Climate change and poverty in Africa: Mapping hotspots of vulnerability

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Abstract

Climate change and increasing climate variability threaten the attainment of the Millennium Development Goals (MDG), and some of the worst effects on human health and agriculture will be in sub-Saharan Africa, particularly in vulnerable regions. The relationships between climate change and the vulnerability of resource-poor croppers and livestock keepers and their resilience to current and future climate variability need to be better understood. This paper describes the generation of information that combines projected climate change in agricultural systems with vulnerability data. The results of the analysis, in terms of vulnerable people particularly at risk for deleterious effects of climate change, are being used for impact assessment, targeting and priority setting, to help identify locations for specific research and adaptation activities. Given the heterogeneity in households' access to resources, poverty levels and ability to cope, vulnerability assessments need to be done at the sub-national level to help improve the adaptive capacity and coping strategies of highly vulnerable households.

Keywords: Agricultural system; Vulnerability; Targeting; Impact assessment; Poverty

Résumé

Le changement climatique et la variabilité toujours croissante du climat menacent la réalisation des Objectifs du Millénaire pour le Développement (OMD), et certains des impacts les plus graves sur la santé humaine et l'agriculture se produiront en Afrique subsaharienne, tout particulièrement dans les régions vulnérables. Il nous faut mieux

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comprendre la relation entre le changement climatique et et la vulnérabilité des cultivateurs et des gardiens de bétail ayant de faibles ressources, ainsi que leur résilience vis-à-vis de la variabilité climatique actuelle et future. Cet article met en lumière la génération d'information regroupant des projections en matière de changement climatique dans les systèmes agricoles et les données traitant de la vulnérabilité. Les résultats de l'analyse, en termes de population vulnérable particulièrement exposée au risque des effets délétères du changement climatique sont utilisés pour l'évaluation de l'impact, la mise au point du ciblage et des priorités ; ceci afin de faciliter l'identification de lieux propices à la recherche spécifique et aux activités d'adaptation. Étant donné l'hétérogénéité de l'accès aux ressources des ménages, les niveaux de pauvreté et la capacité de chacun à se débrouiller, les évaluations de la vulnérabilité doivent être effectuées à un niveau sous national pour permettre l'amélioration de la capacité d'adaptation des ménages plus vulnérables.

Mots clés : *Système agricole ; Vulnérabilité ; Ciblage ; Evaluation de l'impact ; Pauvreté*

1. Introduction

The world's climate is continuing to change at rates that are projected to be unprecedented in recent human history. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) indicated that the global average surface temperature increased by about 0.6°C during the 20th century. The recent Fourth Assessment Report (IPCC, 2007) states that 'most of the observed increase in the globally averaged temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations'. The IPCC climate model projections from 2001 suggest an increase in global average surface temperature of between 1.4 and 5.8°C from the present to 2100, the range depending largely on the scale of fossil-fuel burning between now and then and on the different models used. Recent modeling work indicates that the temperature increases by 2100 may be larger than those estimated in 2001 (Stainforth et al., 2005).

The impacts of climate change are likely to be highly spatially variable. At mid- to high latitudes, crop productivity may increase slightly for local mean temperature increases of up to 1–3°C, depending on the crop, while at lower latitudes crop productivity is projected to decrease for even relatively small local temperature increases (1–2°C) (IPCC, 2007). In the tropics and subtropics in general, crop yields may fall by 10–20% by 2050 because of warming and drying, but there are places where yield losses may be much more severe (Jones & Thornton, 2003). At the same time, developing countries are generally considered more vulnerable to the effects of climate change than more developed countries – this is largely attributed to a low capacity to adapt in the developing world (Thomas & Twyman, 2005). Of the developing countries, many in Africa are seen as being the most vulnerable to climate variability and change (Slingo et al., 2005). The challenges for development are already considerable, and climate change is likely to add substantially to these.

Of the planet's 1.3 billion poor people, nearly 300 million are located in sub-Saharan Africa. About 60% of these depend on livestock for some part of their livelihood (Thornton et al., 2002; Thomas & Rangnekar, 2004). Climate change is likely to have major impacts on poor livestock keepers and on the ecosystems goods and services on which they depend. These impacts will include changes in the productivity of rainfed crops and forage, reduced water availability and more widespread water shortages, and changing severity and distribution of significant crop, livestock and human diseases. As a result, major changes can be anticipated in livestock systems, related to livestock species mixes, crops grown, and feed resources and feeding strategies. These changes will occur over the same period during which Africa's

population is projected to grow from 0.9 billion people in 2005 to nearly 2 billion by 2050 (UNPD, 2007). In addition, the demand for livestock products is rising globally and will increase significantly in the coming decades (Delgado et al., 1999) because of income shifts, population growth, urbanization and changes in dietary preferences. While the increased demand will probably be met mostly by increases in chicken and pig production, ruminant populations are also likely to increase substantially, particularly in Africa. Increased demand for livestock products will undoubtedly present opportunities for livestock keepers to intensify production systems (Staal et al., 2001). However, it is clear that many livestock keepers in Africa are facing a highly volatile situation characterized by rapid change.

Yet despite the critical importance of livestock to poor people and the magnitude of the changes likely, the intersection of climate change, crop production and livestock keeping is a neglected area of research. Little is known about how climate interacts with other drivers of change in agricultural systems and broader development trends. The likely impacts of climate change on the vulnerability of resource-poor croppers and livestock keepers need to be better understood, so that resilience to current climate variability as well as to the risks associated with longer-term climate change can be gauged, and appropriate actions taken to increase or restore resilience where it is threatened. Given the dynamics and complexity of the systems involved, it is clear that in general our understanding of possible local impacts is not yet at a level where we can address them appropriately. One activity that is a prerequisite for increased understanding of local impacts is targeting, to help identify locations for specific research and adaptation activities. In this paper, we outline the first stage of a multi-step targeting process. This involved a broad-brush analysis at continental level to identify areas or 'hotspots' that are already vulnerable and likely to suffer substantial impacts as a result of climate change. We outline this work (which was written up in detail in Thornton et al., 2006a), and the major results. After discussing the limitations of the analysis and how these might be addressed through future work, we conclude by outlining the ways this type of analysis can be used, some policy implications of the results, and the higher-resolution analyses that are needed to refine this targeting work.

