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Assessing the vulnerability of food crop systems in Africa to climate change

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Abstract Africa is thought to be the region most vulnerable to the impacts of climate variability and change. Agriculture plays a dominant role in supporting rural livelihoods and economic growth over most of Africa. Three aspects of the vulnerability of food crop systems to climate change in Africa are discussed: the assessment of the sensitivity of crops to variability in climate, the adaptive capacity of farmers, and the role of institutions in adapting to climate change. The magnitude of projected impacts of climate change on food crops in Africa varies widely among different studies. These differences arise from the variety of climate and crop models used, and the different techniques used to match the scale of climate model output to that needed by crop models. Most studies show a negative impact of climate change on crop productivity in Africa. Farmers have proved highly adaptable in the past to short- and long-term variations in climate and in their environment. Key to the ability of farmers to adapt to climate variability and change will be access to relevant knowledge and information. It is important that governments put in place institutional and macro-economic conditions that support and facilitate adaptation and resilience to climate change at local, national and transnational level.

1 Introduction

Agricultural systems are vulnerable to variability in climate, whether naturally-forced, or due to human activities. Vulnerability can be viewed as a function of the sensitivity of agriculture to changes in climate, the adaptive capacity of the system, and the degree of exposure to climate hazards (IPCC 2001b, p. 89). The productivity of food crops, from year to year for example, is inherently sensitive to variability in climate. Producers in many parts of the world have the physical, agricultural, economic and social resources to moderate, or adapt to, the impacts of climate variability on food production systems. However, in many parts of Africa this is not

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the case, making agricultural systems particularly vulnerable (Haile 2005). This is in part because a large fraction of Africa's crop production depends directly on rainfall. For example, 89% of cereals in sub-Saharan Africa are rainfed (Cooper 2004). In many parts of Africa, climate is already a key driver of food security (Gregory et al. 2005; Verdin et al. 2005).

Climate change due to greenhouse gas emissions is expected to increase temperature and alter precipitation patterns. All projections of climate change are subject to uncertainties arising from limitations in knowledge. Some of these limitations can be quantified: future greenhouse gas levels, for example, cannot be known with precision, but an understanding of socio-economics and atmospheric processes can be used to produce a range of plausible values. This quantification leads to prediction ranges: one study of southeast Africa, for example, projects annual rainfall changes of between −35 and +5% (IPCC 2001a, Fig 10-3). Climate change adds stress and uncertainty to crop production in Africa, where many regions are already vulnerable to climate variability. Crop production in such regions is therefore expected to become increasingly risky (Slingo et al. 2005).

Agriculture in the semi-arid regions of Africa is based on small-scale, climatically vulnerable systems where livestock is an important multi-purpose component of farming systems. Agriculture provides food, income, power, stability and resilience to rural livelihoods (Ruthenberg 1976; Chambers and Conway 1992; Mortimore 1998; Bird and Shepherd 2003). In the adjoining drier areas, food crop production is marginal or not viable due to insufficient length of moisture growing period, high rainfall variability and frequent occurrence of severe drought. Here, agropastoral systems, relying on natural rangelands for forage, dominate but are geographically, agriculturally, socio-culturally and economically linked to the mixed farming systems of the semi-arid regions (Sidahmed 1996; Mortimore 1998). During the times of severe drought stress and emergencies, coping mechanisms in the drier areas rely on the buffer provided by the relatively less vulnerable semi-arid regions. This 'safety net' relationship is not certain to remain intact in the face of climate change; indeed, it may be negatively affected over much of Africa. Further, economic development, increased urbanization and rapid population growth are likely to reduce per capita water availability throughout Africa and climate change is expected to exacerbate this situation, particularly in the seasonally dry areas (Cooper 2004; IPCC 2001b).

Climate change is expected to impact both crops and livestock systems (FAO 2003). This paper focuses principally on three aspects of food crop systems: the sensitivity of crops to climate; the adaptive capacity of farmers; and the role of institutions in adapting to climate change. We start by briefly reviewing the science of African climate change (Section 2). Then, we consider the sensitivity of crop productivity to climate change, and how it can be assessed using numerical climate and crop models (Section 3). The use of these different methods, and the methods that simulate the broader impacts on cropping systems, such as land use, are then discussed (Section 4). Section 5 considers the capacity of farmers to adapt to climate variability and change. Then, the capacity of research and government institutions to react to changes of climate on seasonal to decadal timescales is discussed (Section 6).

2 Climate change in Africa

There are many model-based projections of climate change across Africa. The range of the projected changes is considerable and arises because of the different input assumptions (namely greenhouse gas emission levels) and model physics (usually represented by the range of climate models and/or values of physical parameters used). Furthermore, projections vary geographically, with computer processing power limiting the spatial resolution of climate models. Hence there are inherent uncertainties associated with climate change predictions. The response of climate to greenhouse gas emissions is not equally uncertain across meteorological variables; temperature changes are usually more narrowly constrained than changes in precipitation, for instance. IPCC (2001a) provides more detail on all of these issues.

