World Water Council
World Water Forum

co-operative programme
on water
and climate

IUCN

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International
Water Association

Perspectives on water and climate change adaptation

The Water Variable – Producing enough food in a climate insecure world

This Perspective Document is part of a series of 16 papers on «Water and Climate Change Adaptation»

‘Climate change and adaptation’ is a central topic on the 5th World Water Forum. It is the lead theme for the political and thematic processes, the topic of a High Level Panel session, and a focus in several documents and sessions of the regional processes.

To provide background and depth to the political process, thematic sessions and the regions, and to ensure that viewpoints of a variety of stakeholders are shared, dozens of experts were invited on a voluntary basis to provide their perspective on critical issues relating to climate change and water in the form of a Perspective Document.

Led by a consortium comprising the Co-operative Programme on Water and Climate (CPWC), the International Water Association (IWA), IUCN and the World Water Council, the initiative resulted in this series comprising 16 perspectives on water, climate change and adaptation.

Participants were invited to contribute perspectives from three categories:

1. **Hot spots** – These papers are mainly concerned with specific locations where climate change effects are felt or will be felt within the next years and where urgent action is needed within the water sector. The hotspots selected are: Mountains (number 1), Small islands (3), Arid regions (9) and ‘Deltas and coastal cities’ (13).

2. **Sub-sectoral perspectives** – Specific papers were prepared from a water-user perspective taking into account the impacts on the sub-sector and describing how the sub-sector can deal with the issues. The sectors selected are: Environment (2), Food (5), ‘Water supply and sanitation: the urban poor’ (7), Business (8), Water industry (10), Energy (12) and ‘Water supply and sanitation’ (14).

3. **Enabling mechanisms** – These documents provide an overview of enabling mechanisms that make adaptation possible. The mechanisms selected are: Planning (4), Governance (6), Finance (11), Engineering (15) and ‘Integrated Water Resources Management (IWRM) and Strategic Environmental Assessment (SEA)’ (16).

The consortium has performed an interim analysis of all Perspective Documents and has synthesized the initial results in a working paper – presenting an introduction to and summaries of the Perspective Documents and key messages resembling each of the 16 perspectives – which will be presented and discussed during the 5th World Water Forum in Istanbul. The discussions in Istanbul are expected to provide feedback and come up with sug• gestions for further development of the working paper as well as the Perspective Documents. It is expected that after the Forum all docu• ments will be revised and peer-reviewed before being published.

5 The Water Variable – Producing enough food in a climate insecure world

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The Water Variable – Producing enough food in a climate insecure world

This paper serves as an input for the thematic, regional and political processes of the 5th World Water Forum and focuses on the challenges related to water, climate change and food security. Recent publications related to the anticipated impacts of climate change on water and agriculture are comprehensive, but a global analysis of specific impacts remains limited. The paper summarizes recent food production and food security trends and provides an overview of how climate change, through impacts on global hydrology, could impact food production, and consequently food security, in some key farming systems. However, as climate change is but one of many drivers of agriculture, climate change impacts need to be appreciated in relation to specific farming systems in order to identify appropriate adaptation measures. The paper highlights key drivers and presents possible responses, emphasizing that the scope of policy response will need to be broad if water institutions are to be effective in coping with climate change.

Preface

"*Adapt or Die*". This dramatic headline introduced an article in the Economist last September (2008), addressing the imminent need to focus more on adaptation to climate change, not least on the capacity of poor farmers in developing countries. The article presents data, which estimates that African farmers relying on rain-fed agriculture may loose on average $28 per hectare per year for each 1 °C rise in global temperatures. Although such estimates are speculative they point to the potential economic impacts of climate change at the level of an individual small holder.

Approximately 60% of global food production is derived from rainfed farming systems. The remaining 40% is derived from irrigated agriculture practised on 20% of the world's arable land. This split between rainfed and irrigated production sets the scene for a deeper consideration of the possible impacts of future climates on global food production and possible adaptation strategies. The annual variability in temperature and precipitation are fundamental aspects for agricultural production, but they are just one sub-set of inputs for food production. Fertilisers, pesticides, labour, mechanisation, storage and marketing systems all influence food production and availability to a lesser or greater degree depending upon the farming system (FAO, 2002). Nonetheless, soil moisture deficits and weather related crop damage (physical and biological) still remain the most prevalent constraints to primary agricultural productivity.

Any view of the anticipated impacts of climate change on food production needs to maintain a measured perspective of the relative importance of climatic factors in plant growth and plant/animal disease. It should also be stressed that farming systems are inherently adaptive. They have never been technically or socially rigid and fixed. Rather, they have been opportunistic, using available natural resources, technologies, institutions and market mechanisms to respond to changing human demands and environmental changes. Hence, a consideration of the implications of food production in relation to agricultural water management requires a systemic appreciation of precisely where water is instrumental in maintaining agricultural productivity.

Introduction

This paper is intended to contribute to the 5th World Water Forum as an input for the thematic, regional and political processes and is intended to provoke some discussions within the Forum on the relative significance of agricultural water management. It will briefly discuss some of the challenges related to water, climate change and food security[1], and present some examples of possible policy and management options/areas that merit further consideration. It does not attempt to provide a comprehensive overview of this vast subject area[2].

Numerous recent publications point to the anticipated impacts of climate change on water and agriculture (World Bank, 2007; IPCC, 2007; FAO, 2008a; Bates et al., 2008). However, global analysis of specific impacts on agricultural growth remains limited. Tubiello and Fischer (2007) couple an agro-ecological zone model to a global food trade model for a non-mitigated and a mitigated scenario to examine the impacts on rainfed agriculture. Fisher et al. (2007) deploy the same modelling approach to examine the possible impacts on irrigation water requirements. The resulting projections of agricultural growth, food insecurity and irrigation water requirements under mitigation assumptions are highly mixed with regional 'winners' and 'losers'. However, even with temperature and CO_2 forcing effects taken into account at global scale, the distinction between rainfed and irrigated production and their relative contribution to agricultural production has to be made. Soil moisture deficits in rainfed systems cannot be negotiated, and the production risk is a direct function of rainfall. As soon as irrigation technology is applied, the production risk is buffered by the availability of water withdrawn from store or from flows. Under these circumstances, crop yields are raised and cropping intensities can be doubled or tripled.

It is important to emphasize that climate change impacts on rainfed agricultural production are transmitted through soil moisture deficits and temperature increases. However, for irrigated production the primary impacts are transmitted through the overall availability of water resources. Even if the two production systems are subject to the same set of demand drivers (population growth, income growth), the factors of supply and the points of competition over water resources tend to be quite different. Rainfed agriculture does not have to compete for rainfall. Irrigated production, on the other hand, will continue to compete with other productive sectors and will have to account for its use not just in economic terms, but increasingly in social and environmental domains.

Food production trends

Over the last century, global food production has managed to match population growth. Despite a three-fold global population increase since the turn of the 1900s, global production is still enough to sustain 6.5 billion people even if such indicators as the ratio of global cereal stocks to utilization are declining. Indeed, FAO's latest figures indicate that global cereal production in 2008, estimated at 2,245 million tonnes, enough to cover the projected needs for 2008/09, estimated at 2,198 million tonnes, and to allow a modest replenishment of world stocks. But with only 431 million tonnes, the cereal stocks-to-utilization ratio, at 19.6 percent, is at its lowest level in 30 years.

It is also important to point out that the increase in cereal production in 2008 was accomplished by the developed countries who were able to respond rapidly to more attractive prices. Because of a greater elasticity of their supply relative to demand, they increased their cereal output by 11 percent. The developing countries, by contrast, only recorded an increase of 1.1 percent and if China, India and Brazil are excluded from this group, production in the rest of the developing world actually fell by 0.8 percent. Not surprisingly cereal imports bills for developing countries are estimated at 78 billion dollars in 2007/08 against 34 billion in 2005/06 reflecting a 127 percent increase over a period of two years.