2. A continental-scale assessment of vulnerability to climate change

Work was undertaken during late 2005 and early 2006 at the behest of the UK's Department for International Development (DFID), to attempt some vulnerability mapping for sub-Saharan Africa at a sub-national level that could be used to help guide the DFID's research resource allocation decisions as to which activities should be concentrated where. This work was one piece of a larger set of studies commissioned by the DFID on climate change and appropriate research for development, such as Washington et al. (2004) and Huq & Reid (2005), that helped to clarify critical researchable issues and capacity-building needs and opportunities. The mapping work, by contrast, was designed to throw light on where geographically in sub-Saharan Africa research resources might be concentrated to effectively address the issues of the poor and vulnerable in the face of inevitable climate change.

There are many different notions of what vulnerability is, and how it is related to risk and adaptive capacity (see the reviews by Adger et al., 2004, and Vincent, 2004). O'Brien et al. (2004) summarize two interpretations of vulnerability in the climate change literature. The first, the 'end point' approach, views vulnerability as a residual of climate change impacts minus adaptation. The second, the 'starting point' approach, views it as a general characteristic generated by multiple factors and processes. Viewing vulnerability as an end point considers that adaptations and adaptive capacity determine vulnerability, whereas viewing it as a starting point holds that it determines adaptive capacity. Here we took a 'starting point' approach, viewing vulnerability to climate change as a state that is governed

not just by climate change but by multiple processes and stressors. This involves dealing with two types of vulnerability: biophysical vulnerability – the sensitivity of the natural environment to exposure to a hazard, and social vulnerability – the sensitivity of the human environment to the exposure. An impact is thus a function of hazard exposure and both types of vulnerability.

2.1 Stage 1: Hotspots of climate hazard

The first stage of the analysis was to identify those areas of sub-Saharan Africa that appear to be particularly at risk from climate change in the coming 50 years, i.e. to identify geographic areas where changes in temperatures and rainfall amounts and patterns etc. may be relatively large. This was done by downscaling the outputs from various Global Circulation Models (GCMs) and various scenarios of the future. Length of growing period (LGP) was chosen as a proxy for agricultural impacts as it is crop-independent and a useful integrator of changes in rainfall amounts and patterns and temperatures. We estimated changes in the length of growing season from current conditions to 2020 and 2050 and used these changes as indicators of climate hazard for subsequent analysis.

For looking at various scenarios of climate change to 2050, the dataset TYN SC 2.0 was used (Mitchell et al., 2004). These monthly data cover the global land surface at a resolution of 0.5 degrees latitude and longitude for the period 2001 to 2100. There are 20 climate change scenarios in the complete dataset, made up of permutations of five GCMs and four scenarios that cover a wide range of economic development, fossil fuel and population growth possibilities (the special report on emissions scenarios (SRES) – IPCC, 2000). To cut down on the number of GCM-by-scenario combinations, we chose two GCMs with some ability to simulate observed rainfall patterns for Africa (Liu et al., 2003; McHugh, 2005), on the basis that this would improve confidence in the ability of these GCMs to project future conditions under different scenarios of change, all other things being equal. The GCMs selected were HadCM3, the UK Hadley Centre Coupled Model version 3 (Mitchell et al., 1998) and ECHam4, the European Centre Hamburg Model version 4 (Roeckner et al., 1996). The rainfall differences projected to 2050 by ECHam4 are relatively large, compared with those projected by HadCM3, so these two GCMs provide a useful contrast. To reduce the number of scenarios in the analysis, we chose scenarios A1F1 and B1, on the basis that these two cover most of the range of projected temperature increases to 2050 (IPCC, 2001). The 'A' scenarios emphasize economic growth, the 'B' scenarios environmental protection. The '1' scenarios assume more globalization, the '2' scenarios more regionalization (IPCC, 2000). The 'F' scenario is a relatively fossil-fuel-intensive scenario.

The GCM output data were downscaled to a 10-arc-minute (about 18 km) grid using WorldCLIM, a global gridded dataset of climate normals for the period 1960–1990 (Hijmans et al., 2005) and methods based on MarkSim, a statistical weather generator (details of the algorithms can be found in Jones & Gladkov, 2001, and Jones & Thornton, 2000). Lengths of growing periods were calculated using methods in Jones (1987) for current and future conditions. These results were combined with an agricultural systems classification, on the basis that land-use options define at least part of the livelihood strategies for millions of rural people who depend at least to some extent on natural resources for their well-being. The Seré & Steinfeld (1996) system classification is livestock based, and to expand the classification to include other important communities whose livelihoods are not dependent on livestock we used the FAO farming systems classification outlined in Dixon & Gulliver (2001), which itself is based on a principal livelihoods approach and has been used to assess general trends in the poverty levels associated with each system in the coming decades. The classification

itself is based on FAO data and expert knowledge, and it is probably not entirely 'mappable' from driver variables in global- or continental-level datasets.

We created an extended systems classification by overlaying version 3 of the Seré & Steinfeld classification (Kruska et al., 2003; Kruska, 2006) with the FAO classification, and from those areas that were classified as 'other' (i.e. non-livestock systems), we used five other systems from the FAO typology. The agricultural systems used are shown in Table 1, together with the source of the typology and references to the mapping methods used (it should be noted that the root-based systems make up part of the 'other' category). As might be expected, given the very different ways the two classifications were derived, there are some mismatches between them, in terms of areas that are classified inconsistently. Thus, for example, the coastal artisanal fishing system has goats and poultry (Dixon & Gulliver, 2001), although in our mapping of the Seré & Steinfeld system, these are classified as systems with no livestock. Overall, however, given the continental scale of these datasets, the matching between the two systems was found to be fairly consistent, and adequate for our purposes here.