The results reported in IPCC (2001a,b) suggest temperature changes over the coming decades for Africa of between 0.2 and 0.5°C per decade, with the greatest warming in interior regions. The sign of changes in mean precipitation in many parts of Africa varies across climate models. Of three macro-regions of sub-Saharan Africa (West, East and Southern) reviewed in IPCC (2001b) only one shows consistent temperature and precipitation projections across climate models (the West region shows consistent changes for Dec.–Jan.; the Southern for June–Aug.; see also Washington et al. 2004). More recent studies also show conflicting evidence: for example, Held et al. (2005) show a drier Sahel in the late 21st century, whilst Kamga et al. (2005) show a wetter Sahel. These results reflect the uncertainty described above. The magnitude of projected rainfall changes for 2050 in IPCC (2001b) is small in most African areas, but can be up to 20% of 1961–1990 baseline values. The climate models used by Huntingford et al. (2005) also suggest that changes in mean monthly precipitation (in the African region 5−15°N) may be small. However the results also show an increase in the occurrence of extreme values in both rainfall (wet/dry years) and temperature. These changes, which are likely to be more robust than changes in mean rainfall (Coppola and Giorgi 2005), could have serious repercussions on crop production. Indeed, extreme events have long been recognised as being a key aspect of climate change and its impacts (IPCC 2001a). In a review, Dore (2005) found increasing variance in recent observations of precipitation across the tropics, suggesting the emergent importance of extremes in many regions.

It is changes on the spatial scale of cropping systems (i.e. the field) that are likely to have the greatest impact on crop production. Climate model output does not provide information on this scale. In the long term, ongoing increases in computer power, and hence climate model resolution, may provide information much nearer to this scale. Meanwhile, regional climate modelling (see e.g. Song et al. 2004) provides a tool for downscaling information in a physically consistent way (Wilby and Wigley 1997). For example, using a regional climate model, Arnell et al. (2003) produced high resolution rainfall and runoff scenarios for southern Africa for the 2080s. They found both positive and negative changes in average annual rainfall of up to 40%, though most places showed smaller changes. The changes were of similar magnitude to those in the large-scale climate simulations used to drive the regional climate model.

The importance of spatial scale results not only from the need for high resolution information for sectors such as agriculture. The resolution of climate models has an impact on the skill of the simulations in reproducing observed climate (e.g. Inness et al. 2001). Processes that occur at the sub-grid scale, such as convection, must be parameterised and this can lead to significant errors (e.g. Lebel et al. 2000; Huntingford et al. 2005). Spatial scale, extreme events, model error, and uncertainty are key issues arising from the use of climate change projections with impacts assessments. These issues are revisited over the next two sections.

3 Predicting the sensitivity of crop productivity to climate

The sensitivity of crops to climate change can be investigated through plant experiments that quantify the direct effects of elevated concentrations of atmospheric CO_2 and ozone (e.g. Long et al. 2005) and changes in climate that can result from greenhouse gas emissions, such as: warmer mean temperatures (Roberts and Summerfield 1987) and levels of temperature and water stress (Wheeler et al. 2000; Wright et al. 1991). A doubling of CO_2, for example, increases the yield of many crops by about one third (Kimball 1983; Poorter 1993), primarily as a result of higher rates of photosynthesis in crops that have the C3 photosynthetic pathway (Bowes 1991). The rate of photorespiration is reduced at elevated CO_2 (Drake et al. 1997), and because photorespiration increases with warmer temperatures, any increase in net photosynthesis due to elevated CO_2 is expected to be greatest at warmer temperatures (Long 1991).

The results of plant experiments are used to inform crop modelling. Process-based crop simulation models attempt to provide the equations that describe plant physiology and crop responses to weather and climate. These responses are affected by genotype, environment and farm management practices. A number of broad types of crop simulation models have developed: for example, SUCROS and related models (Bouman et al. 1996), the IBSNAT models (Uehara and Tsuji 1993), and the APSIM model (McCown et al. 1996). All such models allow prediction of crop performance ahead of time, and provide a commonly used tool to simulate how climate (and other factors) will affect crops on seasonal timescales.

It is impossible to directly demonstrate predictability in crop yield in potential future climates on decadal timescales. Nevertheless, the basis for prediction is supported by a number of research efforts:

– Building understanding of fundamental bio-physical processes (e.g. Porter and Semenov 2005).
– Simulation of the processes that are likely to be important under climate change (e.g. Challinor et al. 2006).
– Demonstration of robust relationships between crops and climate using observations (e.g. Camberlin and Diop 1999; Challinor et al. 2003).
– Skilful seasonal prediction by crop models using observed weather data (e.g. Challinor et al. 2004) and reanalysis (Challinor et al. 2005a).
– Operational seasonal forecast systems (Stone and Meinke 2005).

Research effort in crop modelling has focused on the world's major food crops. A consequence of this is that the simulation of some crops and crop varieties common to African farming systems, such as sorghum, millets, banana and yam, is less well developed. The simulation of annual and/or perennial crops grown as intercrops across Africa is also poorly represented; a surprising situation given the vast areas of formal and informal intercropping found across the region.

