Open access • Journal Article • DOI:10.1023/A:1026001626076

Life on the edge: vulnerability and adaptation of african ecosystems to global climate change — Source link

Robert K. Dixon, Joel B. Smith, Sandra Guill

Institutions: United States Department of Energy

Published on: 01 Jun 2003 - Mitigation and Adaptation Strategies for Global Change (Kluwer Academic Publishers)

Topics: Environmental degradation, Global warming, Sustainable development, Vulnerability and Climate change

LIFE ON THE EDGE: VULNERABILITY AND ADAPTATION OF AFRICAN ECOSYSTEMS TO GLOBAL CLIMATE CHANGE

ROBERT K. DIXON[1], JOEL SMITH[2] and SANDRA GUILL[3]
[1]*Office of Power Technologies, US Department of Energy, Washington, DC*
[2]*Stratus Consulting Inc., Boulder, Colorado*
[3]*US Country Studies Programme, US Department of Energy, Washington, DC*

(Received 15 March 2003; accepted in final form 7 April 2003)

Abstract. Donor countries are providing financial and technical support for global climate change country studies to help African nations meet their reporting needs under the United Nations Framework Convention on Climate Change (UNFCCC). Technical assistance to complete vulnerability and adaptation assessments includes training of analysts, sharing of contemporary tools (e.g. simulation models), data and assessment techniques, information-sharing workshops and an international exchange programme for analysts. This chapter summarizes 14 African country studies (Botswana, Côte d'Ivoire, Egypt, Ethiopia, the Gambia, Kenya, Malawi, Mauritius, Nigeria, South Africa, Tanzania, Uganda, Zambia and Zimbabwe) assessing vulnerabilities to global climate change and identifying adaptation options. The analysis revealed that the participating African countries are vulnerable to global climate change in more than one of the following socio-economic sectors: coastal resources, agriculture, grasslands and livestock, water resources, forests, wildlife, and human health. This vulnerability is exacerbated by widespread poverty, recurrent droughts, inequitable land distribution, environmental degradation, natural resource mismanagement and dependence on rain-fed agriculture. A range of practical adaptation options were identified in key socio-economic sectors of the African nations analysed. However, underdeveloped human and institutional capacity, as well as the absence of adequate infrastructure, renders many traditional coping strategies (rooted in political and economic stability) ineffective or insufficient. Future African country studies should be more closely coordinated with development of national climate change action plans

Keywords: adaptation, Africa, agriculture, forests, global climate change, health, vulnerability, water, wildlife

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) requires all signatory countries to communicate reports on their national circumstances and potential vulnerability⋆ to global climate change (UNFCCC 1992). Moreover, each country is also encouraged to describe the steps and actions it

⋆ In the context of this paper, 'vulnerability' is the extent to which climate change may damage or harm a system; it is a function of both the 'sensitivity' of a system or structure to climate and the opportunities for 'adaptation' to new conditions. 'Sensitivity' is defined as the degree to which a system will respond to a change in climatic conditions (e.g. the extent of change in ecosystem composition, structure, and functioning, including primary productivity, resulting from a given change in temperature or precipitation). The responses may result in either beneficial or harmful effects.

Mitigation and Adaptation Strategies for Global Change **8:** 93–113, 2003.

is taking to implement the principles and goals of the Convention especially response (e.g. adaptation) options (Smith and Lenhart 1996). Country studies, or comprehensive analyses and assessments, are a first step towards meeting national reporting and other obligations under the Convention (Dixon et al. 1995). The United States Country Studies Programme (USCSP) was initiated in 1992 to help African developing countries and countries with economies in transition meet their Convention obligations (Amadore et al. 1999).

In its first phase, the USCSP provided technical and financial support to 14 African countries. The primary objectives of USCSP included: (i) enhance the abilities of countries and regions to inventory their greenhouse gas (GHG) emissions (Graham et al. 1990), assess their vulnerabilities to climate change (Watson et al. 1996), and evaluate response strategies for mitigating emissions and adapting to the potential impacts of global climate change (Mwandosya et al. 1996); (ii) enable countries to establish a process for developing and implementing policies and measures to mitigate and adapt to global climate change (Smith and Lenhart 1996), and for re-examining these policies and measures periodically; and (iii) share information that can be used to further national, regional, and international discussions of global climate change issues (Dixon et al. 1995). State-of-the-art technical support and cooperation with study teams from African countries are major USCSP elements (Benioff 1996a,b; Amadore et al. 1999)

In addition to direct funding of global climate change studies, USCSP devoted about 25% of its resources to hands-on training of more than 500 African participants in assessment techniques and development, and sharing of contemporary analytic tools and unique data sets at country and regional technical workshops. Short-term analyst exchange programmes (e.g. 3–6 months) in the United States and technical support of the assessments through dozens of site visits in each country were integral components of the USCSP network. The USCSP developed and distributed international handbooks in vulnerability and adaptation assessment techniques (Benioff et al. 1996). The analytical phase of the USCSP was completed in approximately six years and various technical outputs have been reported by African countries (Dixon et al. 1996a,b; Amadore et al. 1999; Mimura 1999). In cooperation with a number of international and intergovernmental organizations, the USCSP and African country teams conducted over 15 regional workshops to share preliminary results and lessons learned from their studies (Dixon et al. 1995)

The USCSP complements UNFCCC enabling activities implemented by other agencies and donors in Africa, including multilateral programmes (e.g. African De-

'Adaptation' is defined as adjustments in practices, processes, or structures in response to projected or actual changes in climate. Adjustments can be spontaneous or planned, reactive or anticipatory. In some cases (e.g. for many ecosystems), options for planned or anticipatory adaptation may not exist. Adaptations can reduce negative impacts or take advantage of new opportunities presented by changing climate conditions. It is in part because of the uncertainties associated with regional projections of climate change that this paper takes the approach of assessing vulnerabilities, rather than quantitatively assessing expected impacts of climate change.

velopment Bank (ADB), UN Development Programme (UNDP), UN Environment Programme (UNEP), Organization for Economic Cooperation and Development (OECD), European Commission (EC), the World Bank, and the Global Environment Facility (GEF)) and bilateral programmes (e.g. Denmark, Germany, the Netherlands and Sweden). Closely linked activities include co-financed studies in individual countries, jointly organized training, and analytical and information sharing exercises. An electronic global information system supporting global climate change country studies, CC:INFO (climate change information), is maintained and operated by the UNFCCC Secretariat and employed by the African country teams. Participating countries offered reports regarding African country study progress to the Intergovernmental Negotiating Committee (INC), Conference of the Parties (COP), and meetings of the UNFCCC subsidiary bodies (i.e., Subsidiary Body on Scientific and Technological Advice and Subsidiary Body for Implementation from 1993 to the present (Amadore et al. 1999)

Prior to the initiation of high-resolution, bottom-up country studies in Africa, global and regional assessments revealed that many socio-economic sectors (e.g. coastal resources, agriculture and food security, forests, hydrology and water resources, tourism and wildlife, and human health) were potentially vulnerable to global climate change (Watson et al. 1998). Many countries are prone to drought, and the impacts of the El Niño Southern Oscillation (ENSO) on the southern half of Africa are particularly severe (Leatherman et al 1995). The African continent is considered to be among the most vulnerable to the impacts of global climate change because of the widespread poverty, recurrent droughts, land-use patterns, and a dependence on rain-fed agriculture (Watson et al. 1996). Most African countries currently lack the institutional and human capacity, financial resources, and infrastructure to identify and implement appropriate response (e.g. adaptation and mitigation) options (Mwandosya et al. 1996).

