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Climate change, water and food security

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Climate change, water and food security

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by

Hugh Turral
FAO consultant

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

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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

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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.

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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:

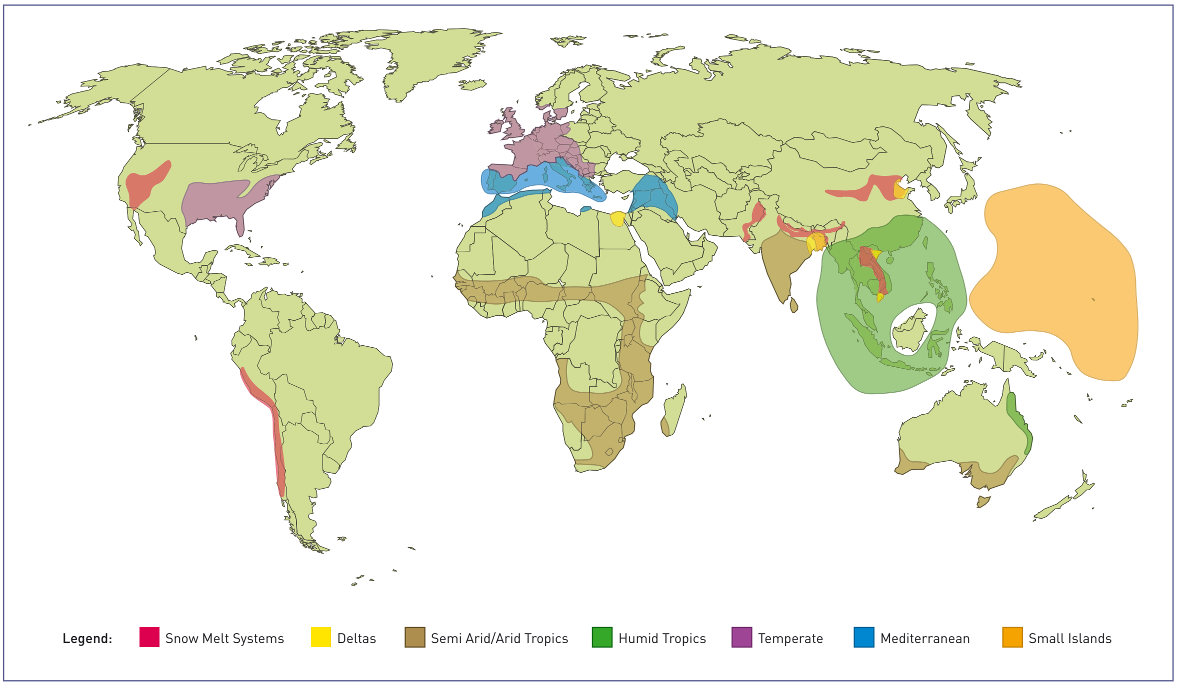
1. Large surface irrigation systems fed by glaciers and snowmelt (notably northern India and China);
2. Large deltas which may be submerged by sea-level rise are increasingly prone to flood and storm (cyclone) damage or experience salinity intrusion through surface and groundwater;
3. Surface and groundwater 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 through better management, placement and precision application, as well as through slow-release formulations, can reduce N_2O losses from cropping. It will be important to make effective variants of such technologies available to poor, small-scale farmers. Improved irrigation efficiency and strategies such as deficit irrigation may reduce energy consumption for pumping, but will not necessarily translate into system wide savings, as this will depend partly on total water use and total pumping effort. Removal of energy subsidies will restrain groundwater pumping and limit groundwater abstraction from uneconomic depths.

New investment in irrigation, particularly in surface and groundwater storage, will need close attention to the energy embodied in construction, as well as to the energy consumed in operation. These will be important decision points in climate-smart development strategies.

Claims are being made for the mitigation potential of organic farming, and the idea of zero-emissions production combined with organic production methods and zero-tillage is attractive. Large-scale organic farming may be an economic prospect in OECD countries, where land can be rotated and fallowed, and where mixed farming (livestock and cropping) may generate sufficient nutrient recycling to maintain productivity. There may be ways of doing this among groups of small subsistence farmers in the tropics and semi-arid tropics, but there are no clear models. It is evident that any production system resulting in lower consumable or saleable production will be unattractive to small farmers with limited land and water resources. Further work on nutrient and input-output balances is needed to ascertain the potential for organic production in much of the developing world, especially as a 60 percent increase is expected in the demand for nitrogen fertilizer by 2030. As the average yield (land productivity) for organic farming systems is lower than for 'conventional' farming methods, it is unlikely that future food needs could be met without the use of fertilizers. Ironically, genetically modified crops already point the way to farming systems with low or zero reliance on pesticides, and nitrogen-fixing cereals may one day become a reality. In the meantime, it will be important to be as efficient as possible in the pursuit of 'industrial' agriculture.

Methane emissions from rice have attracted interest fuss and a flurry of activity to map and estimate global emissions using remote sensing. Although rice and ruminant livestock account for 35 percent of anthropogenic methane production, natural wetlands cover more than ten times the global area of rice. In north America, output from natural wetlands accounts for 75 percent of total continental methane emission. It has been suggested that wet rice can be converted to aerobic rice and thus reduce methane emissions, and this is true where rice is grown on free draining soils that require (much) irrigation water to maintain flooded conditions. However, the natural habitat of rice is low-lying, poorly drained and relatively impermeable land, and even under climate change, a large portion of rice area will remain naturally wet, perhaps wetter than it is at the present time. Methane emissions can be reduced by drying out rice paddies annually (and more frequently) and by incorporating crop residues when the soil is not water logged. The mitigation potential for reducing methane emissions and carbon sequestration in rice production needs to be evaluated in more detail, with better soils information, before practical and effective strategies are implemented.

The soil in croplands can potentially store massive quantities of carbon, perhaps as much as a third of current global emissions. It is possible to accumulate crop residues and enhance inorganic and organic forms of carbon in the soil, although stable conditions are required to maintain long-term levels. No full package of practical technology yet exists; there has been a global trend in declining soil organic matter with resultant acidification of soils and loss of fertility. This trend has to be reversed and then enhanced for soil carbon sequestration to become a reality. The potential for soil carbon sequestration can be mapped using existing soils databases, but in many countries soils maps are coarse and contain limited data on their physical characteristics. The potential for soil carbon storage in arid lands is thought to be low. To date, there has been limited work on carbon sequestration in irrigated soils, but early results are encouraging and it may prove to be a practical focus for mitigation efforts.

There will have to be appropriate incentives to store carbon in the soil, especially for smallholder subsistence farmers, unless the direct benefits of improved soil carbon are sufficient (increased moisture retention, better nutrient status, better root zone aeration and drainage). The chemistry of soil carbon transformation, cycling and storage is poorly understood and should be researched in more detail. Increasing soil carbon content is effectively a one-time activity that requires careful custodianship and maintenance in perpetuity. This poses additional problems for both payment and compliance (transaction costs), especially with large numbers of small farmers.

Overall, the prospects for reducing agriculture's contribution to global emissions are good, and there are opportunities to mitigate a substantial portion of total global emissions. Much research is needed to implement both emission control and soil carbon sequestration at the required scales.

