ISSN 1020-1203

FAO
WATER
REPORTS

36

Climate change, water and food security

Climate change, water and food security

FAO
WATER
REPORTS

36

by

Hugh Turral
FAO consultant

Jacob Burke and Jean-Marc Faurès
FAO Land and Water Division

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2011

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

ISBN 978-92-5-106795-6

All rights reserved. FAO encourages reproduction and dissemination of material in this information product. Non-commercial uses will be authorized free of charge, upon request. Reproduction for resale or other commercial purposes, including educational purposes, may incur fees. Applications for permission to reproduce or disseminate FAO copyright materials, and all queries concerning rights and licences, should be addressed by e-mail to copyright@fao.org or to the Chief, Publishing Policy and Support Branch, Office of Knowledge Exchange, Research and Extension, FAO,
Viale delle Terme di Caracalla, 00153 Rome, Italy.

© FAO 2011

Preface

Under the IPCC emissions scenarios, higher temperatures are projected to affect all aspects of the hydrological cycle. More frequent and severe droughts and floods are already apparent, and their impact increases as a growing population becomes more dependent upon a set of atmospheric and hydrological circulations.

Climate change will impact the extent and productivity of both irrigated and rainfed agriculture across the globe. Reductions in river runoff and aquifer recharge are expected in the Mediterranean basin and in the semi-arid areas of the Americas, Australia and southern Africa, affecting water availability in regions that are already water-stressed. In Asia, the large contiguous areas of irrigated land that rely on snowmelt and high mountain glaciers for water will be affected by changes in runoff patterns, while highly populated deltas are at risk from a combination of reduced inflows, increased salinity and rising sea levels. Everywhere, rising temperatures will translate into increased crop water demand.

Both the livelihoods of rural communities and the food security of a predominantly urban population are therefore at risk from water-related impacts linked primarily to climate variability. The rural poor, who are the most vulnerable, are likely to be disproportionately affected.

Various adaptation measures that deal with climate variability and build upon improved land and water management practices have the potential to create resilience to climate change and to enhance water security. They imply a good understanding of the impact of climate change on available water resources and on agricultural systems, and a set of policy choices, and investments and managerial changes to address them.

This report summarizes current knowledge of the anticipated impacts of climate change on water availability for agriculture. The implications for local and national food security are examined; and the methods and approaches to assess climate change impacts on water and agriculture are discussed. The report emphasizes the need for a closer alignment between water and agricultural policies and makes the case for immediate implementation of 'no-regrets' strategies which have both positive development outcomes and make agricultural systems resilient to future impacts.

It is hoped that policy makers and planners will find in this report the elements of information and guidance that are needed to assess and respond to the challenge that climate change is expected to impose on agricultural water management and food security.

Alexander Müller
ASSISTANT DIRECTOR-GENERAL
Natural Resources Management
and Environment Department

Acknowledgements

This report was prepared by Hugh Turral, FAO consultant, in collaboration with Jacob Burke and Jean-Marc Faurès, from the FAO Land and Water Division. It has benefited substantially from inputs obtained during the Expert Consultation on Climate Change, Water and Food Security organized by FAO in February 2008, in preparation for the High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy, held in Rome, Italy, in June 2008.

Participants in the Expert Consultation were: Petra Döll (University of Frankfurt-Main), Rachid Doukkali (Morocco), Ashley Halls (Mekong River Commission), Bertjan Heij (The Netherlands), Erda Lin (China), Festus Luboyera (UN-FCCC), David Molden (IWMI), Claudia Ringler (IFPRI), Mahendra Shah (IIASA), Mark Svendsen (USA), Marja-Liisa Tapio-Biström (Finland), Francesco Tubiello (Columbia University), and Avinash Tyagi (WMO).

FAO participants in the Expert Consultation were Abdelkader Allali, Rosalud Delarosa, Thierry Facon, Karen Frenken, Theodor Friedrich, Aruna Gujral, Thomas Hofer, Jippe Hoogeveen, John Jorgensen, Marketta Juppi, Amir Kassam, Sasha Koo-Oshima, Parviz Koohafkan, Johan Kuylenstierna, Nadia Scialabba, Reuben Sessa and Pasquale Steduto.