The purpose of this report is to: (i) provide an overview of USCSP goals and approach for assessing vulnerability and adaptation options in African countries; (ii) share the results of 14 country study vulnerability and adaptation assessments (Table I); and (iii) identify options and next steps for African countries as they seek to implement, interpret and employ global climate change adaptation options

2. Materials and Methods

All country study teams participating in USCSP were trained to develop global climate change scenarios and future baseline socio-economic scenarios (Benioff et al. 1996). Country teams were also trained to assess specific vulnerabilities for any or all of eight sectors (coastal resources, agriculture, grasslands and livestock, water resources, forests, fisheries, wildlife and ecotourism, and human health). Information regarding biophysical or socioeconomic characteristics of individual African countries, with regard to the vulnerability and adaptation analysis conducted by the

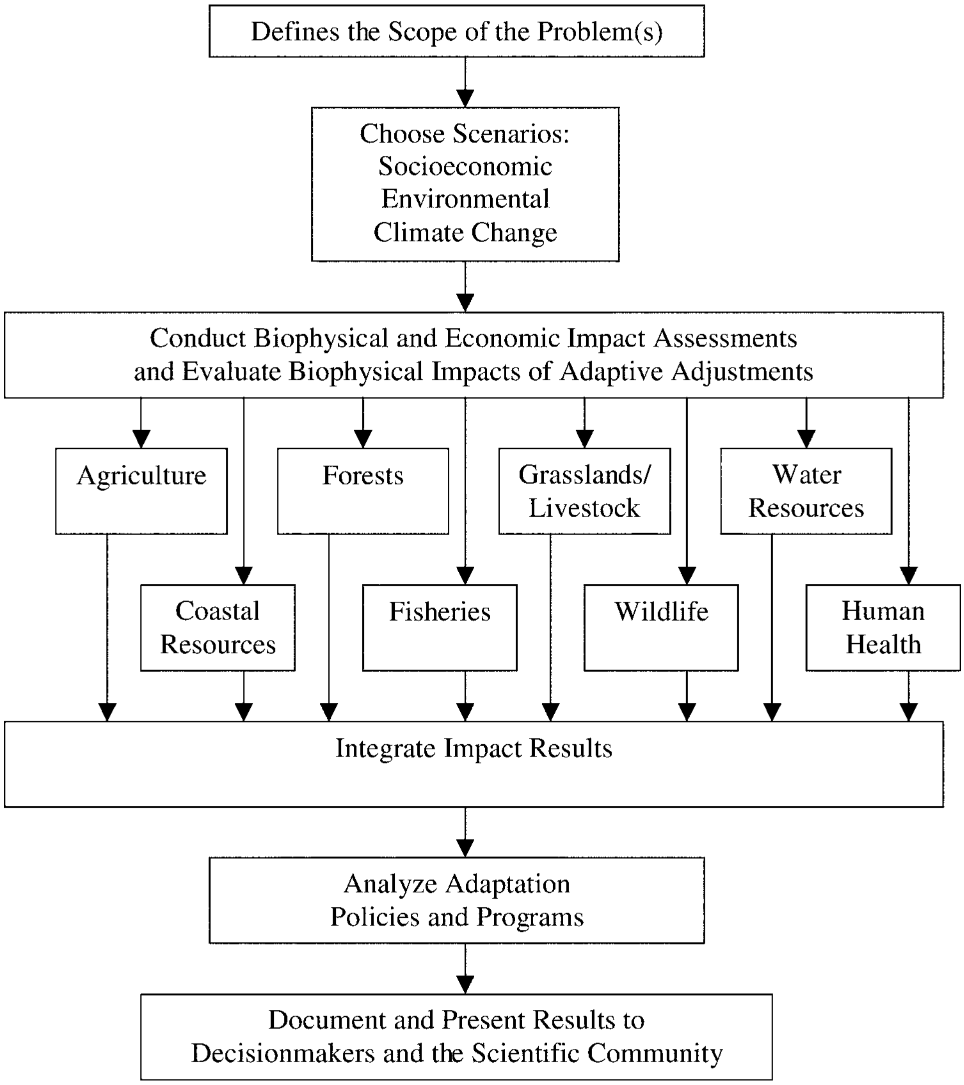

Figure 1. Vulnerability and adaptation assessment process employed by USCSP.

country teams, is summarized by Watson et al. (1996). Also baseline biophysical and socioeconomic information regarding the eight specific sectors can be found in the source reports cited in the References section. The country teams were trained in the various techniques for identifying, screening, and evaluating adaptation options (Smith and Lenhart 1996). In conducting their assessments, most of the countries followed the general approach recommended by the USCSP handbook: *Vulnerability and Adaptation Assessments: An International Guidebook* (Benioff et al. 1996). A schematic description of this assessment approach, which comple-

TABLE I

African country vulnerability and adaptation assessments by USCSP sector.

Country	Coastal Resources	Agri-culture	Grasslands/ Livestock	Water Resources	Forest	Fisheries	Wildlife	Human Health
Botswana			•	•†	•	•		
Côte d'Ivoire	•	•		•	•			
Egypt	•†	•†		•				•
Ethiopia		•	•	•	•			
The Gambia	•†	•	•	•	•	•		
Kenya		•		•	•	•		
Malawi				•	•		•	
Mauritius	•	•		•		•		
Mozambique	•	•	•	•	•			•
South Africa		•	•	•	•	•		•
Tanzania	•	•	•	•	•			•
Uganda		•	•	•	•			
Zambia		•	•	•	•		•	•
Zimbabwe		•			•			

Italic indicates SNAP participant
• Completed vulnerability assessment
• Conducting vulnerability assessment (South Africa)
† Completed adaptation assessment

ments Intergovernmental Panel on Climate Change (IPCC) recommendations, is presented in Figure 1.

