can be expanded to keep pace with climate change, with climatic variations remaining within the coping range or exceeding it sufficiently infrequently that the system can recover after each disturbance and continue to function. In such contexts incremental approaches may be sufficient. However, risks of maladaptation (Box 1) associated with incremental approaches should still be assessed and regularly reviewed. Following the approach above provides a framework for anticipatory transformational adaptation that should help us avoid the need for sudden transformational adaptation out of necessity, and the prospect of forced transformational adaptation after an existing system has collapsed.



Box 1: Maladaptation

The OCED (2009) defines maladaptation as "...business-as-usual development which, by overlooking climate change impacts, inadvertently **increases exposure and/or vulnerability to climate change**. Maladaptation could also include actions undertaken to adapt to climate impacts that do not succeed in reducing vulnerability but increase it instead."

Examples of maladaptation include

- Development of flood plains and low-lying coastal areas that increases the number of people and the value of assets exposed to intensifying hazards.
- The expansion of agriculture into marginal areas that are likely to become unproductive as a result of climate change.
- The expansion of irrigation that cannot be sustained due to a decline in available water resources resulting from climate change.
- Increased economic dependence on other resources that may cease to be available as a result of climate change (e.g. agriculture in marginal zones, increased reliance on at-risk fisheries, tourism predicated on threatened cultural or ecological resources).
- Development of hydro-power in areas where declines in streamflow are likely to compromise the operation of hydro-power plants.
- The construction of hard coastal defences that cut off sediment supply to other areas, increasing erosion and flood risk in these areas.

Certain policies may be maladaptive for some groups and not others. For example, even where agricultural expansion is sustainable under climate change it might result in the loss of dry-season grazing for pastoralists, undermining their ability to cope with and adapt to drought, i.e. increasing their vulnerability to drought.

Where incremental adaptation is likely to be inadequate, maladaptive or simply too costly, transformational approaches will be needed. These might form part of a phased approach, in which incremental changes are pursued in the shorter term, while transformational approaches are developed and tested, with incremental measures yielding to successfully tested transformational measures in the longer term. The IEG (2012) views transformational changes in climatic and environmental conditions as being associated principally with the longer term. However, Brooks et al. (2011) caution that, while the need for transformational approaches is likely to increase over time as climate change accelerates, such approaches might also be required in the near-term in some contexts. This is particularly likely where critical thresholds will be crossed as a result of small changes in climate, and where resilience building or vulnerability reduction is unlikely to expand the coping range by a sufficient amount or with sufficient rapidity.

An example might be a non-irrigated agricultural system in an area where rainfall is close to the limit for rain-fed agriculture, and irrigation is impractical due to infrastructure costs, a lack of adequate or reliable groundwater resources, or questions over its sustainability. If average rainfall (measured over a moving reference period) approaches or even crosses the limit for rain-fed agriculture and interannual rainfall variability increases, it might be possible to sustain existing cropping systems through the use of more drought tolerant and/or faster growing strains, better use of short-term forecasts, more widespread insurance cover, increased investment in labour and other inputs (supported through better access to markets), and other techniques such as soil and water conservation. However, even these measures will be insufficient if rainfall declines below a certain threshold, somewhere between the conventional limit for rain-fed agriculture and the threshold for aridity. In practice, the ratio of precipitation to evaporation might be a more reliable indicator than rainfall alone, as climate change will reduce this ratio as a result of increases in temperature, even if rainfall remains unchanged.

The following section discusses what transformational adaptation might consist of in practice, drawing on the limited literature on transformational adaptation, and on examples from the distant and recent past, identified from the wider literature.

5 Examples and case studies

The continuing emphasis on incremental approaches to adaptation means that it is difficult to identify genuine contemporary examples of transformational adaptation as a response to severe climatic or environmental change (Chung Tiam Fook 2015). The most notable such examples involve responses to actual or anticipated sea-level rise in low-lying coastal areas. For example, the relocation of settlements and populations is planned in the Solomon Islands[2], Kiribati (Wyett 2013), and parts of the Atlantic and Pacific coasts of the United States[3],[4]. Individual settlements have already been relocated in response to sea-level rise in Fiji[5] and Vanuatu[6]. In the United Kingdom, 'managed realignment', involving "the deliberate landwards retreat of the existing line of coastal defence and subsequent tidal inundation of land" in response to coastal habitat loss and sea-level rise has been undertaken at a number of locations (Spencer et al. 2008: 608).

Brooks et al. (2011) identify some hypothetical examples of transformational adaptation, including:

- Phased relocation of settlements and economic activities away from areas at existential risk from sea-level rise (*cf* above examples);
- Shifts in emphasis in large-scale economic activity away from areas/ resources threatened by climate change (e.g. away from water-intensive agriculture, climate-sensitive tourism, high-risk marine resources, to less sensitive activities);
- Large-scale restructuring of agricultural systems based on transitions to new types of crops better suited to changed climatic conditions;
- Transformation of agricultural systems from unsustainable (under climate change) intensive rain-fed or irrigated agriculture to lower input e.g. pastoral or agropastoral systems;
- Development of new water sources on regional scales, for example based on large-scale desalination of sea water and the distribution of fresh water through large infrastructure projects;
- Development of areas where climate change provides new opportunities (e.g. expansion of viable agricultural zones due to changes in rainfall, and changes in temperature at high altitudes and high latitudes).

Of course there are a multitude of challenges to many of the transformational adaptations suggested above. These will be particularly pronounced where such adaptation requires people to abandon their places of residence or radically change their livelihoods and other behaviours. Transformational adaptation involving relocation, economic restructuring, and livelihood transformations may involve winners and losers (Kates et al. 2012; Chung and Foook 2015), with the latter inevitably – and justifiably – resisting change. Where transformational adaptation is associated with high costs, as in the case of large infrastructure investments, financial barriers may be amplified by real or perceived uncertainty as to the necessity of the proposed measures and their costs and benefits (Kates et al. 2012). A "suite of institutional and behavioural barriers that tend to maintain existing resource systems and policies," linked with "the unimaginable nature of possible extreme vulnerabilities and impacts" are likely to represent barriers to transformational adaptation (Kates et al. 2012: 7158). Existing political economies and economic models that encourage unsustainable and maladaptive behaviours, and the tendency of adaptation to be viewed in the context of these models, will also represent barriers to transformational adaptation (Brooks et al. 2009; Heyd and Brooks 2009).

These barriers represent challenges of varying difficulty and complexity, and illustrate the need for anticipatory transformational adaptation to pay close attention to institutional contexts, existing systems of rights and resource allocation, the potential need for conflict resolution, issues of perception and uncertainty, as well as the need to build capacity among those who need to implement adaptation measures. However, the nature and extent of barriers to transformational adaptation will vary significantly across contexts and proposed adaptation measures. Managed, anticipatory transformational adaptation will require significant efforts to (i) raise awareness of climate change risks and potential adaptation responses, (ii) establish enabling institutional and policy environments, (iii) minimise the

2 https://www.uq.edu.au/news/article/2014/08/rising-sea-levels-force-pacific-island-capital-relocate

3 http://insideclimatenews.org/news/15032016/native-americans-federal-funds-isle-de-jean-charles-relocation-climate-change-sea-level-rise

4 https://www.climate.gov/news-features/climate-case-studies/quinault-indian-nation-plans-village-relocation

5 http://www.sbs.com.au/news/article/2014/01/31/rising-sea-levels-prompt-relocations-fiji

6 http://www.abc.net.au/worldtoday/content/2005/s1524755.htm

likelihood of, and the impacts on, the 'losers' (e.g. through compensation or the provision of new opportunities), and (iv) demonstrate the effectiveness of transformational adaptation measures (e.g. through pilots).

While the challenges associated with deliberative, anticipatory adaptation are likely to be significant, it should be emphasised that, *where transformational adaptation is necessary as a result of climatic and environmental changes that make existing systems and activities unviable, it will occur anyway, in one form or another*. This is demonstrated by past severe climatic and environmental changes, to which people responded through transformational adaptation that emerged alongside, or after, these changes. Some of these adaptations were associated with significant costs and a decline in human wellbeing, and might be viewed as 'sub-optimal' (Brooks 2006a). More anticipatory approaches to transformational adaptation will increase the potential for identifying and pursuing the most sustainable and least costly (in terms of both finance and human wellbeing) responses.

5.1 Transformational change and adaptation in the distant past

The impacts of anthropogenic climate change on contemporary coupled natural and human or "social-ecological" systems are increasingly becoming apparent, as climatic conditions begin to depart from the range of historical variability (Coumou and Rahmstorf 2012; Coumou et al. 2013). However, in the absence of massive and urgent action to reduce greenhouse gas emissions, climate change will continue to accelerate over the coming decades and centuries, requiring transformational adaptation on an unprecedented scale and over a multi-generational period. The adaptation case studies that do exist in the literature are likely to be of limited use in helping us navigate future adaptation to rapid and severe climate changes, as (with some notable exceptions, discussed below) they focus almost exclusively on incremental approaches intended to increase resilience to existing climate variability or incrementally worsening but otherwise familiar climate hazards (Chung Tiam Fook 2015). It should also be recognized that the case studies represented in the adaptation literature overwhelmingly represent a narrow time window in the recent past, during which climate change and its impacts have been of relatively low magnitude compared to those we can expect in the foreseeable future (New et al. 2001; Stafford Smith et al. 2011).

To examine actual transformational changes to rapid and severe changes in climate, we need to look outside the envelope of recent historical climate variability and change, and further back into the past. This is associated with its own challenges, principally those of limited data, a reliance on environmental and social/cultural proxies rather than historical records, and the problem of how to establish causality between climatic and environmental change, and social change (Brooks 2013). A number of studies have attempted to link past rapid climate change with large-scale societal disruption, but these have tended to limit their analysis to the identification of temporal correlations between climatic and cultural change, and have taken a rather narrow focus on societal collapse (see Brooks 2013 for a discussion).

More recent studies have examined adaptive responses to transformational changes in climatic and environmental conditions during the 'Middle Holocene Climatic Transition' (MHTC), a period of global climatic disruption and reorganisation characterised by long-term trends in temperature and rainfall punctuated by episodes of rapid climate change, between about 4400 and 3000 BCE (Mayewksi et al. 2004; Brooks 2013; Clarke et al. 2016). The MHTC saw the establishment of a regular El Niño after a long period of quiescence (Reitz and Sandweiss 2001), changes in ocean circulation (McManus et al. 2004), cooling at high latitudes and altitudes in the form of the so-called Neoglaciation (Thompson et al. 1995, 2006), the aridification of the northern hemisphere sub-tropics (deMenocal et al. 2000; Jung et al. 2004; Brooks 2006a, 2010), large regional shifts in vegetation zones and climatic regimes (Lezine et al. 2004), and extreme rainfall and sedimentation events outside the range of long-term (multi-millennial scale) variability (Casseldine et al. 2005; Bar-Matthews and Ayalon 2011).

Consequently, the MHTC was associated with large changes in the availability and distribution of resources including water, pasture, productive land, and other ecosystem services on which human populations depended. The drivers of this transition were very different from those operating today, involving changes in the distribution of solar radiation over the Earth's surface due to orbital variations, rather than large changes in greenhouse gas concentrations and global average surface temperature (Brooks 2013). Nonetheless, the MHTC is the most recent example of global climatic reorganization available to us. It therefore represents a relevant if imperfect analogue to present-day anthropogenic climate change, and provides us with some striking examples of transformational changes in climatic and environmental conditions, that had profound implications for human societies. Despite the different drivers and changes in temperature operating in during the MHTC and the 21st century, many of the changes that occurred during the former period are qualitatively similar to those anticipated as a result of anthropogenic global warming. For example, warming is already resulting in heavier rainfall extremes in many parts of the world (Coumou and Rahmstorf 2012), and climatic desiccation, resulting from a combination of reduced rainfall and higher temperatures, is projected over much of North Africa, the

Middle East, the Mediterranean, Central and South Asia, and southwestern North America (Collins et al. 2014; IPCC 2014; Kirtman et al. 2014). Drying is also projected over parts of West Africa and Southern Africa (Thomas et al. 2005).

Changes in human societies that have been interpreted as possible (transformational) adaptations to rapid and severe climate change in the literature relating to the MHTC are listed in Table 1. These proposed adaptations are largely associated with increasing aridity and resulting resource scarcity (Brooks 2006a, 2010, 2013; Clarke et al. 2016), and tend to involve either increased mobility or sedentism, bi-directional shifts between settled agriculture and mobile herding, out-migration from areas where rainfall falls below critical thresholds (Manning and Timpson 2014), and in-migration to areas where resources are still available in regions where the environment is otherwise deteriorating (Brooks 2006, 2010, citing various sources). A common theme is the concentration of human populations in environmental refugia, where increased population densities in restricted geographic areas with limited resources result in societies becoming both more organized and more unequal (Brooks 2006a, 2010).

Table 1: Possible transformational adaptations identified in the literature relating to the period centred on the Middle Holocene Climatic Transition (MHTC), from approximately 4500-3000 BCE. This table is based on the conclusions of reviews by Brooks (2006a, 2010), Clarke et al. (2016).