List of acronyms and abbreviations

AEZ	Agro-ecological zones/zoning (depends on context)
AOGCM	Atmosphere-Ocean (coupled) Global Climate Model
AQUACROP	Crop model to simulate yield response to water (FAO)
AQUASTAT	Global database on water use in agriculture (FAO)
AR3	Third Annual Assessment Report of the IPCC, also known as 'TAR'
AR4	Fourth Annual Assessment Report of the IPCC
CDM	Clean Development Mechanism
CGIAR	Consultative Group on International Agricultural Research
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent (also CO_2-eq)
COP	Conference of Parties (UNFCCC)
CROPWAT	Crop Water Model (FAO)
DSSAT	Decision Support System for Agrotechnology Transfer
EC	European Commission
EIT	Economies in transition
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency (USA)
ESA	European Space Agency
ETa	Actual evapotranspiration
ETo	Reference evapotranspiration
EU	European Union
FACE	Free-Air Concentration Enrichment
FEWS	Famine Early Warning System
GAEZ	Global agro-ecological zones/zoning (depends on the context)
GCC	Global climate change
GCM	Global circulation model
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographic Information System
GLOWA	Global change and the hydrological cycle project (ZEF)
GM	Genetically modified
GPS	Global Positioning System

GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit, the German international technical assistance agency
GW	Groundwater
ICID	International Commission on Irrigation and Drainage
IWRM	Integrated water resources management
IFPRI	International Food Policy Research Institute, a CGIAR research centre
IMT	Irrigation management transfer
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute, a CGIAR research centre
LEPA	Low energy and pressure application (2x)
LULUCF	Land use, land use change and forestry
MA	Millennium Ecosystem Assessment
MASSCOTE	Mapping system and services for canal operation techniques (FAO)
MDG	Millennium Development Goals
MUS	Multiple use systems
N_2O	Nitrous oxide (a GHG)
NAO	North Atlantic Oscillation
NASA	National Air and Space Agency (USA)
OECD	Organisation for Economic Cooperation and Development
pH	Measure of acidity and alkalinity (below 7 is acid, and above is alkaline)
PRECIS	Providing regional climates for impact studies (Hadley Centre, UK)
RCM	Regional climate model
RWR	Renewable water resources
SAM	Southern Annular Mode
SCADA	Supervisory control and data acquisition
SEBAL	Surface energy balance algorithm for land (Satellite-based hydrological model)
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SSA	Sub-Saharan Africa
SRES	Special report on emissions scenarios (IPCC)
SRI	System of rice intensification
SUA	Supply utilization accounts (FAO's accounting country level food production and consumption balances)
SW	Surface water
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

USGS	United States Geological Survey
WUA	Water users association
ZEF	Center for Development Research (Bonn, Germany)

Units used in the report

Gt	Gigatonne (10^9 t)
ha	hectare
kg	kilogram
km^3	cubic kilometre (= 10^9 m^3)
m	metre
m^3	cubic metre
Mt	Megatonne (10^6 t)
ppm	parts per million
t	tonne

Executive summary

INTRODUCTION

In assessing the anticipated impacts of climate change on agriculture and agricultural water management, it is clear that water availability (from rainfall, watercourses and aquifers) will be a critical factor. Substantial adaptation will be needed to ensure adequate supply and efficient utilization of what will, in many instances, be a declining resource. However, the long-term climatic risk to agricultural assets and agricultural production that can be linked to water cannot be known with any certainty. While temperature and pressure variables can be projected by global circulation models with a high degree of 'convergence', the same cannot be said of water vapour in the atmosphere. The levels of risk associated with rainfall and runoff events can only be determined with provisional levels of precision. These may not be sufficient to define specific approaches or levels of investment (e.g. the costs of raising the free-board on an hydraulic structure) in many locations.

The evidence for climate change is now considered to be unequivocal, and trends in atmospheric carbon dioxide (CO_2), temperature and sea-level rise are tracking the upper limit of model scenarios elaborated in the Fourth Assessment (AR4) undertaken by the International Panel on Climate Change (IPCC). There remain many scientific questions related to cause and effect that are not yet fully explained, but the probable future costs of climate change are so significant that action now is considered to be a prudent insurance. Current negotiations focus on stabilizing end-of-century temperatures at no more than 2 °C to minimize negative impacts. The criticism that climate science has recently taken does not detract from the reality nor the gravity of the clear trends in global climate.