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[1] The FAO (2002) definition of food security is: "A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and health life". FAO (2008a) also states: "To achieve food security, all four of its components must be adequate. These are: availability, stability, accessibility and utilization." According to Schmidhuber and Tubiello (2007), only the first of these four factors is routinely addressed in climate change simulation studies.

[2] or example, it does not include climate change aspects related to fisheries or forestry. There are many interesting, and challenging, perspectives, which a more comprehensive approach to climate change and food security would need to address.

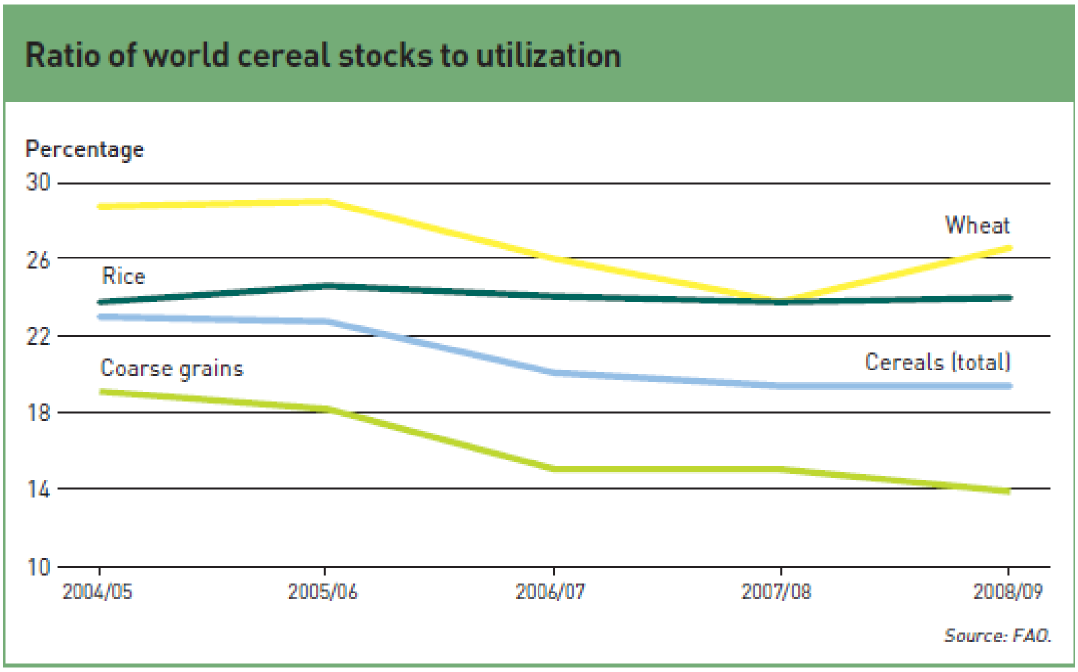

Figure 1: Ratio of world Cereal stocks to utilization. Source: FAO

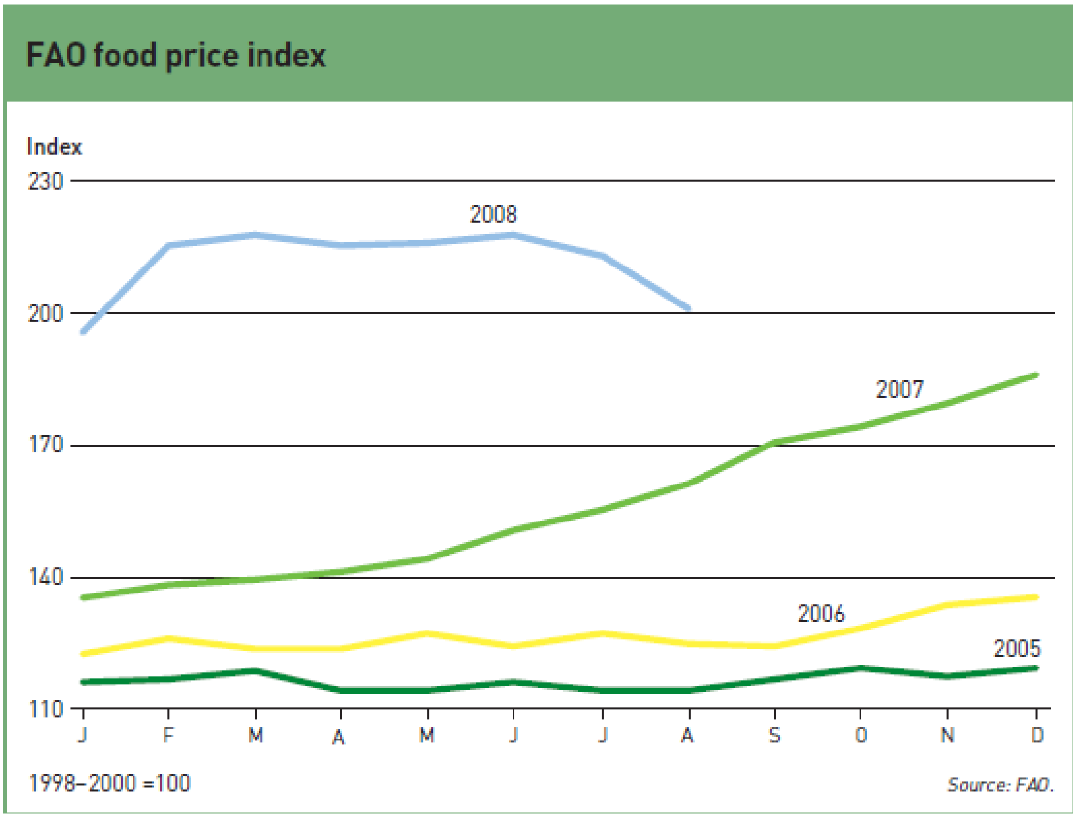

Figure 2: FAO Food Price Index. Source: FAO

The recent volatility in food commodity prices is a strong warning that the globe's food supply systems are not infinitely elastic. Against known trends in demand, disruptions to food supply through adverse weather or the unintended consequences of bio-fuel policies illustrate how sensitive both subsistence and intensive farming systems can be to external shocks (FAO, 2008c).

The increases in agricultural output in the 20th century can be attributed to horizontal expansion of arable land and the capacity to intensify production through the application of seed, fertiliser and pesticide technologies and the ability to store, divert and pump surface and groundwater. Such factors were largely behind the 'green revolution', a period characterized by significant increases in agricultural output in most parts of the world, and notably in countries such as India and China. Dams, diversions and other infrastructure harnessed water (lake, river and groundwater) resources for farming and energy production. In addition, increasing trade enabled food to be transported from surplus countries and regions to countries and regions which did not have enough food production capacity and/or chose to allocate land and water resources to other productive uses. Given the current volatility in global food production, the continued performance of the large contiguous areas of irrigated land needs and their related water infrastructure to be examined.