Table I summarizes the vulnerability and adaptation assessment activities by country and sector. The 14 African countries conducted vulnerability assessments in sectors that are important in their economies or social fabric: coastal resources, agriculture, grasslands and livestock, water resources, forests, fisheries, wildlife and ecotourism, and human health (Dixon et al. 1995; Smith et al. 1996a). Several countries initiated adaptation assessments and identified preliminary adaptation options. Relatively few African countries have completed adaptation assessments that actually select options for implementation (Amadore et al. 1999). In brief, there are three key aspects of USCSP vulnerability and adaptation assessment process: (i) global climate change and socio-economic baseline scenarios that are used as inputs to the assessments; (ii) analytical methods and simulation models used to assess impacts and vulnerability in various resource sectors; and (iii) methods and models used to evaluate and compare adaptation options (Smith and Lenhart, 1996).

2.1. Methods and Data Sources

Vulnerability assessments were initiated with selection of global climate change and baseline socio-economic (population and economic conditions) scenarios extending through 2075 (Smith et al. 1996a,b). The global climate change scenarios were inputs for the biophysical and socio-economic models or methodologies that were used to assess impacts of potential global change (Benioff et al. 1996). Most of these methods permit incorporation of alternative policies to assess the impacts under different adaptation options that may be taken in response to global climate change (Smith et al. 1996b). The vulnerability of each sector was analysed individually, and results were then integrated across relevant sectors to account for interactions among related sectors. For example, the agriculture assessment incorporated changes in water supply from the water resources assessment (Rosenzweig and Parry 1994; Yates 1996).

This vulnerability assessment approach is consistent with and similar to the seven-step analytical framework developed by the IPCC (Benioff et al. 1996). Specific assessment methodologies are described below including scenarios and assessment methodologies for each sector. Additional descriptions of the methodologies can be found in Smith et al. (1996a) and Benioff et al. (1996). In the water resource sector, some countries assessing water resources employed a monthly water balance model called CLIRUN to estimate changes in watershed run-off (Kaczmarek 1993).

2.2. Global Climate Change Scenarios

Country global climate change scenarios were created using estimates of regional global climate change generated from General Circulation Models (GCMs) or using incremental global climate change scenarios (e.g. +2 °C and ±10% change in precipitation). The US National Centre for Atmospheric Research (NCAR) supplied output from the following GCMs to countries participating in the USCSP:

- Goddard Institute for Space Studies (GISS; Hansen et al. 1983);
- Geophysical Fluid Dynamics Laboratory (GFDL or GFD3; Wetherald and Manabe 1988);
- United Kingdom Meteorological Office (UK89; Mitchell et al. 1990);
- United Kingdom Meteorological Office (UKMO; Wilson and Mitchell 1987);
- Canadian Climate Centre Model (CCCM; Boer et al. 1992);
- Geophysical Fluid Dynamics Laboratory Transient (GF01; Manabe et al. 1991);
- Oregon State University (OSU; Schlesinger and Zhao 1989).

These GCMs estimate an increase in average global temperatures of 2.5–4 °C for a doubling of carbon dioxide (CO_2) levels in the atmosphere (Houghton et al. 1992). This result is at the higher end of the estimated range of 1.5–5 °C warming for CO_2 doubling (Houghton et al. 1996). The primary models employed by most countries were the CCCM, GFD3, and GISS because the scenarios were robust (Smith et al. 1996a).

TABLE II

Models and methods typically used for vulnerability assessments in 14 African countries.

Sector	Model or Method	Typical Output
Agriculture	DSSAT 3– CERES models	Changes in yield, change in growing season length
Coastal	IPCC Common Methodology	Land loss to inundation, capital value lost
Fisheries	Habitat Suitability Index	Change in habitat suitability index
Forests	Holdridge Model, GAP models	Change in land cover under different vegetation types
Grasslands/ Livestock	SPUR2	Percent change in biomass, Change in livestock weight at market
Health	Simple mapping, GIS, integrated modelling	Changes in disease vectors
Water Resources	WATBAL	Percent change in run-off
Wildlife	Eco-climate indices	Change in ecoclimate index

2.3. Socio-economic scenarios

Country socio-economic scenarios were developed to help assess vulnerabilities to global climate change that may be affected by changes in population, income, technology, and other factors (Smith et al. 1996a). Information on regional economic growth rates, agricultural production, and deforestation was derived from an IPCC assessment (Leggett et al. 1992; Houghton et al. 1995). These estimates were developed by the IPCC to determine GHG emissions over the next 100 years and the subsequent rate of climate change and are referred to as the IS92a-f set of scenarios.

2.4. Sectoral vulnerability assessment methods

The analyses of biophysical and socio-economic impacts of global climate change in specific sectors used the following methods (Table II):

2.4.1. *Coastal resources*

The coastal zone assessments applied the IPCC common methodology, a seven-step procedure for analysing coastline vulnerability to accelerated sea-level rise (Jallow et al. 1999). Some countries applied aerial videotape-assisted vulnerability analysis (AVVA), which uses field data to identify land and infrastructures that are at risk and determines protection costs for a range of response options (Leatherman et al. 1995).

2.4.2. *Agriculture*

The Decision Support System for Agrotechnology Transfer (DSSAT 3) assessed agriculture vulnerability for the 14 countries. DSSAT 3 is a mathematical model that simulates agronomic crop growth and yield based on anatomic and physiologic characteristics, weather patterns, and edaphic factors. Estimating potential changes in agronomic crop yields and water use was the primary approach used by country teams in assessing vulnerability to global climate change (Rosenzweig and Parry 1994). The crop models, which account for the direct physiological effects of increased atmospheric CO_2, also simulate rain fed and irrigated agricultural systems, as well as adaptations to global climate change at the farm level. The models most frequently employed were CERES-Wheat and CERES-Maize (Makadho 1996).

2.4.3. *Grassland/Livestock*

The SPUR2 suite of models was employed to simulate the effects of global climate change on grassland ecosystem processes and cattle (*Bos*) production (Hanson et al. 1993). This suite includes models for simulating plant growth and yield, soils and hydrologic factors, domestic animal growth and production, competing animals, and potential impacts of insects. SPUR2 includes a generalized cattle model, simulating the life of mature or juvenile animals during a simulated grazing season.

2.4.4. *Water resources*

The water resources assessments employed water balance models (Yates 1996). Monthly mean values of temperature and precipitation were modelled using a basin as a single, homogenous unit. The models included CLIRUN (Kaczmarek 1993) and WATBAL (Yates 1996). Most countries estimated change(s) in watershed runoff, but did not examine management or adaptation implications (Frederick et al. 1997).

2.4.5. *Forests*

The USCSP teams examining forests applied the Holdridge Life Zone Classification (Holdridge 1967), which relates the distribution of major ecosystems (called life zones) to the climatic variables of biotemperature, mean annual precipitation, and the ratio of potential evapotranspiration to precipitation (PET ratio). Some teams also employed forest gap models, in which each tree in a landscape is modelled as a unique entity with respect to the processes of establishment, growth, and mortality (Dixon et al. 1996a,b; Kariuki et al. 1997).

2.4.6. *Fisheries*

The fisheries analyses were qualitative in nature, including analysis of changes in thermal structure of lakes and streams, and changes in habitat (habitat suitability models). Hlohowskyj et al. (1996) describe these USCSP analytical methods.