Climate models typically operate on spatial scales much larger than those of crop models (Hansen and Jones 2000; Challinor et al. 2003; Baron et al. 2005). To overcome this, climate data can be downscaled to the scale of a crop model (e.g., Wilby et al. 1998), or a crop model can be matched to the scale of climate model output (e.g., Challinor et al. 2004). Downscaling of climate output can be done empirically, relying on observed relationships between local climate and large-scale flow. However, these relationships may be violated in future climates (Jenkins and Lowe 2003). Downscaling using a dynamical model provides a more robust method because most of the uncertainty in the climate model is in the large-scale flow. The uncertainty in dynamical downscaling is therefore relatively small (Jenkins and Lowe 2003). Nevertheless, differences between yields simulated with a climate model and those simulated with dynamically downscaled output can still be significant (Mearns et al. 2001; Shin et al. 2006).

High resolution modelling of climate is becoming increasingly feasible as computer power increases (e.g. http://www.earthsimulator.org.uk/index.php). Since even these resolutions are far larger than the scale of traditional crop models, the move towards higher resolution can only aid comparatively large-area crop modelling efforts. The spatial scale of a crop model is related to its complexity; a crop model should be sufficiently complex to capture the response of the crop to the environment whilst minimising the number of parameters that cannot be estimated directly from data (Katz 2002; Sinclair and Seligman 2000). The larger the number of unconstrained parameters the greater the risk of reproducing observed yields without correctly representing the processes involved. Such over-tuning decreases the credibility of the model when it is run with climate change data. Efforts to predict crop productivity using large-scale data inevitably involves some simplification in model input data and/or the way in which crop growth is simulated. This can also reduce the risk of over-tuning.

It is important for studies of climate change to capture the impacts of short-term climate variability on crops. Statistical relationships for the current climate (e.g. Doorenbos and Kassam 1979) will probably cease to hold outside the present range of crop growth and climatic variations as CO_2 concentration rises and patterns of temperature and intra-seasonal precipitation change. Extreme events such as floods, droughts and high temperature episodes may become more frequent in parts of Africa, and this could have large impacts on crop productivity (Wheeler et al. 2000; Porter and Semenov 2005). The importance of climate extremes lead Easterling et al. (1996) to argue that in order to simulate yields under future climates, crop models should first be assessed on their ability to simulate the impact of extreme events. Whilst this is important, the ability of models to simulate the impacts of unprecedented changes in mean climate is clearly important also. However, extreme events can act as an indicator in another sense: the ability of society to deal with extremes of climate, and climate variability in general, can be used to assess vulnerability to climate change (Kates 2000).

Climate models are not always able to accurately simulate current climates. It has even been argued that there is insufficient skill for output from these models to be used in climate change impacts assessments without prior bias correction (Semenov and Barrow 1997). Climate models are particularly prone to errors in rainfall, so that in impacts studies it is sometimes excluded altogether (Mall et al. 2004) or modified prior to use (Žalud and Dubrovsky 2002). If confidence in the daily time series of weather from a climate model is low, the statistics of that time series (possibly differenced with the statistics of a current climate simulation) can be used in conjunction with a weather generator to create a new time series (Semenov and Barrow 1997). This method is often incorporated into statistical downscaling methods, but again relies on current observed relationships to derive future weather. The choice of parameters for a weather generator can alter the magnitude and even the sign of changes in crop yield (Mavromatis and Jones 1998). As an alternative, flux correction can be used with a coupled climate model (Mavromatis and Jones 1999), thus correcting errors (at least in current climates) much closer to the source.

Even on seasonal lead times, climate models are prone to error; seasonal predictions from single climate model ensembles often fail to capture the full range of uncertainty inherent in the initial conditions of the model. Hence, climate models can underestimate uncertainty even on a seasonal timescale. Using a multi-model approach can improve reliability (Palmer et al. 2005). Different climate models can also produce differences in the magnitude and sign of crop yield estimates (Tubiello et al. 2002). Therefore, the use of multi-model ensembles also allows crop modelling studies to sample more fully the variability in climate model output (Challinor et al. 2005b).

4 Assessing the impacts of climate change on cropping systems

The discussion above has focussed on the simulation of crop yield. We now move on to discuss the use of these methods in impacts assessments. It is not only yield impacts that are important here, but also the methods used to simulate and understand changes in land use, adaptive measures, and market mechanisms.

Examples of crop yield impacts assessments for Africa are shown in Table 1. These illustrate the diversity of yield scenarios that have been produced. Whilst the magnitude of the response of crop yield to climate change varies considerably, the sign of the change is mostly negative. However, direct comparison among these studies is difficult. They encompass a range of different regions and crops, and the uncertainty ranges can come from a number of different sources (spatial variability in yield, uncertainty in climate/emissions information, different crop simulation methods). Hence yield impact studies sample uncertainty randomly and the estimates of uncertainty are not precise. Furthermore, whilst there is a consensus that crop yields in many parts of Africa will decrease (both in Table 1, and more broadly: IPCC 2001b), this consensus is not objectively determined. Multi-model ensembles (see Section 3) and model parameter perturbation methods (see Challinor et al. 2005c) enable a move towards a more complete sampling of uncertainty in crop yields.

