Desk Study: Impact Chains for Some Key Crops: Rice, Maize, Millet and Sorghum and Coffee

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Executive summary

The major climate stimuli such as temperature, precipitation (rainfall, flooding), salinization, tropical ozone and tropical storms show different biophysical and socio-economic impacts on four key agricultural crops namely rice, maize, millet, sorghum, and coffee. In view of this, an impact chain approach is employed to further understand the consequences induced by the climate stimuli, to understand the related implications on the crops, as well as to ascertain the required adaptation measures. In tropical areas (e.g. Asia), erratic rainfall, flooding during ripening, salinization and tropical storms cause major biophysical impacts on rice while maize production in Central America is affected primarily by drought, high temperature, storms and heavy rains. Millet and sorghum, mainly grown in dry areas of sub-Saharan Africa, are adversely affected by temperature extremes (too high or too low) whereas the absence of rainfall especially for sorghum during tillering, flowering and grain filling stages causes reduced yields. Lastly, coffee in Latin America is highly sensitive to the impacts of drought and temperature stress (frost, too high temperature).

Research in this field is narrow but evolving, and this paper pinpoints areas where the available knowledge base has to be underpinned and developed, such as improvement of millet/sorghum models, additional focus on perennial crops, consideration of impacts of soil variability and related soil and water resources. Local knowledge on resilience and adaptation practices should be encompassed in appropriate adaptation recommendations.

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Introduction

Agriculture is strongly influenced by climatic changes and diverse crops react differently to the various climatic stimuli. The present study looks at four key agricultural crops that are cash and staple crops essential for ensuring food security and income generation in the respective region (Mesoamerica, Africa, and Asia). The study uses an impact chain perspective to investigate the effects (biophysical and socio-economic) of different climate stimuli on these crops and proposes appropriate adaptation measures to counteract the relevant stimuli. Apart from presenting an overview of the state of knowledge of the impacts of climate stimuli on the considered crops, the study seeks to provide decision-makers with a first indication of where climate impacts may be felt earliest, and where interventions might be needed.

The present study was carried out within the framework of the project, Inventory of Methods for Adaptation to Climate Change (IMACC), which is funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) through its International Climate Initiative (ICI) and jointly implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and the Potsdam Institute for Climate Impact Research (PIK).

Climate impacts and crop modelling

Weather is a key factor in agricultural productivity, despite many technological advances. Climate change is leading to changes in global and regional climates which turn to have severe impacts on the growth of crops as well as on activities associated with agriculture and distribution of food. There is now an extensive and still a growing body of research which considers the impact of climate change and severe weather events on crops and agricultural systems and also applies modelling techniques to simulate their impacts on agriculture. A brief overview of important changes is provided – concerning water and precipitation, extreme weather events, changes at the land surface and CO_2 fertilisation.

Water and precipitation

Agriculture of any kind is significantly influenced by the availability of water. Climate change modifies rainfall, evaporation, runoff, and soil moisture storage. Therefore, changes in total seasonal precipitation or in its pattern of variability are relevant in crop production. The occurrence of moisture stress during flowering, pollination, and grain-filling is harmful to most crops and particularly so to maize and wheat. Increased evaporation from the soil and accelerated transpiration in the plants themselves will cause moisture stress. As a result, there is a need to develop crop varieties with higher drought tolerance. Varieties of crops may have improved responses to heat, cold, drought, salinity and flooding, or the ability to resist specific diseases and pests. At the moment, such crop diversity is only partly reflected in crop models [White, 2011], which can lead to inaccuracies in research applications that are based on these crop models.

Extreme weather events

Extreme events such as drought, flooding, storms and landfalls of tropical cyclones can also have a devastating effect on crops. Unfortunately, the impacts of extreme weather events, especially of short-lived and localised events are not yet part of crop models. Thus, their effects have to be estimated outside such models. This is an area which will require more research efforts.

"*Flooding and submergence are major abiotic stresses and rank alongside water shortage, salinity and extreme temperatures as major determinants of species distribution worldwide. Success or failure of crops in much arable farmland can also be determined by the frequency and extent of flooding.*" [Visser 2003]

Changes at the land surface

The growth of crops alters the biophysical properties (e.g. biomass, photosynthetic activity) of the land surface, affecting surface energy balance and the atmosphere. Many current impact studies do not consider the effect of crops on their environment. Some cutting-edge models [Gornall 2010, Thornton 2009] incorporate a coupling between climate, crops and the characteristics of land surface. Both the crop and the atmosphere evolve dynamically within such models and can respond to, and influence, each other.