Possible transformational adaptation	Locations and timings	Sources
Abandonment of previously productive areas in response to increased aridity, either through out-migration or successive shifts in production systems and settlements, following retreating rainfall.	Sahara ~5000-2500 BCE (dates vary with location, with episodes of abandonment starting earlier in east); south-central Mesopotamia ~3500 BCE; southern Levant ~3800 BCE; South Asia ~3500-3000 BCE	Possehl 2002; Algaze 2008;
Occupation & exploitation of new areas as drier conditions reduce disease burden.	Sahel ~4000-5000 BCE	Smith 1984
Increased exploitation of lake fringes and river environments as surrounding areas become more arid.	Sahara ~Nile Valley ~4500-3500 BCE; Indus/ Sarasvati Valleys (South Asia) ~4000-3000 BCE	Liu 1996; Possehl 2002; Brooks 2006a
In-migration to and concentration of populations in 'refugia' in regions otherwise characterised by environmental deterioration & desertification, resulting in localized increases in population density	Nile Valley ~4500-3200 BCE; South Asia ~3200-4600 BCE; North-central China ~2200 BCE; northern coastal Peru ~3000 BCE; Northern Mesopotamia ~4200 BCE; Southern Mesopotamia ~3500 BCE; Central Sahara ~3000 BCE	Di Lernia 2002; Mattingly et al. 2003; Brooks 2006a, 2010
Increased sedentism in refugia as mobile lifestyles become increasingly unsustainable due to aridification and loss of water and pasture	Eastern Sahara ~3500 BCE; Central Sahara ~3000 BCE;	di Lernia 2002;
Emergence of organized, hierarchical societies based on social stratification & emergence of elites (increased social inequality), where populations concentrate in refugia at times of increased regional aridity – need to manage production & distribution of scarce resources, control of diminishing resources by elites.	Nile Valley ~4500-3200 BCE; South Asia ~3200-4600 BCE; North-central China ~2200 BCE; northern coastal Peru ~3000 BCE; Northern Mesopotamia ~4200 BCE; Southern Mesopotamia ~3500 BCE; Central Sahara ~1000 BCE	Brooks 2006a, 2010
Securing of trade routes through previously inhabited areas abandoned in the face of extreme aridity	Mesopotamia ~3700 BCE	Clarke et al. 2016
Increased mobility (including transhumance) to exploit more sparsely distributed resources and as a strategy to cope with increased climatic variability and uncertainty, generally based on adoption/ intensification of mobile pastoralism	Eastern Sahara ~6000 BCE; Central Sahara ~3800 BCE	di Lernia 2006
Shift from cattle to sheep and goats as aridity further intensifies	Central Sahara ~3000 BCE	di Lernia 2002
Adoption of irrigated agriculture using groundwater when surface water resources disappear due to cessation of rainfall and drying of lakes	Central Sahara ~1000 BCE	Brooks 2006a

A recent paper by Clarke et al. (2016) highlights how different societies appear to have responded in different ways to the same stresses during the MHTC, depending on their geographical contexts, the nature of their livelihood strategies, and their resilience. For example, aridification appears to have been associated with transitions from farming to herding where increased climatic marginality compromised rain-fed agriculture but allowed extensive grazing. In contrast, where rainfall fell below thresholds of viability for mobile pastoralism, transitions occurred from herding to irrigated agriculture along rivers and in oasis areas (Brooks 2010; Clarke et al. 2016). However, the relationship between climatic/ environmental change and changes in subsistence strategies was not deterministic: in the central Sahara, circa 3000 BCE, adaptations based on both increased mobility through a shift from cattle to sheep and goat herding, and reduced mobility based on more sedentary cattle herding in oasis areas, emerged in parallel and continued to coexist for millennia (di Lernia 2002).

A strong message from these studies is that, where increasing aridity reduces resource availability, human populations tended to respond in one of three ways: (i) migrating out, (ii) becoming more mobile to exploit more thinly spread resources, or (iii) becoming more sedentary and intensifying production through innovations in mixed crop-livestock systems in areas where water was still available, often with a concomitant increase in social organization and inequality (Brooks 2006a, 2010). These adaptations are not necessarily exclusive, and can occur in parallel, even in the same areas and among the same populations. The central Sahara, the Nile Valley, Mesopotamia, South Asia, north-central China, and northern coastal Peru all provide us with examples of increasing social 'complexity' against a backdrop of increasing aridity and demonstrable or likely resource scarcity during the MHTC, or associated with continuations of environmental trends established during the MHTC (Brooks 2006a). These are the regions in which the world's earliest cities and states emerged, and Brooks (2006a) goes so far as to propose that the development of these earliest 'civilisations' can be viewed in large part as the outcome of processes of adaptation to environmental deterioration and increased resource scarcity. Not only does this turn on its head the conventional narrative of civilisation as the inevitable product of abundance following the end of the last ice age (e.g. Richardson and Boyd 2000; Gross 2005), it also highlights the potential for severe climatic and environmental changes, and more importantly the way people adapt to these changes, to result in the emergence of radical new production strategies, social systems and relations, and political realities. Furthermore, it highlights the potential costs of transformational adaptation; while the emergence of civilization during the MHCT is viewed in an almost universally positive light today, it was predicated on sustained increases in social and economic inequality, and in some if not all cases on the development of more authoritarian societies (Brooks 2006a, 2010).

5.2 Transformational change and adaptation in the recent past: The Sahel

Examples of transformational adaptation to changes other than actual or anticipated sea-level rise in the more recent past are scarce (Chung Tiam Fook 2015). Nonetheless, some case studies in the adaptation literature describe responses to demonstrable changes in climate that might be described as transformational.

The Sahel region of Africa provides a good context for examining transformational adaptation in the context of the severe and protracted dry episode that commenced in the late 1960s and continued into the 1990s, with very severe droughts in the early 1970s and early-mid 1980s (Figure 2, see also Brooks 2004; Mortimore 2010). This increase in aridity was associated with changes in the behavior of the West African Monsoon, driven by changes in ocean surface temperatures and atmospheric circulation (Giannini et al. 2003). It is likely that anthropogenic global warming and associated increases in ocean surface temperatures in the tropics, combined with cooling over the North Atlantic due at least in part to atmospheric aerosol pollution from Europe and North America, contributed significantly to the drier conditions in the Sahel over this period (Held et al. 2005; Biasutti and Giannini 2006; Booth et al. 2012). The droughts of the 1970s triggered widespread famine, resulting in the loss of hundreds of thousands of lives and millions of head of livestock, and causing widespread societal disruption (Sheets and Morris 1976; Hill 1989; Mortimore and Adams 2001; Mortimore 2010). The impacts of the droughts of the 1970s and 1980s appear to have been amplified by social vulnerability driven at least in part by colonial and post-colonial development policies that (i) sought to 'modernise' agriculture through the growth of the commercial sector (Reynaut 2001), (ii) reduced the mobility of pastoralists through the provision of new water points (Thébaud and Batterby 2001); (iii) emphasised village-based authority and land rights that favoured agriculture and "disregarded pastoralists' claims to commonly-held pastures and water points" (Turner et al. 2011), (iv) encouraged the expansion of agriculture northwards into historically marginal areas and onto traditional pastoral grazing lands, particularly during the wet 1950s and 1960s (Swift 1977; Thébaud and Batterby 2001; Mortimore 2010), and (v) generally undermined traditional reciprocal arrangements between farmers and herders, and livelihoods that had evolved to spread risk in a highly marginal and variable environment characterised by high climatic uncertainty (Hill 1989; Bloch and Foltz 1999; Thébaud and Batterby 2001; Heyd and Brooks 2009).

A handful of studies describe adaptive responses to both increased aridity and socio-economic changes in the Sahel involving changes in livelihoods that might be described in terms of transformational adaptation.

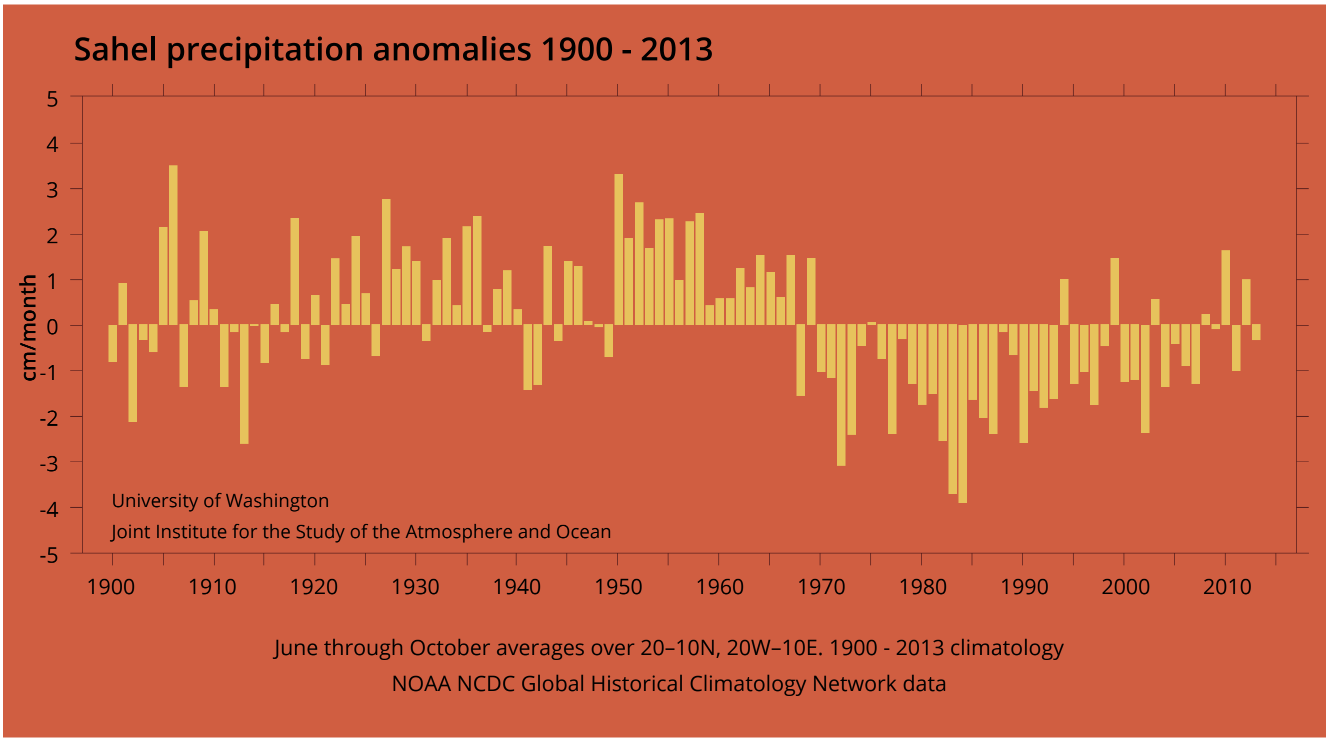


Figure 2: Summer (June-October) Sahel rainfall anomalies over the region from 10°-20°N and 20°W-10°E for the period 1900-2013. Data from the NOAA NCDC Global Historical Climatology Network, graphic from Todd Mitchell, University of Washington[7].

5.2.1 Indigenous intensification of agriculture in northern Nigeria

Adams and Mortimore (1997) describe a process of "indigenous intensification" since the severe droughts of the 1970s and 1980s in a number of locations in northern Nigeria. This has involved reductions in fallow land and increases in the area of continuous cropping, made possible by a transition to manuring based on increased livestock numbers, as well as increased inputs of labour in terms of both peak demands and duration. More drought-tolerant crops have been introduced, such as quick-maturing varieties of cowpea, as well as cow melon, which is planted late in the season, requires only one fall of rain, and grows on residual soil moisture. These strategies are complemented by a high diversity of cultivated crops, the use of wild plants for food and medicine, and the use of trees to combat wind-related soil erosion and to provide an open canopy for grain and legume crops. Tree cover has increased in some areas (Adams and Mortimore 2001). In addition, "there has been a shift from cattle to small ruminants in northern Nigeria, as they are less costly, more hardy, easier to feed and reproduce faster than cattle" (Mortimore and Adams 2001, citing de Leeuw et al. 1995). Interestingly, this shift from cattle to smaller ruminants echoes the similar transition that occurred in the central Sahara some 5000 years ago, as the climate shifted to one of hyper-aridity with limited rainfall occurring only in some higher-elevation regions (di Lernia 2002).

Other changes in livelihood strategies observed in the Sahel include increased soil and water conservation driven largely by indigenous innovation, a shift from export markets to internal markets driven by lower international prices and urbanization, selective breeding of crops by farmers to manage their own (diverse) genetic resources, an increased diversity of cultivars, and the diversification of livelihoods to include more farm and non-farm activities and income sources (Mortimore and Adams 200; Mortimore 2010). Income diversification often involves high levels of mobility between rural communities, urban centres and commercial farming zones, generally undertaken by men. Migration from one village in Northern Nigeria during the drought of 1972-74 involved travelling 800 km to Lagos, where the migrants ultimately identified a niche market for goats that they were well placed to exploit, resulting in a transformation in livelihood and income (Mortimore 2010).

Whether these innovations constitute transformational adaptation is arguable; Mortimore and Adams (2001) emphasise the dynamic nature of farming in the 'unstable but resilient, disequilibrial ecosystems' of the Sahel, and the false dichotomy between coping and adaptation. What these studies demonstrate is the wide spectrum of innovation undertaken by Sahelian farmers, involving a host of measures, some of which might best be viewed as incremental (e.g. better management of soil and water, 'improvement' of crops through selective breeding), and some of which might be seen

7 This and other graphics can be downloaded from: http://research.jisao.washington.edu/data_sets/sahel/#values

as more obviously transformational (e.g. the introduction of new crops, shifts in the types and numbers of livestock, a shift to more diversified and different livelihoods facilitated by migration of household members). Mortimore (2010) describes the importance of regional integration for migration and access to markets, and the importance of markets in mediating livelihood innovation. Nonetheless, some of the innovations and behaviours described here are clearly in response to severe droughts embedded in a significant long-term decline in rainfall, and some have had a transformational effect on people's wellbeing. Adaptation through migration and intensification (as usable productive land has become scarcer), alongside population growth, has resulted in the emergence of labour and land markets (Mortimore 2010), demonstrating how adaptation itself can change lead to social change. Despite the droughts and famines of the 1970s and 1980s, "Sahelian farmers are still in business. There are more of them than there were 25 years ago, they produce more, and (in some areas) they have more animals" (Mortimore and Adams 2001). A key lesson of these studies is that such adaptation has emerged largely from indigenous practices, knowledge and capacity that farmers have developed over long periods as a consequence of negotiating a highly dynamic environment. Mortimore (2010: 137) describes how "new varieties of pearl millet and cowpea, developed originally on research stations, were found to have diffused rapidly through famer-to-farmer exchange, without any government or project promotion (in the study area)." Mortimore (2010: 136) also reports that, in four villages studied in northern Nigeria, "The impact of development projects was marginal or non-existent" in the development of environmental management and adaptation strategies. These conclusions emphasise the importance of preserving and drawing on local knowledge and capacity as a resource that people can deploy to successfully manage the impacts of climate change.

5.2.2 Transformational adaptation to increased aridity by pastoralists in eastern Niger

Thébaud and Batterby (2001) describe how pastoralists in the Diffa region of eastern Niger responded to increased aridity following the droughts of the 1970s, and how these responses were mediated by political economy. Some of these responses might be described as constituting transformational adaptation. For example, some pastoral groups in this region adopted farming, a trend also influenced by the expansion of farming and the increased adoption of livestock husbandry by farmers. The latter was associated with a breakdown of traditional reciprocal arrangements between farmers and pastoralists, as livestock-owning farmers no longer needed to obtain livestock products from pastoralists and had less incentive to trade with them. As a result of these trends there was a shift towards mixed agro-pastoral systems. However, one group, the Daza, converted from cattle herding (and some millet cultivation) to camel herding as increased aridity made the former activities less viable. This involved the reorganisation of household labour and adjustment to the loss of cow's milk butter which previously was crucial in terms of both nutrition and trade.