The type of crop model used in assessments of the impact of climate change should be considered when interpreting the yield projections such as those in Table 1. Integrated assessments (e.g. Fischer et al. 2002, 2005; Parry et al. 2004; Rosegrant and Cline 2003) often use empirical approaches to simulate crop response to water deficits, such as the FAO method (Doorenbos and Kassam 1979), or yield transfer functions (e.g. Iglesias et al. 2000). The FAO method is relatively robust as it is based on a proven conservative relationship between biomass and water use for well-watered and water deficit conditions (see Hsiao and Bradford (1983) and Hsiao (1993) for

Table 1 A selection of studies of the impact of climate change on crop yield in Africa

Region	Crops	Crop response tool	Yield impact (%)	Comments	Reference
Egypt	Wheat rice maize	Not specified	−51 to −5 −25 to −3 −15 to −8	Range from two doubled CO_2 equilibrium scenarios and one transient run.	Yates and Strzepek (1998)
Africa	cereals	FAO method with monthly data	See comments	For 29 countries: −35 M tons of potential cereal production. For 17 countries: +30M tons.	Fischer et al. (2001)
Zimbabwe	maize	CERES crop model	−14 ; −12	Two doubled CO_2 climate scenarios	Smith et al. (1996)
Zimbabwe	maize	CERES crop model	−17	HadCM2 2040–2069 downscaled to 10 min of arc by interpolation.	Jones and Thornton (2003)
Africa	maize millet	Various methods	−98 to +16 −79 to −14	Range is across sites and climate scenarios.	Reilly and Schimmelpfennig: (1999)
Africa	cereals	Yield transfer functions	−10 to +3	Range is across sites and climate scenarios. Includes adaptation.	Parry et al. (1999)
Africa	maize	Yield transfer functions	'falls by as much as 30%'	Similar methodology to Parry et al. (1999)	Parry et al. (2004)

See also IPCC (2001b, Table 5–4).

more recent examples), and the crop specific relationships are normalized across environments. Yield transfer functions are usually derived from crop model output, since this is more easily produced than crop yield observations. However, significant differences can exist between a transfer function and the crop model from which it is derived (Challinor et al. 2006). In general, whilst empirical approaches tend to use a level of complexity that is appropriate to large scales, they use monthly data and therefore do not simulate the impact of changes in intra-seasonal rainfall or temperature variability. Rather, they assume a degree of stationarity in derived crop-weather relationships which, as with the empirical relationships used in weather generators, may not hold as environmental conditions change.

Some climate change studies consider only changes in crop yield for a given number of emissions scenarios. Increased realism and relevance can come from addressing issues such as: how yield may differ as a result of adaptive measures; how production levels might change as the area under cultivation changes and what impact such a change in crop productivity may have on livelihoods. Integrated assessments seek to combine crop yield scenarios with socio-economic scenarios that account for some or all of these factors in order to estimate the societal impact of climate change. Fischer et al. (2002) used four climate models in order to estimate potential changes in both world market prices of crops and GDP for 2080. Market prices showed systematic bias according to climate model. For example, the NCAR model simulated a 10% fall in prices due to climate change for both A2 and B2 emission scenarios, but an increase in prices was found with HadCM3. Thus, firm conclusions are difficult to draw. Nevertheless, GDP in Africa was projected to be lower under climate change than in the relevant reference scenario in 10 out of the 11 simulations.

Incremental use of adaptive measures across a range of timescales is likely to determine the response of food production to climate change. From the adoption of new cultivars, and crop and resource management strategies to changes in the infrastructure supporting irrigation, these timescales vary from a few years up to tens of years (e.g. Reilly and Schimmelpfennig 1999). Some adaptive measures, such as a change in planting date, can be incorporated relatively easily into impacts assessments (e.g. Southworth et al. 2002). Regional-scale measures such as those relating to the development of new cultivars (e.g. Rosegrant and Cline 2003) or irrigation infrastructure can be included (Parry et al. 2004), but are harder to parameterise in a well-constrained fashion in the absence of any meaningful assumptions about the accompanying crop management practices. Such studies will therefore have a high degree of associated uncertainty.

Another adaptive measure is expansion into newly created cropland. The biophysical suitability of land for crop cultivation is a function of climate and soil, and efforts have been made to model this relationship (e.g. FAO 1978–1981; Ramankutty et al. 2002). Whether the increasing demand for food due to population rise will be met primarily by extensification or intensification depends both on this suitability and on the yield attainable from the land (Gregory and Ingram 2000) as well as on the growth of national economies and of income-driven effective demand for food. Trends since the 1980s show both yields and cultivated area rising (Cockcroft 2001). However, yields in Africa remain amongst the lowest in the world: in sub-Saharan regions, for example, mean rainfed cereal yields are 0.8 tons/ha, which is 0.4 tons/ha below the lowest figure for any other region (Cooper 2004). During the past 50 years, some 60% of the growth in cereal output in Africa has been from area expansion and 40% from yield increase. Given the three-fold expected increase in population by the end of this century (United Nations 1999), Africa cannot afford to be complacent about addressing the growing challenge of food security and sustainability as land use expansion and intensification accelerate against the background of increasing vulnerability to climate change.