RECOMMENDATIONS

To help develop practical adaptation and mitigation strategies for agricultural water management in developing countries, the following recommendations for immediate action can be made:

1. Ensure better prediction of the impacts on agricultural systems in closely specified regions and types of production system. This can be carried out using the typology and decision analysis outlined in this publication.
2. Provide assistance in developing and applying downscaling techniques to better analyse agroclimatic futures and in the process, build local capacity in modelling and climate adaptation.
3. Orchestrate targeted analysis of the investment needs for different solutions, which takes into account long-term embodied and operational energy use. These tasks are required for all agricultural impact and adaptation studies, and sit at a higher strategic level than work on irrigation and water use in agriculture.

In tandem with these three activities, it is necessary to expand the density, detail and frequency of monitoring of climatic and hydrologic systems in order to confirm the evolution of trends and modelled predictions, refine the assessment of impacts, and manage adaptive strategies accordingly. Improved information on the nature and dynamics of key production systems is also required, including: higher resolution and more detailed mapping and management of soils; groundwater mapping and monitoring of water use; adaptation of cropping systems and practical forecasting of drought and flood. It will be necessary to evaluate, document and disseminate good practice at farm, system and strategic levels as it emerges. Initially, particular attention should be paid to identifying and promoting effective 'no-regrets' activities for adaptation and mitigation. A global picture of agricultural impacts can be assembled from regional and national studies that work at an appropriate level of detail. There is a strong argument for global studies to be built from the bottom up in the future in order to calibrate the performances of key crop sectors, notably cereals.

It will be challenging, but it is important to tease out the environmental consequences, options and trade-offs involved in both meeting future agricultural demands and accommodating climate change. Many countries will still be pre-occupied with livelihoods and food security, so it will be important that well-targeted and coordinated work continues to implement sustainable development. This will require agricultural and water services to forge strong and open partnerships with key environmental groups, ranging from international and local organisations to line agencies and environmental departments. A more pluralistic approach to integration is thus advocated in general.

Climate change impacts will be global, and development assistance should not overlook highly impacted communities such as small island nations. However, there is a compelling argument to focus on the most vulnerable regions. Many donors and organisations have declared a strong commitment to continued development, and will increasingly view development through a climate-sensitive lens. Solid and appropriate advice will be needed in the development and management of water resources for agriculture, and in the establishment and perpetuation of climate resilient food production systems. Initially it would be wise to prioritize representative locations within the key agricultural systems that are most vulnerable and expected to experience the most severe impacts of climate change. Rigorous analysis and dissemination of the lessons from well-targeted and in-depth practical experience at field, system and sector levels will be instructive and practically useful.

Chapter 1
Introduction

1.1. OVERVIEW

Climate change is now largely accepted as a real, pressing and truly global problem. The main arguments concern how much climate change there will be, what impacts will ensue and how best to adapt to them, or better, mitigate the causes. There remain many objections to both the quality of the science behind global warming and the nature of cause and effect, but politicians are increasingly aware that the risks of climate change are so great, that ignoring or delaying in addressing them would be far more costly than not doing so. The small chance that the science is wrong is not worth taking. The wrangling over costs of adaptation and mitigation at the Copenhagen summit in 2009 is ample evidence of the acceptance of the climate change problem by a broad community.

Scientific evidence for global warming is now considered irrevocable (Allison *et al*., 2009); it is witnessed by unprecedented rates of increase in atmospheric and sea temperatures, and is correlated to rapid increases in atmospheric carbon dioxide. Corroboration for these warming trends is found in the dramatic loss of glaciers in the world's high mountains, and in the rise of sea levels.

It has recently been estimated that developing countries will bear 70–80 percent of the costs of climate change damage (World Bank, 2009a). At the same time, current estimates of total cost of climate 'insurance' through mitigation activity to stabilize temperature rise to 2 °C at an atmospheric carbon dioxide content of 450 parts per million (ppm) would be less than 1 percent of predicted global gross domestic product (GDP) in 2100, which is in any terms 'affordable'. Further assessment of adaptation costs by sector have also been made, notably Parry *et al.* (2009) and the World Bank (2010).

Climate change will affect agriculture through higher temperatures and more variable rainfall, with substantial reductions in precipitation likely in the mid-latitudes where agriculture is already precarious and often dependent on irrigation. Water resource availability will be altered by changed rainfall patterns and increased rates of evaporation. Rainfed farming will become more precarious in the mid and low latitudes, while productivity may rise for a time in the higher latitudes (notably North America and northern Europe). Aquaculture and inland fisheries, which are important to many poor farmers, will likewise be affected by hydrological changes arising from climate change.

This document focuses on the probable impacts of climate change on agricultural water management – a term that encompasses not only irrigation and drainage, but also other forms of water control intended to optimise growing conditions for crops and pasture. The core of the document concerns adaptive and mitigating options and activities that can contribute to maintaining global food security and supporting farmers' livelihoods. Inevitably, the focus is on irrigated systems that currently produce roughly 40 percent of global food output from 20 percent of the global stock of cultivated land, and withdraw more than 70 percent of the volume of water used for human benefit. This focus is warranted, as irrigation practice manages the hydrological cycle directly – rainfed agriculture does not. In some countries (predominantly in arid and semi-arid regions), the consumption of water for irrigation is more than 40 percent of renewable water resources (RWR) but remains a tiny proportion in others. Within countries, there are substantial differences in the utilization of water between different river basins.

After a brief overview of climate change science, trends and predictions (Ch. 2), this document reviews the status and pressures on agricultural water management without the additional stress of climate change (Ch. 3). Continued population growth, changing patterns of food demand and food preferences, increasing environmental responsibility and the needs of rapidly urbanising and industrializing societies will constrain the volume of water allocated for agriculture – both for existing use as well as future expansion. Mid-twentieth century public investment in surface irrigation has given way to more dispersed private investment, much of it dependent upon access to groundwater. It has underwritten the successful adoption of high-yielding varieties and more intensive agriculture in the densely populated countries of South, Southeast and East Asia. By contrast, irrigation development in Africa, excluding Sudan and Egypt, has been patchy and has performed disappointingly: less than 3.7 percent of sub-Saharan agricultural land is irrigated compared with 41 percent in South Asia (FAO, 2010). Globally, there is a large stock of decaying capital infrastructure that must be improved and adapted to meet the needs of a more demanding world facing the additional stresses of climate change.

A more detailed look at the impacts of climate change on agriculture and water resources is presented in Chapter 4, with consideration of the effects of temperature and atmospheric CO_2 concentrations on crop production, coupled to likely changes in rainfall, runoff, and available surface and groundwater resources. Hydrological and agronomic impacts of drought, flooding and water logging have specific regional contexts, and often require more detailed modelling before effective responses can be selected. A typology of agricultural water management systems and their climate change contexts is proposed (Ch. 4) and, in conjunction with other analytical methods, is used to focus the options for, and detail of, adaptive responses (Ch. 5). Adaptive responses are examined from both conceptual and more practical perspectives, based on three closely connected scales – farm, system (irrigation system and catchment) and strategic (river basin and national). Estimating the financial needs for adaptation programmes imposes a discipline on setting out the detail and context of impacts and options. The prospects for mitigation of GHG emissions from agriculture are discussed in Chapter 6, guided by a philosophy that development, adaptation and mitigation activities have synergy, and will prove to be better investments if well matched and coordinated.