We then overlaid the LGP changes on the agricultural systems map, to identify those systems most at risk from both positive and negative (but mostly negative) changes in LGP. An example of the output is shown in Figure 1, which maps the areas of Africa that are classified as LGA and MRA systems (rangeland-based arid-semiarid, and mixed rainfed arid-semiarid, respectively) projected to undergo at least a 20% reduction in LGP to 2050, using downscaled outputs from the HadCM3 model for scenarios A1F1 and B1.

Table 1: Agricultural systems used in the analysis (adapted from Thornton et al., 2006a)

Code	Short system description	Source
COAST	Coastal artisanal fishing-based systems	Defined D&G
FORST	Forest-based systems	Defined D&G
PEREN	Highland perennial-based systems	Defined D&G
LGA	Livestock only systems, arid-semiarid	Defined S&S, mapped K
LGH	Livestock only systems, humid-subhumid	Defined S&S, mapped K
LGHYP	Livestock only systems, hyper-arid	Defined & mapped K06
LGT	Livestock only systems, highland/temperate	Defined S&S, mapped K
MIA	Irrigated mixed crop/livestock systems, arid-subarid	Defined S&S, mapped K
MIH	Irrigated mixed crop/livestock systems, humid-subhumid	Defined S&S, mapped K
MIHYP	Irrigated mixed crop/livestock systems, hyper-arid	Defined & mapped K06
MRA	Rainfed mixed crop/livestock systems, arid-semiarid	Defined S&S, mapped K
MRH	Rainfed mixed crop/livestock systems, humid-subhumid	Defined S&S, mapped K
MRHYP	Rainfed mixed crop/livestock systems, hyper-arid	Defined & mapped K06
MRT	Rainfed mixed crop/livestock systems, highland/temperate	Defined S&S, mapped K
OTHER	Other systems, including root-crop-based and root-based mixed	Defined S&S, D&G, mapped K
RITRE	Rice-tree crop systems	Defined D&G
TREEC	Tree crop systems	Defined D&G
URBAN	Built-up areas	Defined JRL

Sources: D&G: Dixon & Gulliver (2001); JRL: JRL (2005); K: Kruska et al. (2003); K06: Kruska (2006); S&S: Seré & Steinfeld (1996)
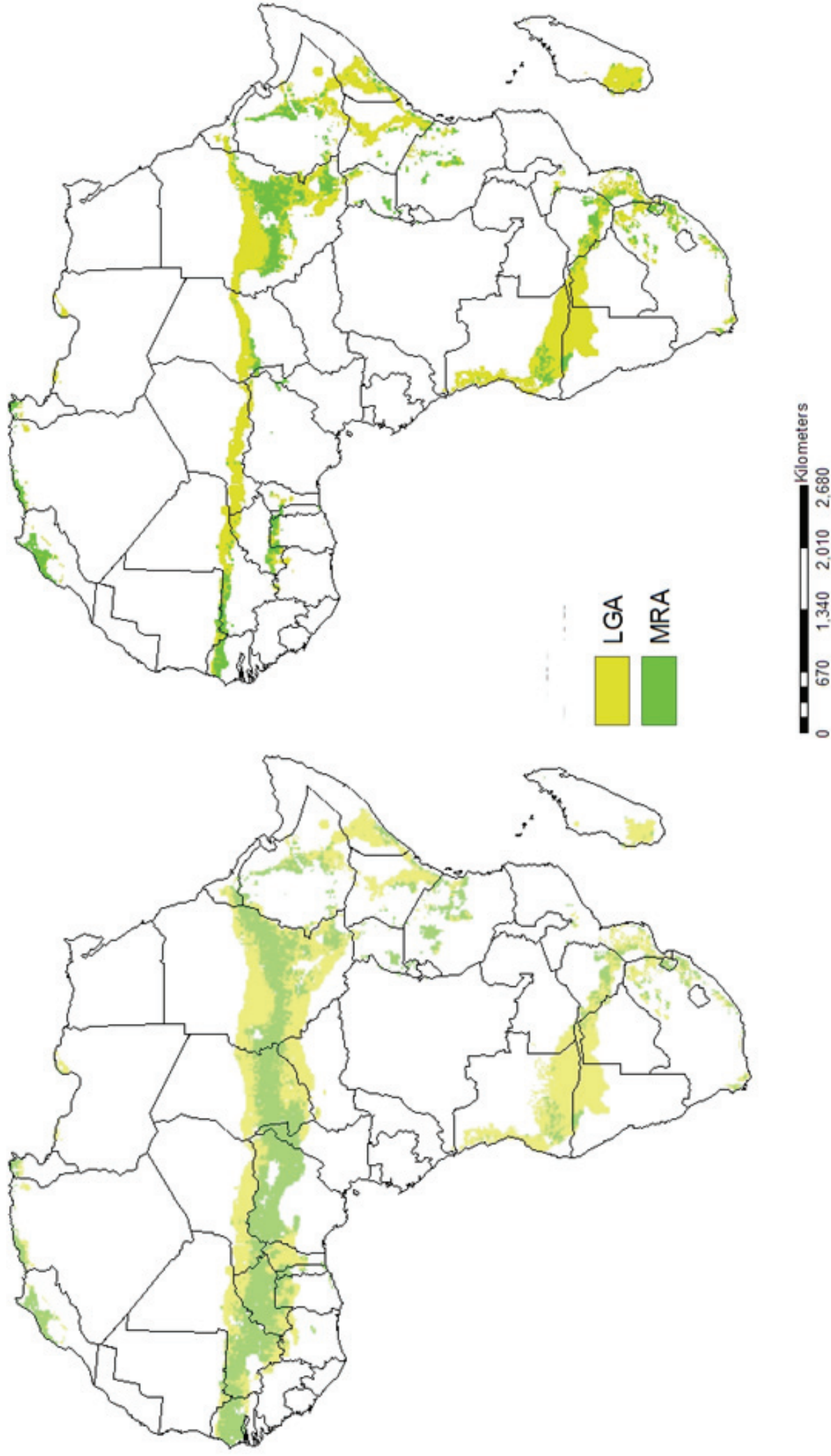
Figure 1: Areas within the LGA and MRA systems projected to undergo >20% reduction in LGP to 2050: HadCM3, A1 (left), B1 (right). LGA, rangeland-based arid-semiarid system. MRA, mixed rainfed arid-semiarid system (from Thornton et al., 2006a)