CO_2 fertilisation

One of the few benefits of increased levels of greenhouse gas in the atmosphere is CO_2 fertilisation. Crops that utilise the C_3 photosynthetic pathway (i.e. rice and coffee) benefit more from increases in CO_2 concentrations than those that utilise the C_4 pathway[1]. In general, optimum temperatures for photosynthesis in C_3 plants are between 20 °C and 25 °C, while for C_4 plants optimum temperatures are between 30 °C and 40 °C. The food crops maize, millet and sorghum belong to the latter class. Estimates (with reference to the global circulation models, GCM) of increased crop yield due to increased CO_2 are about 17% for rice and 7% for maize for a doubled (700 ppm) CO_2 when using 350 ppm as the baseline value (approx. for year 1990). An analysis of 15 years of FACE (Free-Air Carbon dioxide Enrichment) studies, found in 2004 that the response to elevated CO_2 using only FACE estimates slightly increases yield in crop plants (e.g. 5-7% in rice). However, by 2010 a somewhat different (and more comprehensive) picture has emerged, with significant difference in response being observed for different plant species responding also to water availability and the concentration of ozone (O_3). Opposing the effects of elevated CO_2, ozone can nearly offset the associated growth enhancement effect. "*Enhancement of aboveground*

[1] C_4 photosynthesis is advantageous under low atmospheric CO_2 and/or high temperatures. The advantages of C_4 photosynthesis occur in lower CO_2 environments and/or high temperature environments, where photorespiration rates are relatively high in C_3 plants [Ehleringer, 2002].

biomass under elevated CO_2 is partly to completely offset by the increased O_3 levels expected in the future."[2]

This desk study focuses on the impact chains, which demonstrate how a given climate stimulus propagates through an agricultural system via the direct and indirect impacts. Potential impacts of climate change hinder agricultural production which is as a result of deficiencies in yields of the considered crops, and the related socio-economic impacts.

More generally, climate impact chains are the connecting threads / cause-and-effect chains that link climate change stimuli with their potential impacts and adaptation measures.

Methodology

A literature search was conducted looking for studies that analyse the impact of climate stimuli on the different crops. Scientific journal articles and other reports were evaluated. Several researchers were contacted for further input. In addition, the consultant had access to internal GIZ documents.

A first call of reference is the "UNDP Climate Change Country Profiles" resource when considering climate change information for countries which are significantly larger than the dimensions of the General Circulation Model / Global Climate Model (GCM) grid cells. For smaller countries (e.g. some of the countries of Central America), regional climate projections are used, where available[3]. An additional sources has been the newly released "Climate: observations, projections and impacts" reports, published by the Met Office Hadley Centre and associated institutions, available for 23 countries, many of which are relevant for this study [COPI 2011]. Also, a comprehensive and systematic review on food crop productivity for Africa and South Asia has been recently published [Knox 2011], which highlights that for many crops the projected changes in yields are still highly uncertain, especially in the near-future. Climate analogues [Ramírez-Villegas 2011] may offer another way forward while these uncertainties persist.

The climate change analysis and conceptualisation of impact chains are essential for climate proofing. By defining a system of interest or exposure unit for analysis, the essential components of the system are examined along an impact chain with respect to the direct and indirect impact of relevant climate change trends. The sensitivity, adaptive capacity, exposure to climate signals and potential impacts of the system are explored and adaptation

[2] Ground-level ozone concentrations are typically highest in suburban and rural areas, and downwind from emissions sources such as urban or industrialised centres, as elevated NO levels destroy ozone (NO reacts with O_3 to form NO_2). This may complicate realistic modelling and evaluation.

[3] Climate projections have for quite a few years followed SRES (Special Report on Emissions Scenarios), for the next IPCC report (AR5) this is being replaced by RCPs (Representative Concentration Pathway). See e.g. Intergovernmental Panel on Climate Change (2007):"Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies". IPCC Expert Meeting Report (19-21 September, 2007, Noordwijkerhout, The Netherlands). At URL http://www.ipcc.ch/pdf/supporting-material/expert-meeting-ts-scenarios.pdf

measures are identified to either strengthened the adaptive capacity or reduce the sensitivity of the system [GIZ 2010].

Climate Change Signs

Each of the geographical regions and often the countries in them, too, have specific climate change signs – in some cases it is possible to cluster some countries together. Apart from the UNDP Profiles mentioned above, the SEDAC (Socioeconomic Data and Applications Centre) resource on global food production is an important guideline, for rice and maize. However, separate climate stimuli are not available, only SRES[4] scenarios at different time slice. A crop study [Rosenzweig and Iglesias, 1990] had sensitivity analysis for changes in temperature (+2°C, +4°C) and precipitation (±20%). However, extreme events were not taken into account.

For crop cultivation in Africa, projected impacts relative to current crop production levels range from -100% to +168% in econometric, from -84% to +62% in process-based, and from -57% to +30% in statistical assessments [Müller 2010].[5] This means that the reference database is not accurate enough to predict figures that are more precise in describing the projected impact of climate change on crop yields.

Headline results – the most relevant climate stimuli for the key crops:

Rice: Flooding, Drought

Maize: Drought, Heat waves

Millet and Sorghum: Drought (through climate variability), prolonged high temperatures

Coffee:[6] Temperature increase / variability (with maybe more risk to frost exposure at higher altitude); pest can also pose more of a threat; drought, particularly in marginal areas / excess rainfall

Sensitivity and impacts chains of key crops

A recent review of literature [Gornall 2010] states that: "… concerning a wide range of processes through which climate change could potentially impact global-scale agricultural

[4] Special Report on Emissions Scenarios (used for IPCC Assessment Report 4 and work based on the same).

[5] **Econometric models** derive statistical relationships among farmers' incomes, production systems, and environmental conditions, which is strongly limited by available reference data and the assumption that statistical relationships can be extrapolated over a period of several decades into the future. **Statistical models** of agricultural productivity often have little explanatory power and generally are, like econometric approaches, unsuitable for extrapolation to novel conditions such as climate change**.** **Process-based models** are often limited by the lack of site-specific parameterisation of management options and varieties and the risk of overturning.