5 The adaptive capacity of farmers

In the socio-economics literature on rural livelihoods, it is widely accepted that farming households face three main sources of vulnerability (Ellis 2000): shocks (unexpected extreme events, for example the sudden death of a family member, or an extreme weather event), seasonal variations (including variations in periodicity and amount of rainfall) and long term trends (such as increases in input prices, or long term changes in mean temperature and rainfall). The discussion in Sections 2 to 4 suggests that problems from all three are likely to increase in intensity, particularly for farmers relying on rain-fed production.

Small-scale farming provides most of the food production in Africa, as well as employment for 70% of working people. These small-scale producers already face the challenges of climate variability in current climates. For example, intra-seasonal distribution of rainfall affects the timing and duration of the possible cropping season, and periods of drought stress during crop growth. Cropping practices that are often used to mitigate the effects of variable rainfall include:

– Planting mixtures of crops and cultivars adapted to different conditions as formal or informal intercrops.
– Using crop landraces that are more resistant to climate stresses.
– Using crop trash as a mulch.
– Planting starvation-reserve crops.
– A variety of low-cost water-saving measures.

Such coping responses at the farm-level can become insufficient when droughts are more widespread and severe, particularly when consecutive drought years lead to loss of seed stocks and biodiversity and/or draught animals, or are combined with low capital reserves for coping and with other economic or social stresses to the food system. Thus, farmers can cope up to a certain limit and their livelihoods can maintain a measure of resilience to shocks, but not indefinitely. Once their capital assets (e.g. savings, seed stocks, draught animals, social capital) erode away beyond a certain threshold level, they are forced to succumb in the absence of any effective local or national level support mechanism such as for replenishing seed stocks or draught power or non-farm employment. Such was the situation that occurred in the last Zimbabwe drought (Bird and Shepherd 2003).

Extreme climatic events such as drought, as well as major biotic problems, may have a major impact on the availability of, and access to, seed. Strengthening formal and informal seed systems is an important adaptive strategy. In general, the formal seed system does not always function well in Africa and the vast majority of farmers use saved seed or seed from other farmers for planting. Local seed systems can be very resilient, continuing to function following severe climatic or other disasters (Sperling et al. 2004). Initiatives such as Direct Seed Distribution (DSD), or Seeds and Tools (S&T) have been a common and well publicised response to disasters (climatic or otherwise). However, a number of studies from East and Southern Africa suggest that it is only rarely that local seed stocks are completely depleted, and alternative strategies may be more appropriate (Sperling et al. 2004). Indeed, very often it is not seed per se that is the problem, but access to seed – access that is constrained by factors such as livelihood and interactions with local markets.

Building resilience of seed systems to climate change requires several strands:

(1) Seed of most crops grown by African farmers is not, and is unlikely ever to be, commercially produced. Therefore, government has a responsibility to maintain breeder/foundation seed, and ensure quality control over seed production.

(2) Governments need to decentralise the seed system, both seed release and production, and strengthen local seed systems (Tripp 2001). NGOs, local entrepreneurs and seed dealers can and do successfully produce seed. Participatory seed release and promotion approaches (Witcombe et al. 2005) are useful in this regard.
(3) Outdated seed laws should be removed to allow cross-border movement of seed, and to strengthen local systems by allowing 'truthfully labelled seed' (Tripp 2001).
(4) Strategic seed stocks need to be maintained locally and regionally against disaster. Strengthening local seed systems can contribute to this and ensure that seed can be procured locally rather than from outside commercial sources.
(5) Where seed has to be supplied following a disaster, then the Seed Voucher and Fair (SV&F) system, which supports the functioning of local seed systems, may be more appropriate than DSD.

A major question is whether the resilience of farmers to climate variability will alter in a changing climate. Farmers face the challenge of managing water supplies more efficiently and effectively (Cooper 2004). Participatory research between scientists and farmers has shown some local successes in developing more efficient rainwater harvesting techniques but a more concerted effort by scientists to work closely with farmers is called for (Ellis-Jones and Tengberg 2000). Farmers report that among the benefits of improved fallows using agroforestry species are an increase in water infiltration, reduced run-off (and hence erosion) and an increase in the water holding capacity of soils (Kwesiga et al. 2005). In contrast, staple crops may prove no longer viable in some areas, for example maize in the drier reaches of its current production zone, and groundnuts in the dryer parts of the Sahel (Dietz et al. 2004).