2.2 Stage 2: Hotspots of current vulnerability

The second stage of the analysis involved characterizing sub-Saharan Africa, on the same country-by-system basis as for the climate change impacts, in terms of a set of vulnerability indicators. The methodological issues surrounding the choice, use and interpretation of indicators for vulnerability assessments are discussed in Vincent (2004) and Brooks et al. (2005), for example. Given the problems associated with using other people's lists of vulnerability indicators developed for different purposes in different contexts, we developed our own set of proxy indicators, guided by the reviews and experiences of others, particularly TERI (2003), Vincent (2004), Adger et al. (2004) and Brooks et al. (2005). To do this, a list was compiled of possible proxy variables that could be used as vulnerability indicators. It was judged appropriate to use a sustainable livelihoods approach as the basis for the various indicators (Carney, 1998), and so these were grouped into the relevant asset types: human, financial, physical, social and natural. Subsequently the list of indicators was revised in the light of data availability issues, but the original list was left as intact as possible (indicators relating to biodiversity and freshwater fish resources had to be omitted). Indicators of biophysical and social vulnerability were adopted or formed from existing data sources, some at national and some at sub-national level. Details of the 14 indicators used and data sources are shown in Table 2, and a brief summary follows.

Table 2: Vulnerability indicators used in the analysis (from Thornton et al., 2006a)

	Type	Indicator	Descriptor	Hypothesised functional relationship with vulnerability	Data source
1	Natural capital **Crop suit**	Suitability for crop production	For all cropped pixels, derive the agricultural suitability (scale 1 to 8)	The higher the suitability, the higher the potential crop production, the more potential vulnerability of households to substantial changes in climate	Agricultural suitability layer (FAO, 2000) GLC 2000 cropland (JRL, 2005)
2	Natural capital **Soil deg**	Soil degradation due to wind, water and human-induced erosion	Four categories (low to high) of potential soil degradation	The higher the soil degradation potential, the higher the vulnerability	GLASOD (FAO, 2000)
3	Natural capital **Basin**	Internal water resources by sub-basin	A measure of water resources for each pixel, from none to high in 6 classes	The more internal water, the lower the vulnerability of the household	FAO Atlas of Water Resources and Irrigation in Africa (FAO, 2005)
4	Physical capital **Mkt access**	Accessibility to markets	Continuous index based on travel time to nearest urban areas	The closer to the market, the more diversified income can be and the higher the resilience to shocks, even when farm sizes are small. Better access to markets also implies better service provision	Accessibility layer, http://grid2.cr.usgs. gov/globalpop /africa

5	Social capital **HPI**	Human Poverty Index	Composite index: probability at birth of reaching age 40; adult literacy rate; % population with no sustainable access to improved water source; % children underweight for age	Higher HPI-1 implies higher social capital available	UNDP country-level data (UNDP, 2005)
6	Social capital **Gov**	Governance	Country-level data on voice and accountability, and government effectiveness	Better governance promotes foreign investment and creates more jobs. A higher index means more social capital	World Bank composite data (Kaufmann et al., 2005)
7	Human capital **Child 5**	Stunting, poverty	% children under 5 who are stunted	Stunting is one measure of food security and a proxy for poverty	FAO sub-national data www.povertymap.net
8	Human capital **Inf mort**	Infant mortality rate, poverty	Mortality rate of infants	Higher infant mortality rates imply higher levels of vulnerability	CIESIN sub-national data, http://beta.sedac.ciesin.columbia.edu
9	Human capital **Underweight**	% children underweight, poverty	% children under 5 who are underweight for their age	Higher rates of underweight children imply higher levels of vulnerability	CIESIN sub-national data http://beta.sedac.ciesin.columbia.edu
10	Human capital **Malaria**	Malaria risk	Climatic suitability for endemic malaria	Areas with higher risk of malaria are more vulnerable	MARA (1998)
11	Human capital **Pub hlth**	Public health expenditure	Public health expenditure, as a % of GDP	Areas are less vulnerable with higher government expenditure on public health	Country-level data (HDR, 2005)
12	Human capital **HIV**	HIV/AIDS prevalence	Proportion of working population (15–49) with HIV/AIDS	Areas with higher prevalence of HIV/AIDS are more vulnerable	Country-level data (HDR, 2005)
13	Financial capital **GDP Ag**	Agricultural GDP	Agricultural GDP as % of total GDP	Economies with higher dependence on agriculture are less diverse and more susceptible to climatic events	Country level data for 2005, World Bank http://econ.worldbank.org
14	Financial capital **Int con**	Global inter-connectivity	The difference between all exports as a % of GDP and all imports as a % of GDP	Economies with higher dependence on imports are more vulnerable to climate change and extreme events	Country level data for 2005, World Bank http://econ.worldbank.org

Sources: D&G: Dixon & Gulliver (2001); JRL: JRL (2005); K: Kruska et al. (2003); K06: Kruska (2006); S&S: Seré & Steinfeld (1996)

Three indicators relate to natural capital. The first is crop suitability, representing the suitability of different areas for crop production. This is based on a soil production index that considers the suitability of the best adapted crop to each soil's condition in an area and makes a weighted average for all soils present in a cell on the basis of the characteristics of that soil.

Suitability is then ranked on a scale from 1 (least suitable) to 6 (most suitable). This is then overlaid with a binary (absence/presence) crop distribution layer. We hypothesized that vulnerability increases with an increase in crop suitability, as household livelihoods are more at risk from substantial changes in climate.

The second indicator is the severity of human-induced degradation, for which we used the data of FAO (2000). The severity of human-induced wind and water erosion is indicated by a combination of the degree and the relative extent of the degradation process. The erosion categories are classified into six major classes of degradation, from none to very severe. The hypothesis here is that the higher the human-induced soil degradation potential, the higher the vulnerability of the household.