[6] Work at Kew Gardens has identified the following climatic stimuli for wild Arabica in Africa: temperature seasonality, mean temperature of warmest quarter, precipitation of driest month, mean temperature of wettest quarter – [private communication with A Davis]

productivity, and presents projections of changes in relevant meteorological, hydrological and plant physiological quantities from a climate model ensemble to illustrate key areas of uncertainty. Few global-scale assessments have been carried out, and these are limited in their ability to capture the uncertainty in climate projections, and omit potentially important aspects such as extreme events and changes in pests and diseases. There is a lack of clarity on how climate change impacts on drought are best quantified from an agricultural perspective, with different metrics giving very different impressions of future risk. The dependence of some regional agriculture on remote rainfall, snowmelt and glaciers adds to the complexity. Indirect impacts via sea-level rise, storms and diseases have not been quantified. Perhaps most seriously, there is high uncertainty in the extent to which the direct effects of CO_2 rise on plant physiology will interact with climate change in affecting productivity. At present, the aggregate impacts of climate change on global-scale agricultural productivity cannot be reliably quantified."

In the country lists below country names which are <u>underlined</u> have "UNDP Climate Change Country Profiles", if the country name is in *italics*, it means that it is probably too small for the profile to be of much value.

How to use the sensitivity charts

The tables list, for each crop, a number of climatic stimuli and how they impact the crop in various development stadia (biophysical impacts) and socio-economic impacts.

Crop sensitivity chart				
Climatic stimuli	Production phase			
	Germination	**growth/ flowering/fruit setting**	**ripening**	**harvest**
temperature				
Rainfall				
etc.				

The climatic stimuli include: temperature, water sensitivity, drought, rain intensity, ground level (tropospheric) ozone, soil salinization (increased evaporation as well as rising sea water level) and CO_2 level, CO_2 concentration; and other factors which are critical for various stages of plant development.[7]

The colour coding is as follows ("traffic-light system"):

- Red high negative impact

[7] Initially, UV was also considered, however, UV does not have much impact on its own and not enough is known about synergist impacts; a review in 2003 found that out of 129 studies on the effects of UV-B only 25 used experimental conditions and supplemental UV-B irradiance that approached realism [Kakani 2003]).

- Yellow medium negative impact
- Green low or no negative impact (dark green positive impact)
- Blue impact disputed
- Grey not very relevant at present
- [white] if no information present

Coverage of climatic stimuli is uneven for both crops and regions considered, with more information available for rice and maize crops, with less information on millet and sorghum.

Rice (Asia)

Short description of the crop: About 90 % of the world's total rice production is grown in Asia where it is the predominant dietary energy source for 17 countries. More than a billion people (about one fifth of the world's population) depend on rice cultivation for their livelihoods. In addition, rice is the staple food of over half the world's population. In Africa, rice is the fastest growing staple crop in terms of production. However, there is a big gap between demand and supply in sub-Saharan Africa, where rice is cultivated and consumed in 38 countries. In Latin America and Caribbean countries, rice has become one of the most important and fastest growing staple foods among urban consumers and the poor. Rice-based farming systems are the main economic activity for hundreds of millions of rural poor, many of whom do not own their own land. On average, rice accounts for nearly half of the extreme poor's (less than $1.25/day) food expenditure and a fifth of their total household expenditure [IRRI, 2002]

Case study: Disaster & Climate Risk Management in Agriculture Project – Bangladesh

Bangladesh has tripled its rice production in the last 40 years, from 10 million metric tons (mt) in 1971 to over 32 million mt in 2010. The North-West of Bangladesh has experienced more frequent droughts in recent years (approximately 1.3 million ha have been affected). Erratic rains harm the development of rice, especially while the plants are young / flowering. Drought conditions can also lead to an increase in salinity, which has a strongly negative impact on rice yields. Drought effects include [IRRI2012]:

- Inhibition of leaf production and decline in leaf area
- Closure of stomata – leads to reduced transpiration rate and reduced photosynthesis
- Leaf rolling – leads to reduction in effective area for light interception
- Enhanced leaf senescence (leaf deaths) – leads to reduced canopy photosynthesis
- Changes in assimilate partitioning – roots grow more, at the expense of the shoot
- Reduced plant height - reduced in plant height and reduced in the number of spikelets
- Delayed flowering (by up to 4 weeks)
- Reduced number of spikelets / spikelet sterility - water availability during flowering stage greatly affects spikelet sterility
- Decreased grain weight if drought occurs during flowering (as the net effect)

If too much water is in the paddy fields, this can damage the young rice plants. Recently, a new rice variety "scuba-rice" has been developed, which can cope well with being submerged for up to several weeks. Scuba rice was developed by the International Research Rice Institute (IRRI). In a recent field trial, after a 15 day flood, saw 95%–98% of the scuba rice plants recovering, while in the plots planted with a traditional rice variety, only 10%–12% of the plants survived.

Adaptation strategies include building of irrigation ponds that can double up as fishing ponds, co-planting of mango and other fruit trees (e.g. jujube).

Relevant countries: China, India, Indonesia, Bangladesh, Viet Nam, Myanmar, Thailand, Philippines, Japan, Pakistan, Cambodia, Republic of Korea, Nepal, Sri Lanka. Production constitutes nearly 95% of top-20 producers in 2009 according to FAO, with China and India accounting for over 50%.