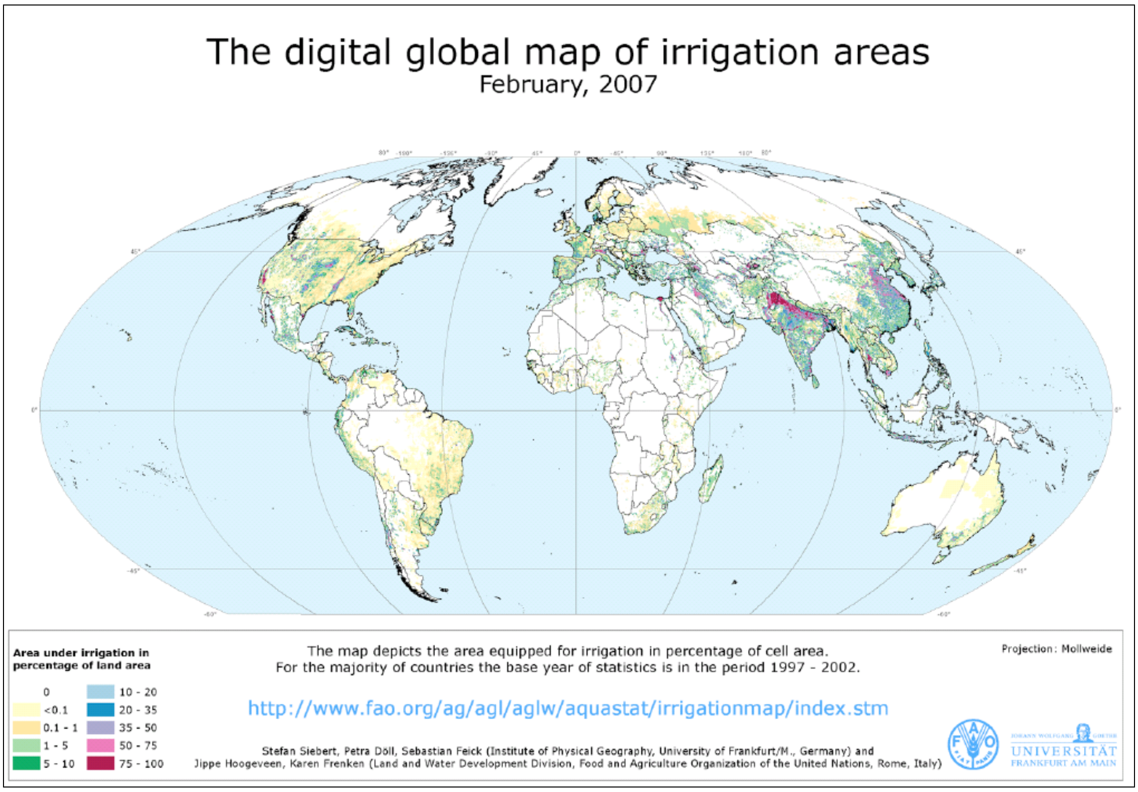

Figure 3: The digital global map of irrigation areas. Source: FAO and Universität Frankfurt am Main.

Food Security Trends

FAO recently presented a framework document on the interrelationships between climate change and food security (FAO, 2008a). This document clearly highlights the significant importance of climate change, but also makes it very clear that food security *"is the outcome of food system performance at global, national and local levels."* It requires a systems approach, as it is "*directly or indirectly dependent on agricultural and forest ecosystem services, e.g., soil and water conservation, watershed management, combating land degradation, protection of coastal areas and mangroves, and biodiversity conservation*".

Despite overall growth, global food security has not been achieved. The number of chronically hungry people in developing countries as a whole started to increase from the late 1990s, and by 2001–2003 the total number of undernourished people worldwide had increased to 854 million FAO 2008b). The recent rise in malnutrition (estimated at 40 million in 2008) to some 963 million people can, at least partly, be attributed to rising food prices[3].

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[3] http://www.fao.org/news/story/en/item/8836/icode.

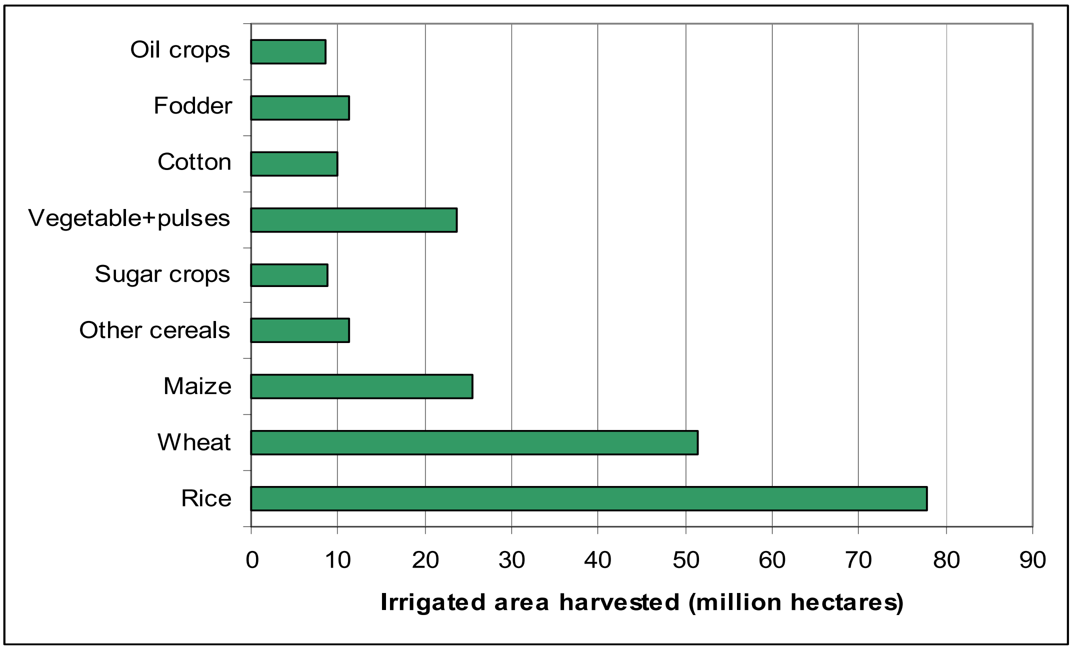

Figure 4: Distribution of crops under irrigation in the world (million ha). Source: FAO estimates based on data and information for 230 million hectares in 100 countries.

This increase has emerged despite political calls to halve the number of undernourished by 2015, made at the Global Food Summit in 1996 and later reiterated in the Millennium Development Goals in 2000. Notwithstanding such increases in absolute numbers, the total percentage of hungry people continues to decrease, but lately improvements have not managed to keep pace with the total population growth. In some regions, the negative trend has been steady over a longer time period. In southern and eastern Africa, the population of food-insecure people has more or less doubled over the last 25 years while per-capita cropped area has declined by 33% (FAO, 2006a).

A range of factors or drivers needs to be considered when looking more carefully at statistics. Population growth continues to be highest in regions with, generally, the least capacity to increase their food production. Insufficient infrastructure (for irrigation, storage, transport) prevails in many countries and regions. Poverty, civil strife, the lack of capacity to implement necessary management changes or investments and lack of human and financial resources are other factors. The impact of higher food prices, which can lead to increased hunger even if food is available, is evident now. But such price increases can be driven by higher costs for energy and other input resources, increased competition, market and trade failure or even market speculations.

FAO projects that a combination of future population growth and economic growth will push food requirements to double current levels by the 2050 (FAO, 2006a), including an increase of grain production from 2 billion to more than 4 billion tons. Current food production consumes more than 2500 billion m^3 of water annually, or 75% of total freshwater consumption (FAO, Aquastat database 2008). This level of demand will have far reaching consequences for the allocation of water resources between all productive economic sectors.

The fact that more than 900 million people in developing countries currently remain undernourished can be attributed to lack of access to food rather than a lack of global capacity to produce enough food. Even though global food stocks are falling and recent agricultural growth has been very sluggish, the global capacity to produce (and waste) food has not been cited as a direct cause of malnutrition. Nonetheless, a combination of limited food stocks and volatile energy costs clearly played an important role to push up consumer prices during 2008 (FAO, 2008b). Given that rising population and incomes drive demand for food in a predictable pattern, will climate change amplify further food supply shocks and will these shocks lead to shortfalls in production that impact global food security?