Farming and food systems in sub-Saharan Africa have proved highly adaptable in the past, both to short term variations and longer term changes in the physical, climatic and socio-economic environment. Boserup (1965) was one of the first to point to the dynamism of farming systems as rural societies in Africa and elsewhere respond to changes in population density, while anthropologists documented the changes in land tenure and other institutions as the planting of new cash crops expanded to meet trading opportunities in the nineteenth century (Hill 1963). The fact that most staple food crops in sub-Saharan Africa have their origins on other continents is a testament to the adaptability of farmers and farming systems to respond to new opportunities created by the movement of knowledge and genetic material along trade routes.

More recently, many local studies have shown how farmers have developed innovative responses to difficult or changing environmental conditions and introduced technological and management changes to create more sustainable and resilient production systems (Reij and Waters-Bayer 2001), even in the relatively marginal environments that characterise much of the farming landscape in African countries (Haggleblade et al. 1989; Tiffen et al. 1994). However, extreme events of a transnational nature such as the severe drought years in the 1970s and 1980s in Sub-Saharan Africa, and more recently in Southern Africa, have shown that the adaptation abilities of many individual farmers and communities do not extend to coping with such extreme events in absence of outside support. Similarly, national and local vulnerability to floods due to extreme climate events was demonstrated in Mozambique not so long ago (NEF 2005). In the light of the above, it is clear that resilience to risks associated with climatic variability and extreme events depends on adaptation and coping strategies at local, sub-national and national, and transnational level. Adaptive capacity varies considerably among regions, countries and socioeconomic groups because the ability to adapt and cope with climate change is a function of governance and national security strategies, wealth and economic development, technology, information, skills, infrastructure, institutions, and equity (IPCC 2001b; Sen 2000).

On a national scale, food systems have been undergoing rapid change as a result of urbanization and the liberalising trade agenda. Imports of 'cheaper' food (e.g. rice and poultry in Ghana: Koomson 2005) to feed the growing urban populations are putting pressure on local production and distribution systems which cannot compete on price. At the same time, Africa continues to require a large quantity of food aid to meet the food needs of people suffering from climate related stress such as drought or floods or locusts. On the one hand, this demonstrates that national food security does not necessarily depend on domestic production: one impact of climate change may well be changes in patterns of trade, with countries whose agriculture is negatively affected relying more on the international market for purchase of food. On the other hand, a downturn in prices due to liberalisation of markets makes it even harder for farmers who are already trying to cope with climate variability and change to maintain their farms and their livelihoods.

At a basic level, for many farmers the challenge will be whether they can continue to farm. Already rural livelihoods at household level are highly diverse, with farming accounting for a lower proportion of disposable income and food security for farming households than 20 years ago. For example, Bryceson (2000) concludes that "diversification out of agriculture has become the norm among African rural populations." There is evidence that households moving out of poverty are those moving either completely or partially out of farming (Ellis and Bahiigwa 2002; Bryceson 2000). It is likely that many households will respond to the challenge of climate change by seeking further to diversify into non-farm livelihood activities either in situ or by moving (or sending more family members) to urban centres. For these households, farming may remain as (or revert to) a semi-subsistence activity while cash is generated elsewhere. This would be simply a continuation of a well-established trend towards pluriactive, multi-locational families and the transfer of resources through urban–rural remittances (Manvell 2005). However, given the acute population and development related challenges faced by most African nations, many households will be forced to remain in the farming sector for livelihood and security for some time to come as the population in Africa undergoes a three-fold increase this century. This will lead to considerable demand for expansion of area under small-farm cultivation for staple crops. Farming for profit, particularly production for international markets, may therefore become more concentrated on fewer farms, as is already happening in the fresh vegetable export market from eastern and southern Africa. Companies with the capital to invest in controlling their production environment through irrigation, netting and crop protection in order to meet stringent quality and bio-safety requirements of European supermarkets are increasing their market share at the expense of smallholders (Dolan and Humphreys 2000; Gregory et al. 2005). This should lead to further irrigation development, and contribute to a recommended doubling of irrigated land by 2015 (Commission for Africa 2005).

Fraser et al. (2003) proposed a theoretical framework for assessing whether societies or nations are well placed to adapt to climate change, building on the two concepts of social resilience and environmental sensitivity and suggest how that might be applied in a subsistence agriculture context. Community management of natural resources can enhance adaptability in two ways: "by building networks that are important for coping with extreme events and by retaining the resilience of the underpinning resources and ecological systems" (Tompkins and Adger 2004). The development of strategies to adapt to variability in the current climate may also build resilience to changes in a future climate (Slingo et al. 2005). It is important that those affected by risk of future events are involved in adaptive measures and that those measures are compatible with existing decision-making processes (Smit and Pilifosova 2001). Smit and Pilifosova (2001) also suggest that the determinants of adaptive capacity include not only the economic resources and technology to deal with change, but also information and skills, institutions, infrastructure and equity. This concurs with Dilley (2000) who concludes that communication of information could contribute to improved management of climate variability due to ENSO events in Africa.