Climatic Requirements of Rice Crop:

Water: Rice tolerates water logged conditions; grown as a low-land crop with standing water as well as upland crop under rain fed conditions; 200 mm of monthly rainfall for lowland rice and 100 mm for upland rice; requires a rainfall of 1250 mm during vegetative stage; no standing water at ripening stage; best suited for regions with assured water supply.

Temperature: Rice requires hot and humid climate; best suited for the regions having high humidity and prolonged sunshine; mean temperature around 22 °C throughout growing period; tolerates day temperature up to 40 °C; minimum of 10 °C for sprouting; optimum of 22 to 23 °C for flowering and 20 to 21 °C for grain formation; above 22 °C, respiration is accelerated and grain filling period is reduced (affect yield) [ICRISAT].

Relevant climate stimuli:

- Temperature - Many annual crops, including rice, have a threshold temperature above which seeds do not form properly. A brief episode of hot temperatures (> 32-36 °C) during flowering can devastate crop yields; large reductions in crop yield can also occur when there are breaks in the monsoon or unseasonal storms [Wassmann, 2009]. A recent study in tropical/subtropical Asia found that rice yields exhibit large but opposing sensitivities to minimum and maximum temperatures during ripening and vegetative phases [Welch 2010].
- Flooding - In the 2011 flood event in Thailand, a quarter of its main rice crop may have been lost [Reuters, 2011].
- Cyclones - Tropical cyclones can damage rice paddies through storm surges that flood low-lying delta areas with salt water.
- Pests and diseases - There are many pests and diseases that can affect rice and some of these pest and diseases could increase under climate change.[8]

Rice sensitivity chart				
Climatic stimuli	Production phase			
	germination	**growth/flowering/fruit setting**	**ripening**	**harvest**
temperature	some controversy			
rainfall	vulnerable to erratic rainfall			
drought	vulnerable			
flooding	vulnerable to prolonged flooding (except e.g. scuba rice)			

[8] For more details see a presentation by Bangladesh Rice Research Institute [BRRI 2008].

trop. ozone	harmful and leads to grain yield decrease			
salinization	problem in dry season			
CO_2 conc.	fairly strong positive effect			

Rice impact chain			
Climatic stimuli	**Biophysical impacts**	**Socio-economic impacts**	**Adaptation measures**
Temperature	Requires hot and humid climate with prolonged sunshine. Too high temperatures (above 40°C) can lead to reduced growth.		Use of heat tolerant cultivars (type of cultivar is region specific).
Rainfall	Highly vulnerable to erratic rainfall and drought periods especially during growth.		Additional irrigation during dry spells especially at growing stage.
Flooding	Tolerates waterlogged conditions during vegetative stage, however cannot withstand standing water during ripening stage (except for scuba rice).	Due to changes of the climatic situation and favourable climate stimuli, rice may be grown in areas previously excluded from rice production.	Drainage during ripening stage.
Tropical Ozone (especially near urban centres)	Reduced yield due to high ozone concentration.	Adverse climate stimuli may cause • Lower production therefore food insecurity, • Reduced income for farmers, • Increased demand for rice causing higher prices at local markets.	No measures applicable.
Salinization	Rice is sensitive to salinity, particularly during the seedling stage and in dry periods.		• Use of irrigation water with low salinity, • Use of salt tolerant varieties (regions specific), • Soil improvement measures (before plantation, flooding of fields helps washing out salts), plantation of soil extracting plants (region specific) as alternative crops.
Tropical storms	Rice is most vulnerable to damage at the heading stage of its development.		Introduction of early warning systems.

Maize (Central America)

Short description of the crop: Maize is the most important cereal crop in sub-Saharan Africa (SSA) and an important staple food for more than 1.2 billion people in SSA and Latin America. All parts of the crop can be used for food and non-food products. Maize accounts for 30−50% of low-income household expenditure in Eastern and Southern Africa. For about 900 million farmers and consumers in low- and middle-income countries, maize is the preferred food crop [IITA]. Well over 90% of resource poor maize farmers and consumers live in tropical and subtropical areas of Africa, Asia, and Latin America. Worldwide production of maize is estimated at 875 million tons (2011), with the largest producer, the United States, producing 42% [IGC, 2013].

Relevant countries: Mexico, Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama. Apart from Mexico (approx. 3% of global top-20), all the remaining countries are considered too small to produce significant amounts to be included in top-20 FAO stats.

Climatic Requirements of Maize Crop:
Water: Maize requires considerable amount of precipitation; 500 - 750 mm of well-distributed rain is required for proper growth; expends water economically and is a relatively drought-resistant crop; after germination and up to tasseling stage crop can tolerate less rainfall; requires more water during reproductive period; needs less water when developing towards maturity.

Temperature: Maize is a “warm weather” crop; thrives in a mean temperature around 22 °C and night temperature above 15 °C; requires considerable warmth from germination to flowering; cultivation not possible when day temperatures are less than 19 °C and night temperatures during the first 3 months falls below 21 °C; during flowering, noon temperature above 35 °C for several days destroys pollen and yields are drastically reduced (susceptible to early heat waves) [ICRISAT].