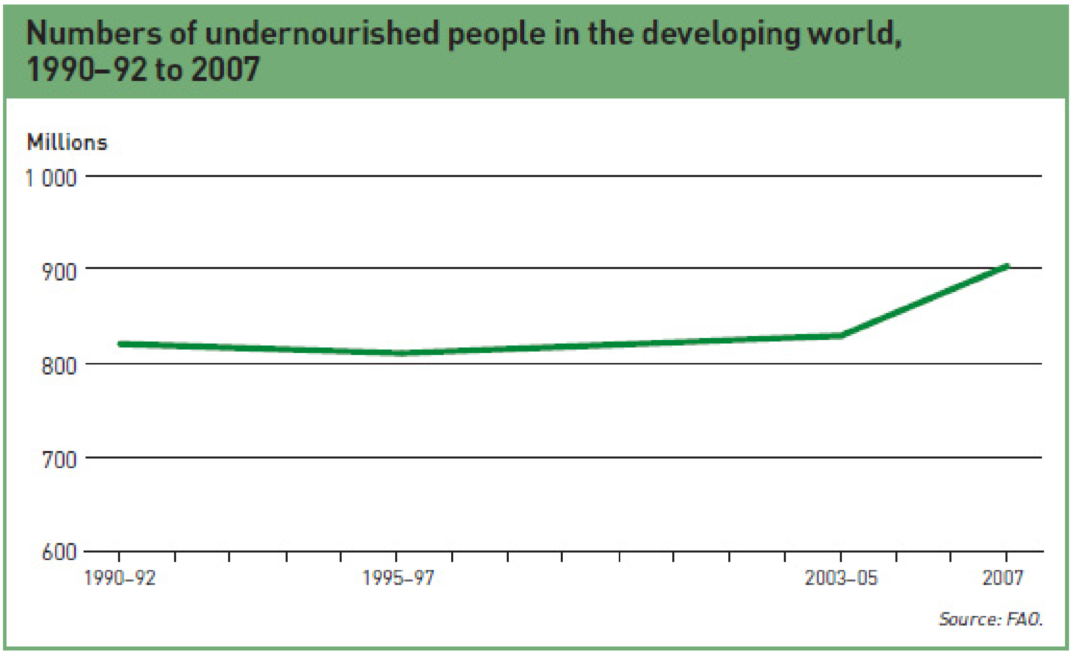

Figure 5: Numbers of undernourished people in the developing world, 1990–92 to 2007.

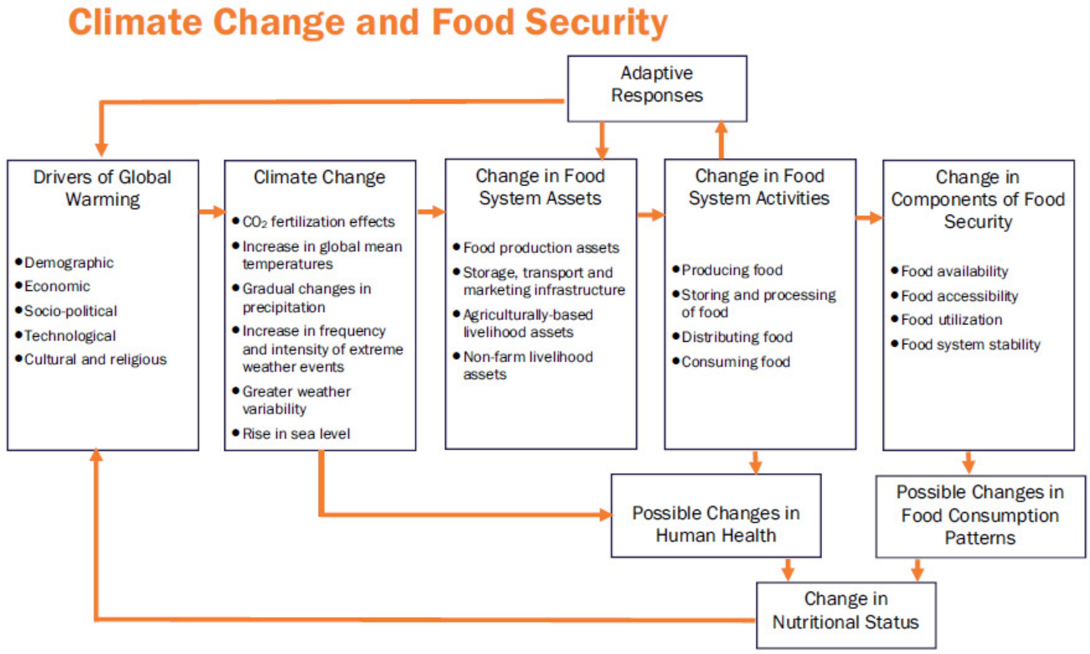

Figure 6: The interrelationships between climate change and food security. Source: FAO.

Anticipated impacts of climate change on global hydrology – transmission of impacts to agriculture

The Fourth Intergovernmental Panel on Climate Change Assessment Report (IPCC AR4), published in 2007, presents the state of the art knowledge, including important references to the modelled climate change impacts on water resources. A more detailed technical paper on climate change and water has been prepared by the IPCC (Bates et al., 2008) and provides a comprehensive synthesis. Since agriculture is practiced in most parts of the world, with the exception of interior deserts and the Polar Regions, all hydrological impacts are of significance to agricultural practice and production.

According to the IPCC AR4 "*warming of the climate system is unequivocal*" with considerable impacts on air and ocean temperatures, snow and glacier melting and a rising sea-level. Both IPCC (2007) and Bates et al. (2008) stress with high confidence that a number of hydrological systems have started to change following changes in climate, for example through increased runoff and earlier peak discharge in snow and glacier-fed river systems.

There is a globally increasing trend in precipitation over land areas of about 3.5 mm/year per decade but this is based on very short observational record (1986–2000) (Wild et al., 2008). Regional scales are more important than global averages. Increasing precipitation trends are evident from the eastern part of the Americas, northern Europe, and northern and central Asia since the beginning of the last century. Decreases have been observed in the Sahel region (from the mid 20th century), the Mediterranean, southern Africa and parts of southern Asia (e.g. IPCC, 2007 and Bates et al., 2008). Changes in precipitation and evaporation have more or less direct impacts on both river and groundwater systems. Already semi-arid areas are vulnerable to small changes, and many such areas are expected to see decreasing rainfall combined with increasing evaporation (from higher temperatures). Certainly, in terms of managing the shallow renewable groundwater circulation, the prospect of climate change should prompt a sharpened appreciation of recharge processes, storage changes and socio-economic response. In addition, for those aquifer systems decoupled from contemporary recharge, the planned depletion may need to be re-evaluated if those aquifers are going to become the lender of last resort.

Ocean temperatures are an important factor to determine changes in precipitation. Events such as the El Niño and La Niña in the Pacific Ocean clearly have strong impacts on regional (and maybe even global) climate, not least precipitation patterns. Recent decreases in precipitation over part of Africa have been attributed to the warming of the Indian Ocean sea-surface temperatures (Funk et al., 2008). The understanding of the coupling of such events to atmospheric circulation (such as El Niño – Southern Oscillation (ENSO),the North Atlantic Oscillation (NAO), and climate change is essential. ENSO, as an example, and the associated cycles of drought and flooding events, could explain as much as 15–35% of global yield variations in wheat, oilseeds and coarse grains harvests (Ferris, 1999).

Increased precipitation (in total or as more intense events within a confined time period) will augment the risks for floods, in particular in flood plains and other low-lying areas. Deltas are particularly vulnerable to changes. Increases in precipitation, with more intense run-off, in combination with higher sea-levels could cause increasing flood risks. Less precipitation (combined with increasing water diversions and use) could, also in combination with higher sea-levels, lead to more intense coastal erosion.

Most mountain glaciers are currently retreating (Lemke et al., 2007, UNDP and UNEP, 2007, 2008, Bates et al., 2008), which at least partly explains changes in annual net flow as well as temporal changes in some rivers. In the Hindu Kush range, changes in the river ecosystem resulting from decline in the glaciers and perennial snow have already been observed. Historically, high-level discharge in these rivers lasted throughout the cropping season, from April–September. It has now shifted into shorter, more intense run off in April and May, leaving increasing periods of the cropping season relatively dry (Eriksson and Jianchu, 2008).

Although total river basin discharges will normally first increase through increased melting, the long term effect will be less run-off as increasingly smaller glaciers and reduced snow-pack reduce storage of precipitation as snow and ice (Jansson et al., 2003). When (or if) a glacier eventually disappears, the effects on the seasonal availability of water in downstream regions can be dramatic. Such changes represent a serious challenge to the one-sixth of the global population that relies on melt-water from glaciers and permanent snow-packs for part of the year (IPCC, 2007), notably in China and India for example.