So, a key ingredient in the ability of farmers to cope with or adapt to climate variability and change is their access to relevant knowledge and information that will allow them to modify their production systems. Some of this knowledge is already part of local knowledge systems, such as varying planting dates in response to seasonal variations in rainfall onset and intensity; some will come from outside the local system, such as new varieties more tolerant to drought or with shorter growing seasons. Current and prospective institutional changes in the way knowledge is created and information communicated offer grounds for cautious optimism that the availability of and access to appropriate knowledge will improve. Monolithic government extension services are giving way to pluralistic, locally responsive information systems where farmers have a stronger voice in determining priorities (Rivera and Alex 2004). Farmer Field Schools and other farmer-centred approaches to learning and communication are becoming more widespread and our understanding of how these processes work is improving (Percy 2005). National research systems are being restructured to increase the relevance of research and technology development, though questions remain over the level of funding that will be made available by national governments and external development partners (Byerlee and Echeverria 2002). Reij and Waters-Bayer (2001) demonstrate that farmer innovation can be facilitated and intensified through supportive policies and institutionalised in the working practices of research and advisory systems. A key issue, then, is whether governments can put in place or encourage institutional and macro-economic conditions that support and facilitate adaptation to a changing climate.

6 Capacity of institutions to adapt to climate change

Central to the effective management of national agricultural and rural development is the system of public institutions set up by governments, and the professionals that work in them. The institutions must have the right kinds of people and contribute to the formulation and execution of policy and institutional services for national development at three interlinked levels – central (national), intermediate (province and districts) and local.

Centrally, at the level of the nation, institutional capacity is required to produce strategic long-term national land use development and management plans to facilitate integrated policy decisions, legislation, administrative actions and budgeting, including emergency responses to provide a safety net and supply replenishments such as seeds. At the intermediate level in provinces and districts, institutional capacity is required to formulate more specific and detailed programmes based on the national strategies and programmes, and to enable and monitor their implementation at the local levels. The institutional capacity at the local levels must be able to provide the field services of different ministries and departments for the different sectors or commodities. Consequently, at all levels, geographically referenced databases of information and knowledge relating to climatic and other natural resources, land use and land potentials, continuously kept up-to-date, are essential for the formulation and execution of policy for sustainable development in agriculture and the rural sector. Few nations have such databases to meet current development needs of their populations. They become even more important for understanding and responding to national and local level vulnerability to climate change of economic activities, particularly agriculture and the water sector. A significant capacity building effort in support of policy and development management has been directed by FAO and its partners in this direction in recent years (e.g., Kassam et al. 1982, 1990; FAO 1993; Voortman et al. 1999; Fischer and van Velthuizen 1996), but much more is needed, including the incorporation of climate induced natural disasters and climate change implications for national and sub-national analyses and development planning.

Institutional capacity for climate risk management preparedness strategies and for agrometeorological adaptation strategies to cope with the consequences of climate change in Africa is poor, or non-existent in many African countries (WMO 2005). Remedying the situation will need sustained efforts to strengthen the agrometeorological capacity of national and regional meteorological services. Given the strategic dependence of livelihoods on natural resources in Africa, efforts will be required to implement effective and longer-term agrometeorological programmes to adapt production systems to climatic resources; to adequately monitor climatic variability and extreme events and in collaboration with other stakeholders to support the generation of other data such as cost-benefit assessments required to characterise their impact and formulate adaptation strategies. Multi-disciplinary institutional capacity is needed to develop national analytical frameworks to provide sound practical guidelines for longer-term investment in food security related infrastructure for disaster mitigation at national level and for evolving livelihood adaptation strategies and risk management at local level. Climate-related insurance (e.g. Sakurai and Reardon 1997; Skees et al. 2005) is one way of reducing exposure to risk at the local level.

Equally important is the institutional capacity to address questions of transnational concerns, particularly in the context of climate variability and change, such as:

(1) Which set of neighbouring countries in Africa may constitute a natural and logistical cooperative unit for trade, food and economic security and development of renewable resources and with whom longer-term strategic collaborative alliance could be fostered in a globalizing world?
(2) What kind of international investment and cooperation will be needed to promote a certain level of regional agricultural and rural development, to expand export markets within Africa, and to maximize complementarities between nations and between regions in meeting future development needs?

Given that the impact of climate change will be felt at transnational scales and along internationally shared water basins, policy challenges including those dealing with climate change can be expected to become more acute and complex in the future as more and more nations attempt to reconcile national priorities with transnational and global priorities and opportunities. Strategic storage capacity for food and water would need transnational attention.

For research and extension services, the complex social, economic and political implications of climate change are also of great importance, and multi-disciplinary thinking is key. One proposed development research framework for rural water management in the context of climate variability and change included: understanding vulnerability-livelihood interactions; establishing the legal, policy and institutional framework; and developing and testing a climate change adaptation strategy from a general framework from which specific goals and activities can be developed (Cooper 2004).