2.4.7. *Wildlife*

To assess wildlife impacts, countries used two analytic methods: climatic correlation and Habitat Suitability Index (HSI) (Mkanda 1999). The climatic correlation (CLIMCORR) technique (Markham 1996) uses the strong correlation between geographic distribution of species, communities, ecosystems, biomes and climate.

The HSI, which was employed by some countries, quantifies the capacity of habitat to support a species (Mkanda 1999).

2.4.8. *Human health*

The relationship between global climate change and human health is quite complex and difficult to model (Patz and Balbus 1996). The methods for assessing the vulnerability of human health included identification and mapping of sensitive populations and pertinent diseases within the country's borders, assessing correlation between hot humid air masses and mortality, and the integrated modelling of vector-borne diseases in the context of climate, ecosystem and societal change (Martens 1996).

2.5. Adaptation assessment methods

The adaptation assessment methods used by the African countries fall into one of three categories (Smith et al. 1996a,b; Smith and Lenhart 1996).

2.5.1. *Multi-attribute analysis*

Multi-attribute analysis examines how well different technical criteria are satisfied by policy options (El Raey et al. 1999). It does not use a common metric to measure how well criteria are satisfied. Its advantage is that its results are transparent; its disadvantage is that cases where one option is superior on one criterion but inferior on another cannot be resolved. Using the USCSP's Adaptation Strategy Evaluator (ASE), decision makers identify policy objectives and subjectively determine how well the adaptation measures meet each objective on a qualitative scale (Smith and Lenhart 1996).

2.5.2. *Cost-effectiveness analysis*

Cost-effectiveness analyses identified the least-cost method of reaching a goal. Typically, a goal is specified (e.g. reduce GHG emissions by 10%) and options are compared based on monetary or other costs. A number of countries applied the Adaptation Decision Matrix (ADM) (Smith et al. 1996b) developed for the USCSP. The ADM evaluates options that have different benefits and costs. A common scoring metric used to evaluate the benefits of options, and options are compared based on which of them costs the least to raise the score one unit. The water sector used ratios of cost to water quantity.

2.5.3. *Benefit-cost analysis*

In a benefit-cost analysis, all quantifiable benefits and costs were expressed in monetary units (e.g. US$) and compared using benefit-cost ratios or net benefits (Smith et al. 1996a,b). A ratio of greater than one reveals that the measure being analysed has positive net benefits. Benefit-cost analysis has the advantage of using a common metric to express all benefits and costs across one or more continents.

3. Results and Discussion

3.1. Coastal resources

Six countries conducted assessments of global climate change impacts on coastal resources: Côte d'Ivoire, Egypt, the Gambia, Mauritius, Mozambique and Tanzania. Land loss is attributable to inundation and erosion due to sea-level rise in four African countries: Côte d'Ivoire, Egypt, the Gambia and Tanzania. With a 0.5 m sea-level rise, about one-half of the land loss is due to erosion and the other half to inundation. At 1.0 m sea-level rise, the portion of land loss attributable to inundation increases faster than the portion due to erosion. The total impacts on coastal zones increase threefold when predicted sea-level rise doubles from 0.5 to 1.0 m. Côte d'Ivoire and Egypt found that sea-level rise impacts on coastal cities have a large socio-economic impact (El Raey 1997; El Raey et al. 1999).

Adaptation options to cope with rising sea level were evaluated by Côte d'Ivoire, Egypt, the Gambia and Tanzania. For example, Tanzania estimated the value of structures (e.g. buildings, roads and bridges) lost because of 0.5 and 1.0 sea-level rise at US$70 and US$121 million, respectively (CEEST 1998). Protection of the vulnerable coastline sections of Dar es Salaam, Tanzania, is estimated to cost US$380 million. Multi-criteria and decision matrix approaches, employed for Alexandria and Port Said, Egypt, reveal that cost is the main barrier to implementation of coastal zone adaptation or protection options (e.g. beach nourishment, groins and breakwaters) (El Raey et al. 1999). The most viable socio-economic option appeared to be integrated coastal zone management (ICZM) of Egyptian coastal resources. In an analysis of sea-level rise impacts on coastal resources in Banjul, the Gambia, and Abidjan, Côte d'Ivoire, several shoreline stabilization techniques were identified: innovative sand management, repair of damaged groins, construction of dikes, breakwater structures, revetments and low-cost sea walls. Improved urban planning, wetland preservation and development of a comprehensive ICZM plan were identified as near-term steps to improve the portfolio of adaptation options in Côte d'Ivoire and the Gambia (Jallow et al. 1999).

The coastal nations of west and central Africa (e.g. Angola, Cameroon, Côte d'Ivoire, Gabon, the Gambia, Nigeria, Senegal and Sierra Leone) have low-lying lagoonal coasts that are susceptible to erosion (Watson et al. 1997). The west coast of Africa is frequently at risk to storm surge, erosion, inundation and extreme events. A number of studies reveal that the Nile River delta is at risk to inundation and erosion with consequent loss of agricultural land and urban settlements (El Raey 1997). Adaptation options (e.g. erection of sea walls or resettlement of vulnerable human populations) have been identified for several African countries, but socio-economic costs, as a proportion of Gross Domestic Product (GDP), are considered to be prohibitive.

TABLE III

Direction of crop yield changes across GCM scenarios for 7 African countries.

Country	Wheat	Maize	Soybean	Rice	Other	Other
Côte d'Ivoire		↓		↓		
Egypt	↓	↓	↓	↓	↑ Cotton	↓ Barley
Ethiopia	↑↓					
The Gambia		↓			↓ Millet	↑ Groundnuts
Kenya		↑↓				
Zambia	↑↓	↑	↑↓	↑	↑ Oils	↑ Cassava
Zimbabwe		↑↓				

3.2. AGRICULTURE

Because of the importance of rain-fed agriculture in African economies, 12 of 14 countries undertook vulnerability assessments in this sector (Mimura 1999; Dixon et al. 1996a,b). These assessments were generally more detailed and extensive than other analyses, and examined the vulnerability of numerous specific agronomic crops and cultivars under a variety of global climate change scenarios (Makadho 1996).

The response of wheat (*Triticum*), maize *(Zea*), soybean (*Glycine*), rice (*Oryza*) and other agronomic crops to projected global climate change varied between countries and sometimes within a country (Table III). Maize yields, in regional or national assessments, declined in response to global climate change scenarios in Côte d'Ivoire, Egypt, the Gambia, Kenya, and Zimbabwe (Makadho 1996). Wheat and rice yields also generally declined in 66% of the African countries conducting an assessment. The yield reduction was generally attributed to ambient temperature or precipitation changes, which reduced the grain-filling period of the crops studied. In contrast to other countries, Zambian regional crop responses (wheat, maize, soybean, rice and cassava (*Manihot*) to global climate change were highly variable. Although the African assessments include many of the most important crops worldwide, several countries also considered the vulnerability of other regionally important crops, such as barley (*Hordeum*), cotton (*Gossypium*) and groundnuts (*Apios*).