Both of the above changes in livelihood strategies involve the replacing of historical livelihood systems with new ones, although the study in question also emphasises how even these dramatic changes in livelihoods, triggered at least in part by large changes in climatic and environmental conditions, are mediated by socio-economic factors. It also highlights the role of policy in the marginalisation of pastoralists in the first place, through legislation and physical interventions around access to groundwater, that undermined traditional systems of rights and access to water and pasture. Thébaud and Batterby (2001: 71) go so far as to say that "economic, social and institutional factors are as much to blame for destabilising pastoral communities as climatic ones." Indeed, Brooks (2006b) takes a long-term perspective on pastoralism and climate change, arguing that mobile pastoralism can and should play a key role in adaptation to twenty-first century climate change, supported by new policies that enhance the ability of pastoralists to adapt, rather than existing ones that increase their vulnerability to climate change and variability. These conclusions are echoed by Birch and Grahn (2007) and Kräti et al. (2013).

Thébaud and Batterby (2001) also describe how environmental change combined with socio-economic and demographic factors to change the territorial relationships between different groups, again highlighting the potential for climate change to result in the emergence of new political economies. Indeed, such an outcome is likely to be an inevitable outcome of transformational adaptation in many contexts.

5.2.3 Transformations in livelihoods and social structures in northern Mali in response to the drying of Lake Faguibine

Djoudi et al. (2013) describe the drying out of Lake Faguibine in northern Mali, the changes in livelihood strategies pursued by different actors in response to this drying, and how these responses have changed the relationships between these actors. Lake Faguibine is fed by the Niger river system, and experienced periodic dry episodes during the twentieth century, but dried almost completely following the droughts of the early-mid 1970s. Since then, forest consisting of Acacia and Prosopis has colonised more than a third of the former lake bed.

The loss of the lake meant the loss of water and arable land, but also increased fodder for livestock from the forest species that colonised the dry lake bed. Some groups that previously practised agriculture on the fringes of the lake adapted through temporary/seasonal migration to other parts of the former lake or to the Niger river to cultivate land under a shared cropping system based on annually negotiated contracts. As it is men who migrate, women experienced increased workloads, and took on roles previously reserved for men. These roles include charcoal production and the herding of small ruminants, both focused on the new forest system on the dry lake bed. While the ecological transition had generally negative impacts on women, Djoudi et al. (2013) highlight the potential for women to exploit opportunities created by male migration and associated changes in gender roles and gendered divisions of labour, for example increasing their influence over decision-making and exploiting markets for forest products as they move into forest-based livelihoods. The linked ecological and social transitions associated with the drying of Lake Faguibine could potentially increase women's economic power and autonomy, However, Djoudi et al. (2013: 502) report that "Even though roles have shifted among and changed within, social classes, ethnic and gender groups, what has not changed is gender inequity regarding access to land." Nonetheless, these changes in the local political economy, precipitated by the ecological transition from lake to forest and mediated by societal factors, echo the links between severe climate change and changes in social organisation proposed for the MHTC (Brooks 2006a, 2010).

6 Transformational adaptation in the agricultural sector in East and Southern Africa

While examples of contemporary transformational adaptation to climate change in the agricultural sector are difficult to identify in East and Southern Africa, there is a large body of literature relating to climate change and its impacts in the region. These, and regional scale studies of potential future changes in climate, make it possible to identify possible future transformational changes in climatic and environmental conditions in this region, and thus to at least begin to address the potential future need for transformational adaptation. However, before discussing what transformational adaptation might look like in East and Southern Africa, it is necessary to understand what sort of changes in climate farmers and livestock keepers in the region might need to adapt to. The discussion of transformational adaptation below is therefore preceded by a summary of recent historical climate trends in the region, projected future changes in climate, and the potential impacts of these changes on agricultural systems. The focus is on drought, the most prevalent risk to agriculture in most of sub-Saharan Africa and one that is expected to intensify as a result of climate change (Müller et al. 2011), and on other changes/impacts that are most likely to be associated with the need for transformational adaptation in the future.

6.1 Regional climate trends and projections

6.1.1 Observed trends and variations in climate

Over the past century (1901-2012), annual average temperatures have risen by some 1-1.5°C over East and Southern Africa, depending on location (Niang et al. 2014). Between 1951 and 2010, rainfall increased in some locations and declined in others, although in most locations the trends are not statistically significant, and many areas are not represented by rainfall data (Niang et al. 2014).

Nonetheless, Dutra et al. (2012) and Lyon (2014) identify a drying and increase in drought frequency in the Horn of Africa during the season of the March-May 'long-rains' after 1998. Williams and Funk (2010) discuss a longer-term decline in rainfall between 1979 and 2005 in the main growing seasons in eastern Africa (the long rains of March-May) and southern Africa (the summer rains of December-February). A more recent paper by Nicholson (2014) describes drought in the Greater Horn of Africa from 2008-2011, during which rainfall was 30-75% below normal, after which intense rainfall resulted in flooding. Sonwa et al. (2016) describe an increase in drought frequency in northern Kenya from approximately once every ten years to at least once every five years. They report that "82% of respondents in the Turkana region noted that drought severity and frequency had increased, with drought becoming an almost regular and permanent phenomenon" (Sonwa et al. 2016: 8).

In East Africa, El Niño is associated with drought during the June-August short rains in west-central Ethiopia, with six of the 10 driest seasons in recent decades associated with El Niño events (Lyon 2014). La Niña is "related to drought in areas having an OND [October-December] seasonal rainfall maxima [sic] to the south and east" (Lyon 2014: 7971), and is associated with drought during the short rains in eastern Ethiopia, Kenya, Somalia and northern Tanzania. However, neither EL Niño nor La Niña represent the single dominant factor in the development of drought in these contexts (Lyon 2014). El Niño is more strongly correlated with drought conditions in southern Africa; indeed, since the late 1960s droughts in southern Africa have become more intense and widespread, and this has been linked with an increased statistical association between rainfall in the region and the El Niño-Southern Oscillation (ENSO) phenomenon (Fauchereau et al. 2003; Roualt and Richard 2005).

6.1.2 Projected changes in climate

Climate models suggest a further warming (relative to the 1986-2005 mean) in sub-Saharan Africa of up to about 3°C by around 2050 and 6°C before 2100 under a high emissions scenario compatible with current emissions trends and global climate policies, with the highest temperature increases occurring in the interior of southern Africa, particularly the west-central areas. Warming is projected to be lower in East Africa, with projected increases of up to about 2.5°C and 4.5°C by about 2050 and 2100 respectively (Niang et al. 2014). Projected temperature increases are lowest in the Greater Horn of Africa region. Under a low emissions scenario with strong mitigation requiring drastic, immediate and sustained global action on emissions (which currently seems extremely unlikely), warming remains below 2°C across the entire African continent (Niang et al. 2014). Hachigonta et al. (2013: 14) report modelled increases in monthly mean maximum temperatures over southern Africa of 1°C to over 3.5°C between 2000 and 2050, depending on location and the climate model used, with the greatest warming in the interior regions.

Climate models used by the IPCC (Niang et al. 2014) indicate drying over Southern Africa and the southern and western parts of East Africa, with wetter conditions over the remainder of East Africa. However, these latter projections are at odds with recent trends in increased drought frequency in East Africa, driven by a rapid warming of the Indian Ocean that has acted through atmospheric mechanisms to suppress the long rains of March-June (Williams and Funk 2010). Lyon (2014) suggests that the recent increase in drought frequency and severity in the Greater Horn of Africa may not be a consequence of global warming, but cautions that the models simulating wetter future conditions in this region are poor at representing annual rainfall cycles and historical rainfall variability on decadal timescales. While climate models have exhibited a high degree of consistency in simulating wetter conditions over much of East Africa (Shongwe et al. 2011; Niang et al. 2014), much uncertainty remains about the drivers of future (and indeed current and historical) climate in this region, and this should not be assumed. In a study of the 2011 East African drought based on comparisons between multiple climate simulations and observed climate data, Lott et al. (2013: 1177) find "no evidence for human influence on the 2010 short rains," but conclude that "human influence was found to increase the probability of long rains as dry as, or drier than, 2011." Cook and Vizy (2013) use a regional climate model to examine the simulated impacts of climate change on East African rainfall in the mid-21st century, and find that (i) the rains in eastern Ethiopia and Somalia are cut short, (ii) the long rains in Tanzania and southern Kenya are reduced throughout the season, and (iii) the season of the short rains in southern Kenya and Tanzania is lengthened. The most useful message here is that, where rainfall is bimodal, climate change may change the proportion of annual precipitation occurring in the short and long rains. Even if annual rainfall increases or remains relatively constant, it may be necessary to adapt to reduced rainfall in one season (here the long rains), and to changes in the length, onset and termination of the wet seasons.

Rising temperatures will have potentially large impacts on water resources even in the absence of significant changes in rainfall. Where rainfall declines, these impacts will be amplified. Schewe et al. (2013) examine global changes in streamflow, based on an average across five general circulation models and 11 global hydrological models for a global warming of 2°C relative to 1980-2010, likely to be reached by the middle of the century (Collins et al. 2014). Their results indicate declines in streamflow of up to 30% over large parts of southern Africa, reaching 50% in the far southwest of southern Africa, and increases of up to 50% over the Greater Horn of Africa, with a high level of consensus across models. A study by Döll (2009) indicates significant reductions in groundwater recharge by the 2050s for much of southern Africa, particularly in southern and western regions.

While the majority of studies of potential future climate focus on the middle or late 21st century, it is important to appreciate that the projected conditions for these periods will not materialise overnight, and significant changes in rainfall, temperature, water resources and other climate-related phenomena may occur much earlier. For example, soil moisture is projected to decline over southern Africa in the near-term, with average reductions of between 1% and 5% or more for the period 2016-2035, relative to 1986-2005 (Kirtman et al. 2014). Dai (2010) presents global maps of historical and projected drought as represented by the Palmer Drought Severity Index (PDSI) and based on historical datasets and climate model projections. These maps illustrate how both meteorological and agricultural[8] drought is projected to increase substantially over southern Africa by 2030-2039, and progressively increase in extent and intensity throughout the 21st century over the entire African continent, except in the Greater Horn of Africa region. Dai (2011: 59) states that people in most of Africa and in many other parts of the world "may see a switch to persistent severe droughts in the next 20-50 years, depending on how ENSO and other natural variability modulate the GHG [greenhouse gas]-induced drying."

Two recent studies conclude that climate change will result in an increased frequency both of extreme El Niño and La Niña events (Cai et al. 2014, 2015). The studies, based on climate model simulations, suggest a four-fold increase in the frequency of extreme El Niño events from one in 60 to one in 15 years (Cai et al. 2014). The frequency of extreme La Niña events could approximately double, from one every 23 years to one every 13 years, with extreme La Niña events tending to follow extreme El Niño events (Cai et al. 2015). These findings suggest a future increase in the frequency of severe droughts, and perhaps in the frequency of droughts in general, in both Eastern and southern Africa, given the

8 The PDSI incorporates a moisture anomaly index that responds quickly to changes in soil moisture and is therefore useful in tracking agricultural drought.

existing links between El Niño and La Niña and drought in these regions (Fauchereau et al. 2003; Roualt and Richard 2005; Lyon 2014).

Most of the above studies focus on changes in temperature, rainfall, associated variables such as streamflow and soil moisture, and changes in drought intensity, rather than more 'holistic' changes in climatic and environmental conditions. In this context it is worth mentioning a study by Thomas et al. (2005), which examined potential climate-driven changes in the landscape of the Greater Kalahari region. This part of southern Africa is characterised by 'fossil' dunes stabilised by vegetation. Thomas et al. (2005) used three global climate models, a range emissions scenarios and a 'dune mobility index' to examine the impacts of climate change on these dune systems. They found that, under all scenarios, activity (i.e. mobility of exposed dune sands) is significantly enhanced in the southern dunefields by 2039, and in the eastern and northern dunefields by 2069. "By 2099 all dunefields are highly dynamic, from northern South Africa to Angola and Zambia" (Thomas et al. 2005: 1218). This projected process of desertification reflects the transformational transition to hyper-aridity that occurred in the Sahara some five millennia ago, as discussed above.

6.2 Climate change impacts on agriculture in East and Southern Africa

A large number of studies have examined the potential impacts of climate change on agriculture globally and regionally, including in sub-Saharan Africa. These impacts will result from a suite of complex, interacting factors operating in different directions. For example, increased atmospheric CO_2 levels may increase rates of photosynthesis, water use efficiency, nitrogen use efficiency and thus crop yield. However, these effects vary depending on plant type (specifically C3 versus C4 plants) and temperature (with C3 plants responding better at lower temperatures and C4 plants responding better at higher temperatures) (Anwar and Liu 2013), and they will be countered by other, adverse climate change impacts. These adverse impacts will operate through higher temperatures, deficient rainfall, increased evapotranspiration, intensified drought stress, increased climatic variability (including more erratic rainfall), and increases in risk from certain types of extreme climate events, as well as other mechanisms such as sea-level rise and associated impacts such as periodic inundation and the salinisation of groundwater in coastal agricultural areas (Gornall et al. 2010; Awar and Liu 2013). Long et al. (2005) suggest, based on Free-Air Concentration Enrichment experiments, that increased low-level ozone concentrations alone could reduce yields of rice, wheat, maize and soybean by some 20% by the 2050s. Climate change will also change the prevalence of weeds, pests and diseases in unpredictable ways (Thornton et al. 2011).