The publication draws on material prepared for, and arising from, an expert meeting on climate change, water and food security held in Rome, 26–28 February 2008. Later in June 2008, FAO convened a High Level Conference on climate change that brought together the broader range of sub-sectors and perspectives in agriculture, livestock, fisheries and food. The emerging importance of biofuels and their dramatic impact on grain production and commodity prices in 2007 were also high on the agenda.

Developing countries are the primary focus of this paper, for reasons that are consistent with the likely impacts of climate change on human development (Alexandratos, 2005), and because of the mandate of the FAO. Nevertheless, where relevant information, context and observation from more developed countries is useful, it is included, beyond the more general global discussion. In particular, this applies to material from Australia. It gives the perspective of a country with a large, export-oriented agriculture and irrigation sector operating in perhaps the most variable climate in the world; one that is suggested to be already experiencing the impacts of climate change, over and above its natural variability and pre-disposition to extended drought. Other high profile questions include the possibility of collapse of agricultural systems under the combined pressures of future human needs and climate change.

The final section of this document (Ch. 7) suggests future focus and activities in supporting agricultural adaptation to climate change, particularly in application of appropriate and effective adaptation measures. It also suggests where more efforts are needed in elaborating and solving the research needs in countries. In summary, the main focus is on adaptation and mitigation within (irrigated) agriculture, and ultimately on the development of adaptive capacity and climate sensitive agricultural development.

1.2. TRENDS VERSUS PREDICTIONS

The Copenhagen Diagnosis (Allison *et al*., 2009) provides an interim update to the climate change modelling, scenarios and impact assessment undertaken in the IPCC AR4 report (2007) (see Ch. 2). In the past four years, there have been considerable advances in modelling capacity and techniques, with more sophisticated and historical analysis of observed trends in climatic parameters. It shows that temperature rise has been tracking the upper end of the envelope of predictions made using the SRES scenarios. More concrete evidence for the acceleration of the water cycle is provided by consistent measurements of rising average atmospheric moisture content, and some of the process and modelling uncertainties resolved since AR4 indicate a more rapidly changing and more sensitive climate. Insolation reaching the earth is at its lowest recorded level, but this 'global dimming' has not affected photosynthesis and it is hypothesized that diffuse light is used more efficiently than direct sunlight. The modelling undertaken for AR4 has generally under-predicted many observed trends, resulting in more worrying estimates of impacts in the future.

The most high profile of these is that sea-level rise since 1989 is 80 percent greater than predicted in the Third Assessment Report (AR3, also known as TAR, 2001a), and the projected rise to 2100 has gone from 59 cm to closer to 1 m, with important ramifications for delta agriculture and small islands. The contributions from thermal expansion and melting ice in the Arctic, Greenland, from glaciers, sea ice and ice shelves have been either underestimated in the past, or are presently rising. Summer melting of Arctic ice has exceeded the worst AR4 projections. Contributions from the Antarctic remain modest, but it is now thought that, on average, the region has warmed by 0.5 °C since 1957, with most warming in the west. The report notes that the Antarctic is a relatively small land mass surrounded by a large ocean, whereas the Arctic is a small sea surrounded by a large land mass, and that this broadly explains a difference in dynamics between the two regions. Updated oceanic maps show significant increases in the Northern Hemisphere sea temperatures, although they are not likely to affect the regional climate modes (Northern Atlantic Oscillation (NAO), El Niño Southern Oscillation Index (ENSO), and Southern Annular Mode (SAM)).

General predicted rainfall trends in some parts of the world have been confirmed, but the general limitations of GCMs in predicting detailed spatial patterns of rainfall remain. However, the newest Atmosphere-Ocean (coupled) Global Climate Models (AOGCMs) are starting to include land surface interactions and feedbacks (topography, elevation and albedo). There is increasing evidence of acceleration of the El Niño cycle and of correlation between higher sea surface temperature (SST) and more vigorous cyclone activity, but GCMs cannot model them effectively yet. The extent of average ocean acidification has been quantified at -0.1 pH units since 1750.

Recent outbreaks of large forest fires, together with peat combustion, have added weight to expectations of reinforcing positive feedbacks from the land surface, due to global warming. Sudden deforestation (dieback and bush fires) releases enormous quantities of CO_2 to the atmosphere. It is now considered most likely that the Amazon rainforest will decline under future low rainfall with resulting large net emissions of CO_2; thus leading to renewed urgency in the calls to preserve global forest cover.

The permafrost zone in North America is shifting northwards at faster than predicted rates, and the large quantities of peat that underlie the Arctic will, if exposed, increase N_2O emissions as well as liberate large quantities of methane.

Most of the analysis in this document remains based on the scenarios and projected impacts developed in AR4. The guiding target from global warming remains 2 °C, despite the increasing likelihood that the world will fail to meet this goal, and that inertia in the global climate system will see temperatures continue to rise beyond 2050, even if the target is met.

Chapter 2
Setting the scene

2.1. WATER, FOOD SECURITY AND ENVIRONMENT

A recent review of food security and climate change (Schmidhuber and Tubiello, 2007) assesses the likely impacts of climate change on four key dimensions of food security - availability, stability, access, and utilization. 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 healthy life."*

Clearly not all crop production is dedicated to food security. Industrial crops (fibre and biofuels) and beverage crops make no direct contribution to kilocalorie consumption by human beings although some industrial crop residues are used as livestock fodder. But overall, water management in crop production tends to be concentrated on food crops where the timing and reliability of supply is critical. Water management (irrigation, drainage and water conservation and control) achieves stability of crop production by maintaining soil conditions close to optimum for crop growth. Irrigation allows the cultivation of crops when rainfall is erratic or insufficient, insures high-value, high-risk horticulture from failure and has played a major role in achieving national and regional food security in Asia, as well as improving individual livelihoods (Hussain, 2005). The extent and area of irrigation has grown massively in the twentieth century but has depleted surface and groundwater flows, often with severe consequences for aquatic eco-systems and those dependent on them (Emerton and Bos, 2004; FAO, 2004a; Burke and Moench, 2000). It is increasingly recognized, although rarely common practice, that greater net socio-economic benefit can be obtained from maintaining the integrity of managed ecosystems (Cai *et al*., 2001; FAO, 2004a).

In the future, food security strategies will be more complex. Higher temperatures will increase water demand, and where rainfall declines, many will seek more irrigation to ensure food security and maintain livelihoods. At the same time water supplies available for irrigation will become more variable and will decline in many parts of the world. New agricultural demands will be further tempered by the need to achieve better equity in access to reliable food supplies than in the past. As irrigation has been practised on only 20 percent of the world's cultivated land, there have been many, often the poorest, who have missed out on its benefits. The need to maintain viable aquatic eco-systems will place further stress on water resources, especially where the poorest are dependent on them for their livelihoods. Water allocations to agriculture may fall in many parts of the world owing to the combined impacts of climate change, environmental needs and competition from higher value economic sectors. There will be strong pressure to produce more with less water, and to spread the benefits of all water use more widely and wisely. This task will be even more challenging because higher temperatures will reduce potential land and water productivity. These are not academic considerations. Climatic variability in south-eastern Australia has had more profound impacts on water allocations and associated livelihoods in agriculture than even the most prudent farmers had anticipated and big changes lie ahead. But this is an economy with alternatives: if this magnitude of change occurs in developing countries, the impacts on poverty are expected to be much more profound (Sperling ed., 2003).