Extreme events transmitted through the hydrological cycle, can have severe direct impacts on agriculture. From 1992 to 2001, nearly 90 percent of all natural disasters were of meteorological or hydrological origin (e.g. WWDR, 2006). However, it is still difficult to detect trends in small-scale events such as dust storms, hail and tornados and there are no obvious long-term trends in relation to the annual number of tropical cyclones (IPCC, 2007). Although a substantial increase is evident in the Atlantic since the early 1970s, periods of equally high number have occurred earlier in the 20th century.

However, measured effects from extreme events are dubious. In part, this is in because the interactions are complicated and not linear, but also because a range of non-climate factors governs the observed effects. Modified landscapes and infrastructure development as well as changes in hydrological systems (river modification) strongly influence the effects of the climate signal. Flooding may increase in one area, but it remains a challenge for a planner to determine how much of the increase is due to climate change exacerbating precipitation and run-off and how much results form non-climate factors such as land use changes, river modifications etc. A drought may appear more straight forward, but the effects can be amplified by factors such as poor land management, land use changes and increased water use.

Regional rainfall projections and runoff are particularly interesting. Possible changes in runoff over the 21st century, based on results from 12 rainfall-runoff models, were presented in a paper by Milly et al. (2005). They show that there is a strong agreement between models on increases (10–40% by 2050) in the high latitudes of North America and Eurasia, in the La Plata basin of South America, in eastern equatorial Africa and in some major islands of the equatorial eastern Pacific Ocean. Similarly, decreasing average annual runoff (typically 10–30%) could be expected in southern Europe, the Middle East, mid-latitude western North America, and southern Africa. In other regions, there is less agreement between the models. An interesting and more detailed case also showing such challenges is the effort to predict rainfall changes over the Amazons (Li et al., 2006). Eleven models were used in the IPCC AR4 to predict rainfall. Out of these, five predicted an increase of annual rainfall, three predicted a decrease, and the other three models predicted no significant changes in rainfall. This is the planning reality many policy makers and managers will have to work from.

Precipitation patterns may also be affected by other factors. In a recent article in Nature, Cox et al. (2008) focuses on the increasing risk of Amazonian drought due to decreasing aerosol pollution. The correlations between such factors in this region can be difficult, as drought is a recurring phenomenon during El Niño – Southern Oscillation (ENSO) events. However, the drought occurring in 2005 did not correspond to such an ENSO event and it was therefore possible to look at other potential parameters affecting precipitation. This serves as an illustration of how difficult it is to find straightforward correlations and cause-effects. If there has been a significant cooling effect from relatively high atmospheric aerosol content, future warming could actually become even higher if we are successful in reducing the atmospheric content of such particles (see for instance Andreae et al., 2005).

Anticipated impacts on food production – how significant is the water variable?

The links between climate, water and food production may be complex, but the equation between temperature, water and plant physiology is essentially fixed. For any C3 (e.g. wheat) or C4 plant (e.g. maize), a fixed amount of evapotranspiration and carbon dioxide is required to assimilate carbon (Steduto et al., 2007). Put simply, more food or fibre production requires more soil water – whether it is derived from rainfall or from surface and groundwater sources through irrigation. While 'more crop per drop' may be an objective for overall management of irrigation and delivery of water to the soil horizon, any increase in biomass can only be attained through increased water availability in the soil horizon. While climate already determines what can be grown at any particular location, it is the range of hydrological changes that are anticipated under the various emissions scenarios that gives cause for concern. Impacts on crop production systems can be anticipated, from failure of rainfed crops in highland areas to inundation of irrigated crops in coastal deltas.

From a water management perspective, the first question to ask is how any climate change impact will translate to higher or lower temperatures and more or less water availability in the root zones of the staple crops upon which humans and animals depend. If this can be established with an adequate degree of precision for specific farming systems (Tubiello and Fischer, 2007; Fischer et al., 2007), the second question to ask is whether water management can facilitate the adaptation of farming systems to mitigate climate risk or exploit climatic opportunities. The levels of confidence attributed to the modelling of climatic impacts under the SRES emission scenarios notwithstanding, at the global level it is not a simple case of agriculture systems coping with higher temperature and less water. Purely in terms of climatic variables, the regional contrasts are significant. When super-imposed upon the mosaic of socio-economic development, the actual impact of climate on soil moisture availability and water supply to agriculture will be felt in terms of global food security as a second or third order effect. To the extent that water serves as the transmitter of climate changes to society, decisions over how water is allocated to meet basic human needs and the demands of productive sectors will constitute the primary adaptation measure.

Rainfed systems will be impacted by the first order effects of climate change – temperature, relative humidity and rainfall. Once soil moisture deficits in the root zone falls below the wilting point of staple crops, the assimilation of carbon and biomass is attenuated and yields fall off. Zero rainfall or lower than expected rainfall equates to zero or reduced crop yields and cannot be negotiated. Improvements to soil structure and moisture holding capacities can be made by agricultural practice, but if soils do not reach field capacity in any year, production will be zero or sub-optimal. Because of these first order effects, the productivity of rainfed systems under climate change assumptions can be modelled in terms of agro-ecological response (Fischer et al., 2007), but this does not detract from the fact that production from rainfed systems will continue to be inherently volatile. Under climate change projections, amplification of this volatility is expected.

Irrigated systems of all kinds, from village gardens to the large irrigation schemes associated with river valleys and coastal deltas are designed to buffer soil moisture deficits and remove the agricultural production risk both in subsistence and commercial farming systems. In this sense they have already adapted to climates with no or limited annual replenishment of soil moisture and will be impacted by second order effects of climate change – runoff and groundwater recharge. High temperatures and high insolation encourage growth of key staples such as rice, and low relative humidity keeps down pests and disease. Unlike rainfed systems, irrigated agriculture cannot be analyzed in the same way as the rainfed systems under Agro Ecological Zones (AEZ) assumptions (Fischer et al., 2007). Indeed AEZ modelling copes with irrigated areas as a 'mask'.

Regions already struggling with complex food-related challenges (marginal areas, subsistence farming, poverty, management challenges etc.) will clearly be more sensitive. The larger agricultural systems, such as the areas of continuous irrigation in Asia, may be more buffered in terms of runoff sources and recharge and the ability to apply technology, but basin-wide shifts in temperature, evapotranspiration and water availability would have greater impacts on global food supply. Assessing the scale impacts of climate change, hydrology and global food production is, therefore, a key challenge to modellers and statisticians. While there are a range of adaptation options already available, many of which are frequently used to cope with current climate variability, such options may only be suited to cope with moderate climate changes, but limited in dealing with more severe changes (Howden et al., 2007).

Thus, climate influences agriculture in various direct and indirect ways. Maximum, minimum and average temperatures set boundary conditions for crop growth, and changes in any of these parameters, therefore, have direct or indirect positive or negative effects on the food production potential of a specific crop and region. Temperature changes may eventually shift entire climate zones. Observations from many regions show that several natural systems are affected by regional climate changes (IPCC, 2007), but it remains a challenge to isolate the climate signal from other drivers of change occurring simultaneously. Direct effects from temperature changes on agriculture have been noted with 'medium confidence' in Northern Europe (IPCC, 2007) but are harder to detect in other parts of the world. Less extreme cold temperatures but more heat-waves are becoming increasingly likely (IPCC, 2007).

There is strong consensus that continued greenhouse gas emissions will cause further warming. In the shorter term, a range of emission scenarios points toward a 0,2 °C warming per decade. On longer time-scales (over the next century), scenarios indicate an increase between 1.1 and 6.4 °C (IPCC, 2007). Clearly, uncertainty remains high. As these are global averages, regional differences are likely to be substantial. Temperature increases are generally expected to be higher both at high latitudes and altitudes. For instance, the measured temperature increase at 3000 meters in the Himalayan region is three times higher than at sea-level over the last 100 years (Eriksson and Jianchu, 2008).