Relevant climate stimuli:

- Drought - in 2011 Mexico has experienced its worst drought in 7 decades, followed by a dry and warm winter period in 2012. The projected harvest figures are down to 20 million tons, a previous estimate for the 2011 maize harvest was 23 million tons. Compounding the effects of the drought was a cold snap at the start of 2011 [Reuters 2011, AP 2012].
- Hurricanes – Increasing extreme weather event like hurricanes can damage the region's maize crop and in the recent past there have been examples where damages from such storms (which are “weather shocks”) occurred. Tropical cyclone intensities are likely to increase in both the Gulf of Mexico and East Pacific basins with climate change, affecting the countries considered.
- Pests and diseases - There are a number of pests and diseases that can affect maize; however, not much general researches have been published on how climate change may affect such organisms in the regions of interest.

Maize sensitivity chart					
climatic stimuli	Production phase				
	germination	**growth/ flowering/ fruit setting**	**ripening**	**harvest**	**production/ storage/ other factors**
temperature	low temperature can be harmful	decreases growth and grain yield			
rainfall					
drought		affects grain filling			
flooding	damaging effect, but not well quantified				
trop. ozone	few studies, but found some decreases in yield				
salinization	good tolerance		poor tolerance		
tropical storms		hurricanes can damage crop through high wind / heavy rain			
CO_2 conc.	[weak effect, as C_4 plant]				

<table>
<tr><th colspan="4">Maize impact chain</th></tr>
<tr><th>Climatic stimuli</th><th>Biophysical impacts</th><th>Socio-economic impacts</th><th>Adaptation measures</th></tr>
<tr><td>Temperature</td><td>Low temperature causes germination inhibition, leading to growth and yield depression.

High temperature: decreased growth and grain yield, increased pest pressure and damage.</td><td rowspan="3">In general extreme weather events can cause:
• lower yield which leads to lower production therefore food insecurity, as well as reduced income for farmers,
• increased demand for maize causing higher prices at local markets</td><td>• Use of heat tolerant cultivars</td></tr>
<tr><td>Rainfall</td><td>High-intensity rains can cause increased erosion,

Absence of rainfall or long dry periods between rainfalls causes delay in germination and reduced growth or growth failure. Absence of rainfall during grain formation causes reduced grain filling and yield.</td><td>• In case of high rainfall, adopt erosion protection measures,
• Increasing soil water infiltration rates through soil improvement measures (e.g. increasing the organic matter content, crop rotation with deep rooting plants),
• Additional irrigation in case of absence of rain during germination and grain formation periods,</td></tr>
<tr><td>Flooding</td><td>Flooding during germination can cause reduced growth.</td><td>Change of field for growing maize in case of repeated flooding, application of soil amelioration measures (e.g. improved drainage).</td></tr>
</table>

Tropical Ozone (especially near urban centres)	Reduced yield due to high ozone concentration		No measures applicable
Salinization	High tolerance for soil salinity during germination. However, damages occur later on during growth and ripening.		• Change of cropping field , • use of salt tolerant varieties (region specific), • Soil improvement measures (before plantation, flooding of fields helps washing out salts), plantation of soil extracting plants (region specific as alternative crops. • Use of irrigation water with low salt content.
Tropical storms	Damage due to the layering of crop at ripening and harvesting stages.		Establishment of wind protection belts.

Millet / Sorghum (Africa)

Short description of the crop: Millets are major food sources in arid and semi-arid regions of the world, particularly in Africa; sorghum is considered as one of the main branches of millet. In arid, less developed regions of Africa, sorghum is an important food crop, especially for subsistence farmers. Grain sorghum is the fifth most important cereal crop grown in the world and it is a leading cereal grain produced in many African countries. Nigeria is Africa's largest producer of grain sorghum (worldwide, only USA and India produce larger quantities).

Relevant countries: Nigeria, Niger, Mali, Burkina Faso, Senegal, Uganda, Chad, Sudan, Ethiopia, Ghana, Tanzania, Gambia (production constitutes some 55% of top-20 producers in 2009 according to FAO).

Climatic Requirements of Millet Crops (Sorghum, Pearl Millet, etc.):
Water: Millet crops have low moisture requirement; drought resistant; exceptionally high capacity for soil water uptake through their root systems; crops become dormant during moisture stress but reverts to normal growth subsequently; Pearl Millet is more drought resistant than Sorghum; minimum of 280 to 350 mm rainfall is required for the crop to be successful and can be grown in areas having an average annual rainfall between 600-1000 mm.

From flowering to seed setting, a minimum of 2.5 mm of water per day for normal growth and 3.7 mm for higher yields is required; germination, tillering, flowering, and grain filling stages are critical periods for moisture stress.

Temperature: Warm conditions are required but millet crops can be grown under a wide range of conditions; can tolerate high temperature throughout its life cycle better than most other crops; best yields when the mean temperature around 26 to 29 °C during growing period (germination to harvest); higher yields are rarely obtained below a mean temperature of 24 °C; tolerates day temperature up to 40 °C; 26-30 °C temperature for optimal growth; minimum of 8 to 10 °C for germination [ICRISAT].

Relevant climate stimuli:

- Drought stress: In West and Central Africa (WCA), growing conditions of pearl millet (*Pennisetum glaucum*) are characterised, among other hazards, by highly variable beginnings and endings of the rainy season, and unpredictable drought stress at any time during the growing season [Haussmann, 2007). Sorghum is sensitive to flooding especially during 30 days after emergence.
- Pests and diseases: There are a number of pests and diseases that can affect millet / sorghum, however, not enough research have been published on how climate change may affect such organisms.
- Storms: Storms and strong winds can flatten sorghum during ripening and harvesting periods. Millets are shorter and less susceptible towards yield reduction by storms.