Overall, the results suggest that while agricultural impacts may not be catastrophic, especially when potential adaptation measures are considered, individual countries and regions within countries could experience significant negative or positive impacts (Rosenzweig and Parry 1994). While some crops may be less vulnerable to global climate change because increased CO_2 may enhance their growth, other crops (e.g. maize, sugar cane (*Saccharum*), millet (*Panicum*) and sorghum (*Sorghum*)) may be more vulnerable to global climate change. For instance, maize yields decreased in about two-thirds of the African countries, and this response is consistent with other continental studies of global climate change impacts (Watson et al. 1997).

Some countries found that current inter-annual climate variability may be of more immediate concern than long-term global climate change. For example, South Africa determined that the vulnerability of its agriculture sector to ENSO effects under current climate conditions is greater than the vulnerability to global climate change over the next 20 years. However, in 60 years the effects of global climate change could be as great as current ENSO effects. Other factors that are important in understanding vulnerability of African agriculture to global climate change include: warmer ambient temperatures generally increases pests and diseases harmful to crops; changes in frost-free dates may affect soil nutrient availability; and changes in precipitation may induce flooding or drought, causing direct physical impacts on agricultural lands (Rosenzweig and Parry 1994). The assessments also examined farm and ranch management adaptations that could mitigate global climate change impacts in the agriculture sector, including shifts to alternative planting dates and changes in fertilizer (Nitrogen) applications (Makadho 1996; Sanchez and Benites 1987).

While these adaptation options are hypothetically available, financial costs may be prohibitive to resource-poor farmers. Thus, farming may become an unacceptably risky activity in some regions of Africa.

Agriculture is the most important economic sector in many African countries and contributes up to 30% of GDP in sub-Saharan countries and 55% of all African exports (Gregerson et al. 1989; Rosenzweig and Parry 1994). Farming and ranching in Africa is highly dependent on seasonal rainfall, a situation that makes this continent highly vulnerable to global climate change. Historically, droughts have had serious impacts on food security, particularly in the Horn of Africa and southern Africa. Adaptation options could be employed, even those as basic as traditional coping strategies to extreme weather events, but in the long term these countries' adaptation capabilities are hindered by widespread poverty, recurrent droughts, and inequitable land distribution (Watson et al. 1998).

3.3. Grasslands and Livestock

Eight African countries conducted vulnerability analyses for the grasslands and livestock (e.g. cattle) sector: Botswana, Ethiopia, the Gambia, Mozambique, South Africa, Tanzania, Uganda and Zambia. Country teams evaluated specific ecosystems or regions, because there is considerable variability within countries. A sustained increase in mean ambient temperatures results in significant changes in rangeland species distribution, composition, patterns and biome distribution (Hanson 1993). Although not directly comparable across all countries in the assessment, average biomass generally increased for warm-season grasses and decreased for cool-season forbs and legumes as optimal grassland conditions migrated from low

TABLE IV

Change of annual run-off for 5 African countries based on results from GCFM models

Country	Change in Annual Run-off	
	Minimum	Maximum
Botswana	-53%	+17%
Côte d'Ivoire	-22%	- 4%
Ethiopia	-33%	+40%
The Gambia	-69%	+63%
Malawi	-40%	+162%

to high latitudes. African desert organisms are already at tolerance levels and may not be able to adapt.

In the African country studies there appear to be smaller impacts on livestock yields than on grassland biomass, because livestock can adjust consumption (e.g. cattle can graze over a larger area should grassland productivity decline). To some extent, this implies current excess capacity of grasslands in the livestock sector or that analysts are assuming that the area of production can increase. Several countries discovered that changes in inter-annual climate variability could influence grassland and livestock productivity. For example, South Africa found that because seasonal variability is already a major concern for farmers and increased variability or extreme climate events would be detrimental to the production of livestock. Some countries did find positive net impacts of global climate change, such as Tanzania, where scenarios with increased precipitation and temperature led to increased rangeland carrying capacity (CEEST 1998).

3.4. Water resources

All but one of the countries in the USCSP assessment, Zimbabwe, conducted an assessment of global climate change impacts on water resources. While most of the vulnerability analyses of water resources focused on run off that is, the portion of precipitation on land that ultimately reaches rivers or lakes, some countries also considered factors such as water supply and demand, flooding and drought, river salinity, water quality, irrigation, and hydroelectric generation (Mutua 1996; Strzepek et al. 1996).

Botswana, Côte d'Ivoire, Ethiopia, the Gambia and Malawi all observed significant changes in annual run-off in response to the global climate change scenarios selected in this assessment (Table IV).

Of the 19 countries around the world currently classified as water-stressed, more occur in Africa than any other continent (Watson et al. 1997). The reduction in precipitation projected by some GCMs for the Sahelian and southern African countries, if accompanied by higher inter-annual variability, could be highly detrimental to the hydrological balance of the continent and water-dependent activities (Hailemariam 1999). A drop in the water level in reservoirs and rivers could adversely affect the quality of water by concentrating sewage and industrial effluents, thereby exacerbating water-borne diseases and reducing the quality and quantity of fresh water available for domestic use (Strzepek and Kaczmarek 1996).

Developing adaptation strategies for fresh water resources affected by global climate change is complicated by the fact that water supplies could either increase or decrease, based on inter-annual precipitation patterns and extreme events. Therefore, countries may need to plan adaptation strategies for both drought and flooding conditions (Smith and Lenhart 1996). In spite of the uncertainties about global climate change impacts on water resources, there are many adaptation strategies that are likely to reduce long-term vulnerability and current climate variability, regardless of whether run-off increases or decreases (Frederick et al. 1997).

Several types of adaptation options were evaluated by the African countries (Smith et al. 1996a). These assessments accounted for future uncertainties regarding water supply and quality. Five countries evaluated options to increase domestic water supply, either nationwide by adding or upgrading storage capacity, or locally through interbasin transfers. Interestingly, four of the countries noted the possibility of increasing water use from international river basins (e.g. the Nile River) although this option was not always feasible. Implementing such an option would require international cooperation. Botswana considered technological or outreach options to decrease the demand for water. These options involved programmes to either increase efficiency in use or find ways to decrease demand, such as decreasing irrigated farmland or switching to crops that require less water (Frederick et al. 1997).

3.5. Forests

Twelve of the 14 countries participating in the USCSP assessment conducted forest sector vulnerability assessments (Table I). These studies evaluated changes in the forestland area and biomass based on the Holdridge Life Zone classification system (Holdridge 1967). This assessment method does not consider CO_2 fertilization, which could enhance forest growth and reduce water demand (Neilson et al. 1998).