The prediction of impacts relies heavily on simulation modelling with global climate models (GCMs) that have been calibrated as closely as possible to historical climate data. Modelling scenarios have been standardized from a set defined by the IPCC Special Report on Emissions Scenarios (SRES) to allow more consistent comparison of predicted impacts. The predictive ability of climate models is currently much better for temperature than for rainfall. Indeed, models tend to solve primarily on temperature and pressure. The spatial and temporal patterns of rainfall are affected by land-atmosphere interactions that cannot be accomodated in the existing algorithms, and the models' spatial resolution is anyway too coarse to capture many topographic effects on climate patterns. The predictions for one scenario of economic development vary considerably from model to model, and contradictory predictions, such as increased or decreased precipitation, can result for specific parts of the world. Ensemble modelling has become increasingly useful in identifying both the range, and the most likely future conditions for a given scenario, and rapid progress is being made with the development of finer resolution Regional Climate Models (RCM) to downscale predictions to national and river basin scales.

The impact of climate change on water and agriculture requires the use of simulation models to predict the distribution and extent of change in key variables that govern crop growth (temperature and evaporative demand) and water availability (rainfall, evaporation, stream flow and groundwater recharge). Water management for agriculture encompasses all technologies and practices that sustain optimum soil moisture conditions for plant growth; these range from enhancing the capture and retention of rainfall to full-scale irrigation of crops where there may be no rainfall at all. It also includes the provision of drainage, and the avoidance and mitigation of flooding. Irrigated agriculture is the largest user of raw water and therefore the main concern of this publication.

The anticipated impacts of climate change pose an additional stress on food production systems under pressure to satisfy the food needs of a rapidly growing and progressively wealthier world. As agriculture develops and becomes more intensive in its use of land and water resources, its impact on natural eco-systems becomes more and more apparent. Damaging the integrity of these ecosystems undermines the food-producing systems that they support. The assessment of viable and effective adaptations to the impacts of climate change on water and agriculture will require a sound understanding and integration of agronomic science with water management and hydrology. Due regard for the resulting environmental interactions and trade-offs will be essential.

This publication first summarizes the challenges facing agriculture and water without climate change. It then ~~considers~~ the broad and more specific impacts of climate change in different regions of the world, and looks at the options for adaptation and mitigation in some detail. It attempts to reach a practical focus without excessive generalization. The conclusion focuses on action needed to assist countries, in particular developing countries, in assessing probable climate change impacts on irrigated agriculture and on food production, and in adapting agricultural water management to cope with the range and depths of anticipated impacts.

AGRICULTURE FOOD AND WATER - TODAY AND TOMORROW

The irrigated area of the world increased dramatically during the early and middle parts of the twentieth century, driven by rapid population growth and the resulting demand for food. Irrigation provides approximately 40 percent of the world's food, including most of its horticultural output, from an estimated 20 percent of agricultural land, or about 300 million ha worldwide. The Green Revolution technology of high inputs of nitrogen fertilizer, applied to responsive short-strawed, short-season varieties of rice and wheat, often required irrigation to realize its potential in Asia. Public funding for irrigation development peaked in the 1970s, reducing to a trickle by the 1990s in the aftermath of disappointment with the performance of formal large canal systems, corruption and rent-seeking associated with construction, and rising awareness of the impacts of large-scale water diversion on aquatic and riparian eco-systems.

In crude terms, the Green Revolution is credited with providing the springboard for many Asian countries to transform from agrarian to industrializing economies, through increasing rural wealth and aspiration. Unfortunately, it has made very little impact on Africa, either in terms of food security or wealth creation, as rural economies failed to deepen to make rural investment 'stick'. The relatively small potential for irrigation in Africa as a whole has contributed to this stasis.