How the above factors will affect agriculture yields is highly uncertain. Müller et al. (2011) review impact assessments for African agriculture that represent periods ranging from the 2020s to the 2100s, and find a wide range of modelled changes in crop yields. In the models examined, changes in crop yield range from -100% to +168% in econometric models, -84% to +62% in process-based models, and -57% to +30% in statistical assessments. The models reviewed by Müller et al. (2011) represent only negative changes in yield by the 2020s (based on just two models) and a range from approximately -50% to +50% for the 2030s (based on four models). Müller et al. (2011: 4313) recognize that: "The range of projected impacts is very broad because of the range of underlying assumptions, such as greenhouse gas emission trajectories, climate model parameterizations, biophysical impact estimates, management practices, and socioeconomic conditions in the future." While adaptation will inevitably occur, it is difficult to predict what form it will take, how widespread it will be, and how rapidly it will be implemented. Therefore, arguably the most useful studies are those that examine the potential impacts of climate change on existing systems in the absence of adaptation, as these can help us identify where the implications of climate change are potentially most serious, and where adaptation is most needed. Such studies are the focus of the discussion below.

Müller et al. (2011: 4134) emphasise the importance of changes in rainfall, stating that: "Rainfall patterns are the dominant climatic factor for agricultural production in Africa," although they acknowledge the potentially "considerable" impacts of higher temperatures. Schlenker and Lobell (2010) highlight the importance of temperature impacts in a study examining changes in yields for maize, sorghum, millet, groundnuts and cassava in sub-Saharan Africa for the period 2046-2065 relative to 1961-2000, based on historical relationships between country-level yields and weather data including daily average, minimum and maximum temperatures, and data from climate projections. Each crop exhibits a range of negative changes in yield, except cassava, for which the range includes both positive and negative changes. The median changes in production are -22, -17, -17, -18 and -8% for maize, sorghum, millet, groundnut and cassava respectively. Disaggregating the effects of changes in precipitation and changes in rainfall, Schlenker and Lobell (2010) demonstrate that, in this study, the projected production changes are almost entirely due to changes in temperature. It should be noted that this study does not address the impacts of CO_2 fertilisation, or the role of adaptation, suggesting that declines in yield might be reduced through appropriate adaptation measures.

Burke et al. (2009) examine projected changes in temperatures in the maize, millet and sorghum growing areas in sub-Saharan Africa for the 2020s, 2050s and 2070s. They conclude that growing season temperatures will shift outside the range of historical variation by the middle of the century, stating that "expected changes in growing season temperature are considerable and dwarf changes projected for precipitation, with the warmest recent temperatures on average cooler than almost 9 out of 10 expected observations by 2050" (Burket et al. 2009: 317). Battisti and Naylor (2009) present similar findings for many low-middle latitude land areas, including in Africa, in a global study of projected growing season temperatures and food insecurity. They conclude that "growing season temperatures in the tropics and sub-tropics by the end of the 21st century will exceed the most extreme seasonal temperature recorded from 1900 to 2006" (Battisti and Naylor 2009: 240).

Over East Africa, the simulated changes in rainfall in the study by Cook and Vizy (2013) described above are associated with projected changes in the number of growing season days (in the 2050s) ranging from around +50 in some highland areas, to around -50 in much of Somalia, eastern Ethiopia, the low-lying parts of southern and western Kenya and northern Tanzania, and (although only partially covered by the study) the interior of southern Africa. Most low-lying parts of East Africa experience some reduction in the number of growing season days. Thornton et al. (2011) examine the implications of a rise in global temperature of 5°C, plausible by the late 21st century in the absence of very strong measures to mitigate greenhouse gas emissions in the very near future (Collins et al. 2014). They find that the length of the growing period in the 2090s; averaged across the output of 14 global climate models; (i) increases by up to around 20% across much of Kenya and in parts northern Tanzania (ii) exhibits little change in most of the remaining areas of Kenya and Tanzania; much of northern Zambia; southeastern Uganda; most of the tip of the Horn of Africa; and the more arid areas of southwestern South Africa and in dry southern and western Namibia); (iii) declines by over 20% over almost all of the remainder of southern Africa south of about 12°S; (iv) declines by 5-20% in the remaining areas of East and Southern Africa; including northern Angola; the Mozambique-Tanzania border region; southern Somalia; most of Ethiopia; Eastern South Sudan; and western and northern Uganda. Thornton et al. (2011) consider both temperature and moisture availability, but ignore drought in these calculations, and caution that while the length of the growing season in their study is a proxy for the number of grazing days, it is not necessarily a useful proxy for cropping success. They also report a projected increase in season failure rates over all of sub-Saharan Africa except central Africa; in southern Africa the increase is such that "nearly all rain-fed agriculture below 15°S is likely to fail one year in two" (Thornton et al. 2011: 121). Using crop models, Thornton et al. (2011) find that increases in the length of the growing season in East Africa do not translate into increased productivity, with simulated production declining by 19% for maize and 47% for beans, with little or no change for pasture. They also point out that "a substantial proportion of this region that is currently cropped already experiences season failure rates of 25 per cent or more, and these areas will increase in size substantially in the future" (Thornton et al. 2011: 122). Thornton et al. (2011) cite Arnell (2009) as concluding that some 35% of current cropland is likely to become unsuitable for cultivation in East and Southern Africa, compared to 15% globally (offset by an extra 20% becoming available globally in cooler areas due to warming). They also calculate that, under a 5°C global warming, some 1.2 million km^2, or around 5% of the land area of sub-Saharan Africa, is likely to shift from mixed cropping and livestock systems to predominantly rangeland-based systems.

It is important to be cautious when interpreting studies such as those summarised above, which provide quantitative, and often quite precise, estimates of changes in growing areas, the duration of growing seasons, and crop yields. Such studies should not be used in a reductive fashion to drive decision making, but rather to identify broad risks and highlight which locations and activities are likely to require adaptation support. These locations and activities can then be the focus of monitoring initiatives that track climatic and environmental changes, crop yields, and other potential climate change impacts. Adaptation strategies can then be developed for these higher risk locations and activities on the basis of evolving changes in climate and associated impacts. For example, these strategies might include the development of transformational adaptation measures once crop failure rates or yields exceed a certain threshold that is judged indicative of the need for such adaptation in the foreseeable future.

A study by the International Food Policy Research Institute (IFPRI) (Hachigonta et al. 2013) examines the potential impacts of climate change on agriculture in Southern Africa using the medium-emissions A1B scenario developed by the IPPC, and four climate models. Projected changes in yield losses between 2000 and 2050 are presented on a per-country basis for rain-fed maize, sorghum and wheat, for Botswana, Lesotho, Malawi, Mozambique, South Africa and Swaziland. While these projections suggest yield losses of more than 25% for at least one crop in each country, in at least one model, the only country in which current areas of production are projected to be lost is Botswana. Current areas of rain-fed maize production are projected to be lost in southwestern Botswana in the region around Ukwe and Tshane in two out of the four models (Zhou et al. 2013). Areas of production of rain-fed sorghum are projected to be lost in a much larger area around and to the south and west of Ukwe and Tshane in two models, and in the far southwest of the country in one of the remaining models (Zhou et al. 2013).

A second IFPRI study (Waithaka et al. 2013) applies the same methodology to examine the potential impacts of climate change on agriculture in East Africa. Areas of production are projected to be lost for sorghum and wheat in some western and central areas of Eritrea in two out of four models (Ghebru et al. 2013: 140-141); for maize, wheat and sorghum in restricted areas in central, northern and southwestern Ethiopia in three out of four models (Admassu et al. 2013: 169-172); for maize in west-central Kenya in one out of four models (Odera et al. 2013: 204); for sorghum in the southern regions of Sudan in three out of four models (Taha et al. 2013: 301); for irrigated wheat in eastern Sudan in all four models (Taha et al. 2013: 302); and for rain-fed maize in the far east of Uganda (Bashasha et al. 2013: 366).

Once again, these results should be treated with caution given the uncertainty in the climate projections and resulting yield estimates, which in some cases are of opposite signs in the projections from different models. However, they highlight the need for further assessment and monitoring of changes in agro-climatic conditions in specific locations, and of the production of specific crops in those locations, which will be a precondition for determining if transformational adaptation is likely to be required in these locations in the future.

6.3 Current approaches to adaptation and agricultural development

As argued at the beginning of this paper, most current approaches to adaptation are incremental in nature, and consist of the deployment of familiar measures in new areas, or the 'scaling up' of these measures to cover larger areas and populations (Kates et al. 2012; Chung Tiam Fook 2015). Indeed, many 'adaptation' interventions focus on building resilience or reducing vulnerability to existing (albeit evolving) climate variability and its associated risks. There is therefore often little difference between interventions branded with the adaptation label and regular development interventions, with adaptation discourses "being used … to enable the re-legitimisation and repetition of old development practices as well as to open a space for new practices and imagining of alternatives." (Ireland 2012: 92).

In sub-Saharan Africa and globally, there is currently a strong focus on 'climate smart agriculture' (CSA), defined by the Food and Agriculture Organization of the United Nations (FAO 2013: ix) as consisting of the following "three main pillars:

1. sustainably increasing agricultural productivity and incomes;
2. adapting and building resilience to climate change;
3. reducing and/or removing greenhouse gases emissions [sic], where possible."

FAO (2013: x) emphasise that CSA is not a single specific agricultural technology or practice that can be universally applied, but rather "an approach that requires site-specific assessments to identify suitable agricultural production technologies and practices." These will include a suite of measures ranging from the mainstreaming of climate change into the agriculture sector and its associated institutions, through the improvement of agricultural extension/farmer support services (including finance), to practices for managing natural resources, water and soils (FAO 2013; Mutamba and Mugoya 2014).

In low input smallholder contexts such as those found across East and Southern Africa, the focus of CSA is on productivity and the reduction of risks associated with familiar hazards such as drought and rainfall variability, through measures described variously as seeking to reduce smallholders' vulnerability, increase their resilience, and build their adaptive capacity (Campbell et al. 2014; Mutamba and Mugoya 2014). In sub-Saharan Africa there has been a particular emphasis on conservation agriculture, based on soil and water conservation measures and frequently involving minimum tillage (Andersson and D'Souza 2013). For example, Malawi and Zambia have prioritized CSA "with the aim of improving the productivity of their smallholder agricultural systems under climate change", with a focus on agroforestry and conservation agriculture (Kaczan et al. 2013). Kaczan et al. (2013) conclude that agroforestry has well-documented yield and profitability benefits, but that evidence for the benefits of conservation agriculture, while present, is weaker. Conservation agriculture has been heavily promoted in sub-Saharan Africa as a means of enhancing production, but its assessment has generally been undertaken in contexts in which adoption is heavily incentivized, and there are doubts about the sustainability of its adoption (Andersson and D'Souza 2012). Furthermore, recent studies have questioned the efficacy of conservation agriculture in sequestering carbon (Palm et al. 2014; Powlson et al. 2014). Gattinger et al. (2011) also question the extent of yield benefits and labour savings from conservation agriculture involving 'no-till' approaches.

There are, therefore, questions as to the efficacy of past interventions labelled as CSA, particularly those associated with conservation agriculture and low or no-till practices, such as have been widely promoted in sub-Saharan Africa.

Even where the benefits of CSA can be demonstrated, the question remains as to whether CSA as currently conceived is sufficient to address climate change. The FAO definition of CSA refers to adaptation *and* resilience, i.e. as distinct entities, and thus opens the door to transformational adaptation as something that is separate from, although potentially complementary to, resilience building. However, as discussed earlier in this paper, current adaptation initiatives overwhelmingly focus on increasing resilience through incremental approaches (Kates et al. 2012; Chung Tiam Fook 2015), and this holds true for CSA. Indeed, Neufeldt et al. (2013: 1) conclude that the relationship between the three pillars of CSA as defined by the FAO (2013) "is poorly understood, such that practically any improved agricultural practice can be considered climate smart." Arguably, this encourages a focus on 'quick wins' based on the scaling up of familiar measures. This is evident in a recent CGIAR blog post by Rijsberman and Campbell (2015)[9] that focused heavily on the registration of farmers on cell phones so that they can receive seasonal forecasts and participate in weather index insurance schemes, and on the dissemination of forecasts by radio. Such initiatives may be hugely beneficial, but they are firmly located in the arena of incremental responses.

It is, or course, entirely possible that incremental approaches will be sufficient to sustain agriculture in many contexts, particularly in areas projected to experience lower rates and magnitudes of warming, and limited changes in rainfall. In these contexts, changes in planting times, a switch to faster-growing crop strains, better use of seasonal and short-term forecasts, increased uptake of weather-based insurance, soil and water conservation, better access to markets, and increased investment in farm inputs including labour, may enable farmers to 'keep up' with changes in temperature and rainfall. Even where more transformational approaches will be required, they may not be needed for many years or decades. In such contexts, incremental approaches can act as 'bridging' strategies, as more transformational ones are developed and piloted, as capacity for transformational adaptation is built, and as the required enabling policy and institutional environments are developed.

In this context it is worth noting the conclusion of Bezabih et al. (2010) that increased capital and labour investment might offset climate change related losses in agricultural productivity until around 2030 in Tanzania, after which adaptation becomes much more challenging. A similar progression from familiar agricultural improvement initiatives to more innovative adaptation measures is indicated by Rippke et al. (2016: 1), who conclude that "yield gains from adaptation through crop management and varietal substitution…are highest with moderate or low (<+3°C) levels of warming, suggesting that more profound systemic and/or transformational changes may be required when and where higher levels of warming occur." These conclusions raise the question of (i) whether, and if so when, the transition from incremental to transformational adaptation will need to be undertaken in any given location and agricultural context, and (ii) what adaptation strategies and measures need to be added to the existing portfolio of CSA technologies and practices in order to sustain livelihoods and food security in the face of climate change that results in conditions moving outside the range of historical variability?

9 http://www.cgiar.org/consortium-news/whats-next-for-climate-smart-agriculture/

6.4 Possible transformational changes in climate and adaptation responses in East and Southern Africa

The projected changes in climate and associated impacts on agriculture reviewed above strongly suggest that transformational approaches to adaptation will be required in some contexts in East and Southern Africa. Anwar and Liu (2013: 225) describe how “farmers have adapted in an autonomous manner” to “gradual changes of climate in the past”, but propose that “with large and discrete climate changes anticipated by the end of this century, planned and transformational changes will be needed”. Rippke et al. (2016: 1) write that “Transformational change implies shifts in locations for production of specific crops and livestock, or shifting to farming systems new to a region or resources system.” They also conclude that transformational adaptation is likely to be necessary for nine major crops[10] that constitute 50% of African agricultural production (by quantity) under a high-emissions scenario compatible with current greenhouse gas emissions trajectories, in some locations.