Climate change will alter the productivity of aquatic ecosystems and the services they provide in significant ways, both directly, for example in changes in rainfall patterns and rising sea levels, and indirectly, through shifts in demand and trade of commodities.

2.2. IPCC 4TH ASSESSMENT AND THE STERN REVIEW

2.2.1 The IPCC 4th Assessment and associated analysis

The International Panel on Climate Change (IPCC) regularly reports the findings of its three working groups, most recently in the Fourth Assessment Report (AR4), published in 2007. The working groups investigate the physical science underlying climate change; adaptation to the impacts of climate change; and the possibilities for mitigation of greenhouse gas (GHG) emissions and global warming. AR4 provides the reference thinking and information on climate change for the discussion and analysis in this paper, but much knowledge and capacity has been added since 2007. The recent Copenhagen Diagnosis (2009) is the most comprehensive update on AR4, and is an interim statement of the work that will contribute to the Fifth Assessment (AR5). In 2008, the IPCC published a special report on Climate Change and Water (Bates *et al.*, 2008).

Prior to AR4, comparison between different predictions and scenarios was difficult, because of inconsistencies in model behaviour, supporting evidence, and in the specification of scenarios and time frames for their impacts. AR4 adopted a standard set of scenarios that were previously defined in the IPCC's Special Report on Emissions Scenarios (SRES, IPCC, 2001c). SRES defines 40 emissions scenarios based on likely profiles of greenhouse gas (carbon dioxide, methane, nitrous oxide and sulphate) emissions arising from contrasting patterns of economic development and population growth for the period 2000-2100.

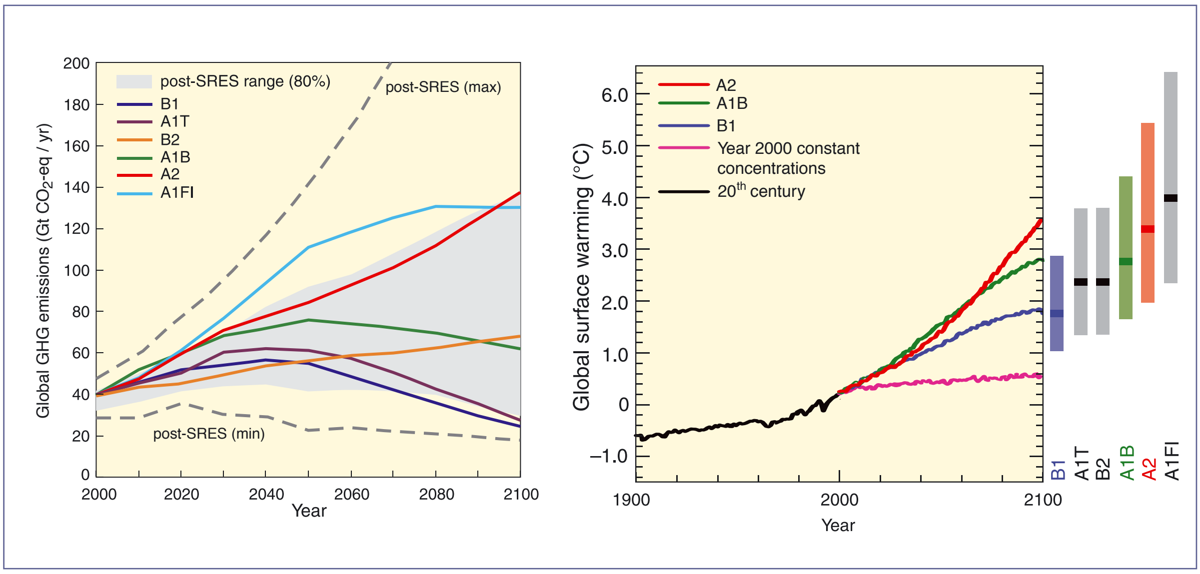
AR4 reports on modelling of four main 'storylines' (A1, A2, B1 and B2) with around ten variants of each one (Box 2.1). The models are calibrated against historical climate and the replication of observed trends, and have steadily improved in performance over the last ten years with the incorporation of AOGCMs. Since AR4 in autumn 2007, there has been a broader scientific consensus on the certainty of future projections based on: better description of climate processes; a broader range of scenario assessment; and better scientific understanding of positive and negative feedbacks included in the models. Nevertheless, there are still areas for further improvement related to 1) Scale and spatial representation (125–400km grid cells at present); 2) land–surface atmosphere interactions and their representation; 3) the trends and behaviour of aerosols in the atmosphere. These are partially included at present, but one conundrum is that global rates of actual evaporation have been declining, when current modelling suggests that they should be increasing (Barnett *et al.*, 2005). New scenarios are being defined in preparation for AR5; these are likely to be published before the end of 2010.

Uncertainties in climate projections feed through to predicted impacts, making it harder to evolve appropriate and effective adaptation and mitigation strategies. More probable outcomes are obtained from a range of scenarios run through an ensemble of GCMs so that the different results obtained from individual models (with different algorithms and structure) are 'averaged'. Therefore we see future projections of temperatures varying from significant to slight increases for different scenarios (Figure 2.1), but with a high likelihood of occurrence, and good consistency between models. By comparison, the predictions of rainfall are far less consistent, with some models predicting increases in rainfall where others predict decreases for the same scenario. The resulting rainfall maps show the majority result from ensemble modelling, and show where predictions have mostly the same trend (up or down).

Climate variability is thought likely to increase, but it is harder to predict by how much and over what time period. The combined effect of a change in climate and an increase in variability results in more frequent and larger (negative) impacts than a change in either one on its own, as illustrated for temperature in Figure 2.2. As more data becomes available, it will be possible to understand better how variability is changing. The frequency of extreme precipitation is predicted to increase dramatically in countries and climates as far apart as the United Kingdom (5 times in north and west) and Bangladesh (3–7 times) with consequent increases in the duration, extent and severity of flooding (Palmer and Raisanen, 2002).

FIGURE 2.1

An illustration of the range of scenario prediction for GHG emissions (right panel) and global warming (left panel) (IPCC, 2007)



Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.5. IPCC, Geneva, Switzerland.

Supporting evidence for more extreme climate is beginning to emerge (Allison *et al.*, 2009), with evidence of increased frequency of heat waves in North America and Europe, coupled to a decreased occurrence of cold shocks. Evidence of recent heavy increases in precipitation has been found for the United States, based on five-year moving averages, and elsewhere, rates of increase in variability have exceeded those predicted in climate modelling studies. Although too early to develop robust relationships, evidence is emerging for a 5–10 percent increase in heavy precipitation rates per degree Celsius temperature rise.