Millet and Sorghum sensitivity chart				
climatic stimuli	Production phase			
	germination	**growth/ flowering/ fruit setting**	**ripening**	**harvest**
Temperature	grain yield, pollen viability, and seed-set can be affected if temperatures are too high			
Rainfall	reduction with less rainfall			
Drought				
Flooding	[not much information]			
trop. Ozone	[not much information]			
Salinization	growth parameters and plant nutrient contents become decreased, and can depend on the cultivar			
CO_2 conc.	[small effect as C_4 crop]			

Millet and Sorghum impact chain			
Climatic stimuli	**Biophysical impacts**	**Socio-economic impacts**	**Adaptation measures**
Temperature	Low temperature causes germination inhibition, leading to growth and yield depression. Can tolerate higher temperatures during the life cycle. If temperatures are too	• In general lower yield leads to lower production therefore food insecurity, as well as reduced income for farmers,	• Use of heat tolerant cultivars (region specific)

	high seed set can be affected.		
Rainfall	High-intensity rains can cause increased erosion. Millet has a higher drought tolerance than sorghum: absence of rainfall for long periods causes delay in germination and reduced growth. Absence of rainfall during fruit formation causes reduced yield.	• increased demand for millet and sorghum causing higher prices at local markets	• In case of high rainfall, adopt erosion protection measures • Increasing soil water infiltration rates through soil improvement measures (e.g. increasing the organic matter content, crop rotation with deep rooting plants), • If possible additional irrigation during fruit formation throughout dry spells.
Flooding	Millet can withstand short periods of water logging; Sorghum is more sensitive especially during 30 days after emergence: prolonged flooding leads to yield reductions.		Change of fields for growing Millett and sorghum in case of repeated flooding, application of soil amelioration measures (e.g. improved drainage).
Tropical Ozone (especially near urban centres)	Reduced yield due to high ozone concentration		No measures applicable
Salinization	Millet is a salt tolerant annual crop while sorghum is less salt tolerant and higher salt concentrations in the soil reduce the yield drastically.		• Use of salt tolerant varieties (region specific), • Soil improvement measures (before, plantation flooding of fields helps washing out salts), plantation of soil extracting plants (region specific) as alternative crops.
Tropical storms	Damage due to the layering of crop, especially for Sorghum, at ripening and harvesting stages.		Establishment of wind protection belts.

Coffee (Latin America)

Short description of the crop: Coffee is one of the most valuable primary products in world trade, and in many years, second in value only to oil as a source of foreign exchange to producing countries. Its cultivation, processing, trading, transportation and marketing provide employment for hundreds of millions of people worldwide. Coffee is crucial to the economies and politics of many developing countries; for many of the world's Least Developed Countries, exports of coffee account for more than 50 per cent of their foreign exchange earnings. The world's largest coffee producing region is Latin America and the Caribbean. Production in Southeast Asia (e.g. Indonesia, Vietnam) is increasing steadily and has surpassed Africa [ICO].

Case study: How climate change will affect coffee & supply chains - comparative look at Nicaragua/Mexico

In Nicaragua, coffee is the largest national export, and over 30,000 coffee farmers' families rely on its production. Declines in prices at the beginning of the decade significantly affected production, and the sector's recovery was likely compromised by climate variability in later years, e.g., during El Niño of 2006. Climate models predict increasing stresses in years to come.

The projected mean annual temperature increase is just over 2°C by 2050, while annual precipitation will likely fall from 1740 to 1610 mm, a decrease of over 7%. As a consequence, the national production area will shrink from 114,600 ha today to 16,700 ha in 2050, a loss of 98,200 ha, or 85%. All this translates to an expected income loss of over US$74.7 million in 2050 alone, an 82.9% decrease from 2010.

However, opportunities exist to adapt to such changes. Part (67.9%) of the current production areas where coffee will likely lose suitability will remain apt for a range of other crops. In these regions, programs to promote the productive diversification may be successful. However, there are also regions (28.6%) where both coffee and other crops will lose suitability, mainly due to decreased rainfall. In such cases, non-agronomic options for economic diversification will have to be pursued [Laderach 2011].

Relevant countries: Brazil, Colombia, Peru, Mexico, Guatemala, Honduras, Costa Rica, Nicaragua, El Salvador, Venezuela -Coffee production constitutes 60% of top-20 producers in 2009 according to FAO, with Brazil accounting for nearly 1/3 of the total. Climate models for Mesoamerica indicate that the mean annual temperature will rise between 2 to 2.5°C which will influence coffee production (faster ripening of coffee berries induce low quality). The high-quality Arabia coffee variety that needs lower temperatures will, in the long run be replaced by the Robusta variety (lower quality) that is better adapted to higher temperatures and can even be grown in low altitude areas.