Most of the African countries reported a shift in forest type in response to the global climate change scenarios examined (e.g. subtropical forests changing to tropical forests). Kenya and Zimbabwe found that changes from dry to moist forest or vice versa were largely driven by changes in precipitation regimes rather than shifts in ambient temperature (Kariuki et al. 1997; Maraira and Mwamuka 1996). Generally, biomass declined under most GCM scenarios. However, some countries such as the Gambia found potential increases in forest biomass.

Within many African countries, global climate change impacts are amplified by current non-sustainable land-use practices such as subsistence farming, deforestation and forest degradation (Barnes 1990). For example, in Zambia, more than 80% of households use either fuelwood or charcoal for their domestic energy requirements. Zambia is currently losing 250,000–300,000 ha of its forest cover annually to human activities, and a decrease in forest productivity could make the situation worse. Zambia concluded that climatic changes that affect the resilience of forest vegetation types could grossly affect income and welfare.

In Cameroon and Ghana, from 1970 to 1990, forest area declined 0.6–1.3% annually due to deforestation and forest degradation (Dixon et al. 1996a, 1996b). The areal distribution of remaining forests in these two countries are projected to shift 5–15% based on the GCMs employed in this assessment. Loss of forest habitat in Cameroon and Ghana due to land use is projected to dramatically increase plant and animal species loss (Alpert 1993; Dixon et al. 1996b). Application of traditional low-input, indigenous forest resource management, which has been practised on a sustainable basis for centuries, may be a feasible adaptation option (Dixon et al. 1996). These traditional forest management options may also be effective tools to sequester and conserve carbon (C) pools in low-latitude West African forests (Unruh et al. 1993; Dixon et al. 1994).

3.6. Fisheries

Five African countries, Botswana, the Gambia, Kenya, Mauritius and South Africa, conducted fisheries vulnerability assessments. Global climate change is projected to alter freshwater temperatures, water chemistry (e.g. oxygen levels), and circulation. Qualitative analyses suggest that fish in small rivers and lakes – or where temperature or precipitation changes are greatest – are most at risk. Significant portions of people in African countries depend on fish for protein, thus near-term impacts on the fishery sector may also affect human nutrition and health (Hlowhowskyj et al. 1996). Fish farming (e.g. aquaculture) and transplanting are two practical adaptation options in some regions of Africa.

Marine and estuarine fisheries of Mauritius will likely be warmer and the change in thermal niches will alter species distribution and productivity. Estuarine fisheries will also be affected by sea-level rise, which could inundate wetlands and allow salt water to move inland. Loss of coral reefs, due to bleaching and other factors, will adversely affect habitat and fish populations (Watson et al. 1996). Coastal protection measures, such as bulkheads or dikes, are possible but very costly relative to GDP (Mimura 1999).

3.7. Wildlife and ecotourism

The impacts of global climate change on African wildlife have not been intensively studied relative to other anthropogenic impacts (Markham 1996). Wildlife is likely to be affected by ambient precipitation and temperature changes, as well as by geographic shifts in ecosystems (habitat). Animals dependent on intermittent streams or lakes may be at particular risk. Migratory species such as birds are likely to alter the timing of their migrations and could be at risk if prey and other food are no longer available. In addition, wildlife is likely to be affected by ecosystem changes such as shifts in vegetation and availability of prey. The IPCC concluded that wildlife populations in Africa are at particular risk from drought (Watson et al. 1998).

Two countries, Malawi and Zambia, used the Habitat Suitability Indices (HSI) to examine the vulnerability of key species to climate change (Mkanda 1999). Although it is difficult to generalize from only two country assessments, the vulnerability of wildlife to global climate change primarily appears to be a function of changing habitat. Current human activities may be causing habitat fragmentation, which is probably the greatest current stress on wildlife. This could be exacerbated under extreme or rapid global climate change impacts.

In Malawi, vulnerability studies reveal potential declines in nyala (*Tragelaphus*) and zebra (*Equiferus*) in Lengwe and Nyika national parks (Mkanda 1999). Nyala is a vulnerable species that may not adapt easily to climate-induced habitat changes. In contrast, if increased ambient temperature is accompanied by lower precipitation, as projected in two GCM scenarios, ecotourism might increase because increased ambient temperature could improve accessibility to parks with dry lands. However, eco-tourists might be less likely to visit the parks because of the loss of nyala.

In Zambia, increased or decreased rainfall could significantly affect wildlife habitat through changes in rangelands and bushlands (under increased precipitation) or desert-like conditions (under decreased rainfall). In addition, increased or decreased precipitation would significantly affect the behaviour and habitat of migratory wetland species. Given the vulnerability of Zambian wildlife to drought and habitat disturbance, it is likely that global climate change, whether it leads to increased or decreased rainfall, could dramatically affect the size, distribution and diversity of many populations (Markham 1996).

3.8. HUMAN HEALTH

Five African countries conducted assessments in the human health sector (Table I). Each country found that human health is sensitive to climate and synoptic weather patterns, because many maladies are related to temperature and precipitation regimes. Higher temperatures can increase the incidence of heat stress, as well as spread of infectious diseases such as malaria and dengue fever. For example, because of their cooler temperatures, the East African highlands have low risk of malaria. Higher temperatures would make the climate suitable for the survival of malaria-carrying mosquitoes. In contrast, higher temperatures would also reduce risks of health problems related to cold, such as cardiovascular mortality (Patz and Balbus 1996). Zambian analyses reveal that malaria, bilharzia/schistosomiasis, cholera, dysentery, bubonic plague, and malnutrition could be exacerbated by global climate change. Human populations especially at risk include those that live in poorly ventilated structures or lack clean water and sanitary services. A key factor affecting the vulnerability of human health is the strength of the public health systems. Countries with weak public health systems may be at more risk because they would be less able to prevent or contain outbreaks of diseases or other health problems associated with global climate change (Watson et al. 1996).

4. Summary and Recommendations

The IPCC distinguishes between sensitivity, how a sector is directly affected by global climate change (e.g. change in agronomic crop yield); adaptability, how a system could respond to global climate change (e.g. crop rotation); and vulnerability, the net effect after sensitivity and adaptability are evaluated (Watson et al. 1996). The African assessments presented in this report focused on identifying global climate change sensitivities and adaptability of sectors. Without thorough consideration of underlying socio-economic changes, integrated impacts, and adaptability in sensitive sectors, only preliminary conclusions regarding the vulnerability of African countries to global climate change can be drawn from these assessments (Benioff et al. 1996).

The African continent is vulnerable to the impacts of global climate change in many socio-economic sectors including coastal resources, agriculture, forest, wildlife and ecotourism, and human health (Watson et al. 1996). This vulnerability is exacerbated by widespread poverty, recurrent droughts, inequitable land distribution, environmental degradation and stress, natural resource mismanagement and dependence on rain-fed agriculture (Amadore et al. 1999). A wide range of adaptation options have been identified for key sectors in representative countries of Africa. However, the underdeveloped human and institutional capacity of African countries, coupled with the absence of key infrastructure, renders traditional Western coping strategies ineffective. Such response options are well beyond the financial resources of most African countries (Smith et al. 1996b).