The third indicator relating to natural capital is the extent of internal renewable water resources (IRWR) within a sub-basin (of which there are some 600 in Africa) in mm per year. These data are from FAO (2005) and express the difference between the natural outflow and the natural inflow calculated by simple water-balance and hydrological models, thus representing the sub-basin contribution to the overall runoff of the major basin. In cases where the natural outflow is less than the natural inflow, IRWR is zero. The hypothesis is that the more internal water available in the landscape, the lower the vulnerability of the household.

We included one indicator of physical capital, accessibility to markets. This is a continuous index, calculated on the basis of a road network with a 'travel time' associated with each stretch of road and a map of populated places. For each node on the road network, accessibility potential is calculated based on the weighted population of the nearest populated places on the network. The weights are based on the travel time to the nearest market centers. The index represents the relative accessibility to markets for every pixel in the study area. From a livelihoods perspective, the hypothesis here is that the closer a household is to the market, the more diversified household income sources can be. The household is also likely to have better service provision.

For social capital, we used two indicators. One is the human poverty index for developing countries (HPI-1). This measures deprivation in the three basic dimensions of human development captured in the Human Development Indicator (HDI):

- The probability of death at a relatively early age, measured by the probability at birth of not surviving to age 40;

- Exclusion from the world of reading and communications, as measured by the adult illiteracy rate;

- Lack of access to overall economic provisioning, as measured by the unweighted average of two other indicators: the percentage of the population without sustainable access to an improved water source, and the percentage of children underweight for their age.

Details of HPI-1 are given in UNDP (2005), and data are at a national level. The assumption here is of a linear inverse relationship between HPI-1 and vulnerability.

The second indicator of social capital relates to governance. Kaufmann et al. (2005) present national indicators for six dimensions of governance: voice and accountability, political instability and violence, government effectiveness, regulatory quality, rule of law, and control of corruption. Their indices are based on several hundred individual variables measuring perceptions of governance drawn from many data sources. Each indicator is normally

distributed with a mean of zero and a standard deviation of unity. These six indicators cannot meaningfully be averaged for a particular country so, following Brooks et al. (2005), we took two of the six (voice and accountability, and government effectiveness) and assigned the scores to quintiles, averaged the quintile scores and then rearranged these into new quintiles. 'Voice and accountability' includes several indicators that measure various aspects of the political process, civil liberties and political rights, together with the independence of the media. 'Government effectiveness' combines information on the quality of public service provision, the quality of the bureaucracy, the competence of civil servants, the independence of the civil service from political pressures, and the credibility of the government's commitment to policies.

The next six indicators are related to human capital. The first three of these have been widely used as proxies for poverty, and the hypothesis is of a direct relationship between vulnerability and these indicators:

- The rate of chronic undernutrition, using stunting in growth among children under five years of age as an indicator. This reflects long-term cumulative effects of inadequate food intake and poor health conditions as a result of lack of hygiene and recurrent illness in poor and unhealthy environments. The FAO sub-national dataset was used, located at www.povertymap.net.

- Infant mortality, derived by dividing the number of babies who die before their first birthday by the number of live births in that year, and multiplying by 1000. The sub-national dataset from the Socioeconomic Data and Applications Center (SEDAC) at CIESIN (Center for International Earth Science Information Network) was used.

- The percentage of children under five years of age who are underweight for their age. Wasting indicates current acute malnutrition. The sub-national dataset from CIESIN was used for this indicator.

The fourth human capital indicator used was the malaria risk (MARA, 1998). This is a theoretical model based on available long-term climate data and shows the theoretical suitability of local climatic conditions for stable malaria transmission in an average year. It should be noted that malaria transmission can vary substantially from one year to the next, as a result of climatic conditions and malaria control activities. Where the climate is suitable, malaria is very likely to be endemic, and where it is unsuitable, malaria is likely to be epidemic or absent. Areas with a higher risk of malaria are hypothesized to be more vulnerable.

The fifth indicator of human capital used relates to public health expenditure. Country-level data from UNDP (2005) were used, representing the current and capital spending on health from central and local government budgets, external borrowing and grants, and social or compulsory health insurance funds, expressed as a percentage of the country's Gross Domestic Product (GDP). The hypothesis here is that the higher the health expenditure as a proportion of GDP, the lower the vulnerability.

The sixth indicator of human capital used was the prevalence of HIV/AIDS. Country-level data from UNDP (2005) were used, referring to the percentage of people aged 15–49 infected with HIV. The hypothesis here is that areas with higher rates of HIV/AIDS are more vulnerable. HIV/AIDS is a major development issue facing sub-Saharan Africa, reducing

accessibility to labor and diminishing household productivity, among other impacts (Drimie, 2002).