As argued above, the direct climate impacts on the hydrological systems are essential to agriculture. According to IPCC (2007) and Bates et al. (2008) climate change is in general expected to exacerbate water stress. This may have severe impacts, in particular in regions already under sever stress from population growth, rapid economic development, land-use changes, pollution and urbanization. The combined changes in both precipitation and temperature also affect groundwater recharge and run-off, and may therefore strengthen (warmer/less rain) or counteract (warmer/more rain) each other. IPCC points out that there is a high level of confidence that the negative impacts from climate change on freshwater systems will outweigh the potential benefits. As there will also be an intensification of the hydrological cycle, there are increasing risks of more heavy rain-falls, increasing direct crop damage and/or causing flash-floods and floods.

The direct impacts on food production depends on region and time scale. Although crop productivity is projected to increase some at mid- to high latitudes when mean temperature increases 1–3 °C, it is expected to decrease as the temperature increase becomes higher. In the seasonally dry and tropical regions, sensitivity to even small shifts in temperature is higher, and it is expected that productivity will decrease. In total (global scale), food production is projected to first increase but later decrease following continuously higher average temperatures. It is also important to consider other effects. The effects of CO_2 on plant growth present a good example. Although CO_2 acts as a fertilizer, it is the combination with the temperature changes and availability of nutrients which will give a net effect (Melillo et al., 1993 and Tubiello et al., 2007). CO_2 fertilization is, therefore, most profound in tropical wet climates and less so in cold climates. Other important aspects to consider are the changing patterns of weeds, pests and (pollinating) insects following changes in temperature and precipitation.

Although uncertain, IPCC also provides some disturbing examples of the effects that could be expected if not appropriately managed. In Africa alone, 75–250 million people are projected to be exposed to increased water stress, and yields from agriculture are expected to decrease as much as 50% in some countries. The area of semi-arid and arid land will increase. Land areas classified as very dry have already doubled since the 1970s (Bates et al., 2008). In Asia, freshwater availability in many large rivers may decrease and changes in water availability from glacier and snow melting will have extensive effects on water availability and thus indirectly on agriculture. In the Middle East, an increase in average temperature of 1 °C is likely to increase agricultural water demand by 10%. The costs can be significant and scenarios projecting a high significant temperature increase suggest costs equal to a 3,5% loss in GDP due to loss of arable land and threats to coastal cities (FAO, 2008d). In Latin America, there could be gradual replacement of tropical forests by savannah and productivity of some important crops is projected to decrease. Lobell et al., (2008) points out that South Asia and Southern Africa are two regions with food production based on crops that are likely to be negatively affected by climate change. However, the effects are in the end strongly dependent upon changes in other socio-economic parameters and the projected range of increasing numbers of hungry people in the future is very wide (Schmidhuber and Tubiello, 2007).

Climate change impacts are not only confined to developing countries. Agriculture and forestry is expected to become increasingly difficult in eastern Australia as aridity intensifies. In Europe, the already significant regional differences in water availability will increase and drought will be even more common in the Mediterranean region. North America will experience potential increases in rain-fed agriculture in the eastern and northern parts while decreasing snow and ice will reduce summer flows in already water scarce western regions. An article presenting potential hot-spots in North America represents an interesting overview (Kerr, 2008) of such challenges. In addition, there could also be severe effects on water quality, which, in turn, could have adverse effects on agriculture (e.g. Bates et al., 2008).

System	Current status	Climate change drivers	Vulnerability	Adaptability	Response options
1 Snow Melt Systems					
Indus System	Highly developed, water scarcity emerging.Sediment and salinity constraints	20 year increasing flows followed by substantial reductions in surface water and groundwater recharge. Changed seasonality of runoff and peak flows. More rainfall in place of snow. Increased peak flows and flooding. Increased salinity. Declining productivity in places	Very high (run of river): medium high (dams)	Limited room for manoeuvre (all infrastructure already built)	Water supply management: Increased water storage and Drainage; Improved reservoir operation; Change in crop and land use; Improved soil management; Water demand management including groundwater management and salinity control
Ganges Brahamaputra	High potential for groundwater, established water quality problems. Low productivity		High (falling groundwater tables)	Medium (still possibilities for groundwater development)	
North Western China	Extreme water scarcity and high productivity		High (global implications, high food demand with great influence on prices)	Medium (adaptability is increasing due to increasing wealth)	
Red and Mekong	High productivity, high flood risk, water quality		Medium	Medium	
Colorado	Water scarcity, salinity		Low	Medium: excessive pressure on resources	
2 Deltas					
Ganges Brahmaputra	Densely populated. Shallow groundwater, extensively used. Flood adaptation possible; low productivity	Rising sea level. Storm surges, and infrastructure damage. Higher frequency of cyclones (E/SE Asia); Saline intrusion in groundwater and rivers; Increased flood frequency. Potential increase in groundwater recharge.	Very high (flood, cyclones)	Poor except salinity	Minimise infrastructure development; Conjunctive use of surface water and groundwater; Manage coastal areas.
Nile river	Delta highly dependent on runoff and Aswan Storage – possibly to upstream development		High (population pressure)	Medium	
Yellow river	Severe water scarcity		High	Low	
Red River	Currently adapted but expensive pumped irrigation and drainage		Medium	High except salinity	
Mekong	Adapted groundwater use in delta - sensitive to upstream development		High	Medium	
3 Semi-arid / arid tropics: limited snow melt / limited gw					
Monsoonal: Indian sub continent	Low productivity. Overdeveloped basin (surface water and groundwater)	Increased rainfall. Increased rainfall variability. Increase drought and flooding. Higher temperature.	High	Low (surface irrigation); Medium (groundwater irrigation)	Storage dilemma; Increase groundwater recharge and use; higher value agriculture (Australia)
Non monsoonal: sub-Saharan Africa	Poor soils; Flashy systems; over-allocation of water and population pressure in places. Widespread food insecurity	Increased rainfall variability. Increase frequency of droughts and flooding. Lower rainfall, higher temperature. Decreasing runoff	Very high. Declining yields in rainfed systems. Increased volatility of production.	Low	
Non monsoonal: Southern and Western Australia	Flashy systems; overallocation of water; competition from other sectors		High	Low	
4 Humid Tropics					
Rice: Southeastern Asia	Surface irrigation. High productivity but stagnating	Increased rainfall. Marginally increased temperatures. Increased rainfall variability and occurrence of droughts and floods	High	Medium	Increased storage for second and third season; Drought and flood insurances; crop diversification
Rice: Southern China	Conjounctive use of surface water and groundwater. Low output compared to northern China		High	Medium	
Rice: Northern Australia	fragile ecology		Low	High	
Non-rice - surface irrigation			low	Medium	
Non-rice - groundwater irrigation			Medium	Medium	
5 Temperate (supplementary irrigation)					
Northern Europe	High value agriculture and pasture	Increased rainfall; Longer growing seasons; Increased productivity	Surface irrigation: medium; groundwater irrigation: low	Surface irrigation: low; groundwater irrigation: high	Potential for new development. Storage development; Drainage
Northern America	Cereal cropping; groundwater irrigation		Medium	Medium	Increased productivity and outputs; Limited optyions for storage
6 Mediterranean					
Southern Europe	Italy, Spain,Greece	Significantly lower rainfall and higher temperatures, increased water stress, decreased runoff	Medium	Low	Localised irrigation, transfer to other sectors
Northern Africa	Morocco,Tunisia: High water scarcity		High	Low	Localised irrigation, supplementary irrigation
West asia	Fertile crescent	Loss of groundwater reserves	Low	Low	
7 Small islands					
Small islands	Fragile ecosystems; groundwater depletion	Sea water rise; saltwater intrusion;increased frequency of cyclones and hurricanes	High	Variable	Groundwater depletion control; Water demand management

Table1: Climate change impacts and response options for agricultural water management, (FAO, 2008c).