Climatic Sensitivities of Coffee (Arabica):
As temperatures rise, coffee will ripen more quickly, leading to a fall in quality; both mean and maximum temperature increases have an adverse effect on coffee yields. Episodes of frost can harm coffee plants. Drought has a negative impact on coffee. If shade trees themselves become more stressed (e.g. through drought) they need to be replaced by more hardy species adapted to harsher conditions. Marginal coffee growing areas are already being negatively affected by climate change. Work at Kew Gardens has identified the following climatic stimuli for wild Arabica in Africa: temperature seasonality, mean temperature of warmest quarter, precipitation of driest month, mean temperature of wettest quarter – [private communication with A. Davis].

Relevant climate stimuli:

- Drought stress - A review of the impacts of drought and temperature stress on coffee physiology and production concludes that drought and unfavourable temperatures are the major climatic limitations for coffee production; shading can be used as a means for buffering climatic fluctuations, as well as for increasing environmental sustainability [DaMatta 2006, Baker 2007].

- Pests and diseases - The pest and disease pressure will increase due to changes in temperature and rainfall. Even coffee at high altitudes will be more susceptible to the fungal disease, coffee rust (Hemileia vastatrix) and the coffee berry borer (Hypothenemus hampei).
- Hurricanes - Hurricanes can damage the region's coffee crop and in the recent past there have been examples where damage from such storms (including landslides) was very significant.

Coffee sensitivity chart

climatic stimuli	Production phase				
	germination	**growth/flowering/ fruit setting**	**ripening**	**harvest**	**production/storage /other factors**
temperature			speeds up ripening		pests
rainfall		flowering triggered by onset of rainy season	too little or too much damage fruits		
drought			fruits fall off		
flooding	e.g. from hurricanes, can cause landslides				
trop. ozone	[so far nothing published]				
salinization	[in the main areas of cultivation not very relevant]				
CO_2 conc.	probably positive, but not that well understood				

Coffee impact chain

Climatic stimuli	Biophysical impacts	Socio-economic impacts	Adaptation measures
Temperature	Low temperature, especially frost harms coffee plants. Higher temperatures speed up ripening, however, decreasing quality and higher pest infestation (coffee borer) may occur.	Damaged plants lead to lower harvest and thus to less income. Change in quality lead to less income.	Introduction of early warning systems especially for frost.
Rainfall	High-intensity rains cause increased erosion. Drought has a negative impact on coffee (reduced yield); too much rain damages fruit as well.	Shift of rain patterns causes reduced income for farmers due to lower production in „traditional" coffee zones.	• Erosion protection measures (contour bunds, mulching, and terraces). • Additional irrigation during dry spells.

			• Increasing soil water infiltration rates through soil improvement measures (e.g. increasing the organic matter content, crop rotation with deep rooting plants).
Flooding	Landslides and increased fungal infection (coffee rust) damages crops.	Damaged plants (by physical harm or pests) lead to lower yields and thus to reduced income.	Application of soil amelioration measures (e.g. Improved drainage).
Tropical Ozone (especially near urban centres)	Not known	Not known	No measures applicable
Salinization	Water for irrigation of coffee should be low in salinity.		• Use of salt tolerant varieties, • Use irrigation water with low salt content.
Tropical storms	Damage of coffee trees due to high winds leads to overall yield reduction.	Reduced yield means reduced income.	Establishment of wind protection belts.

Comments on quantitative crop modelling

For modelling temperature effects on crops, the following widely quoted statement sums up the current situation: "*Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation […]*" [Lobell 2008] and another one cautions: "*Crop simulation models are widely used to analyse temperature effects on crop growth, development, and yield. Unfortunately, temperature responses of models often are not examined critically to ensure that a model is appropriate for a given research application.*" [White 2005]. Another group chose the following title for their article to establish the uncertainties of modelling climate change impacts on crop production "*Wading through a swamp of complete confusion: How to choose a method for estimating soil water retention parameters for crop models*" [Gijsman 2002].

In addition, a recent and fairly comprehensive review of some 220 papers concludes: "*In conducting a preliminary review of papers that examined the simulated effects of climate change and increased CO_2 on agriculture, we encountered such a large diversity in how simulations were conducted and reported that efficient comparison of impact across studies appeared difficult at best.*" [White 2011].

Most of the studies on global agriculture assessed by Schneider et al. (i.e. IPCC AR4 WG2 2007) did not incorporate a number of critical factors, including changes in extreme events, or the spread of pests and diseases. The studies did also not consider the development of specific practices or technologies to aid adaptation. Hence, policy and decision makers should be careful when using the results of such studies because they do not consider the whole picture, that is far more complex and the value of those predictions is limited.

According to Knox 2011, rice production in Asia has no common pattern to the trend of the predictions, with positive to negative forecasts in the ratio of 2:3. Most of the studies suggest small variations; for the predictions on a country by country basis, the results are sensitive to the study area, methodology used, and the effects being predicted. For sorghum, effects of climate change appear to be negative when studying specific countries and around zero with the possibility of having positive and negative effects when regarding larger areas, with exception of the Sahel, where yield variation is forecasted to be negative. For millet, the predicted effects are reported to be both negative and positive when no adaptation measures are taken into account, again depending on the study area; in the 2030s millet yield could increase up to 8% in the Sahel; in Western Africa it might increase by up to 4% or decrease by 1%, while in the Central Africa region it is predicted to reduce by up to 20%.

Remarks on non-linear response-modelling, tipping points etc.