There are two indicators of financial capital. One is the share of total GDP that is associated with agriculture. Economies with a higher dependence on agriculture are hypothesized to be less diverse and thus more susceptible to climatic events and changes. Data are at national level and taken from UNDP (2005). The second relates to global interconnectivity, and is the trade balance in terms of all goods and services exported and imported, expressed as a percentage of GDP. Economies with a higher dependence on imports are hypothesized to be more vulnerable to climate change and variability.
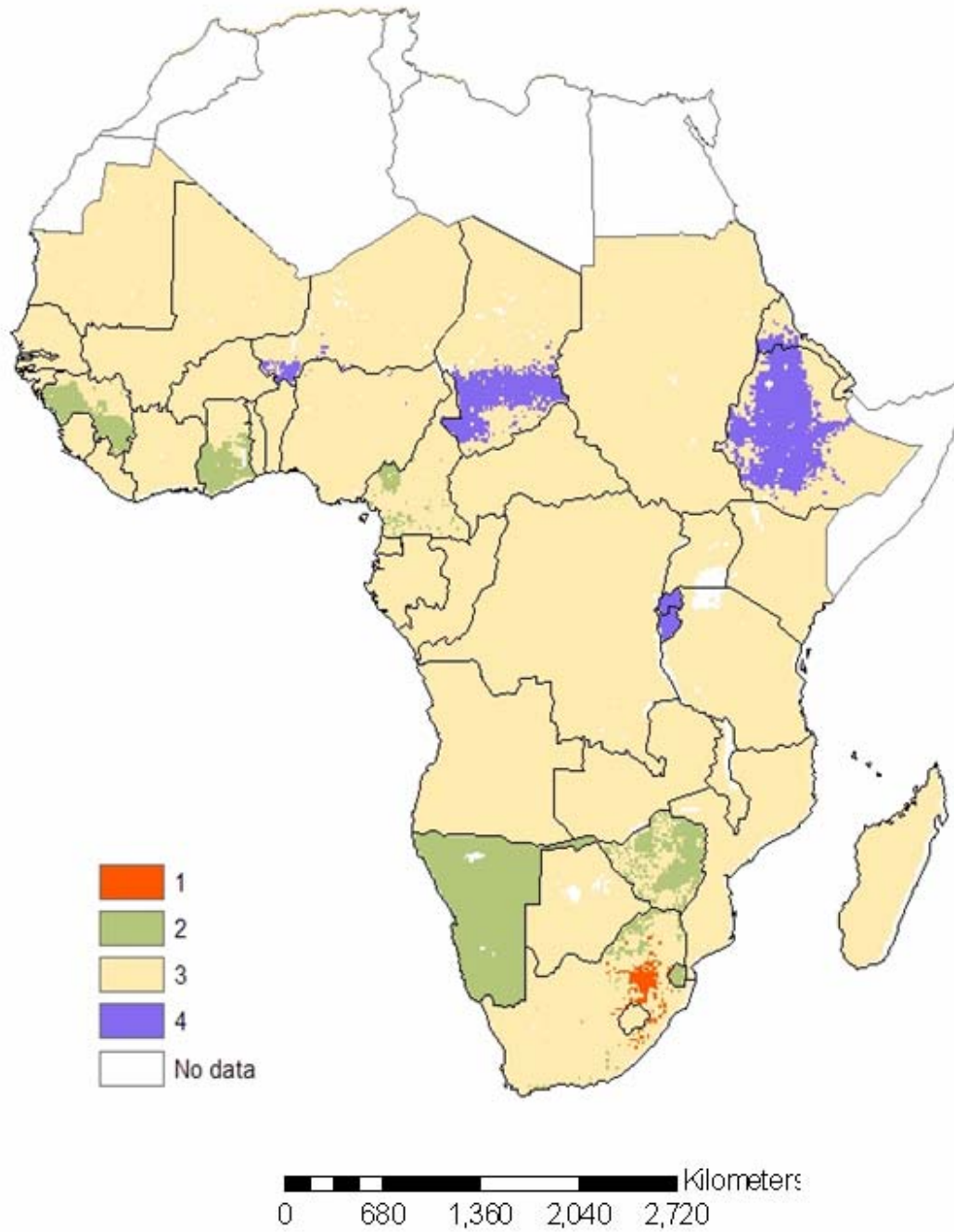
To help characterize the hotspots of climate hazard identified in Section 2.1 above in terms of their vulnerability, we distilled the 14 indicators that were identified above to a smaller number of indicators, using a Principal Components Analysis (PCA). All data were pixelized, whatever the resolution, and PCA was carried out on all pixels that had valid data for all 14 indicators. PCA is an example of factor analysis, a class of statistical methods that attempts to reduce the complexity of multivariate datasets by producing a set of new factors or components that are orthogonal, thereby avoiding the problems of correlation among indicators. A disadvantage is that the new factors may not be easily interpretable. The PCA was done with a Varimax orthogonal rotation, and new factors were selected that had an eigenvalue greater than unity (SAS, 1994). Before the analysis, all indicators were transformed so that increases in their value were associated with increases in vulnerability.

The correlation matrix for the 14 indicators is shown in Table 3. All but six of these are statistically significant at the 1% level. The relationships between governance, public health and the poverty proxies (stunting, wasting and infant mortality) are noteworthy. Increasing HIV/AIDS prevalence is strongly associated with increasing 'public health vulnerability' (i.e. lower levels of government expenditure on public health), but apparently negatively associated with wasting, for example. From the PCA we identified four new factors (combinations of the 14 original indicators), and between them these four factors explained 63% of the variance in the original dataset. To derive an 'overall' vulnerability indicator we calculated the weighted sum of the four components, and for weights we used the percentage of variance explained. The resulting indicator was then normalized, and we grouped pixels into quartiles, and aggregated the data into systems by country. For combinations of country and system where there were missing data we used the national mean quartile across all other systems for which there were data, as a proxy for the missing system. Human development indicator data are not reported for Somalia in UNDP (2005), so Somalia was omitted from this piece of the analysis. The quartiles of the resulting composite indicator are mapped in Figure 2.

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Table 3: Correlation matrix for the 14 vulnerability indicators in Table 2 for sub-Saharan Africa (from Thornton et al., 2006a)

	Malaria	Soil deg	Pub hlth	Child 5	Crop suit	GDP Ag	HPI	Inf mort	Int con	Gov	HIV	Undweight	Mkt access
Soil deg	-0.19												
Pub hlth	0.06	-0.25											
Child 5	-0.08	0.05	-0.52										
Crop suit	0.11	0.03	-0.10	0.06									
GDP Ag	-0.07	-0.11	0.78	-0.52	-0.10								
HPI	0.12	-0.04	0.35	-0.27	-0.08	0.54							
Inf mort	0.27	-0.01	-0.48	0.43	0.11	-0.48	-0.24						
Int con	-0.14	0.01	-0.38	0.34	0.05	-0.37	-0.32	0.27					
Gov	0.23	0.08	-0.42	0.24	0.11	-0.35	-0.06	0.37	0.07				
HIV	-0.32	-0.18	0.58	-0.13	-0.25	0.47	0.17	-0.34	-0.04	-0.37			
Undweight	0.05	0.16	-0.77	0.65	0.15	-0.64	-0.25	0.56	0.42	0.43	-0.53		
Mkt access	-0.15	0.20	0.14	-0.31	-0.04	0.20	0.12	-0.24	-0.18	-0.18	0.02	-0.25	
Basins	-0.12	-0.01	<0.01	0.14	-0.11	-0.11	0.16	<-0.01	0.20	-0.19	0.23	0.10	-0.09

Note: Variable codes are shown in **bold** in Column 2 of Table 2.