For more than 30 years the market price of all major commodities decreased annually in real terms, further lessening the incentive to invest public and aid finances in irrigated agriculture. However, over the same period private investment in groundwater was stimulated by the availability of cheap pumps, power and well construction methods, taking off in the 1980s and continuing apace in India, China and much of Southeast Asia. Not only did irrigated areas continue to grow, but canal irrigation had become the minor player in India by the year 2000 as individual access to groundwater services expanded. Consiquently, aquifers are depleted in many parts of the world where they are most important – China, India and the United States - sometimes facilitated by perverse incentives of subsidized energy and support prices for irrigated products.

As the global population heads for more than nine billion people by 2050 (under medium growth projections), the world is rapidly becoming urbanized and wealthier. Food preferences are changing to reflect this, with declining trends in the consumption of staple carbohydrates, and an increase in demand for luxury products – milk, meat, fruits and vegetables – that are heavily reliant on irrigation in many parts of the world. The production efficiency of animal products is lower than for crops and so extra primary production from pastures, rangelands and arable farming is needed to meet food demands. Future global food demand is expected to increase by some 70% by 2050, but will approximately double for developing countries. All other things being equal (that is a world without climate change), the amount of water withdrawn by irrigated agriculture will need to increase by 11% to match the demand for biomass production.

The long downward trend in commodity prices made an abrupt turnaround in 2007–2008 when a combination of run-down strategic reserves, poor harvests, droughts and a sudden rush to plant biofuels in the United States and Europe reduced trade volumes. Prices for rice doubled and although commodity prices have fallen back since, the fundamentals (oil price, biofuel development and continued rising food demand) are now expected to drive a period of high volatility in food prices.

In the wake of this market turmoil, food security and agricultural livelihoods have regained importance in development planning, although some countries such as China seem ever more likely to balance further agricultural development and investment with imports.

The world has a large stock of under-performing canal irrigation infrastructure, and a vibrant groundwater sector that is competitively depleting its own lifeblood. Both create significant environmental externalities, which need to be managed. Not only that, there are calls for water to be reserved to maintain environmental flows in rapidly developing river basins and restored to ecosystems in over-allocated ones.

SUMMARY OF IMPACTS OF CLIMATE CHANGE ON WATER MANAGEMENT IN AGRICULTURE

Climate change will significantly impact agriculture by increasing water demand, limiting crop productivity and by reducing water availability in areas where irrigation is most needed or has comparative advantage.

Global atmospheric temperature is predicted to rise by approximately 4 °C by 2080, consistent with a doubling of atmospheric CO_2 concentration. Mean temperatures are expected to rise at a faster rate in the upper latitudes, with slower rates in equatorial regions. Mean temperature rise at altitude is expected to be higher than at sea level, resulting in intensification of convective precipitation and acceleration of snowmelt and glacier retreat.

In response to global warming, the hydrological cycle is expected to accelerate as rising temperatures increase the rate of evaporation from land and sea. Thus rainfall is predicted to rise in the tropics and higher latitudes, but decrease in the already dry semi-arid to arid mid-latitudes and in the interior of large continents. Water-scarce areas of the world will generally become drier and hotter. Both rainfall and temperatures are predicted to become more variable, with a consequent higher incidence of droughts and floods, sometimes in the same place. Runoff patterns are harder to predict as they are governed by land use as well as uncertain changes in rainfall amounts and patterns. Substantial reductions (up to -40 percent) in regional runoff have been modelled in southeastern Australia and in other areas where annual potential evapotranspiration exceeds rainfall. Relatively small reductions in rainfall will translate into much larger reductions in runoff, for example, a 5 percent fall precipitation in Morocco will result in a 25 percent reduction in runoff. In glacier-fed river systems, the timing of flows will change, although mean annual runoff may be less affected.

As temperature rises, the efficiency of photosynthesis increases to a maximum and then falls, while the rate of respiration continues to increase more or less up to the point that a plant dies. All other things being equal, the productivity of vegetation thus declines once temperature exceeds an optimum. In general, plants are more sensitive to heat stress at specific (early) stages of growth, (sometimes over relatively short periods) than to seasonal average temperatures. Increased atmospheric temperature will extend the length of the growing season in the northern temperate zones, but will reduce it almost everywhere else. Coupled with increased rates of evapotranspiration, the potential yield and water productivity of crops will fall. However, because yields and water productivity are now low in many parts of the developing world, this does not necessarily mean that they will decline in the long term. Rather, farmers will have to make agronomic improvements to increase productivity from current levels.