Milly *et al.*, (2002) found that the frequency of (what were) 1:100 year floods in 29 large basins covering an area of more than 200 000 km^2 increased considerably during the twentieth century. Even a 2 °C rise in Africa is predicted to be of graver consequence than originally thought due to the continent's high sensitivity to more frequent extreme events. La Niña in Kenya and El Niño effects in southern Africa are exemplified by higher frequencies of drought and are estimated to already be costing 15 percent of GDP in Africa (Barclays and Met Office, 2009).

BOX 2.1

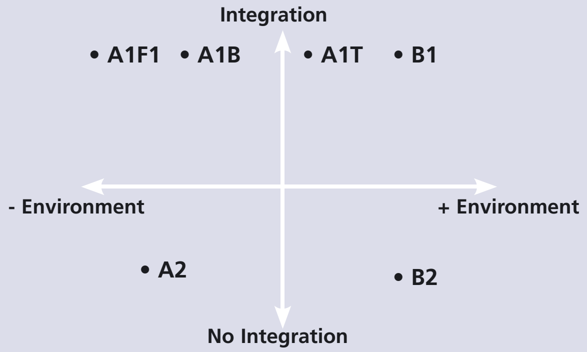
SRES (Special Report on Emissions Scenarios) storylines

A1. The A1 scenarios envisage a world that has developed rapidly, with strong interactions and convergence between regions and a much more even distribution of per-capita income across nations. Global population peaks around 2050 and declines thereafter; it is accompanied by the rapid introduction of innovative and more efficient technologies. Three broad directions in technology are foreseen: A1F1 is dominated by continued use of fossil fuels and is closest to a 'business as usual' scenario: A1T proposes a substitution of fossil fuels by other energy sources and A1B provides an intermediate balance of use across both types of energy source.

A2. In contrast, A2 presents a more varied world, where individual nations value self-reliance, and follow their own aspirations. Thus population growth rates vary considerably across the globe and converge slowly, with a more populous world than in A1. Per capita economic growth is also more variable, whereas technological development is slower and more fragmented.

B1. The basic assumptions of convergence and stabilizing population of A1 are married to a world that veers towards a service and information economy, with a significantly lower use of natural resources and the adoption of 'cleaner' more efficient technologies. There is a strong emphasis on global solutions to environmental, economic and social sustainability and the achievement of greater equity between communities.

B2. Although B2 emphasizes local solutions and a continuously expanding population, it is focused on economic, social and environmental stability. However, it experiences lower population growth than A2 and lower rates of technological development than A1 or B1.



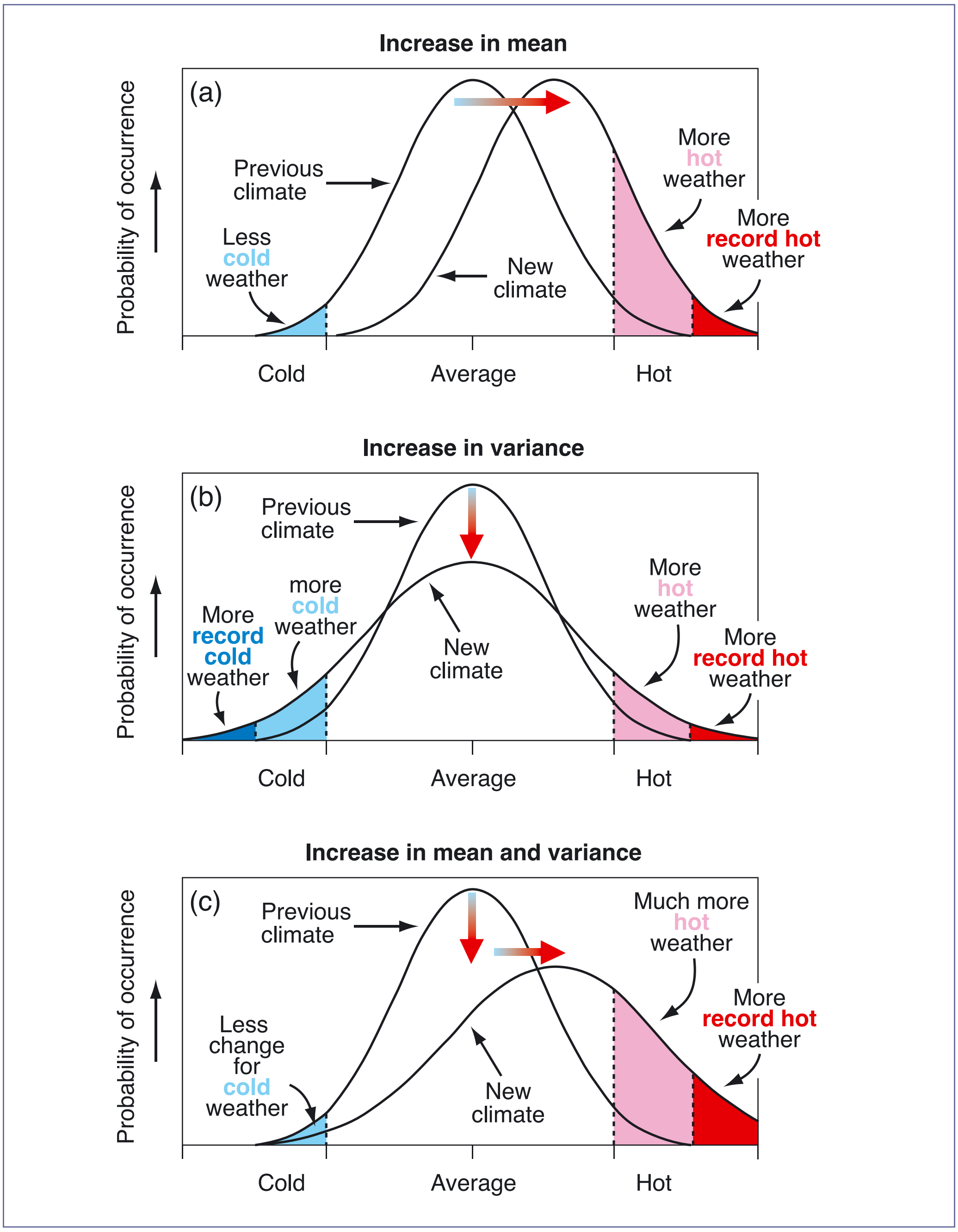
Scenario characteristics	SRES Scenario examples, 2100				
	1990	A1	A2	B1	B2
World Population (billion)	5.25	7.1	15.1	7.2	10.4
CO_2 concentration (ppm)	354	680	834	547	601
Mean global temp increase (C)	-	2.52	3.09	2.04	2.16
Range of temp rise (C)	-	1.7–3.66	2.12–4.41	1.37–2.99	1.45–3.14
Global mean sea-level rise (m)	-	0.58	0.62	0.50	0.52
Range in sea-level rise (m)	-	0.23–1.01	0.27–2.07	0.19–0.90	0.20–0.93

Source: SRES scenarios (Third Assessment Report of the IPCC, 2001c)

All discussion of climate impacts should be properly tied to a specific scenario, time frame and location and the sensitivity analysis associated with uncertainty should also be stated to put observations in the correct context. It is not easy to read or to keep track of such qualified writing. As this document proceeds, we will argue for a progressively location-specific analysis of spatially disaggregated projections and the evolution of appropriate adaptation strategies. A key factor in the improvement of climate model performance at global and regional scales, at least in terms of narrowing the range of projected outcomes, is the incorporation of land-use feedbacks, which are responsible for modifying climate into weather.