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Figure 2: Country-by-systems, showing quartiles of the vulnerability indicator derived through PCA (quartile 1, 'less vulnerable' – quartile 4, 'more vulnerable') (from Thornton et al., 2006a)

2.3 Stage 3: Hotspots of vulnerability to climate change

Because of the dangers of overinterpreting the results, we did not carry out a detailed characterization of the climate change hotspots and areas of high vulnerability. Rather, we made a qualitative synthesis of the results, linking those systems in broad regions of Africa that are both vulnerable and possibly subject to losses in LPG by 2050. The results are shown in a table that divides the vulnerability/climate change space into four quadrants (Table 4). This information was derived from inspection of the vulnerability quartiles map (Figure 2), maps of the land-based livelihood systems tabulated in Table 1, and maps similar to Figure 1 showing the projected percentage of LGP changes by 2050 for the four different GCM-scenario combinations. For this synthesis, the LGP changes projected by both the HadCM3 and ECHam4 GCMs were qualitatively combined.

Table 4: Synthesis of possible regions and systems affected in terms of LGP loss and vulnerability quartile, for the A1 (top) and B1 (bottom) scenarios (both ECHam4 and HadCM3). LGA, rangeland-based arid-semiarid system. MRA, mixed rainfed arid-semiarid system (from Thornton et al., 2006a)

A1F1	Highest vulnerability quartile (4)	Second-highest vulnerability quartile (3)
Possibly severe LGP loss (>20% to 2050)	• Some MRA systems in Sahel • Mixed rainfed and highland perennial systems in Great Lakes region of E Africa • LGA systems in parts of E Africa	• MRA, LGA systems in large parts of Sahel • Livestock systems and some mixed systems in parts of E and southern Africa • Coastal systems in E and parts of southern Africa
Possibly moderate LGP loss (5–20% to 2050)	• Mixed systems in parts of E Africa	• Coastal systems of parts of W Africa • Tree crop systems in parts of W Africa • Forest-based systems in central Africa • Root-based and root-mixed systems in south central Africa

B1	Highest vulnerability quartile (4)	Second-highest vulnerability quartile (3)
Possibly severe LGP loss (>20% to 2050)	• Some MRA systems in Sahel • Some mixed and LGA systems in parts of E Africa	• Scattered MRA, LGA systems in parts of Sahel • Livestock systems and some mixed systems in parts of southern Africa • Coastal systems in E and parts of southern Africa
Possibly moderate LGP loss (5–20% to 2050)	• Mixed rainfed systems in Great Lakes region of E Africa • Some MRA systems in Sahel	• Forest-based systems in central Africa • Livestock systems and some mixed systems in parts of southern Africa • Mixed systems in parts of W Africa

Under the A1F1 scenario, there are several areas that are both in the highest vulnerability quartile and subject to possibly severe climate change. These include some of the MRA (mixed rainfed, arid-semiarid) systems in the Sahel, mixed rainfed systems and highland perennial systems in the Great Lakes region of East Africa, and LGA (rangeland, arid-semiarid) systems in parts of East Africa. Also in the highest vulnerability quartile in areas where moderate LGP losses are possible are the mixed systems in parts of East Africa. The areas in the second-highest vulnerability quartile that may be subject to possibly severe climate change include the MRA and LGA systems in large parts of the Sahel, livestock systems and some mixed systems in parts of East and southern Africa, and coastal systems in East and parts of southern Africa. Other areas in the second highest vulnerability quartile that may suffer moderate climate change include the coastal systems and tree-crop systems in parts of West Africa, forest-based systems in Central Africa, and the root-based and root-mixed systems in the southern parts of Central Africa.

The situation under the B1 scenario is qualitatively similar. While there are fewer areas in the highest-vulnerability-severest-climate-change quadrant than for the A1F1 scenario, MRA systems are still affected in the Sahel, as are LGA and some mixed systems in parts of East Africa. The climate change effects on the Great Lakes region of East Africa are less than in the A1F1 scenario, but this is still a vulnerability hot-spot. The situation is similar for the areas in the second highest vulnerability quartile that may suffer severe climate change: the coastal systems in East and southern Africa are still in this quadrant, as are the livestock and some mixed systems in southern Africa particularly. The effects in the MRA and LGA systems of the Sahel are more scattered than in the A1F1 scenario, but they are still likely to be very important. For the moderate climate change impacts and the second highest vulnerability quartile, the forest-based systems in Central Africa are in this quadrant, as in the A1F1 scenario, and there are still quite large areas in the livestock and, to a lesser extent, mixed systems in southern Africa that fall in this quadrant.

3. Discussion

There are several limitations associated with the analysis. An important one is that we are probably underestimating the extent of climate-related hazards because no direct account is taken of extreme events such as droughts and flooding, nor of the fact that the variability of weather patterns in many places is increasing and with it the probability of extreme events and natural disasters (Kasperson et al., 2005). In addition, there are various uncertainties associated with the GCMs themselves. While the science of GCM development is continuing to develop rapidly, different models have different capabilities for representing current (and possible future) conditions, and there are considerable uncertainties in the science of climate modeling itself.

Another limitation relates to the choice of vulnerability indicators. Considerably more exploratory analysis could be undertaken with a wider range of candidate vulnerability indicators, perhaps using other data reduction methods. Whether the broad vulnerability groupings derived are relatively robust or not remains to be investigated, but the PCA methodology does have the advantage of dealing with correlations between component indicators, and it seems that this is one way also to deal with data layers at different resolutions. It is likely that some of the richness of the component indicators is lost in the process, however.

There are also limitations with the analysis related to its coverage. One limitation is the treatment of coastal ecosystems, which are among the most productive yet highly threatened

systems in the world. Such systems produce disproportionately more human well-being services than most other systems, even those covering much larger areas (Agardy & Alder, 2005). Nearly 40% of the people in the world live within 100 km of coasts, and coastal populations are increasing rapidly – populations that are at risk from flooding and a rise in sea-level (Nicholls, 2004), something else not considered here. Another limitation is the absence of any treatment of fisheries and fresh-water aquaculture (we were unable to find continental-scale data on fisheries and aquaculture issues). While the vulnerability analysis did include indicators related to malaria risk and HIV/AIDS, there are many other potential impacts of climate change on human health in the form of infectious diseases (Patz et al., 2005).