6.4.1 Temperature shifts outside the range of historical variability

Temperature changes that shift average growing season temperatures outside the range of experienced, historical seasonal temperatures may have occurred or be well underway by 2050 in the maize growing areas of East and Southern Africa, where they are projected to be most advanced in Burundi, Rwanda, Zambia, Tanzania, Mozambique, Kenya, Ethiopia, Uganda, the northeast and far southwest of South Africa, and northeastern Zimbabwe (Burke et al. 2009). This transition is projected to be complete across the region by 2075 (Burke et al. 2009). Such a transition does not necessarily mean that existing crops will cease to be viable, but it does raise the possibility that new crops and/or new livelihoods may be required for new climatic conditions. Transformational adaptation in these contexts might involve the development of non-agricultural livelihoods, the relocation of agriculture within countries, or a shift to different crops that are more suited to new conditions.

Burke et al. (2009) develop the concept of ‘analogues’ for future climates: current climatic conditions in one location that resemble the conditions expected to pertain in another location in the future. Adaptation might consist of importing agricultural systems, crops and practices from an analogue location to the location where the adaptation is needed. Burke et al. (2009) examine the extent to which such current analogues for maize growing season temperatures projected for 2050 exist within countries in sub-Saharan Africa, where adaptation might involve ‘importing’ systems, crops and practices from one part of a country to another. In all but two of the countries in the East and Southern African regions addressed here, future growing season temperatures over 40-90% (the “% overlap”) of a country’s area have present-day analogues within the same country. In other words, while temperatures at any given location within a country may shift outside the range of historical variation at that location (i.e. representing “novel” climatic conditions), in over 40% of cases/locations it is possible to find another location within the same country where the temperatures projected for 2050 are already experienced. The exceptions are Namibia and Somalia, where the per cent overlap is zero and around 2% respectively. This is presumably a consequence of the limited spatial variability in mean temperature within these countries today; whereas other countries experience internal geographic shifts in temperature gradients, these two countries simply move into a new temperature regime outside the previous historical range.

Burke et al. (2009) also examine the extent to which analogues for growing season temperatures in 2050 may be found in other countries (i.e. the % overlap with other countries). All the countries in East and Southern African relevant to this review have such country analogues, indicating that learning from and emulating existing agricultural systems from elsewhere in a country or from another country in sub-Saharan Africa provides one potential avenue for transformational adaptation across East and Southern Africa.

6.4.2 Transitions from cropping to extensive livestock systems

Temperature shifts outside historical ranges, and increasing marginality of cropping systems, may lead to transitions from mixed cropping and livestock systems to systems of extensive livestock management in rangeland contexts (Thornton et al. 2011). Jones and Thornton (2009) argue that such transitions are likely to be necessary to preserve food security and income-generating options in areas that are already marginal for agriculture. Based on an examination of downscaled climatic conditions for 2050, they identify such possible “transition zones” in parts of South Africa, Zimbabwe, Zambia, Mozambique, Tanzania, Kenya, Ethiopia, South Sudan, Somalia, Angola, as well as throughout the Sahel and in parts of Mediterranean North Africa (Jones and Thornton 2009: 422). These studies highlight the importance of policy

10 Banana, cassava, bean, finger millet, groundnut, pearl millet, sorghum, yam and maize.

support for extensive livestock systems, and of recognising the vital role that mobile pastoralism has to play in adapting to climate change (Nori and Davies 2007; Kräti et al. 2013).

6.4.3 Possible transitions to aridity: The Greater Kalahari region

Changes in rainfall and temperature may result in transformational changes in landscapes in some parts of East and Southern Africa such as those described for the Greater Kalahari region by Thomas et al. (2005). As summarised above, this study suggests a possible transition from vegetated, stabilised dune systems to denuded, mobile dunes, in other words a process of desertification resulting in conditions more akin to those of the hyper-arid Sahara. In the study by Thomas et al. (2005), this transition occurs in the area around the borders between Botswana, Namibia and South Africa (southern dune field) before 2040, in the Botswana-Namibia-Angola-Zambia and Botswana-Zimbabwe border areas before 2070, and from northern South Africa to Angola, and eastern Namibia to Western Zambia and Zimbabwe, before 2100.

Such a transition would have profound implications for the viability of agriculture and livestock systems in this region, and the most likely adaptation options may be for people to move out of the affected areas and/or transition to non-agricultural and non-livestock based livelihoods. This would present a challenge for the economies of the region in terms of the provision of jobs and services, which would require a degree of economic restructuring. On the one hand significant planning and state intervention, based on a pro-active and anticipatory approach, would be required to manage such a transition. On the other hand, any interventions to promote such drastic changes to people's lives and livelihoods would need to be based on additional, convincing evidence that this worst-case climate scenario is likely to be realised. While such changes in the Greater Kalahari landscape are highly plausible, they are by no means certain. This example illustrates the potential challenges of transformational adaptation, which will often need to balance the need for long-term, anticipatory approaches with significant uncertainty about the future changes in climate that the adaptation in question is intended to address.

6.4.4 Increasing marginality and increased frequency of crop failure

The transformational changes and associated adaptations discussed above are associated with timescales of several decades. The studies of changes in the length of the growing season discussed above (Thornton et al. 2011; Cook and Vizy 2013) also take a long-term perspective. However, in the nearer term, it is possible that smaller changes in the length of the growing period, coupled with increased drought risk, more variable and unpredictable rainfall and other factors (pests, diseases, flooding, etc.), could result in crop failures becoming so frequent that the agricultural systems and livelihoods that depend on those crops become economically unviable. An increased frequency of crop failures could also result in food crises occurring with such frequency that relief and recovery efforts cannot keep up with crop failures to the extent necessary to address rising food insecurity. In fact, it might be argued that such conditions already exist in some parts of East and Southern Africa.

In these nearer-term contexts a key question will be whether incremental approaches are sufficient to address increasing climate risks, or whether more transformational approaches are required. Where risks continue to increase and agricultural systems become increasingly marginal, the question might not be "whether", but "when" a transition from incremental to transformational adaptation is required. The answer to this question might depend on the practicalities of shifting from a model based on increasingly frequent emergency responses to one based on preparedness and advance planning. For example, transformational adaptation might be triggered once emergency responses are required with such frequency or regularity that they are no longer cost effective when compared with more transformational approaches.

It is possible that incremental measures will themselves be 'transformational' if they are pursued in certain combinations, over sufficiently long periods, and/or at the appropriate scales. For example, use of forecasts and insurance, combined with improved market access, could conceivably increase household incomes to the extent that farmers can invest in non-farm activities, eventually transitioning to livelihood models in which agriculture plays a much more limited role. Where transitions to such models occur, households may effectively be adapting to climate change by reducing their dependence on agriculture and thus their immediate vulnerability to local climate shocks, although they may still be exposed to more systemic shocks such as increases in commodity prices, which themselves might occur as a result of climatic disruption. Of course, there is also a risk that incremental approaches will not be transformational, and will instead result in the persistence of production systems that are increasingly ill-matched to changing climatic conditions until those systems finally collapse.

Whether incremental approaches can be sustained successfully in contexts of increasing marginality will depend on the rate and magnitude of climate change, and how this relates to any (possibly dynamic) thresholds of viability for the agricultural systems concerned.

6.4.5 Loss of productive land to sea-level rise

The latest report of the IPCC includes projections of global mean sea-level rise (SLR) with an upper limit approaching 1m by 2100 under a high-emissions scenario (Church et al. 2014). Other studies have reported higher upper limits, ranging from 1.4m to 1.9m (Nicholls and Cazenave 2010). Even modest increases in sea-level will be problematic for low-lying coastal regions. Where SLR does not result in the permanent inundation of agricultural land in low-lying coastal areas, it will increase the risk of episodic flooding during storm surges, and accelerate the intrusion of salt water into coastal aquifers, potentially pushing productive agricultural areas further inland.

Sappa et al. (2015) present evidence for seawater intrusion into groundwater in Dar es Salaam, where it can result in groundwater being periodically unsuitable for irrigation. Brown et al. (2011) identify a number of African cities exposed to sea-level rise, including Port Sudan, Djibouti, Mogadishu, Mombasa, Dar es Salaam, Maputo, Durban, Port Elizabeth and Luanda. Of all the countries in East and Southern Africa, Mozambique has the largest proportion of its population (>25%) in the low-elevation coastal zone (Brown et al. 2011). The most exposed coastal areas in East and Southern Africa are located along the eastern coast, with parts of the Mozambican and Kenyan coasts being particularly exposed[11]. Brown et al. (2010) emphasise the vulnerability of agriculture to sea-level rise around Mombasa, Lamu, Malindi and Kilifi in Kenya, and discuss the conversation of coastal wetlands to agriculture, which increases exposure to sea-level rise and compromises coastal ecosystems.

Brown et al. (2010) discuss adaptation measures for African countries that could reduce the increasing risks of coastal flooding and significantly reduce the impacts of such floods. The adaptation measures considered are the construction of new flood defence dykes and increases in the height of existing dykes, and beach nourishment to manage erosion. These are incremental approaches, involving the expansion or strengthening of existing measures. While these measures may help to manage coastal floods, they will be less successful at addressing seawater intrusion into coastal aquifers, and might increase the risks of severe flooding if they fail. Alternative strategies based on transformational adaptation might involve the relocation of agriculture away from the coast, the development of alternative livelihoods, and surrendering land to the sea through a strategy of managed realignment that allows coastal ecosystems to migrate inland as sea levels rise.

6.4.6 Transformational adaptation through the exploitation of opportunities

While the impacts of climate change on agriculture in East and Southern Africa are likely to be overwhelmingly negative, they may also present opportunities. The potential expansion of extensive grazing areas can be viewed as an opportunity for pastoralists. If climate change results in drier conditions in currently humid areas this may reduce barriers associated with parasitic diseases such as trypanosomiasis, enabling the penetration of cattle into new areas[12]. Such an expansion of cattle herding into new areas where climate change is likely to have reduced disease burdens occurred during the Middle Holocene as the Sahel region became drier (Smith 1984). Opportunities for agricultural expansion may arise in highland areas, where warming results in shifts or expansions of suitable crop areas to higher elevations. While these examples might represent extensions of existing systems and practices, they will represent transformational changes in the use of the new areas.

Transformational changes may occur in national economies as a result of large-scale movements out of agriculture due to increasing climate risks and declining productivity, structural economic changes, or a combination of the two. They might also occur as a result of successful adaptation that allows agriculture to become more economically productive. Market changes and policy changes might hasten movements out of agricultural livelihoods, or help agriculture become more economically productive, promoting investment and increasing the likelihood of successful adaptation. Climate change is likely to interact with increases in human populations and economic development to increase the prices of agricultural commodities, as demand for these commodities increases and supply is affected by declining productivity and more frequent and severe climate shocks in some regions. Countries that can successfully adapt their agricultural systems stand to gain from increased demand for agricultural exports. These exports might include animal products from well managed livestock systems; support for such systems can enable pastoralists to exploit a growing demand for animal products (principally meat for human consumption) while addressing the problem of emissions and environmental degradation associated with intensive animal husbandry. Increased support for pastoralists through pro-pastoralist policies, the provision of services to pastoralists (health, education, insurance, social protection, etc.) and improved access to domestic, regional and international markets, can help facilitate the transitions from crop systems to extensive grazing that will be necessary in some areas (Jones and Thornton 2009).

11 Areas at risk from inundation by different increases in global mean sea-level can be examined using the Global Sea Leve Rise Map at http://geology.com/sea-level-rise/.

12 FAO: http://www.fao.org/Wairdocs/ILRI/x5443E/x5443e04.htm.

6.5 Timing and extent of transformational change and adaptation in East and Southern Africa

Transformational adaptation might be pursued even where there is a high degree of uncertainty regarding future changes in climate, if it involves strategies and measures that deliver development benefits in the near term (so called 'win-win' measures) and that are robust under a wide range of possible future climatic conditions (so called 'no regrets' measures). However, where it involves significant costs, is likely to be disruptive, risks creating losers as well as winners, and requires significant efforts to remove barriers to action, transformational adaptation needs to be approached with caution. In these more challenging contexts the case for transformational adaptation will need to be made carefully, based on climate risk assessments that interrogate the appropriateness and likely success and sustainability of incremental approaches. In these contexts, transformational adaptation is likely to be appropriate only where incremental approaches can be demonstrated to be unviable. Even so, significant efforts are likely to be required to create the conditions under which transformational approaches are likely to be feasible, acceptable and effective. The creation of such 'enabling environments' is discussed in Section 6.6 below.

Just as important as the question of whether transformational adaptation is necessary is that of *when* it should be implemented, and how it relates to existing incremental approaches. It will be neither practical nor desirable to undertake transformational adaptation 'overnight', meaning that, in practice, transformational approaches are likely to overlap with incremental ones.

Rippke et al. (2016:1) propose three overlapping phases of agricultural adaptation, consisting of:

1. "An incremental adaptation phase focused on improvements to crops and management";
2. "A preparatory phase that establishes appropriate policies and enabling environments";
3. "A transformational adaptation phase in which farmers substitute crops, explore alternative livelihood strategies, or relocate."

Rippke et al (2016) envisage the preparatory phase being triggered once a period is entered in which a cropping system is unviable in 5 out of 20 years, typically some 15-20 years ahead of the transformational adaptation phase. This approach provides a framework within which the need for transformational adaptation can be anticipated in advance based on the frequency of crop failure, where observed climate trends and/or climate projections indicate a high probability that such failures will become more frequent as climate change progresses. However, it is somewhat mechanistic, and presupposes that transformational adaptation will be undertaken in response to very specific types of predictable, even linear, climate trends. In practice, transformational adaptation might occur before the envisaged transformational adaptation phase, driven by a combination of the changing costs and benefits associated with existing cropping systems, farmers' perceptions of risks and opportunities, and wider contextual changes in markets, policy environments and social and economic trends. In a national context in which transformational adaptation in agricultural systems is anticipated, policies might be developed to facilitate transitions to alternative livelihoods, rather than to manage specific, location-based transitions over prescribed timescales.