Future African country vulnerability and adaptation assessments could be improved by:

- Developing more robust or incremental regional or local-global climate change scenarios coupled with GCMs (Watson et al. 1996);
- Refining methods for developing baseline socio-economic scenarios and incorporating the results into vulnerability and adaptation assessments;
- Applying state-of-the-art/science assessment models and tools that can be used by analysts in African countries;
- Designing vulnerability assessments to produce results that can feed directly into adaptation assessments (CEEST 1998);
- Coupling fundamental research with assessments in each socio economic sector;

- Developing protocols for assessing adaptation options across a suite of countries (Smith and Lenhart 1996);
- Examining adaptation analyses that are useful to decision and policy makers (Gelil et al. 1997).

Based on the vulnerability assessments completed by national teams, Egypt and Tanzania are developing action plans that integrate results from their studies into comprehensive national policy responses (Table I). African countries can use these action plans as the basis for their National Communications to the FCCC (UNFCCC 1992). Many African countries are integrating global climate change concerns into other national planning activities and processes (e.g. national environment plans), as well as catalysing consensus and support for global climate change adaptation measures that will contribute to sustainable development (CEEST 1998; Gelil et al. 1997).

Acknowledgements

Dr Dixon was formerly Director, U.S. Country Studies Program (USCSP) 1993–1998. The multiple contributions of the USCSP Management Team and over 500 African country analysts to this report are gratefully acknowledged. The authors thank Dr Neil de Wet for his review of the early draft of the chapter.

References

Alpert, P.: 1993, 'Conserving biodiversity in Cameroon', *Ambio* **22**, 44–49.

Amadore, L., Huq, S., Kipondya, W.D., Korkorin, A., Martinez, J., Mkanda, F., Pilifosova, O., Ramos-Mane, C., Wu, Z., Benioff, R., Owens, B., Sathaye, J., Meyers, S., Braatz, B. and Smith, J.: 1999, *Climate Change: Mitigation, Vulnerability and Adaptation in Developing and Transition Countries*, US Country Studies Programme, Washington, DC, USA.

Barnes, R.F.W.: 1990, 'Deforestation trends in tropical Africa', *African J. Ecol.* **28**, 161–173.

Benioff, R., Guill, S. and Lee, J. (eds.): 1996, *Vulnerability and Adaptation Assessments: An International Handbook*, Dordrecht, The Netherlands, Kluwer Academic Publishers.

Boer, G.J., McFarlane, N.A. and Lazare, M.: 1992, 'Greenhouse gas-induced climate change simulated with the CCC second-generation general circulation model', *Bull. Amer. Meteor. Soc.* **5**, 1,045–1,077.

CEEST: 1998, *National Action Plan on Climate Change in Tanzania*, Dar es Salaam, Tanzania, The Centre for Energy, Environment, Science, and Technology.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C. and Wisniewski, J.: 1994, 'Carbon pools and flux of global forests systems', *Science* **263**, 185–190.

Dixon, R.K., Guill, S., Hlohowskyj, I. and Mkanda, F.X. (eds.): 1995, 'Vulnerability and adaptation of African ecosystems to global climate change', *Climate Research* **6**, 1–140.

Dixon, R.K., Perry, J.A. and Hiol Hiol, F.: 1996a, 'Carbon sequestration and conservation in forest systems: preliminary assessments in Ghana and Cameroon', *Envir. Prof.* **18**, 112–118.

Dixon, R.K., Perry, J.A., Vanderklein, E.L. and Hiol Hiol, F.: 1996b, 'Vulnerability of forest resources to global climate change: case study of Cameroon and Ghana', *Climate Res.* **12**, 127–133.

El-Raey, M.: 1997, 'Vulnerability assessment of the coastal zone of the Nile Delta, Egypt, to the impacts of sea-level rise', *Ocean Coast. Zone Manag.* **37**, 29–40.

El-Raey, M., Dewidar, K. and El Hattab, M.: 1999, 'Adaptation to the impacts of sea-level rise in Egypt', *Climate Res.* **12**, 117–128.

Frederick, K.D., Major, D.C. and Stakhiv, E.Z.: 1997, 'Water resources planning principles and evaluation criteria for climate change: summary and conclusions', *Climatic Change* **37**, 291–313.

Gelil, I.A., El-Mahgary, Y. and Khella, A.F.A.: 1997, *Egypt's Policies and Measures to Mitigate Climate Change*, Cairo, Organization for Energy Conservation and Planning.

Graham, R.L., Perlack, R.D., Prasad, A.M.G., Ranney, J.W. and Waddle, D.B.: 1990, *Greenhouse Gas Emissions in Sub-Saharan Africa*, Oak Ridge National Laboratory, Oak Ridge, No. ORNL-6640, USA.

Gregerson, H., Draper, S. and Elz, D.: 1989, *People and Trees: The Role of Social Forestry in Sustainable Development*, Washington, DC, USA, EDI Seminar Series, The World Bank.

Hailemariam, K.: 1999, 'Impact of climate change on the water resources of Awash River Basin, Ethiopia', *Climate Res.* **12**, 91–96.

Hansen, J., Russell, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R. and Travis, L.: 1983, 'Efficient three-dimensional global models for climate studies: models I and II', *Monthly Weather Rev.* **111**, 609–622.

Hanson, J.D.: 1993, 'Comparison of the effects of different climate change scenarios on rangeland livestock production', *Agric. Syst.* **41**, 487–502.

Hlohowskyj, I., Brody, M.S. and Lackey, R.T.: 1996, 'Methods for assessing the vulnerability of African fisheries resources to climate change', *Climate Res.* **6**, 97–106.

Holdridge, L.R.: 1967, *Life Zone Ecology*, San Jose, California, Tropical Science Centre.

Houghton, J.T., Filho, L.G., Callander, B.A. and Varney, S.K. (eds.): 1992, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge, UK, Cambridge University Press.

Houghton, J.T., Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds.): 1996, *Climate Change 1995: The Science of Climate Change*, Cambridge, UK, Cambridge University Press.

Houghton, J.T., Filho, L.G., Bruce, J., Lee, H., Callander, B.A., Haites, E., Harris, N. and Marshall, K. (eds.): 1995, *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, Cambridge, UK, Cambridge University Press.

Ikeme, J.: 2003, *Climate change adaptational deficiencies in developing countries: the care of sub-saharan Africa*. Mitigation and Adaptation Strategies for Global Change **8**, 29–52.

Jallow, B.P., Toure, S., Barrow, M.M. and Mathieu, A.A.: 1999, 'Coastal zone of the Gambia and the Abidjan region of Côte d'Ivoire: sea-level rise vulnerability, response strategies and adaptation options', *Climate Res.* **12**, 129–136.