For the African research community, it is incumbent that a critical mass of disciplinary expertise in agroclimatology, hydrology, water management, climate, environmental physiology, agroecology, analytical agronomy, and systems development (including sociologists and anthropologists) is maintained to address livelihood related issues of crop, animal and system adaptability to climatic variability and climate change. Such a critical mass is not always present (see Washington et al. 2004), and co-ordinated international research programmes can have a role in addressing this gap (e.g. African Multi-disciplinary Monsoon Analysis; http://amma.mediasfrance.org/). Coping strategies in communities invariably are dynamic integrated systems in space and time, deploying elements ranging from the cellular and seeds to crop and livestock mixtures to storage systems to various livelihood assets to sociocultural boundaries in resource access and use and safety nets (Bunting and Kassam 1986; Harwood and Kassam 2003; Cernea and Kassam 2005). These community level coping strategies need to be complemented by national level support and crisis response capacity. Thus, understanding and researching coping strategies is a task that cannot simply be left in the hands of breeders, biotechnologists or conventional crop productionists and economists. Agroclimatologists and agroecologists in particular are noted by their absence in strategic and applied biological and agricultural research in national and international agencies in Africa. One approach to strengthening climate related research capacity would be to embed some of the strategic capacity in the regional research organizations (de Janvry and Kassam 2004) such as those in agriculture (e.g. CORAF, ASARECA, ARRINENA) and climate (see Washington et al. 2004, for a brief review of these institutions). This approach is particularly favourable given the importance of transnational implications of climate change to agriculture and water resource development.

7 Conclusions

The IPCC (2001b) describes Africa, the world's poorest region, as "the continent most vulnerable to the impacts of projected changes because poverty limits adaptation capabilities." Agriculture plays a dominant role in supporting rural livelihoods and economic growth over much of Africa, given the preponderance of the poor who are rural and are dependent for the most part on agriculture. With the expected unprecedented increase in population in Africa during this century, agriculture is currently seen by many development experts including economists and policy makers as a sector that can make a significant contribution to the alleviation and mitigation of poverty in the medium term alongside the growth in non-agricultural sectors (Hazel and Haddad 2001; Runge et al. 2003; Lipton 2005; Conway 1997; Cleaver 1997). Although this view is contested (Bryceson et al. 2000; Collier 2005) several countries in eastern and southern Africa have policies in place for the "modernization" or "revitalization" of agriculture as a central plank in poverty reduction strategies (Republic of Uganda 2000; Republic of Zambia 2002; Republic of Kenya 2004). Endorsement of such aspirations comes from the Commission for Africa (2005), IAC (2004), IFAD (2000) and IFPRI (Hazell and Haddad 2001) and also from the consortia of donors who are supporting these initiatives either through projects or budget support. These plans, particularly as they relate to poverty reduction, are predicated on the increasing integration of small-scale farmers into national and international markets, through increased productivity, quality and value-added. Climate change will make it more difficult for these national and individual aspirations to be realized.

Tools to quantify the impacts of climate change on agriculture are a key part of the assessment of impacts on poverty. Assessments of the sensitivity of crops to climate variability and change using numerical climate models and crop simulation models are becoming increasingly skilful. Matching the spatial and temporal scales of crop and climate models remains an important research issue, with no solution yet to the provision of seamless assessments of crop productivity impacts across the continuum from field to district, country and region. The importance of sampling the full range of uncertainties in crop and climate predictions is also recognised. Advances in the underpinning science may well reduce these uncertainties, but the need to work with, and communicate, the implications of uncertainties in impact predictions to a range of stakeholders will remain.

The high sensitivity of food crop systems in Africa to climate is exacerbated by additional constraints such as heavy disease burden, conflicts and political instability, debt burden and unfair international trade system. Good governance, political will and positive economic development are central to systems for the coping with climate stresses. Consequently, Africa is being considered to be a special case for climate change (IPCC 2001b) that according to major NGOs calls for a new test on every policy and project, in which the key question will be, “Are you increasing or decreasing people’s vulnerability to climate?” (NEF 2005). One way of achieving resilience is to build capability in seasonal forecasting (Washington et al. 2006). The human response to seasonal forecasts can be simulated, allowing estimates of their impact at the village-level, and so increasing understanding of climate change adaptation strategies (e.g. Bharwani et al. 2005). Whatever the time scale considered, observation networks in both weather and agriculture (crop yield, planted area) are vital to the development and assessment of forecasting systems (Verdin et al. 2005; Haile 2005; Washington et al. 2004).

Increased support for small-scale agriculture and securing livelihoods at the local, household and community level, including strengthening adaptive strategies and resilience, requires complementary national level policy and institutional development to: identify climatic risks and vulnerabilities; and prepare for, and mitigate disasters at both community and national level (Haile 2005; Washington et al. 2004). This should include community-based disaster management planning by local authorities, including training activities and raising public awareness.

There is evidence that farmers and farming systems can respond creatively and adaptively to environmental change (Section 5). Given that the first priority of any African farmer is to secure material and economic survival, adapting to climatic risks would be an instinctive livelihood response. As agriculture will remain an important economic activity at the local and national level for some time to come, it is important that governments put in place institutional and macro-economic conditions that support and facilitate adaptation. At the very least, in line with the recommendation of the Commission for Africa, climate change should be ‘mainstreamed’ within development policies, planning and activities by 2008. Given the current weakness in the institutional capacity of most African nations, this is indeed a tall order that will demand committed international support.

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