Rippke et al. (2016) examine the extent and timing of transformational changes under a high-emissions scenario in sub-Saharan African cropping systems, for nine major African crops (banana, cassava, bean, finger millet, groundnut, pearl millet, sorghum, yam and maize). They define transformational adaptation as switching from one crop type to another over a geographic area of 0.3 Mha, as a result of the crossing of a threshold of viability. They conclude that transformational adaptation will be required for all crops, but with large variations in extent and location across these crops. The "vast majority of the present suitable area was projected to stay suitable" for cassava, finger millet, groundnut, pearl millet, sorghum and yam (Rippke et al. 2016: 1). However, transformational adaptation will probably be required over more than 30% of the current maize and banana growing areas, and over 60% of the current bean growing area. Transformational adaptation is likely to be required before the 2050s throughout the Sahel, and in Namibia, Angola, Botswana, Zimbabwe and Mozambique, particularly for maize. Transformation is projected for bean growing areas in East Africa (mostly) after the 2050s, particularly in Uganda and Tanzania. Critically, Rippke et al. (2016: 2) state that: "In most of the areas projected to undergo transformational change during the twenty-first century, preparatory phases occur very early or should already be in place."

Early requirements for transformational adaptation, between 2015 and 2035, are indicated for:

i. banana in coastal areas of central and northern Mozambique, northwestern Tanzania, southwestern South Sudan and western Madagascar;

ii. cassava in southern Mozambique, northern and eastern Zimbabwe, central Tanzania and southern Madagascar;

iii. bean in northeastern South Africa, Zimbabwe, southeastern Angola and isolated pockets of northern Mozambique and southern Tanzania;

iv. groundnut in parts of Zimbabwe, northern Tanzania, northern Ethiopia and eastern South Africa;

v. pearl millet in small areas in southern Ethiopia, eastern Botswana and western Zimbabwe, and northern Angola;

vi. sorghum in northern Botswana, northeastern South Africa, southern Zimbabwe, and small parts of southern Mozambique, central and southern Kenya, northern Ethiopia and southwestern Madagascar;

vii. yam in northern Mozambique and parts of central and West Africa, with small pockets in western Ethiopia, southern South Sudan and west-central Madagascar, and

viii. maize in northern Botswana, northern Namibia, eastern Zimbabwe, southern and western Mozambique, and parts of southern South Sudan. The areas requiring transformational adaptation in East and Southern Africa exhibit large increases over time for bean and maize, and smaller increases for sorghum (in northwestern South Africa and southern Zimbabwe) and banana (southwestern South Sudan and southeastern Tanzania) (Rippke et al. 2016: 2).

Rippke et al. (2016) also suggest substitute crops for areas where transformational adaptation in the form of crop switching is required. A region extending between Lesotho and the border with Botswana is notable for the lack of available substitutes in this study. Elsewhere, the most 'promising' substitute crops are pearl millet, finger millet, sorghum, groundnut and cassava. In most areas Rippke et al. (2016) propose a mix of substitute crops, but the dominance of pearl millet as a potential replacement crop in a zone running from across northeastern Namibia through northern Botswana and into western and southern Zimbabwe is notable. Pearl millet is also suggested as the main substitute in parts of northeastern South Africa. However, while pearl millet may be climatically suited to these areas in the future, it is grown mainly for subsistence and presents limited commercial opportunities, although it is grown commercially as forage in some locations (RSA 2011). Transitions to the production of pearl millet are therefore unlikely to be desirable from a livelihood perspective, and might represent instances of 'sub-optimal' adaptation, in which people can maintain their livelihoods and subsistence, but at a reduced level of income and overall wellbeing. A preferable option under such circumstances might be to move out of agricultural livelihoods, or to relocate to a more productive location. Either of these options might be facilitated through policies and transformational adaptation interventions informed by prior planning.

Transitions from production systems based on crops to ones based on extensive grazing (Jones and Thornton 2009), shifts to novel growing season temperature regimes (Burke et al. 2009), reductions in the length of the growing season (Cook and Vizy 2013), possible landscape transitions in parts of the greater Kalahari region (Thomas et al. 2005), and transformational changes in crop viability in certain locations (Rippke et al. 2016), are all projected to occur before 2050. Based on the phased approach proposed by Rippke et al. (2016), these anticipated changes suggest that preparatory activities to establish policies and enabling environments that can facilitate transformational adaptation should commence by the late 2020s at the latest, and before 2020 in some areas.

6.6 Facilitating transformational adaptation

Where climate change means that existing systems and behaviours simply become unviable, transformational adaptation will be inevitable. Under such circumstances, but also where transformational adaptation may be beneficial but not 'mandatory', anticipatory approaches to such transformations will be desirable. Such approaches have the potential to make transformational adaptation less disruptive, and to reduce the likelihood that adaptation will involve winners and losers. However, as discussed above and in the limited body of relevant literature, there are considerable barriers to anticipatory transformational adaptation. Table 2 lists such barriers, as identified in the literature.

Table 2: Barriers to transformational adaptation as identified in the limited literature relating to this topic.

Barrier	Source
Uncertainty about future climate change and its impacts, associated with a lack of climate information, uncertainty in projections, and/or the absence of institutional processes and mechanisms for decision-making under uncertainty.	Bierbaum et al. 2013, citing various sources; Kates et al. 2012
Uncertainty about the benefits of adaptation, associated with uncertainty about climate change risks	Kates et al. 2012
The "unimaginable nature of possible extreme vulnerabilities and impacts"	Kates et al. 2012: 7158
Lack of resources to begin and sustain adaptation efforts, including finance and, in institutional contexts, staff	Bierbaum et al. 2013, Chung Tiam Fook 2015
Fragmentation of decision-making, e.g. associated with poor coordination across different institutions, jurisdictional boundaries	Bierbaum et al. 2013
Institutional constraints including current laws and regulations, lack or mandates for action	Bierbaum et al. 2013
Existing systems of rights, usage and privileges (e.g. relating to land or water use)	Kates et al. 2013
Institutional and behavioural barriers that tend to maintain existing resource systems and policies	Kates et al. 2012
Lack of leadership	Bierbaum et al. 2013
Divergent perceptions of risk, e.g. nature and impact of climate change	Bierbaum et al. 2013
The perceived costs of transformational actions	Kates et al. 2012
Psychological barriers associated with resistance to social change	Chung Tiam Fook 2015
Views of transformational adaptation as threatening and disruptive	Chung Tiam Fook 2015
Lack of capacity, knowledge and access to relevant information, particularly for small communities (compounded by remoteness and poor communications)	Chung Tiam Fook 2015
Lack of examples of successful transformational adaptation	

The pursuit, indeed the possibility, of 'anticipatory' transformational adaptation will depend on the creation of enabling environments at the institutional and wider societal levels. Initiatives to raise awareness of both the potential risks posed by climate change and the possible response options should target both decision makers in relevant institutions and the wider public (or specific beneficiary/interest groups). At the institutional level, general training and sensitisation will need to be complemented by the integration or 'mainstreaming' of risk assessment into decision-making processes, for example through the regular screening of activities (e.g. projects, programmes and policies) for climate change risks, and more detailed assessments where potential risks are identified. These assessments will need to incorporate considerations of critical thresholds (e.g. for current cropping systems) and options for both incremental and transformational adaptation to changes in climate that exceed these thresholds. Institutions should have clear mandates for addressing climate change. The establishment of institutional mechanisms for addressing climate change risks and associated adaptations will need to be supported by the allocation of appropriate resources, mechanisms to ensure coordination with other relevant institutions, training of key staff, the appropriate use of climate information, the development of mechanisms for decision-making under climatic uncertainty (e.g. for longer-term planning), participation of all relevant stakeholders in decision-making processes, and initiatives to increase the awareness of stakeholders, beneficiaries and society at large of climate change risks and available/potential responses (Brooks et al. 2013).

Awareness raising of risks and response options among stakeholders and intended beneficiaries of adaptation support is vital to the creation of enabling environments for transformational adaptation, which will need to balance scientific/expert assessments of risk (e.g. based on climate projections) with the development of measures supported and accepted by local stakeholders. These measures might build on existing practices, for example deployed in different locations or at much larger scales, or build on and support local innovation, for example the trialling and adoption of new crops or crop varieties as described by Mortimore (2010).

Sensitisation and action to mainstream climate change into decision-making processes might be accelerated following significant climate hazards and disasters, so called "focusing events" that result in widespread attention to the relevant risks (Kates et al. 2012). The problem of "unimaginable" climate change impacts might be addressed through the use of analogues. These might include analogues from the distant past that illustrate the kinds of climatic and environmental changes that are possible, for example shifts from savannah to desert and large changes in sea-level. They might also include recent experiences of extreme conditions that climate projections suggest could become the norm, for example extreme droughts, extreme hot seasons, or extreme high tides. An example is the use of so-called "king tides", the highest tide at a given location in a year, to preview the effects of sea-level rise, raising awareness of potential sea-level rise impacts, and identifying flood-prone locations.[13] Awareness raising of potential climate change impacts might also use spatial analogues, in which a location's potential future climate is illustrated by identifying other locations that already experience the conditions anticipated at the 'target' location. Spatial analogues have been used in this way by the Australian government (Whetton et al. 2012) and have been proposed as tools for the identification of transformational adaptation options by Burke et al. (2009).

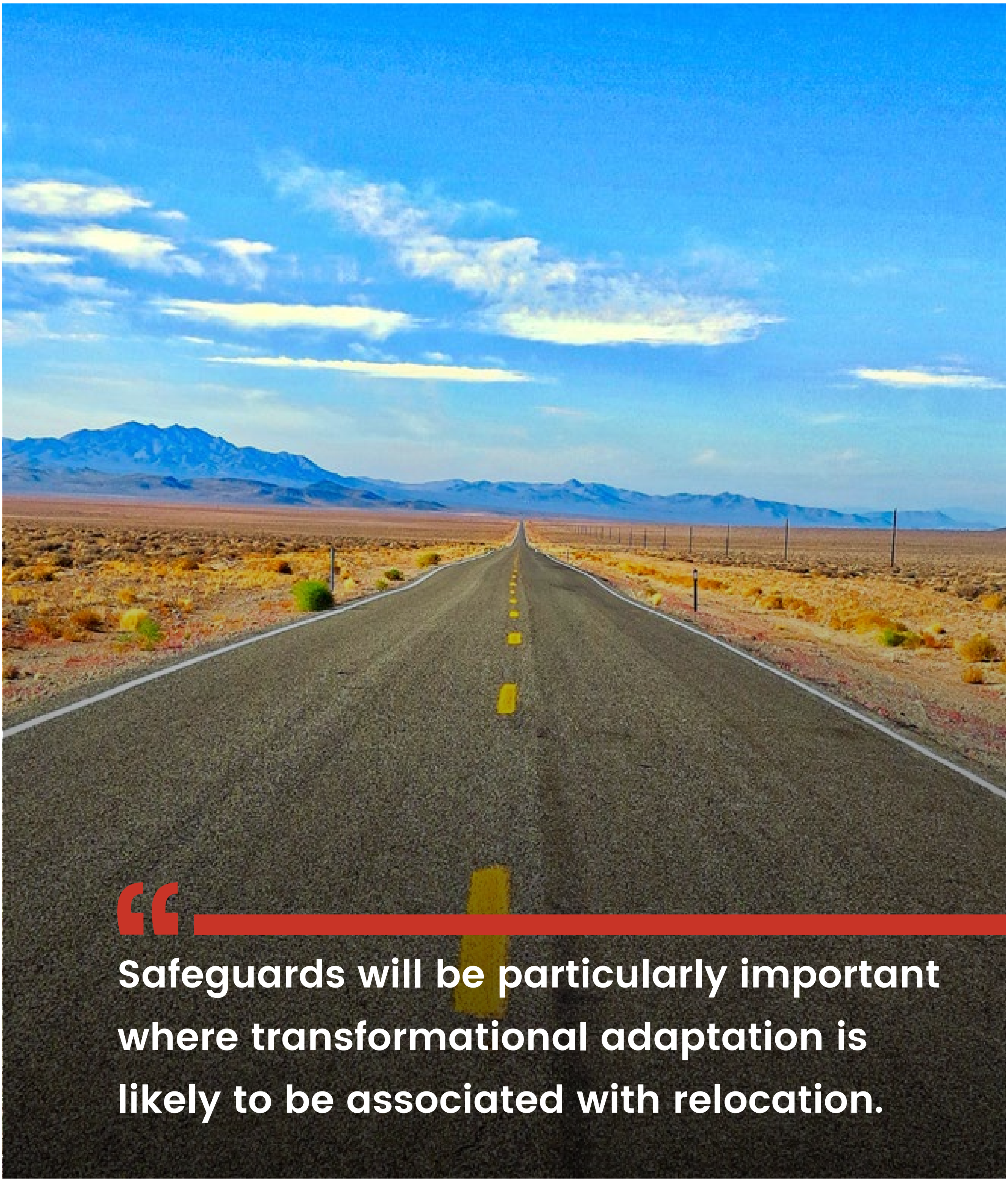
Ownership of transformational adaptation strategies and measures by the people affected by them will be vital for the success of transformational adaptation, and will help in reducing conflict around it. Participatory processes that ensure buy-in, and that bring together experts and local stakeholders in the design of adaptation strategies and measures, will be necessary if transformational adaptation options are to be accepted and pursued. These processes will need to align expert assessments of climate change risks with stakeholder assessments of adaptation options, for example through the prioritization of options based on locally acceptable criteria (e.g. Baas and Ramasamy 2008).

In some cases, transformational adaptation may be "low regret", providing alternatives to current practices that are robust under a range of future climate scenarios. It might also be "win-win", delivering development benefits even in the absence of significant changes in climate as well as adaptation benefits. However, transformational adaptation might also be disruptive and associated with significant opportunity costs, as well as with risks of winners and losers. Where this is the case, it will only be desirable to pursue such a course of action if there is high confidence that it is necessary. Where the potential need for transformational adaptation has been identified, but the actual need has not been demonstrated with a high level of confidence, it will be important to monitor the relevant climatic variables and the systems affected by the phenomena they represent. This will enable decision-makers to identify where and when a system or practice is approaching a threshold of viability, beyond which transformational adaptation may be a necessity (e.g. if incremental approaches cannot push the coping range of that system or practice beyond the current threshold). Rippke et al. (2016) emphasise the need to develop effective systems for monitoring climate as well as agricultural systems for precisely these reasons.

Where the potential or actual need for transformational adaptation can be anticipated, phased approaches such as that advocated by Rippke et al. (2016) and described above, can be implemented. Such approaches are highly desirable, and perhaps essential, for successful transformational adaptation, which will require systemic changes that will need time to be realised. Anticipatory, phased approaches also enable transformational adaptation measures such as the introduction of new crops or livelihood options to be piloted on small scales. During such pilot phases, these measures can be assessed based on performance and acceptability, with successful measures subsequently being 'scaled-up'.