In more realistic models, non-linear responses to multiple variables (stimuli) are considered, some of which will have synergistic effects, while others will partially cancel each other out. Such non-linear models can exhibit behaviours which linear models lack, in particular they can switch from one state into another (hysteresis, bifurcation, tipping point) or behave chaotically, i.e. their results are sensitive to initial conditions. Under such circumstances a reliable prognosis becomes difficult if not impossible. Sampling the parameter space with multiple (and slightly different) model runs (ensembles) is a practical, if computationally expensive way forward. Recently identified tipping points that could have a major impact on the investigated crops are: West African monsoon, Indian summer monsoon and the El Niño / Southern Oscillation (ENSO) amplitude increase – all have a "low probability / high impacts" risk characteristic.

A recent research article on nonlinear heat effects on maize [Lobell 2011] denotes the risks posed by climate change and the likely mechanisms of potential damage from climate change: "*Present approaches to addressing both of these needs are limited, especially in developing countries. For example, simulation models have been calibrated mainly in temperate systems, do not include all potentially relevant processes, and are dependent on inputs that prescribe cultivar characteristics, management practices, soil properties and initial conditions, all of which are imperfectly known.*"

Conclusion

There is an extensive body of research covering effects of climate change on crops and a growing body of research and observations regarding the effects of extreme weather events on crops in published literature. Numerous crop models exist that allow simulations on how climate change will affect crop yields. Typically these models are driven by daily outputs from climate models and inherit uncertainties in projections, most notably uncertainties in future precipitation patterns. Adding to the spread of resulting yields, are the uncertainties in crop parameters, as used by the crop models. The best way forward in these areas are ensemble calculations and sensitivity tests for crop models; the resulting distributions should give policymakers some guidance. It is important to also include local knowledge on resilience and adaptation practices.

Much of the reviewed research literature focuses on the agronomic impacts of climate change on major annual crops, however, not much is currently known about the impacts on perennial crops, which are less adaptable and could therefore be more susceptible to potential damage. Some of these perennial crops are of high socioeconomic importance (e.g. coffee) and predicting the impacts of climate change on yield and quality will be needed to prioritize future adaptation strategies.

The study explores for four reference crops (rice, maize, millet\sorghum, coffee) the sensitivity, adaptive capacity and exposure to climate stimuli as well as their potential impacts and adaptation measures. Climate stimuli charts are developed to show which climate stimulus is most critical at different crop production stages. The following crop impact chain chart shows the biophysical impact of the different climate stimuli as well as the socio-economic impact and lists the possible adaptation measures for the respective crop. To provide detailed adaptation guidelines for other crops, respective charts (climate stimuli charts and crop impact chains chart) can be developed for practitioners on the basis of the samples provided in the report.

Research in future needs to be directed towards improved assessment of climate change in in agroecosystems in the following fields[9]:

- Extreme weather events of short duration need to be included in crop models. It may be worth collecting observational evidence and reported losses from the most recent decades, similar to the Local Climate Impact Profiles (LCLIPs) used in the UK.
- Improved millet/sorghum models and the provision of quality datasets are required.
- Few models focus on perennial crops and the requisite simulation modelling. However, perennial crops are more difficult to adapt when there is rapid climate change. Thus, this calls for developing of adequate perennial crop models (such as coffee).
- The selection of the simulation model has to be justified and the model has to be described with sufficient detail to allow a reader to understand how key processes are represented.
- The assumed baseline greenhouse gases and corresponding time period have to be clearly specified, ensuring that baselines for the simulations and for climate data are consistent with each other. When appropriate, current IPCC greenhouse gas scenarios should be used.
- It has to be stated which weather variables are modified and if applicable, how outputs from GCMs and/or RCMs are downscaled.
- Impacts of soil variability, which might include season to season differences in initial conditions and local spatial variation, need to be assessed.
- Adaptation strategies presented should also include a set of alternatives, preferably explored by consulting with producers and other stakeholders familiar with the target production environments.
- Examine impacts beyond economic yield, especially as related to soil and water resources.

[9] Some points adapted from [White 2011].

- Assess impacts in terms of risk, preferably using probability distributions rather than simple statistics such as coefficients of variation.
- To provide a balanced assessment of climatic risk in relation to other sources of variation, simulate effects of other sources of variability such as sowing dates and seed rates.
- Investigate suitability of crop-insurance which take weather events (e.g. via weather indices) into account. However, index insurances based on meteorological data bear the risk that the crop-loss of the individual farmer, particularly the small-scale farmer, may not be taken sufficiently into account (indices may be too coarse).

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Glossary & Abbreviations

Crop Models: are computer programs that mimic the growth and development of crops. Data on weather, soil, and crop management are processed to predict crop yield, maturity date, and efficacy of fertilizers and also other elements of crop production. The calculations in the crop models are based on the existing knowledge of the physics, physiology and ecology of crop responses to the environment.

GCM: General Circulation Model / Global Climate Model

GISS: Goddard Institute for Space Studies

IPCC: Intergovernmental Panel on Climate Change

IRRI: International Research Rice Institute

LCLIP: Local Climate Impact Profile

Metric: An analytical measurement intended to quantify the state of a system

Ozone: Ground level or tropospheric ozone (as opposed to stratospheric ozone)

RCM: Regional Climate Model (driven by output from a GCM)

RCP: Representative Concentration Pathway (for IPCC AR5)

SEDAC: Socioeconomic Data and Applications Center

SRES: Special Report on Emissions Scenarios (used for IPCC AR4 and work based on it)