FIGURE 2.2

An illustration of the effects of climate change (increase in mean, in variance and in mean and variance) (IPCC, 2001 a and b)



Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2.32. Cambridge University Press.

Since AR4, considerable effort has gone into constraining the range of modelling predictions through ensemble modelling, improvement of process description (adding land surface interactions to some of a newer generation of AOGCMs) and further refinement of spatial scale (reducing grid cell size). However, probabilistic interpretation of scenarios will remain at the centre of analysis for the foreseeable future, with constant refinements to models resulting in increasingly accurate, consistent and more nuanced prediction.

The interpretation of specific impacts and river basin and national scales requires more detailed, downscaled modelling driven by GCM forcings under different climate scenarios. This is especially true for agriculture, hydrology and land-use impact assessment. But it is only where good meteorological control data is available that downscaling becomes sufficiently precise to justify long-term rainfall projections (Timbal *et al.*, 2009).

2.2.2. Climate versus weather - the downscaling problem

The problem of scale underwrites the interpretation of all projections in global climate change modelling. Although the highest resolution models have a grid size of 125 km^2, many are as coarse as 500 km^2 per cell. Global climate models have become increasingly complex and integrate most of the processes that drive climate, with perhaps the exception of the land–surface–atmosphere interactions. Climate patterns are long-term and relatively stable expressions of temperature, relative humidity, rainfall, and circulation patterns at global and regional scale. Weather is famously more variable and difficult to predict. Weather is short term, highly variable over space and time and is affected by multiple interactions between topography, land use, and local scale atmospheric processes that all occur at scales smaller than one or a small cluster of GCM grid cells. Climate drives weather and some climatic processes (such as El Niño) exhibit cyclic behaviour that can be used (through indicators such as ENSO and ocean surface temperatures) to predict general weather patterns.

Regional scale climate models (RCMs) can be nested within GCMs, at scales ranging from 20–100km^2 per pixel, and, in theory, should do a better job of predicting climate variables. The simulations of RCMs are based on climatic forcings derived from the GCMs under different scenarios of climate change. To date, it is fair to say that RCMs are not as developed nor as well calibrated as GCMs. Given the higher variability in weather patterns at regional scale, this is not surprising. RCMs and short-range weather models require considerably more computer processing power than even GCMs and they also incorporate more process detail. RCM temperature outputs agree with local observations and with GCM forcings to a large extent (McInnes *et al.*, 2003) but can generate quite divergent patterns and quantities of estimated rainfall.

RCMs will continue to be developed and refined and will be increasingly deployed at local scale. However, they remain relatively coarse-scaled compared with real measurements on the ground. Some countries have relatively dense hydro-meteorological networks (mostly OECD countries and those of the former Soviet Union), whereas data may be very sparse, for example most of sub-Saharan Africa and somewhere in between in places such as India and China. Remote sensing offers great opportunities to infill data at higher resolution than most RCMs – down to 1 km^2 for actual evapotranspiration (using procedures such as the satellite-based hydrological model SEBAL) and for net radiation and surface temperatures (Bastiaansen *et al.*, 1998). The spatial distribution and amount of rainfall can be increasingly better estimated through correlation of satellite measurements with ground-station data (McVicar and Jupp, 2002) using platforms such as Tropical Rainfall Measuring Mission (TRMM), Geosynchronous Meteorological Satellite (GMS) and the weather forecast satellite, Meteosat, at scales of a few square kilometres.

Alternatives to RCM analysis include statistical downscaling and other empirical downscaling. Naylor *et al.*, (2007) report on the use of empirical downscaling models in Indonesia, where long-term detailed spatial data is sparse, but sufficient to generate empirical relationships. They report a robust relationship between local sub grid-scale precipitation and large-scale atmospheric variables being simulated reliably by the GCMs, with good account of topographical features. A recent study on the Okavango encountered difficulty in downscaling and validating rainfall due to lack of long-term data and the effects of multi-decadal climate patterns. Ensemble outputs for temperature and atmospheric pressures were consistent but the downscaled prediction of increased rainfall was not consistent with regional scale GCM modelling (Wolski, 2009).

The problems of scaling are not unique to climate prediction, but are fundamental to the modelling and understanding of hydrological processes (Beven and Freer, 2001). Inconsistencies between GCMs may confound the analysis of impacts on hydrology and agriculture in large river basins, such as the Nile (Conway, 2005). There is an even clearer mismatch between predicted and observed data at sub-basin scale, where considerably more detailed hydrological and meteorological data is available within the coverage of a GCM grid cell of 125 km^2 (Serrat-Capdevila *et al.*, 2007). Even achieving satisfactory country level analysis can be challenging (Hewitson and Crane, 2006, on South Africa) and large island countries such as Sri Lanka and even Indonesia are not represented as land masses in most GCMs.

The prediction of rainfall by GCMs is often poor as the variables that force rainfall patterns are dominated by topography and to a lesser extent vegetation. The rainfall patterns predicted by ensembles of GCMs for India completely miss the higher rainfall areas of the sub-Himalaya and the western Ghats, although they slightly over-estimate current average rainfall, while modelled peak daily rainfall intensity was only two-thirds of that recorded (Lal *et al.*, 2001).

Later studies with nested modelling using ensembles of AOGCMs linked to an RCM (PRECIS) give better spatial representation of orographic rainfall and better capture monsoon behaviour (Kumar *et al.*, 2007). In contrast to the 2001 work, the RCM study predicted a big increase in winter rainfall, as well as increases throughout the rest of the year (pre-monsoon and monsoon). However, the downscaled models have inherited some of the bias (over-estimating current rainfall) of the parent GCMs, and so it is argued that both process and spatial representation in GCMs still needs to be improved. Work is continuing with ensembles of RCMs to reduce uncertainty in the range of outputs.

While runoff reflects rainfall pattern, future projections of hydrologic impacts are more uncertain than is desirable. A summary of recent downscaling exercises across the United States (USDA, 2008) revealed that there was conflicting evidence on rainfall from ensemble GCM modelling and that 'off-line' RCM modelling predicted mean increases in rainfall and runoff in contradiction to earlier GCM and ensemble GCM-based work for at least four major river basins (Milly *et al.*, 2005; Christensen and Lettenmeier, 2007). Possible explanations include: slight differences in scenario specification; downscaling techniques do not necessarily preserve total GCM precipitation per grid cell; GCM grids tend to smear out gradients, especially for rainfall; and poor representation of an anticipated shift to winter dominated rainfall in the Colorado Basin and in California – a change that will enhance runoff.

Scaling problems related to agronomy are mostly concerned with the representation of the climatic and terrestrial factors that govern the processes simulated in crop models. Unlike hydrological modelling, they are not related to the scale of the processes themselves, but to the input data used to drive the models. Processes within crop models themselves are usually empirical to semi-empirical, and represented in terms of regression relationships between photosynthetic processes, radiation, water and nutrient status. There remains some uncertainty as to how well crop model processes calibrated to a current range of conditions represent what will happen in future climate projections. Some studies (Gommes *et al.*, 2009; Fischer *et al.*, 2007) assume that future crop productivity will be similar to present productivity under irrigation, whereas the expectation from crop physiologists (Smith *et al.,* 2008; Nelson *et al.*, 2009) is that potential productivity may fall.