Socio-Economic Drivers of Change

That climate change will determine shifting patterns of plant growth and present challenges and opportunities to current agricultural practice is not in dispute. But the rate at which any climate change will apply has to be considered against rates of change in the socio-economic systems upon which they are superimposed. Future socio-economic development will strongly influence the impacts of climate change on food security (Schmidhuber and Tubiello, 2007). The interaction with socio-economic drivers such as population and income growth has the potential to exacerbate and counteract the direct impacts of climate change. Management responses to environmental variability and socio-economic change are themselves varied, and have exhibited varying degrees of success and failure. For example, the Millennium Ecosystem Assessment (2005) finds that humans have changed ecosystems more rapidly and extensively than ever before in the last 50 years in order to meet our growing demands for food, freshwater, timber, fibre and fuel.

Below are presented a number of key drivers that will interact with climate change.

Population growth – Although the population growth rate has started to decrease, it is estimated that the global population will only level out at 8–11 billion around 2050. The best current guess is just above 9 billion, which means the global population will increase by almost 50% in 50 years. Regional differences will be dramatic and most of the population increase will coincide with countries already facing severe development and management problems or scarcity of resources (not least related to land and water).

Population distribution and dynamics – Populations will not only increase but also move. Urbanization will continue to drive development patterns. In 2007 humans became more urban than rural for the first time (United Nations, 2005). At the same time, 900 million people were confined to urban slums (WWDR, 2006). Urbanisation can exacerbate climate change impact on water by changing physical properties (run-off, soil water and groundwater recharge, evaporation, etc.), thus influencing the capacity for agriculture in the vicinity of the city, but growing cities are also a competitor for water. In addition, urbanization has a general impact on consumption patterns. The urbanization trend will continue and by 2050, the urban population is expected to have doubled.

Overall Economic development – Economic development can be both a negative and positive driver. There is, for example, a direct relationship between Gross Domestic Product (GDP) and diet, and as global economy is expected to grow at a rate far exceeding population growth, this is clearly a factor that needs to be considered. Economic growth tends also, in more general terms, to lead to increasing competition over natural resources, including land and water. At the same time, economic development also generates resources that can be reinvested in agriculture, for example to implement mitigation and adaptation measures to deal with climate change.

Consumption patterns – According to a recent report, the livestock sector generates more greenhouse gas emissions as measured in CO2 equivalent – 18 percent – than the transport sector. It is also a major driver of land and water degradation (FAO, 2006b). This is one example of how trends in consumption patterns can shape future resource use and impacts. With increased prosperity, people are consuming more meat and dairy products every year. Global meat production is projected to more than double from 229 million tonnes in 1999/2001 to 465 million tonnes in 2050, while milk output is set to climb from 580 to 1043 million tonnes. Understanding the effect of consumption patterns is also essential from a wider climate change mitigation perspective.

Natural resource constraints and competition – Development related drivers, such as economic growth, would increase pressure on natural resources. Resource constraints and increased competition are in themselves drivers that could have potentially serious effects on food production capacities – competition over land, water, energy, and fertilizers, just to mention a few. Constraints may be a result of the lack of adaptation to the physical limitation of the resource, weak distribution systems and lack of relevant infrastructure, capacity (management and economic) problems, or a combination of these factors. Economic development, urbanization and population growth will also require more resources for other 'sectors' – such as energy, industry etc.

Although there are economic activities that will 'compete' with agriculture, the energy sector is likely the single most important. Water and energy is intrinsically correlated, and it is through the shared requirements of abundant water resources that agriculture and energy are so closely linked. Climate change, making less water available in some regions, can entail increased competition (e.g. hydropower versus irrigation).

Energy production requires water resources in the production phase (hydropower, bio-energy, geothermal energy, wave and tidal energy) or for cooling purposes. Although not always a consumptive user of water, there are direct water related challenges, for example increased evaporation from reservoirs, water use for bio-energy production or water quality degradation. If current policies are maintained, global energy demands are expected to grow by as much as 55% until 2030 according to the International Energy Agency (IEA) 2007 World Energy Outlook. Developing countries are expected to account for 74% of the total increase. Although the statistics from the same agency stress that oil, coal and gas will continue to dominate, other sources of energy will also need to expand. Renewable energy production (including biomass and hydro-power) is expected to increase by 60% until 2030 but will, nonetheless, still only cover a very small portion of total energy demand.

Bio-energy – Bio-energy is a special case. Increases in bio-fuel production have direct impacts on water consumption and food availability. Although biofuels could be a potential for many poor countries, areas already or on the brink of experiencing water stress could see reduced water availability for more basic needs of people as well as for vital ecosystems. As Varghese (2007) states, "*the indiscriminate promotion of bio-fuel development as a 'cheap and green' energy option may interfere with optimal water allocation, and/or the pursuit of appropriate public water policies that will help address the water crisis*". Although bio-fuel feedstock currently accounts for only 1 percent of the total area under tillage, and a similar percent of crop water use, production is likely to grow rapidly. Impacts are still poorly understood. Demand for biofuels based on agricultural feed-stocks will be a significant factor over the next decades and it has already contributed to higher food prices (FAO, 2008c).

Dealing with uncertainty

It is important to stress that uncertainty, or simply the lack of data or information, should not be a reason for inaction. Investments are already needed to better cope with ongoing climate variability and changes, be they natural or human induced. Such investments, in hardware (infrastructure) or software (human capacity), are critical adaptation measures under current levels of uncertainty about the future. If adequately implemented on a 'no regrets' basis, they have the potential to make society better prepared for and less vulnerable to future climate change.

The need for more precise understanding of biophysical and social processes remains just as pressing, climate change or not. The wish-list could be extensive, but Bates et al. (2008) provide an interesting overview on some major gaps related to climate change and water. They note that the "*ability to quantify future changes in hydrological variables, and their impacts on systems and sectors, is limited by uncertainty at all stages of the assessment process*". There are observational needs, needs to better understand what the climate projections are really depicting and what the impacts would be and, not least, what the appropriate adaptation and mitigation options are. There is also a range of other complex changes and interrelationships that must be further addressed. How will sea-surface temperatures change due to climate change? How will the content of aerosols change? What are the effects of changing albedo due to land-use changes, changes in snow and ice cover etc. What are the feed-back effects of such changes? All such factors will have a substantial effect on our capability to project changes in precipitation, among other factors. Results from current climate models, which are often contradictory in relation to rainfall changes, serve as a clear example.

In addition, there are still knowledge gaps related to CO_2 and climate responses for many crops, including many that are important for the rural poor (Tubiello et al., 2007). For water resources or agricultural planners operating at the local or even national level, the global climate models will still need further refinements: "*There is a scale mismatch* *between the large-scale climatic models and the catchment scale, which needs further resolution*" (Kundzewicz et al., 2007). Projected temperature shifts are still mainly provided as regional or global averages and regional differences will continue to be substantial. For a farmer, such global averages are not very helpful and the challenge to make projections on a more regional and even local scale will remain and need to be improved. To strengthen the capacity to 'translate' shifts in global circulation to regional and local weather conditions is therefore essential. The understanding of the impacts of natural large-scale phenomena such as the El Niño – Southern Oscillation (ENSO) (see for example Meehl and Washington, 1996 and Ferris, 1999) or the North Atlantic Oscillation (NAO) events must also be further improved, as they have substantial weather related impacts on, e.g., agriculture.

Another example of knowledge gaps is the lack of information about development impacts in other sectors. In the case of Energy, for example, the future impacts from bio-energy production more or less remain as uncertain as climate change impacts. A few years ago, bio-energy was, at most, a parenthesis in discussions, regardless of whether the focus was on energy development or land, water and food issues. Due to the necessity for climate change mitigation strategies, the whole situation has shifted in just a few years. A dramatic production increase of bio-energy could drastically alter future water and land requirements – and thereby have a substantially greater impact on food production capacities than climate change itself. With some estimating that as much additional water is needed to meet bio-energy needs in a few decades (under current projections) as to meet our food needs, this issue will only grow in importance.