13 As described on the website of the US Environmental Protection Agency at https://www.epa.gov/cre/king-tides-and-climate-change.

Awareness raising of risks and potential response options, piloting of adaptation measures, and phased approaches to the introduction and scaling up of these measures, will be vital if transformational adaptation is to be acceptable and successful. Such approaches will help to ensure that transformational adaptation is neither coercive nor entirely 'top down', imposed on communities and other stakeholders by governments or other actors. It is essential that top down, coercive approaches are avoided, in order to reduce the potential for conflict, increase stakeholder 'buy-in', ensure adaptation measures are locally appropriate, and increase prospects for the success and sustainability of transformational adaptation. This might be achieved, or at least supported, through the development of safeguards for transformational adaptation that extend the environmental and social safeguards currently applied to development activities (e.g. ADB 2014; World bank 2015). Safeguards will be particularly important where transformational adaptation is likely to be associated with relocation, where uncertainty is high, and where there are risks of winners and losers (e.g. the marginalization or increased vulnerability of certain groups).



7 Conclusions

While the body of work on transformational adaptation remains small, there is increasing recognition in the academic/research literature of the potential limitations of incremental approaches to adaptation, intended to maintain existing systems and practices. In recent years, studies of transformational adaptation have moved beyond the general, into specific areas including agriculture (e.g. Rickards and Howden 2012), with some notable studies focusing on sub-Saharan Africa (Burke et al. 2009; Rippke et al. 2016). Nonetheless, examples of transformational adaptation remain few and far between, and there seems to be little appetite for such approaches at the level of development practice. This is understandable given the huge challenges related to the efficiency and productivity of some agricultural systems even in the absence of climate change, and the many challenges associated with transformational adaptation (Kates et al. 2012; Bierbaum et al. 2013).

Nonetheless, it is likely that transformational adaptation will be required in the foreseeable future, on timescales relevant to present-day decision-making, in at least some locations and contexts. Burke et al. (2009) conclude that growing season temperatures will move largely outside the range of historical experience by the mid-21st century in much of East and Southern Africa. Rippke et al. (2016) conclude that transformational adaptation will be required in a minority of these areas by the 2030s for Banana, Cassava, Bean, Groundnut, Pearl Millet, Sorghum, Yam and Maize, with Yam, Groundnut and Cassava being most affected. However, the study by Rippke et al. (2016) strongly suggests that in most growing areas incremental approaches should be sufficient up to this period. More extensive transformational adaptation will be required by the middle to late 21st century for maize and beans (Rippke et al. 2016). Other studies suggest that for a warming of 4 °C or more (unlikely until well into the latter half of the 21st century under the most pessimistic climate change scenarios), around 35% of crop land in East and Southern Africa will become unsuitable for cultivation (Thornton et al. 2011). Jones and Thornton (2009) and Thornton et al. (2011) highlight the likely shift from cropping to rangeland systems in some parts of sub-Saharan Africa (including many areas in West Africa) as a result of climate change, indicating that this is a likely option for transformational adaptation in some areas.

Studies such as those mentioned above can help us identify areas where transformational adaptation is likely to be required. However, the details of these studies should be treated with caution, given the uncertainty inherent in climate projections and impacts studies based on those projections. That is not to say the impacts described in these studies should be viewed as unlikely; indeed, it is possible that such studies are optimistic. Rather than being used as prescriptive frameworks for transformational adaptation planning, these studies are most usefully treated as broad risk assessments that help decision makers to identify areas where climatic trends and the performance and viability of agricultural systems should be monitored closely, contingency plans for transformational adaptation drawn up, and transformational adaptation measures piloted. This will facilitate a phased approach in which existing systems and practices are supported through incremental approaches until such a time as the need for transformational approaches becomes clear, after which transformational adaptation can be pursued based on prior preparation and piloting. Awareness raising, participatory scenario planning and wider capacity building, targeting both key institutions and society at large, should be key elements of this planning. Prior planning for transformational adaptation should identify a suite of potential transformational measures, building on local innovation and experience, informed by external expertise, and drawing on the experiences of others through the use of current or past analogues for future climatic conditions. While CSA discourses currently exhibit little sign of grappling with the potential need for transformational adaptation, the piloting of potential transformational adaptation measures within existing CSA frameworks focusing on diversification represents a promising entry point for linking transformational adaptation with CSA.

References

Adams, W. M. and Mortimore M. J. 2001. Agricultural intensification and flexibility in the Nigerian Sahel. *The Geographical Journal* 163: 150-160.

ADB 2014. Safeguards Operational Review ADB Processes, Portfolio, Country Systems, and Financial Intermediaries. Independent Evaluation Department of the Asian Development Bank. Mandaluyong City, Philippines. Available: http://www.adb.org/sites/default/files/evaluation-document/89401/files/ces-safeguards.pdf.

Admassu, H., Getinet, M., Thomas, T. S., Waithaka, M. and Kyotalimye, M. In Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M. (eds.) 2013. *East African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 149-182.

Adger, W. N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D. R., Naess, L. O., Wolf, J. and Wreford, A. 2009. Are there social limits to adaptation to climate change? *Climatic Change* 93: 335-354.

Algaze, G. 2008. *Ancient Mesopotamia at the dawn of civilization: The evolution of an urban landscape*. University of Chicago Press, Chicago.

Andersson, J. A. and D'Souza, S. 2013. From adoption claims to understanding farmers and contexts: A literature review of Conservation Agriculture (CA) adoption among smallholder farmers in southern Africa. *Agriculture, Ecosystems and Environment* 187: 116-132.

Anwar, M. R. and Liu, D. L. 2013. Adapting agriculture to climate change: a review. *Theoretical and Applied Climatology* 113: 225-245.

Arnell, N. 2009. Beyond 4°C: impacts across the global scale. In *Int. Climate Conf., 4 Degrees and Beyond: implications of a global climate change of 4+ degrees for people, ecosystems and the earth system, Oxford, 28–30 September 2009*. Oxford, UK: Environmental Change Institute. See http://www.eci.ox.ac.uk/4degrees/ppt/1-3arnell.pdf.

Baas, S. and Ramasamy, S. 2008. Community based adaptation in actions: a case study from Bangladesh. Food and Agriculture Organization of the United Nations and Department of Agricultural Extension, Rome and Dhaka. Available: http://www.fao.org/3/a-i0481e.pdf

Bar-Matthews, M. and Ayalon, A. 2011. Mid-Holocene climate variations revealed by high-resolution speleothem records from Soreq Cave, Israel and their correlation with cultural changes. *The Holocene* 21: 163-171.

Bashasha, B., Thomas, T. S., Waithaka, M. and Kyotalimye, M. 2013. Uganda. In Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M. (eds.) 2013. *East African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 347-376.

Battisti, D. S. and Naylor, R. L. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 323: 240-244.

Bezabih, M., Chambwera, M. and Stage, J. 2010. *Climate change, total factor productivity, and the Tanzania economy*. Environment for Development Discussion Paper Series, June 2010, EfD DP 10-14. Environment for Development.

Biasutti, M. and Giannini, A. 2006. Robust drying in response to late 20th century forcings. *Geophysical Research Letters* 33: L11706.

Bierbaum, R., Simth, J. B., Lee, A., Blair, M., Carter, L., Chapin, F. S., Fleming, P., Ruffo, S., Stults, M., McNeeley, S., Wasley, E. and Verduxco, L. 2013. A comprehensive review of climate adaptation in the United States: more than before, but less than needed.

Birch, I. and Grahn, R. 2007. *Pastoralism – Managing Multiple Stressors and the Threat of Climate Variability and Change*. Human Development Report Office Occasional Paper. UNDP, 12pp.

Bloch, P. and Foltz, J. 1999. Recent Land Tenure Reforms in the Sahel: Assessment and Suggestions for Redirection. BASIS/Land Tenure Centre, Madison.

Booth, B. B., Dunstone, N. J., Halloran, P. R., Andrews, T. and Bellouin, N. 2012. Aerosols implicated as a prime driver of twentieth century North Atlantic climate variability. *Nature* 484: 228-232.

Brooks, N. 2004. *Drought in the African Sahel: Long-Term Perspectives and Future Prospects,* Working Paper No. 61. Norwich: Tyndall Centre for Climate Change Research, University of East Anglia.

Brooks, N. 2006a. Cultural responses to aridity and increased social complexity in the Middle Holocene. *Quaternary International* 151, 29-49.

Brooks, N. 2006b. *Climate change, drought and pastoralism in the Sahel*. Discussion note for the World Initiative on Sustainable Pastoralism, IUCN.

Brooks, N. 2013. Beyond collapse: climate change and causality during the Middle Holocene Climatic Transition, 6400-5000 years before present. GeografiskTidsskrift-Danish Journal of Geography 112: 93-104.

Brooks, N., Brown, K. and Grist, N. 2009. Development Futures in the Context of Climate Change: challenging the present and learning from the past. *Development Policy Review*27, 741-765.

Brooks, N. 2010. Human responses to climatically-driven landscape change and resource scarcity: Learning from the past and planning for the future. In I. P. Martini and W. Chesworth (eds.) *Landscapes and Societies: Selected Cases*, pp. 43-66. Springer, Dordrecht, Heidelberg, London, New York, 478 pp.

Brooks, N., Anderson, S., Ayers, J., Burton, I. and Tellam, I. 2011. *Tracking Adaptation and Measuring Development.* IIED Working Paper No. 1, November 2011. IIED, London/Edinburgh.

Brown, S., Kebede, A. S. and Nicholls, R. J. 2010. Sea-Level Rise and Impacts on Africa, 2000-2010. University of Southampton.

Burke, M. B., Lobell, D. B. and Guarino, L. 2009. Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. Global Environmental Change 19: 317–325.

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmerman, A., Santoso, A., McPhaden, M. J., Wu, L., England, M. H., Wang, G., Guilyardi, E. and Jin, F-F. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*: DOI:10.1038/NCLIMATE2100

Cai, W., Wang, G., Santoso, A., McPhaden, M. J., Wu, L., Jin, F-F., Timmerman, A., Collins, M., Vecchi, G., Lengaigne, M., England, M. H., Dommenget, D., Takahashi, K. and Guilyardi, E. 2015. Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*: DOI: 10.1038/NCLIMATE2492.

Campbell, B. M., Thornton, P., Zougmoré, R., van Asten, P. and Lipper, L. 2014. Sustainable intensification: What is its role in climate smart agriculture? *Current Opinion in Environmental Sustainability* 8: 39-43.

Casseldine, C., Thompson, G., Langdon, C., and Hendon, D. 2005. Evidence for an extreme climatic event on Achill Island, Co. Mayo, Ireland around 5200-5100 cal. yr BP. *Journal of Quaternary Science* 20: 169–178

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merri eld, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clarke, J., Brooks, N., Banning, E. B., Miryam Bar-Matthews, M., Campbell, S., Clare, L., Cremaschi, M., di Lernia, S., Drake, N., Gallinaro, M., Manning, S., Nicoll, K., Philip, G., Rosen, S., Schoop, U-D., Tafuri, M. A., Weninger, B. and Zerboni, A. 2016. Climatic Changes and Social Transformations in the Near East and North Africa During the 'Long' 4th millennium BC: A Comparative Study of Environmental and Archaeological Evidence. Quaternary Science Reviews 136: 96-121.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner. 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cook, K. H. and Vizy., E. K. 2013 Dai, A. 2011. Drought under global warming: a review. *WIREs Climate Change* 2: 45-65.

Coumou, D. and Rahmstorf, S., 2012. A decade of weather extremes. *Nature Climate Change*, *2*(7), pp.491-496.

Coumou, D., Robinson, A. and Rahmstorf, S. 2013. Global increase in record-breaking montly-mean temperatures. *Climatic Change* 118: 771-782.

Cullen, H.M., deMenocal, P.B., Hemming, S., Hemming, G., Brown, F.H., Guilderson, T., &Sirocko, F. (2000). Climate change and the collapse of the Akkadian empire: Evidence from the deep sea. Area(4), 379–382.

deMenocal, P., Ortiz, J., Guilderson, T. and Sarnthein, M., 2000. Coherent high-and low-latitude climate variability during the Holocene warm period. *Science*, *288*(5474), pp.2198-2202.

di Lernia, S. 2002. Dry climatic events and cultural trajectories: Adjusting Middle Holocene pastoral economy of the Libyan Sahara. In F.A. Hassan (Ed.), Droughts, food and culture: Ecological change and food security in Afri- ca's Later Prehistory (pp. 225–250). New York, NY: Kluwer.

Djoudi, H., Brockhaus, M. and Locatelli, B. 2013. Once there was a lake: vulnerability to environmental changes in northern Mali. *Regional Environmental Change* 13: 493-508.

Döll, P. and Zhang, J. 2010. Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences* 14: 783-799.

Dutra, W., Magnusson, L., Wetterhall, F., Cloke, H. L., Balsamo, G., Boussetta, S. and Pappenberger, F. The 2010–2011 drought in the Horn of Africa in ECMWF reanalysis and seasonal forecast products. *International Journal of Climatology*. Published online: DOI: 10.1002/joc.3545

FAO 2013. Climate-Smart Agriculture Sourcebook. Food and Agriculture Organisation of the United Nations, 570 pp.

Fachereau, N., Trzaska, S., Roualt, M. and Richard, Y. 2003. Rainfall Variability and Changes in Southern Africa during the 20th Century in the Global Warming Context. *Natural Hazards* 29: 139-154.

Filho, A. J., Pezza, A. B., Simmonds, I., Lima, R. S. and Viana, M. 2010. New perspectives on the synoptic and mesoscale structure of Hurricane Catarina. *Atmospheric Research* 95: 157-171.

Pereira Filho, A.J., Pezza, A.B., Simmonds, I., Lima, R.S. and Vianna, M., 2010. New perspectives on the synoptic and mesoscale structure of Hurricane Catarina. *Atmospheric Research*, *95*(2), pp.157-171.

Chung Tiam Fook, T. 2015. Transformational processes for community-focused adaptation and social change: a synthesis. *Climate and Development*. DOI: 10.1080/17565529.2015.1086294.

Ford, J.D., Berrang-Ford, L. and Paterson, J., 2011. A systematic review of observed climate change adaptation in developed nations. *Climatic change*, *106*(2), pp.327-336

Gattinger, A., Jawtusch, J., Muller, A. and Mäder, P. 2011. Climate Change and Agriculture Report No. 2, MISEREOR, Aachen, Germany, 24 pp.