Kaczmarek, Z.: 1993, 'Water balance model for climate impact analysis', *ACTA Geophys. Polonica* **41**, 1–16.

Kaoma, J., Nkomoki, J. and Mulenga, P.: 1997, *Vulnerability and Adaptation Assessment*, Environmental Council of Zambia.

Kariuki, J.G., Omenda, T.O., Oballa, P.O. and Kamweti, D.M.: 1997, *Potential Impacts of Climate Change on Forests in Kenya*, Nairobi, Kenya, Ministry of Research, Technical Training and Technology.

Leatherman, S.P., Nicholls, R.J. and Dennis, K.C.: 1995, 'Aerial videotape-assisted vulnerability analysis: a cost effective approach to assess sea-level rise impacts', *J. Coast. Res.* **14**, 15–25.

Leggett, J., Pepper, W.J. and Stewart, R.J.: 1992, 'Emissions scenarios for IPCC: an update', in J.T. Houghton, B.A. Callander and S.K. Varney (eds.), *Climate Change 1992 – The Supplementary Report to the IPCC Scientific Assessment*, Cambridge, UK, Cambridge University Press.

Makadho, J.M.: 1996, 'Potential effects of climate change on corn production in Zimbabwe', *Climate Res.* **12**, 147–151.

Manabe, S., Stouffer, R.J., Spelman, M.J. and Bryan, K.: 1991, 'Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part 1: Annual Mean Response', *J. Climate Change* **4**, 785–818.

Mararira, C.H. and Mwamuka, F.C.: 1996, 'Vulnerability of Zimbabwe forests to global climate change', *Climate Res.* **12**, 135–136.

Markham, A.: 1996, 'Potential impacts of climate change on ecosystems: a review of implications for policymakers and conservation biologists', *Climate Res.* **12**, 179–191.

Mati, B.M. and Karanja, F.K.: 1997, 'Sensitivity of maize growing zones to climate change: The effect of climate change on maize production trends in zones III-IV of Kenya', *Kenya Country Study on Climate Change*, Nairobi.

Mimura, N.: 1999, 'National assessment results of climate change: impacts and responses', *Climate Res.* **12**, 77–230.

Mitchell, J.F.B., Manabe, S., Tokioka, T. and Meleshko, V.: 1990, 'Equilibrium change', in *Climate Change: The IPCC Scientific Assessment*, Cambridge, UK, Cambridge University Press.

Mkanda, F.X.: 1999, 'Drought as an analogue climate change scenario for prediction of potential impacts of Malawi's wildlife habitats', *Climate Res.* **12**, 215–222.

Mutua, F.M.: 1996, *Sensitivity of the Hydrologic Cycle in the Tana River Basin Due to Climate Change*, Nairobi, Department of Meteorology, University of Nairobi.

Mwandosya, M.J., Makundi, W.R., Meyers, S.P. and Wiel, S. (eds.): 1996, 'Greenhouse gas mitigation for African countries', *Envir. Prof.* **18**, 1–134.

Neilson, Ronald P., Smith, B., Kittel, T. and Viner, D.: 1998, 'Simulated changes in vegetation distribution under global warming. Appendix C', in R.T. Watson, M.C. Zinyomera, and R.H. Moss (eds.), *the Regional Impacts of Climate Change: An Assessment of Vulnerability*, Cambridge, UK, Cambridge University Press.

Patz, J.A. and Balbus, J.M.: 1996, 'Methods for assessing public health vulnerability to global climate change', *Climate Res.* **12**, 113–125.

Rosenzweig, C. and Parry, M.L.: 1994, 'Potential impact of climate change on world food supply', *Nature* **367**, 133–138.

Sanchez, P.A. and Benites, J.R.: 1987, 'Low-input cropping for acid soils of the humid tropics', *Science* **238**, 1,521–1,527.

Schlesinger, M.E. and Zhao, Z.C.: 1989, 'Seasonal climatic changes induced by double CO_2 as simulated by the OSU atmospheric GCM/mixed-layer ocean model', *J. Climate* **2**, 459–495.

Smith, J.B. and Lenhart, S.S.: 1996, 'Climate change adaptation policy options', *Climate Res.* **12**, 193–201.

Smith, J.B., Huq, S., Lenhart, S., Mata, L.J., Nemesova, I. and Toure, S.: 1996a, *Vulnerability and Adaptation to Climate Change: Interim Results from the US Country Studies Programme*, Dordrecht, Kluwer Academic Publishers.

Smith, J.B., Bhatti, N., Menzhulin, G., Benioff, R., Campos, M., Jallow, B., Rijsberman, F., Budyko, M.I. and Dixon, R.K. (eds.).: 1996b, *Adapting to Climate Change: An International Perspective*, New York, USA, Springer-Verlag.

Strzepek, K.M. and Kaczmarek, Z. (eds.): 1996, 'Water resources vulnerability and adaptation to climate change: the US Country Studies Programme', *Int. J. Water Res. Devel.* **12**, 109–229.

Strzepek, K.M., Yates, D.N. and El Quosoy, D.E.: 1996, 'Vulnerability assessment of water resources in Egypt to climatic change in the Nile Basin', *Climate Res.* **6**, 89–95.

Unruh, J.D., Houghton, R.A. and Lefebvre, P.A.: 1993, 'Carbon storage in agroforestry: an estimate for Sub-Saharan Africa', *Climate Res.* **3**, 39–52.

UNFCCC, 1992, *United Nations Framework Convention on Climate Change*, Geneva, Switzerland, United Nations.

Watson, R.T., Zinyowera, M.C., Moss, R.H. (eds.): 1998, *The Regional Impacts of Climate Change: An Assessment of Vulnerability*, Cambridge, UK, Cambridge University Press.

Watson, R.T., Zinyowera, M.C., Moss, R.H. and Dokken, D.J.: 1997, *The Regional Impacts of Climate Change: an Assessment of Vulnerability, Summary for Policy Makers*, Nairobi, Kenya, UNEP.

Watson, R.T., Zinyowera, M.C. and Moss, R.H. (eds.): 1996, *Climate Change 1995: The IPCC Second Assessment Report: Scientific-Technical Analyses of Impacts, Adaptations, and Mitigation of Climate Change*, Cambridge, UK, Cambridge University Press.

Wetherald, R.T. and Manabe, S.: 1988, 'Cloud feedback processes in a general circulation model', *J. Atm. Sci.* **45**, 1,397–1,415.

Wilson, C.A. and Mitchell, J.F.B.: 1987, 'A doubled CO_2 climate sensitivity experiment with a global climate model including a simple ocean', *J. Geophys. Res.* **92**, 13,315–13,343.

Yates, D.N.: 1996, 'WATBAL: An integrated water balance model for climate impact assessment of river basin run-off', *Water Res. Devel.* **12**, 121–139.