Given the uncertainties and limitations, many of which warrant considerably more work, it is likely that we have been fairly conservative in identifying hotspots. The results of the analysis are thus indicative only. Even so, they are useful for several purposes. First, they can be used for targeting appropriate research and adaptation interventions, to help answer questions about where scarce research and development resources might appropriately be expended. The analysis outlined above has been used at the DFID to help identify hotspots where climate change related intervention activities might be concentrated. More generally, as these data analyses are refined over time, they could provide standardized input to a broad range of targeting work, including regional site selection for specific types of intervention (such as in Thornton et al., 2006b, for example).

Second, these results can be used to answer more complex questions about priority setting, such as the comparative economic analysis of a range of different interventions, to assess likely impacts on the environment and on poverty, for instance. In the same way as for targeting, such data could provide standardized input to regional priority setting exercises such as that carried out by ASARECA (2005). Vulnerability information can usefully inform the search for effective and feasible research and policy interventions, in relation to particular characteristics of the development domains that are under consideration.

Third, the results can be used as input to formal ex ante impact assessment studies that seek to quantify the costs and benefits of specific research-for-development activities, in terms of likely impacts on key outputs of interest such as poverty levels and producer incomes. These spatial vulnerability data can be used to help locate and characterize the populations that may be affected by specific activities (which may be crop or livestock based, for instance), and also to help quantify specific impacts. While no generic and comprehensive framework yet exists for assessing adaptation and mitigation options for the farming households of Africa, many of the components needed for such a framework already exist. Vulnerability data will be a key constituent of generic impact assessment tools in the future.

In addition to highlighting various systems that may be particularly at risk, the work here has underlined one other important message: macro-level analyses, while useful, can hide an enormous amount of variability in what may be complex responses to climate change. There is considerable heterogeneity in households' access to resources, poverty levels and ability to cope. Vulnerability and impact assessment work can certainly be usefully guided by macro-level analyses, but ultimately this work has to be done at higher resolutions. Targeting might thus usefully be seen as a multi-stage process, where hotspots are identified through broad-brush analysis, followed by subsequent zooming-in to these hotspots to allow more detailed impact assessment to be carried out at the community or household level. Such work calls for different tools, and these might include crop, livestock and household simulation models so that the resource, economic and household well-being implications of changes in climate and climate variability can be appropriately assessed. Additionally, there are likely to be

significant trade-offs to consider. As a simple example, there are many areas of sub-Saharan Africa where maize yields are likely to decrease, and these decreases may be substantial in some areas (Jones & Thornton, 2003). In the maize-based mixed systems of sub-Saharan Africa, maize stover is a key dry-season feed resource for cattle. A question to ask is what the implications are of decreases in both maize grain yield and stover yield on human food security at the household level and on livestock productivity, and what options are available to the household to secure adequate supplies of food for household members and feed for cattle. There is a clear dichotomy between the magnitude of the problems facing sub-Saharan Africa on the one hand, and the necessity of helping local communities adapt in ways that fit (highly variable) local conditions on the other. To deal with this, policy and research outputs and interventions will have to be far better targeted in future. At the same time, there will need to be many institutional and organizational changes that ensure that communities take centre stage in conducting vulnerability analysis and implementation to enhance their long-term capacities for adaptation (Yamin et al., 2005).

4. Conclusions and policy implications

Climate change poses a serious threat to development. Scholes & Biggs (2004) refer to sub-Saharan Africa as the food crisis epicenter of the world, and conclude that projected climate change during the first half of the 21st century will make this situation worse. Climate change will add to the burdens of those who are already poor and vulnerable. At the same time, agriculture in sub-Saharan Africa will continue to play a crucial role through its direct and indirect impacts on poverty, as well as in providing an indispensable platform for wider economic growth that reduces poverty far beyond the rural and agricultural sectors (DFID, 2005). The indicative results of this analysis show that many vulnerable regions are likely to be adversely affected in sub-Saharan Africa, including the mixed arid-semiarid systems in the Sahel, arid-semiarid rangeland systems in parts of East Africa, the systems in the Great Lakes region of East Africa, the coastal regions of East Africa, and many of the drier zones of southern Africa.

There are at least two policy implications of the work reported here. One is the seemingly perennial problem of data, in terms of both its availability and its use. The availability of appropriate data for carrying out vulnerability and impact analyses is a key issue, and in many parts of Africa there are serious problems with the existing data collection systems (Lynam, 2006). It is clear that vulnerability analyses such as that outlined above make use of a wide range of information, and Table 2 illustrates the numerous sources and scales of the information needed. There is a continuing need for baseline data to improve targeting and priority setting and, as Lynam (2006) and others note, considerable and widespread collaboration is needed for data collection and utilization activities in the African context, which are likely to require an increase in policy action.

The second policy implication is linked to the spatial heterogeneity of both farming and livelihood systems in much of Africa and of the localized impacts of climate change. While this certainly highlights the need for higher-resolution system studies, as noted above, it also highlights the need to acknowledge that there may be a considerable mismatch between the magnitude of the problems facing sub-Saharan Africa and the size of the likely development domain for specific options for helping communities adapt that are appropriate to local conditions. The development domains for climate change interventions may thus be geographically relatively small. If this is indeed the case, then there are clear lessons for the design, implementation and assessment of research and development activities designed to

address the problems brought about by a changing climate and changing climate variability. The results of the work reported here argue strongly against large 'magic bullet' approaches, and in favor of smaller, better targeted local approaches and interventions. In sum, considerable future work is needed to refine the hotspots analysis and increase the resolution of impact studies and thus contribute to our understanding of the issues facing millions of people who depend on natural resources for part of their livelihood and help them adapt to inevitable change.

Acknowledgements

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