2.2.3. The agricultural implications of the IPCC Working Group I report (Physical Science)

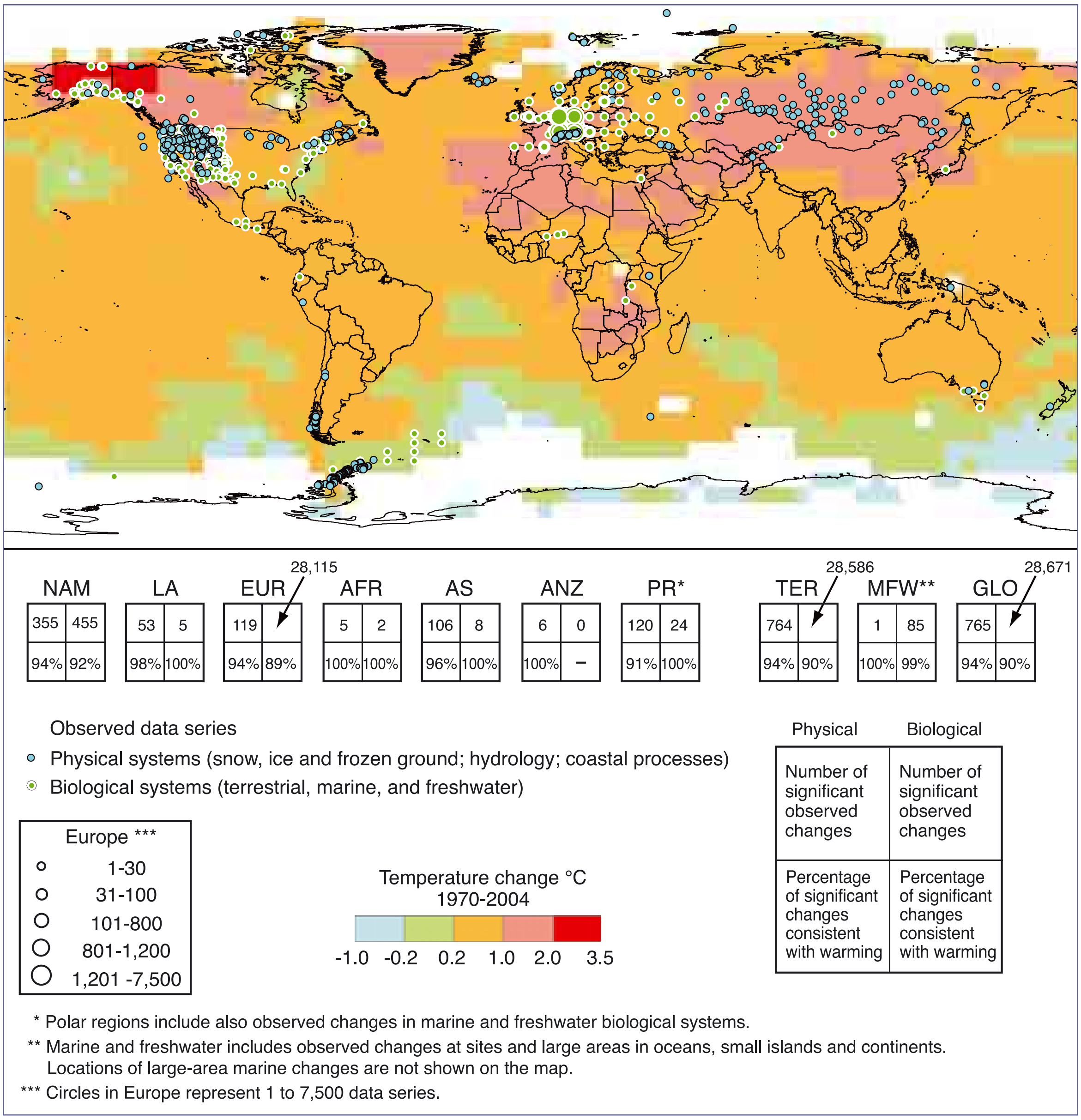
AR4 (IPCC, 2007) foresees a temperature rise in the range of 2 to 6 ˚C by 2100. This compares with temperature increases in the Millennium Assessment scenarios that fall in a lower range from 1.5 to 2.0 ˚C above pre-industrial in 2050, to between 2.0 and 3.5 ˚C in 2100 (Alcamo *et al.,* 2005). One of the main reasons for the higher temperature estimates by 2100 in AR4 is the better understanding of positive feedbacks that further increase carbon dioxide concentrations in the atmosphere, partly due to saturation of the absorptive capacity of the seas and terrestrial vegetation and soils. Other temperature reinforcing feedbacks result from the melting of polar and mountain ice caps at +4–5 ˚C (reduced albedo and reflection), thawing of permafrost with release of large volumes of methane, and higher atmospheric retention of CO_2 in future at higher temperatures. It is also anticipated that there will be considerable mobilisation of GHGs when temperature rise reaches around 5–6 ˚C, with expected large releases of methane from Tundra and permafrost areas in the northern latitudes. These temperature and CO_2 concentration changes will have direct impacts on plant growth. The pattern of actual temperature change between 1970 and 2004 is given in Figure 2.3, which reflects the patterns predicted for later in the twenty-first century, with 2 ˚C rises already evident in the mid-latitudes and interiors of large continents.

The balance of impacts from increasing temperature on aquatic ecosystems (rivers and lakes) is not clear. This is because of competing effects between reduced oxygen concentration in water at higher temperatures and higher aquatic productivity, with a likely net increase in oxygenation (there is more day-time photosynthesis than night-time respiration). Adding in the impacts of changed flow regimes (positive or negative) and other factors such as non-point source pollution from agriculture (N and P), the situation will require individual assessment. There are attendant implications for aquaculture and flood production systems (such as deep-water rice), as well as drains and drainage management, but these have not been sufficiently explored.

Since the specific moisture capacity of air increases as the square of its temperature, higher temperatures inevitably increase evaporative demand. Overall impacts on crops are a combination of direct temperature effects on respiration and photosynthesis, increased water demand (due to increased evaporative demand), and the availability of soil moisture as determined by rainfall, runoff and applied water. The suitability of crops to different climates (including microclimates modified by topography and elevation) is classified into agro-ecological zones (AEZ) (FAO, 2000).