Increased atmospheric concentrations of CO_2 enhance photosynthetic efficiency and reduce rates of respiration, offsetting the loss of production potential due to temperature rise. However, early evidence was obtained from plant level and growth chamber experiments and has not been corroborated by field-scale experiments; it has become clear that all factors of production need to be optimal to realize the benefits of CO_2 fertilisation. Early hopes for substantial CO_2 mitigation of production losses due to global warming have been restrained. A second line of reasoning is that by the time CO_2 levels have doubled, temperatures will also have risen by 4 °C, negating any benefit.

Agriculture will also be impacted by more active storm systems, especially in the tropics, where cyclone activity is likely to intensify in line with increasing ocean temperatures. Evidence for this intuitive conclusion is starting to emerge. Sea-level rise will affect drainage and water levels in coastal areas, particularly in low-lying deltas, and may result in saline intrusion into coastal aquifers and river estuaries.

Estimates of incremental water requirement to meet future demand for agricultural production under climate change vary from 40–100 percent of the extra water needed without global warming. The amount required as irrigation from ground or surface water depends on the modelling assumptions on the expansion of irrigated area – between 45 and 125 million ha. One consequence of greater future water demand and likely reductions in supply is that the emerging competition between the environment and agriculture for raw water will be much greater, and the matching of supply and demand consequently harder to reconcile.

The future availability of water to match crop water requirements is confounded in areas with lower rainfall – those that are presently arid or semi-arid, in addition to the southern, drier parts of Europe and North America. Runoff and groundwater recharge are both likely to decline dramatically in these areas. Where rainfall volume increases and becomes more intense (Indian monsoon, humid tropics), a greater proportion of runoff will occur as flood flow that should be captured in dams or groundwater to be useable.

About 40 percent of the world's irrigation is supported by flows originating in the Himalaya and other large mountain systems (e.g. Rocky Mountains in the western United States and Tien Shan in Central Asia). The loss of glaciers worldwide has been one of the strongest indicators of global warming. At present, the estimates of the rates of glacier mass loss are being reviewed by the IPCC. Notwithstanding the long-term evolution of glacier mass balance, the contribution of snowmelt to runoff is important in terms of base flows and timing of peak flows, but is more variable in its proportion of total runoff. The impacts on some river systems (such as the Indus) are likely to be significant and will change the availability of surface water for storage and diversion as well as the amount of groundwater recharge. In general, the probable impacts of climate change on groundwater recharge have not been sufficiently explored, but aquifers in arid and semi-arid areas, where runoff will decline, can expect severe reductions in replenishment.

Since the scale of GCM simulation precludes the analysis of specific impacts at river basin and even national scales, there is increasing effort to downscale modelling in order to assess agricultural and hydrological consequences in a specific location. Downscaling can be achieved empirically, statistically and by using regional climate models (RCMs) that are driven by GCM forcings. All downscaling techniques incorporate effective calibration to historical rainfall patterns, although they do not always preserve the mass balance of GCM outputs. In essence, agricultural impacts cannot be studied meaningfully without the downscaling of global climate simulations but the rainfall data to calibrate downscaled projections are not adequate for global application. Often, where the projections would be most useful, like in sub-Saharan Africa, data are absent.

TYPOLOGY OF AGRICULTURAL SYSTEMS AND CLIMATE IMPACTS

The global impacts of climate change on agriculture will depend on shocks at local and regional levels and it is therefore important to understand the likely impacts at these scales. A typology is proposed to help refine where irrigation and other forms of agricultural water management are important and will be impacted by climate change:

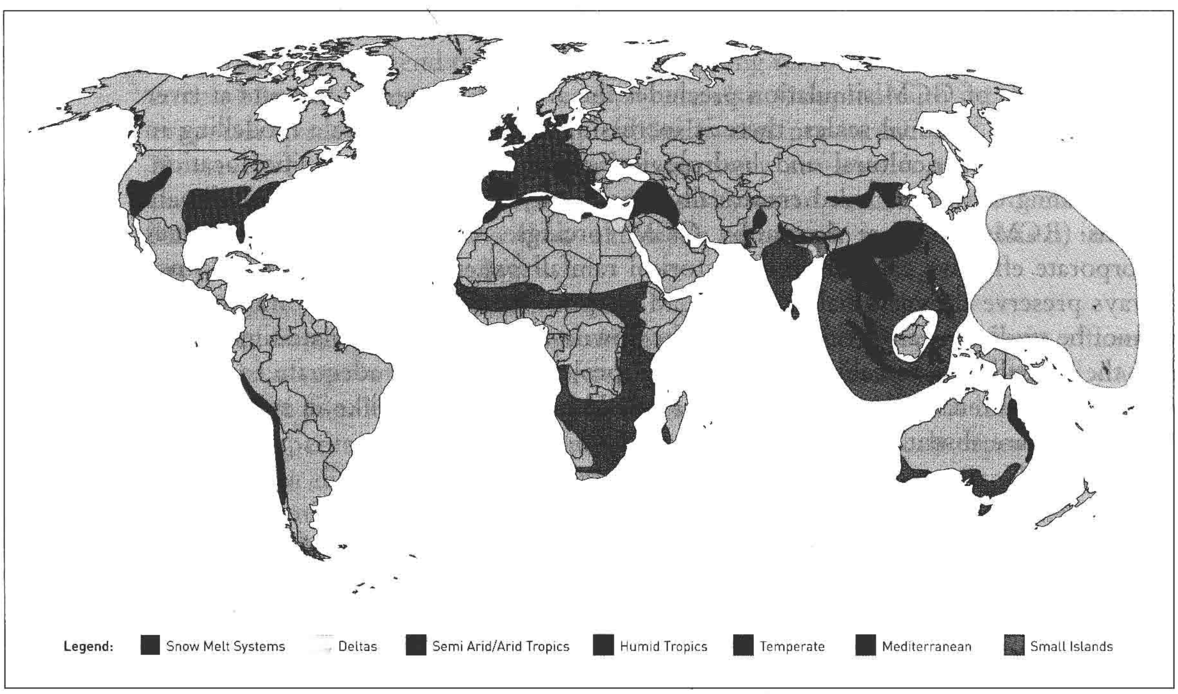
1. Large surface irrigation systems fed by glaciers and snowmelt (notably northern India and China);
2. Large deltas which may be submerged by sea-level rise are increasingly prone to flood and storm (cyclone) damage or experience salinity intrusion through surface and groundwater;
3. Surface and groundwater systems in arid and semi-arid areas, where rainfall will decrease and become more variable;
4. Humid Tropics that experience seasonal storage systems in monsoon regions, where proportion of storage yield will decline but peak flood flows are likely to increase;
5. All supplemental irrigation areas where the consequences of irregular rainfall are mitigated by short-term interventions to capture and store more soil

> moisture or runoff. This comprises 1) temperate regions (in Europe and North America) that will experience seasonal drying, even with increased annual rainfall, and 2) the Mediterranean and seasonally arid regions.

A preliminary map of these agricultural systems is given in Figure (i). Small islands are also shown on this map, although not elaborated in the typology. Small islands are highly vulnerable to sea-level rise, and lower-lying ones may eventually be lost altogether. Island agriculture is by nature precarious, and vulnerability increases across the board with all aspects of climate change.

Refinements of the basic typology can made on the basis of existing water resources development as well as the current and future potential of groundwater. Hydrological and crop models need to be nested within the climate modelling (GCM-RCM or GCM-statistical downscaled model) in order to predict direct impacts on crop production and water availability, and hence assess likely sustainable balances between rainfed and irrigated farming. Good examples are already documented, and much more work is anticipated in this field.

Figure i: Main agricultural water management systems that climate change is expected to impact



Recent studies since AR4 highlight Africa and South Asia as being the most vulnerable to climate change. The poor existing levels of food security in Africa and the low level of economic development conspire with high levels of climatic risk, whereas large populations, heavily exploited natural resources and climate risk threaten South Asia's poor.