Ghebru, B., Araia, W., Ogbazghi, W., Gebresekassue, M. and Thomas, T. S. 2013. Eritrea. In Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M. (eds.) 2013. *East African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 121-148.

Giannini, A., Saravanan, R. and Chang, P. 2003. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* 302: 1027-1030.

Gornall, J., Betts, R., Burke, E., Clarke, R., Camp, J., Willett, K. and Wiltshire, A. 2010. Implications of climate change for agricultural production in the early twenty-first century. *Philosophical Transactions of the Royal Society B* 365: 2973-2989.

Gross, L. 2005. Go west, early man: modelling the origin and spread of early agriculture. *PLoS Biology* 3: 2054-2055.

Hachigonta, S., Nelosn, G. C., Thomas, T. S. and Sibanda, L. M. (eds.) 2013. *Southern African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, 370 pp.

Hachigonta, S., Nelson, G. C., Thomas, T. S. and Sibanda, L. M. 2013. Overview. In Hachigonta, S., Nelosn, G. C., Thomas, T. S. and Sibanda, L. M. (eds.) *Southerm African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 1-24.

Held, I. M., Delworth, T. L., Lu, J., Findell, K. L. and Knutson, T. R. 2005. Simulation of Sahel drought in the 20th and 21st centuries. Proceedings of the National Academy of Sciences 102: 17891-17896.

Hertel, T.W. and Rosch, S.D., 2010. Climate change, agriculture, and poverty. *Applied Economic Perspectives and Policy*, p. ppq016.

Heyd, T. and Brooks, N. 2009. Exploring cultural dimensions to climate change. In W.N. Adger, I. Lorenzoni and K. O'Brien (eds.) Adapting to Climate Change: Thresholds, Values and Governance, pp. 269-282. Cambridge University Press.

Hill, A. G. 1989. 'Demographic responses to food shortages in the Sahel', *Population and Development Review* 15: 168–192.

IEG 2012. *Adapting to Climate Change: Assessing World Bank Group Experience. Phase III of the World Bank Group and Climate Change*.

IPCC, 2014: 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. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge.

Ireland, P. 2012. Climate change adaptation. Business-as-usual aid and development or an emerging discourse for change? *International Journal of Development Issues* 11: 92-110.

Jones, P. G. and Thornton, P. K. 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science and Policy* 12: 427-437.

Jung, S.J.A., Davies, G.R., Ganssen, G.M. and Kroon, D., 2004. Stepwise Holocene aridification in NE Africa deduced from dust-borne radiogenic isotope records. *Earth and Planetary Science Letters*, *221*(1), pp.27-37.

Kaczan, D., Arslan, A. and Lipper, L. 2013. *Climate Smart Agriculture? A Review of Current Practice of Agroforestry and Conservation Agriculture in Malawi and Zambia.* ESA Working Paper No. 13-07, Agricultural Development an Economics Division, Food and Agriculture Organization of the United Nations

Kates, R. W., Travis, W. R. and Wilbanks, T. J. 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences* 109: 7156-7161.

Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi and H.J. Wang. 2013. Near-term Climate Change: Projections and Predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kräti, S., Huelsebusch, C., Brooks, S. and Kaufmann, B. 2013. Pastoralism: A critical asset for food security under global climate change. *Animal Frontiers* 13: 42-50.

Leeuw, P.N. de, Reynolds, L. and Rey, B. 1995. Nutrient transfers in West African agricultural systems. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (Eds.), Livestock and Sustainable Nutri- ent Cycling in Mixed Farming Systems of Sub-Saharan Africa. Proceedings of an international conference, 22}26 November, 1993. Vol. II: Technical papers. International Livestock Centre for Africa. Addis Ababa, pp. 371}392.

Lesnikowski, A., Ford, J., et al. 2011. Adaptation to health impacts of climate change: A systematic study of UNFCCC Annex I countries. *Environmental Research Letters* 6 (4).

Liu, L. 1996. Settlement patterns chiefdom variability, and the development of early states in North Chine. *Journal of Anthropological Archaeology* 15: 237–288.

Lott, F. C., Christidis, N. and Stott, P. A. 2013. Can the 2011 East African drought be attributed to human-induced climate change? *Geophysical Research Letters* 40: 1177-1181.

Long, S. P., Ainsworth, E. A., Leakey, A. D. B. and Morgan, P. B. 2005. Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. *Philosophical Transactions of the Royal Society B* 360: 2011-2020.

Lyon, B. 2014. Seasonal Drought in the Greater Horn of Africa and Its Recent Increase during the March–May Long Rains. *Journal of Climate* 27: 7953-7975.

McManus, J. F., Francois, R., Gherardi, J-M., Kelgwin, L. D. and Brown-Leger, S. 2004. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* 428: 834-837.

Mattingly, D.J., Reynolds, T., Dore, J. 2003. Synthesis of human activities in Fazzan. In: Mattingly, D.J. (Ed.), *The Archaeology of Fazzan: vol. 1, Synthesis*. Department of Antiquities, Tripoli and Society for Libyan Studies, London, pp. 327–373.

Manning, K. and Timpson, A. 2014. The demographic response to Holocene climate change in the Sahara. *Quaternary Science Reviews* 101: 28-35.

Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlen, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. R., &Steig, E. J. 2004. Holocene climate variability. *Quaternary Research* 62: 243–255.

Morgan, C. L. 2011. *Limits to Adaptation: A review of limitations relevant to the project "Building Resilience to Climate Change – Coastal Southeast Asia."* IUCN, Gland, Switzerland.

Mortimore, M. 2010. Adapting to drought in the Sahel: lessons for climate change. WIREs Climate Change 1: 134-143.

Mortimore, M. and Adams, W. M. 2001. Farmer adaptation, change and 'crisis' in the Sahel, *Global Environmental Change* 11: 49-57.

Müller, C., Cramer, W., Hare, W. L. and Lotze-Campen, H. 2011. Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences* 108: 4313-4315.

Mutamba, M. and Mugoya, M. 2014. *Climate-Smart Agriculture: Farmers' Perspectives.* SACAU/EAFF.

Neufeldt, H., Jahn, M., Campbell, B. M., Beddington, J. R., DeClerck, F., De Pinto, A., Gulledge, J., Hellin, J., Herrero, M., Jarvis, A., LeZaks, D., Meinke, H., Rosenstock, T., Scholes, M., Scholes, R. Vermeulen, S., Wollenberg, E. and Zougmoré. 2013. Beyond climate-smart agriculture: toward safe operating spaces for global food systems. *Agriculture & Food Security* 2: 12.

New, M., Liverman, D., Schroder, H. and Anderson, K. 2011. Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A* 369: 6-19.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J. and 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. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nicholls, R. J. and Cazenave, A. 2010. Sea-Level Rise and its Impact on Coastal Zones. *Science* 328: 1517-1520.

Nicholson, S. 2014. A detailed look at the recent drought situation in the Greater Horn of Africa. *Journal of Arid Environments* 103: 71-79.

Nori, M. and Davies, J. 2007. *Change of Wind or Wind of Change: Climate Change, Adaptation and Pastoralism*. World Initiative for Sustainable Pastoralism.

National Research Council 2008. Potential Impacts of Climate Change on U.S. Transportation, Special Report 290 (*National Academies, Washington, DC*).

Odera, M. M., Thomas, T. S., Waithaka, M. and Kyotalimye, M. 2013. Kenya. In Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M. (eds.) 2013. *East African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 183-212.

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L. and Grace, P. 2014. Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems and Environment* 187: 87-105.

Possehl, G.L., 2002. The Indus Civilization: A Contemporary Perspective. Altamira Press, Oxford.

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A. and Cassman, K. G. 2014. Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* 4: 678-683.

Reitz, E.J., Sandweiss, 2001. Environmental change at Ostra Base Camp, a Peruvian Pre-ceramic site. Journal of Archaeological Science 28, 1085– 1100.

Rickards, L. and Howden, S. M. 2012. Transformational adaptation: agriculture and climate change. *Crop and Pasture Science* 63: 240-250.

Richardson, P. J. and Boyd, R. 2000. Instititutional evolution in the Holocene: the rise of complex societies. British Academy/Novartis Foundation meeting on The Origin of Human Social Institutions organized by W.G. Runciman. Draft 8 22 00.

Rijsberman, F. and Campbell, B. 2015. What's next for climate-smart agriculture? CGIAR and Reuters Foundation, March 16, 2015. Available: http://www.cgiar.org/consortium-news/whats-next-for-climate-smart-agriculture/.

Rippke, U., Remirez-Villegas, J., Jarvis, A., Vermeulen, S. J., Parker, L., Mer, F., Diekkrüger, B., Challinor, A. and Howden, M. 2016. Timescales of transformational climate change adaptation in sub-Saharan Africa. *Nature Climate Change*. DOI: 10.1038/NCLIMATE2947.

Roualt, M. and Richard, Y. 2005. Intensity and spatial extent of droughts in southern Africa. *Geophysical Research Letters* 32: doi:10.1029/2005GL022436.

Sappa, G., Ergul, S., Ferranti, F., Sweya, L. N. and Luciani, G. 2015. Effects of seasonal change and seawater intrusion on water quality for drinking and irrigation purposes, in coastal aquifers of Dar es Salaam, Tanzania. *Journal of African Earth Sciences* 105: 64-84.

Schewe, J., J. Heinke, D. Gerten, I. Haddeland, N.W. Arnell, D.B. Clark, R. Dankers, S. Eisner, B. Fekete, F.J. Colón-González, S.N. Gosling, H. Kim, X. Liu, Y. Masaki, F.T. Portmann, Y. Satoh, T. Stacke, Q. Tang, Y. Wada, D. Wisser, T. Albrecht, K. Frieler, F. Piontek, L. Warszawski, and P. Kabat, 2013. Multi-model assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America*. doi:10.1073/pnas.1222460110.

Schlenker, W. and Lobell, D. B. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters* 5: 014010.

Sheets, H. and Morris, R. 1976. 'Disaster in the desert', in Glantz, M. H. (ed.) *The Politics of Natural Disaster: The Case of the Sahel Drought*. New York: Praeger, pp. 25–76.

Shongwe, M. E., van Oldenborgh, G. J. and van den Hurk, B. 2008. Projected Changes in Mean and Extreme

Precipitation in Africa under Global Warming. Part II: East Africa. *Journal of Climate* 24: 3718-3733.

Smith, A. B. 1984. Environmental limitations of prehistoric pastoralism in Africa. *The African Archaeological Review* 2: 99–111.

Sonwa, D., Dieye, A., El Mzouri, H., Majule, A., Mugabe, F. T., Omolo, N., Wouapi, H., Obando, J. and Brooks, N. 2016. Drivers of climate risk in African Agriculture. *Climate and Development.* doi.org/10.1080/17565529.2016.1167659.

Spencer, K. L., Cundy, A. B., Davies-Hearn, S, Hughes, R., Turner, S. and MacLeod, C. L. 2008. Physicochemical changes in sediments at Orplands Farm, Essex, UK following 8 years of managed realignment. *Estuarine, Coastal and Shelf Science* 76: 608-619.

Stafford Smith, M., Horrocks, L. Harvey, A. and Hamilton, C. 2011. Rethinking adaptation for a 4° world. *Philosophical Transactions of the Royal Society A* 369: 196-216.

Taha, A. Thomas, T. S. and Waithaka, M. 2013. Sudan. In Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M. (eds.) 2013. *East African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 279-312.

Thébaud, B. and Batterby, S. 2001. 'Sahel pastoralists: opportunism, struggle, conflict and negotiation: a case study from eastern Niger', *Global Environmental Change* 22: 69–78.

Thomas, D. S. G., Knight, M. and Wiggs, G. F. S. 2005. Remobilization of southern African desert dune systems by twenty-first century global warming. *Nature* 435: 1218-1221.

Thorpe and Fennell 2012. Climate Change Risks and Supply Chain Responsibility. Oxfam Discussion Papers.

Thornton, P. K., Jones, P. G., Ericksen, P. J. and Challinor, A. J. 2011. Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Philosophical Transactions of the Royal Society A* 369: 117-136.

Tierney, J.E. and Ummenhofer, C.C., 2015. Past and future rainfall in the Horn of Africa. *Science advances*, 1(9), p.e1500682.

Tafuri, M. A., Weninger, B. and Zerboni, A. 2015. Climatic Changes and Social Transformations in the Near East and North Africa During the 'Long' 4th millennium BC: A Comparative Study of Environmental and Archaeological Evidence. Quaternary Science Reviews.

Waithaka, M., Nelson, G. C., Thomas, T. S. and Kyotalimye, M. (eds.) 2013. *East African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, 434 pp.

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society 9: 5. [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art5

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M. and Jeandel, C., 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science*, *351*(6269), p. aad2622.

Whetton, P., Hennessy, K., Clarke, J., McInnes, K. and Kent, D. 2012. Use of Representative Climate Futures in impact and adaptation assessment.' Climatic Change 115, 433-442. 10.1007/s10584-012-0471-z.

Williams, A. P. and Funk, C. 2010. A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. *Climate Dynamics* 37: 2417-2435.

Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M. and

Campbell, B. 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change* 28: 325-336.

Wisner, B., Blaikie, P., Cannon, T. and Davis, I. 2003. *At risk: natural hazards, people's vulnerability and disasters*. Routledge.

World Bank 2015. Review and Update of the World Bank's Safeguard Policies. Environmental and Social Framework (Proposed Second Draft) – Consultation Paper. July 1, 2015. World Bank, Washington D.C. Available: https://consultations.worldbank.org/consultation/review-and-update-world-bank-safeguard-policies

Wyatt, K. 2013. Escaping a Rising Tide: Sea Level Rise and Migration in Kiribati. Asia & the Pacific Policy Studies 1: 171–185.

Zhou, P. P., Simbindi, T., Ramokgotlwane, G., Thomas, T. S., Hachigonta, S. and Sibanda, L. M. 2013. Botswana. InHachigonta, S., Nelosn, G. C., Thomas, T. S. and Sibanda, L. M. (eds.) *Southern African Agriculture and Climate Change: A Comprehensive Analysis*. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 41-70.

Scan the code to read more on Vuna's work in East and Southern Africa.

Contact Us:

T: +27 12 342 3819

E: contact@vuna-africa.com

W: www.vuna-africa.com

Search for **Vuna Africa**