As such developments are more market driven, they are likely to progress much faster than our ability to conduct necessary research based assessments on potential impacts. Some targets are already set. What will be the impacts of the US Energy Policy Act of 2005, which promotes further use of bio-fuels, considering that by 2015 bio-fuels may account for about 23% of the country's maize output? What will be the impacts of the European Union target stipulating a 5.75% market share of bio-fuels in the petrol and diesel market by 2010? There are some signs that biofuel production contributed to the 60 percent increase in the price of maize between 2005 and 2007, because of the U.S. ethanol program in combination with reduced stocks in major exporting countries (World Bank, 2007). To make informed, long-term decisions, more knowledge is clearly required in these areas – but can we get it fast enough?

Responses to water and food challenges

Climate change, water and agriculture must be priority issues for policy and decision makers in the coming decades. The 2008 World Development Report (World Bank, 2008) made this case very clearly, pointing out that 75 percent of the world's poor live in rural areas in developing countries. At the same time, only about 4 percent of official development assistance goes to agriculture, although it has been increasing over the last few years (World Bank, 2007).

If a growing population is to be fed and the volatility of rainfed systems adequately buffered to maintain global food security, only the delivery of more water into the root zone of productive land can assure the required production. Socio-economic drivers and climate change impacts will condition where this can be achieved. In this respect rainfed systems will need to become more opportunistic, harvesting soil moisture where possible, and irrigated farming systems will need to become much more flexible in their use of limited water resource. It is at this point of competition for surface and groundwater resources that agricultural agencies will have to become much smarter and responsive to a broader array of socio-economic drivers. Agriculture has always been the residual user of available water resources, but is still the largest user and the only productive user of water with a negotiable margin. Improvements in potable water supply management will still need to be made when raw water is scarce, but the volume of use will remain insignificant when compared to that of agriculture.

Policies and actions related to climate change, water and agriculture clearly need to be better incorporated into existing key development related processes. To a large degree, the drivers causing the problems, and therefore holding the potential solutions, are outside the immediate domain of the water using sectors. In the face of such uncertainty, water institutions will need to become more flexible, capable of anticipating changes in user behaviour and then implementing an intelligent mix of water resource use and regulation.

Below, some key policy and management responses are presented to prompt discussion. It is important to remember that economic sector responses to climate change many need to be extensive, ranging from specific field-level investments to major shifts in public policy support.

1 **Access to information relevant for policy and management is a strategic issue.** Having access to relevant information for policy making and for the development of management responses will be a fundamental prerequisite to better cope with and adapt to changes. Scientific data and state of art knowledge needs to be translated into policy and management relevant information that could be of direct relevance to decision making at various levels. The issue of scale will be fundamentally important. Overview maps, such as a recent example presented in Science (Kerr, 2008) showing potential hot-spots or broad-scale analysis to identify major areas of particular concern (e.g. Lobell et al., 2008) could be vitally important as tools to better communicate potential climate change challenges and impacts on regional and even local scales. Such hot-spots are not necessarily confined to regions suffering from direct climate-related challenges (low or erratic precipitation, high annual and decadal variability) but could also be represented by regions with weak adaptation capacity (e.g. many developing countries) or high impact risks (e.g. low-lying coastal areas etc). The provision of more relevant information will require:

- **An increased focus on how climate change interacts with natural climate related processes.** As an effect of direct impacts from changes in temperature or indirect effects through climate change impacts on water resources (and other parameters), other drivers may exacerbate or reduce the overall climate change impact (positive and negative feed-back effects). Climate change will interact with important natural climate related phenomenon such as El Niño – Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). This can either strengthen or weaken the climate change signal, but our understanding is still superficial. As events such as ENSO and NAO have substantial weather related impacts of direct interest to agriculture, better understanding of climate change impacts on such events will be essential for improved regional and local projection capacities.
- **An increased focus on knowledge transfer and capacity building at the user's level.** For a farmer, urban planner or water resources manager, projected global climate change averages are not of real practical use. The capacity to make projections at regional and local scales need to be strengthened, and further investments are required to improve information disbursement and to strengthen the capacity of users to interpret and use such information, from the individual farm level to more large-scale urban planning or sector management strategies. However, as stated by FAO (2007) "*Improved access to knowledge is only theoretical for many in poor countries especially in rural areas*" as long as efficient technologies, including the internet, are not available. A range of methods to share knowledge at user level would therefore be appropriate.
- **Tools to better assess current technological solutions from a climate change adaptation perspective.** Technology and infrastructure will be essential to efforts to adapt to and mitigate climate change. They also, however, present challenges. Arguably, reliance on technological fixes has made us more vulnerable to previously climate change. If technology and investment has enabled agricultural practice to be pushed into marginal lands, then increased resource use has pushed some regions and countries close to or even beyond their natural resource limits. Hence technological progress may encourage a false sense of security and even inhibit adaptation measures. Therefore an assessment of the styles of water investment that can result in positive adaptation is an obvious first step. For example, the scope for high intensity investments such as dam storage to buffer production risk may need to be compared with economic result of dispersed low intensity investments in groundwater development and management.

2 **A focus on adaptation and mitigation strategies in agriculture that goes both deep and wide.** The integration of climate change-related challenges with other drivers is essential (Howden et al., 2007). If interacting drivers are not appropriately considered, there is a risk that investments will be made in vain or even become counter-productive. Land use

changes, large-scale water diversions, economic development, changes in consumption and production patterns (agriculture, industry), changes in population and population dynamics will all influence water resources availability and quality. In many cases these socio-economic changes may eclipse the local-regional manifestation of short to medium-term climate change. Reviewing such feedback systems needs a carefully measured application of science and economics, but a better understanding of such linkages forms the foundation for more effective policy interventions.

3 Shift the policy and management emphasis. The increasing focus on adaptation rather than risk mitigation is a positive step forward. But it is not enough. It will be essential to:

- **Increase focus on overall resilience building in all systems, particularly in the most vulnerable farming systems.** Moving from simply coping with impacts and managing risks to making well judged investments in adaptation and building long-term resilience needs sustained policy guidance. Ultimately, achieving improved resilience towards global changes, including climate change, needs to underpin more or less all planning and decision-making. In particular long-term and large-scale investments in water infrastructure and institutions need to be assessed in terms of their resilience.
- **Focus more on how the potential positive impacts of climate change can be harnessed.** Climate change will have beneficial impacts in some regions. Adaptation strategies also need to consider these implications in terms of local, national and international markets. For example, ensuring that agricultural production can increase in such regions in order to balance deficits elsewhere may require radical changes in food policy, particularly for countries that have cut back on their agricultural production capacity in recent decades.

4 Move beyond the sectors. Agricultural production and adaptation is clearly not just the mechanical application of bio-chemistry and water technology, and solutions to food-security challenges will need to be sought outside the water and agricultural disciplines. Macro-economic policies (notably those influencing social structures, market conditions and international trade), infrastructure development, and spatial planning will probably have the greatest impacts on demand for agricultural production and the capacity to adapt to changes. Thus, there are clear limitations to the adaptation measures that can be designed and implemented within the water and agriculture sectors. From a global food security perspective, influencing global trade policies on agricultural products, for example, may prove to be one of the more important climate change adaptation strategies. Climate change may increase food production imbalances and such imbalances will need to (at least partly) be dealt with through increases in regional and global trade. Such approaches to adaptation can be politically complex, as was recently demonstrated by the failure of WTO Doha 'development' round (United Nations, 2008). Given this, introducing climate change adaptation perspectives within such a process may be optimistic. However, wider market mechanisms and marked based instruments (such as the Clean Development Mechanism) can be expected to play a fundamental role in shaping adaptation and mitigation.

It will be essential to encourage more integrated or 'joined-up' policy processes to obtain appropriately scaled responses to climate change. But incorporating the varied interests of agriculture, water and energy sectors as well as policy makers influencing actors in market development, trade and infrastructure will be a challenge. Therefore a focus on the development of integrated management and decision-making tools is recommended. This may require an assessment of existing economic and legal planning instruments, including adaptation assessment frameworks (e.g. Howden et al., 2007) and more operational local/national management frameworks such as National Adaptation Programmes (NAPs).

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