PROSPECTS FOR ADAPTATION

It is expected that adaptation strategies will focus on minimising the overall production risk. Adaptation needs are uncertain, but can be defined by specific prediction of likely climate impacts in a specific context. In practice, continued refinement of soil, water and crop management will contribute much of the necessary adaptation except in what are already water stressed conditions. 'Climate-smart' development will need to incorporate as much adaptive innovation as possible, and prioritize activities that have benefit whether or not climate change manifests itself as anticipated. A good example is the improvement of nitrogen fertilizer efficiency and the consequent reduction of the amount applied. The result is that production costs are reduced, output and income increased, while the Greenhouse Gas (GHG) costs of production are lessened and the mobilisation of nitrous dioxide (a GHG) reduced. Such 'no-regrets' policies point the way to integrating adaptation and mitigation in development, which may ease financing and boost poverty reduction. Adaptation and mitigation activities are unlikely to be implemented at the scale unless they can address socio-economic development of rural populations.

A more elaborate diagnostic process is proposed to identify the context and options for climate change adaptation. It superimposes a decision process over the typology of impacts by refining the nature of impacts in different contexts. It will inevitably require more detailed modelling in which options for adaptation are clearly identified.

The options for adaptation can be defined at three levels:

- farm;
- irrigation system or catchment (system level); and
- river basins and nations (strategic or planning level).

Many options are generic, but will be applied in different combinations in specific contexts. There are strong linkages in both directions between farm and river basin. System level adaptation will respond to strategic policy at national and basin scale, for example in water storage in reservoirs, groundwater or on-farm. Farmers on the other hand are likely to be highly innovative and proactive in adapting to climate constraints. Therefore a good understanding of what they do will be required both to match system service to their needs and to assist in broader adoption and dissemination of beneficial practices across irrigation schemes catchments and basis.

In all but the most severe arid and semi-arid conditions, there are ready-made adaptive packages of existing good practices. Climate change is likely to move farming systems progressively to the margins; semi-arid croplands may become rangelands, humid seasonally dry lands may take on a more semi-arid nature, and so on. Sometimes, the only option at the margin will be the retirement or abandonment of crop and pastoral lands. For the most part, existing ready-made crop patterns can substitute one crop for another, for example, dry rice or dry-footed crops for wet paddy rice where rainfall declines and water logging is no longer natural. It is likely that factors other than climate change (demand, preference, price) will have a greater impact on crop choice than climate change per se. Where rainfed cropping systems are displaced to the margins, the provision of irrigation is likely to play a strategic role in either stabilising the production of grains (a return to protective irrigation) or in supporting a low-risk, high-value production system with a strong commercial focus.

As the reliability of water supply will often decrease and supplies become more variable within season and over time, the extent to which irrigation areas can be maintained, intensified or expanded will depend on the combinations of impacts and contexts in a given situation. The need for water storage will increase, but its reliability (and cost effectiveness) will decrease. Furthermore, storages will have to cope with more variable and extreme flows, and are likely to be set in a more environmentally sensitive landscape. Storage options will need to be flexible and have low capital and operating costs: large surface water storage sites have mostly been developed already and groundwater recharge technology is still immature, while the costs of abstracting deep groundwater are high; highly diffuse on-farm water storage may prove to be appropriate and manageable in a wide range of situations. For sure, the debate on storage will become quite intense in the future, not least because of its investment and environmental costs.

It is widely contended that irrigation is inefficient and therefore great opportunities exist to save water and re-use the savings. Sometimes this is true, but there are many fully allocated river basins where all the divertible water is used and this implies close to 100 percent efficiency of use at the river mouth. Therefore, the concept of basin efficiency needs to be distinguished from that of scheme or field efficiency and the importance of depletion accounting needs to be emphasized. It is concluded that improving efficiency and making real water savings will be possible in some river basins, but careful analysis and accounting will be required.

More generally, water accounting in most developing countries is very limited, and allocation procedures are non-existent, ad hoc or poorly developed. Acquiring good water accounting practices (hydrological analysis of water resource availability and actual use) and developing robust and flexible water allocation systems will be a first priority.

Improved data gathering would support better forecasting of both droughts and floods. Technologies for forecasting, even to the optimisation of rainfall use, already exist and are commercially available in some (developed) countries. The quality of forecasting needs to improve, and much needs to be done to improve the communication and understanding of forecasts if they are to have a positive adaptive benefit.

Crop patterns can be adjusted to allow earlier or later planting, to reduce water use, and to minimize or optimize irrigation or supplementary irrigation supplies. Yield and water productivity can be enhanced by adopting better soil moisture conservation practices and better management, as well as by increasing provision of other factor inputs (NPK fertilizer, weed and pest control). The options for different mixes of rainfed and irrigated land, for expansion and intensification, will vary for each situation according to the relative priorities accorded to equity in benefits to users, impacts on ecosystems and costs. Sometimes national perspectives in urban food security will dominate, but in others, a rural focus will prevail.

Soil moisture can be enhanced by practices such as zero and minimum tillage, which improve soil structure and organic matter contents. Deep-rooted crops can be planted to better exploit available soil moisture, and agroforestry systems hold promise for maximising benefits at farm scale and providing sufficient shade to allow even high-value crops to be grown. Plastic mulching has been used widely in northern China and is one example of broadly useful soil moisture conserving technology, albeit one that uses petrochemical products.

Amid calls for new green revolutions in Africa, and hopes for the development of drought resistant crops and varieties with higher water use efficiency, the prospects for crop breeding for climate adaptation is limited. One of the main problems lies in the fact that drought induces 'multi-dimensional' crop responses at different levels of plant organization, and that there are therefore no single traits that confer global drought tolerance to plants. Protagonists of genetically modified (GM) products are looking to develop drought resistant varieties of some important crops including maize. Successes have been anticipated several times but biotechnology based plant improvement for drought tolerance has had very limited impact so far. GM crops may have an edge where they have pesticide or herbicide resistance and may contribute to maintaining or enhancing productivity, but the range of crops being researched remains small and limited to those with significant commercial value. Nevertheless, breeders seem to agree that molecular biology and bio-technology applied to conventional breeding offer the prospect of more rapid cross-breeding, testing and replication. Some pessimism coming from crop physiologists is due to the recognition that water productivity improvement can come only from some genetic breakthroughs which would change the intrinsic processes associated with biomass production. Such breakthroughs are extremely difficult to achieve, and in any case the time frame for them to occur must probably be counted in decades.

Institutional change will be a key component of adaptation strategies, since the management of natural resources, agriculture, water, and ecosystems will become more complex and involve more people, perspectives and specialist knowledge. Greater inter-agency cooperation, clear consultation and communication, and active and meaningful participation will be important, if difficult challenges. Above all, adaptation is likely to be knowledge-rich rather than technology driven.

Strategic options exist to enhance crop storage from household level to national reserves. The extent to which individual nations rely on the global market will depend on many factors: the politics of self-sufficiency; diversification in the economy; ability of the nation and its rural and urban dwellers to purchase imported foods; and price levels or, more importantly, price volatility in the market.

PROSPECTS FOR MITIGATION

Agriculture contributes about 14 percent of global annual GHG emissions and indirectly accounts for another 4–8 percent from forest clearance for rangeland and arable development. CO_2 is generated by fossil fuels used in cultivation, transport, crop processing; pumping irrigation water; and in the production of nitrogenous fertilizer. Inefficient and excessive use of artificial N-fertilizer generates nitrous oxide (N_2O), a short-lived but more damaging GHG. Methane, another potent GHG, is generated by ruminant livestock and wet rice cultivation.

Little precise data exists, but it is likely that irrigated agriculture generates proportionately more GHG than rainfed agriculture, at least in developing countries, as it makes more intensive use of all production inputs. Highly mechanized intensive rainfed farming in the Organisation for Economic Co-operation and Development (OECD) countries also has a high carbon footprint.

There is strong potential to mitigate GHG emissions from agriculture, and to make inroads into emissions from other sectors. Energy saving and efficiency improvement will have direct benefits for farmers while reducing CO_2 load; this will enhance prospects for zero and minimum tillage. Substitution of fossil fuels can be achieved using methane derived from bio-digestion and recycling of organic matter, in addition to direct use of biofuels grown on farm. Solar and wind power may contribute on larger farms that have a strong capital base. Improvements in fertilizer efficiency