The global patterns of predicted changes in temperature, precipitation and air-pressure rise illustrated for 2080–2099 for 'winter' (December, January, February - DJF) and 'summer' (June, July, August - JJA) seasons are presented in Figure 2.4; these are derived from SRES A1B. The figure illustrates: the expected worldwide rise in temperatures;

FIGURE 2.3
Actual pattern of global temperature change 1970–2004. Source: IPPC SPM II (IPCC, 2007)



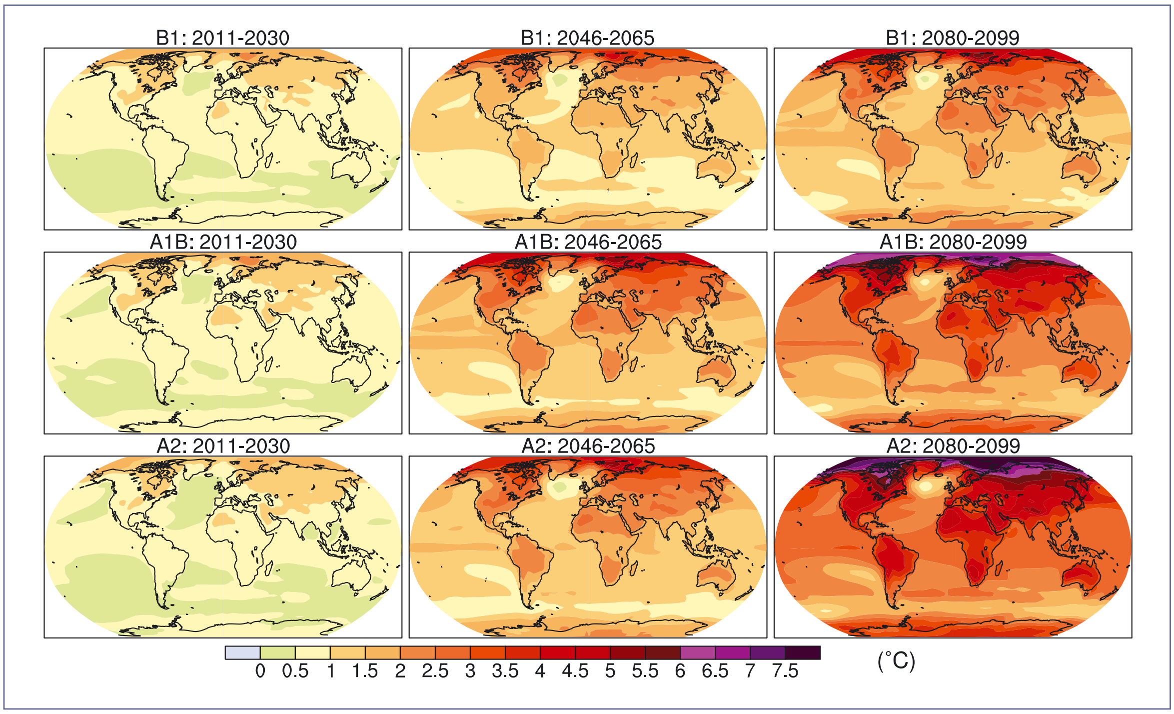
Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 1.2. IPCC, Geneva, Switzerland.

the increase of precipitation in higher latitudes and humid equatorial tropics in contrast to the fall in precipitation in semi-arid and arid areas falling in the inter-tropical convergence zones; and a notable increase in air pressures in the Southern Hemisphere. At this scale, there is clear correlation between the areas of lower expected rainfall (and higher temperature), and the areas currently featuring extensive irrigation – India, China, western United States and Mexico, Southeast Asia, North Africa and Australia.

Predicted sea-level rise as a result of thermal expansion and ice-melt to 2070 is 0.7–1.0 m, and will have significant impact on coastlines and deltas in particular. Irrigation is commonly found in major deltas in South, East and Southeast Asia, and their vulnerability in terms of displaced people as a result of current trends to 2050 is illustrated in Figure 2.5. Sea-level rise due to climate change will further exacerbate this vulnerability.

FIGURE 2.4

Temperature, precipitation and sea-level pressure change by quarter year (DJF and JJA), for SRES A1B, in 2080–2099 relative to 1980–1999 (source: Meehl *et al.*, 2007)



Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 10.9. Cambridge University Press.

The impacts of sea-level rise include greater and more frequent storm surge damage, and likely saline intrusion in estuaries and to coastal groundwater systems, with NE China being especially vulnerable due to the extent of depletion in existing coastal aquifers.

With the caveat that detailed patterns of runoff will vary considerably with improved resolution and scaling of rainfall patterns, the global implications for runoff are summarized in Figure 2.6 (AR4, 2007), with illustrative stress points noted on different continents.

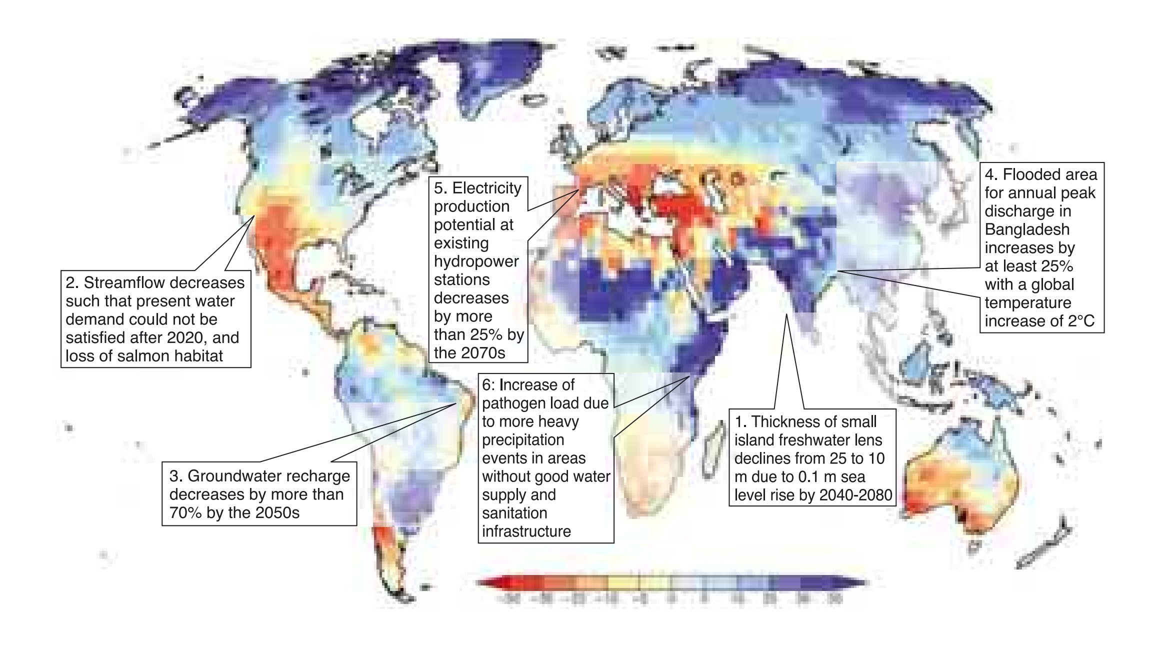
FIGURE 2.5

Relative vulnerability of coastal deltas as indicated by estimates of the population potentially displaced by current sea-level trends to 2050 (extreme: >1 million; high: 1 million to 50 000; medium: 50 000 to 5 000)

Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure TS.8. Cambridge University Press.

FIGURE 2.6

Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions. The background shows ensemble mean change of annual runoff, in percent, between the present (1981–2000) and 2081–2100 for the SRES A1B emissions scenario; blue denotes increased runoff; red denotes decreased runoff



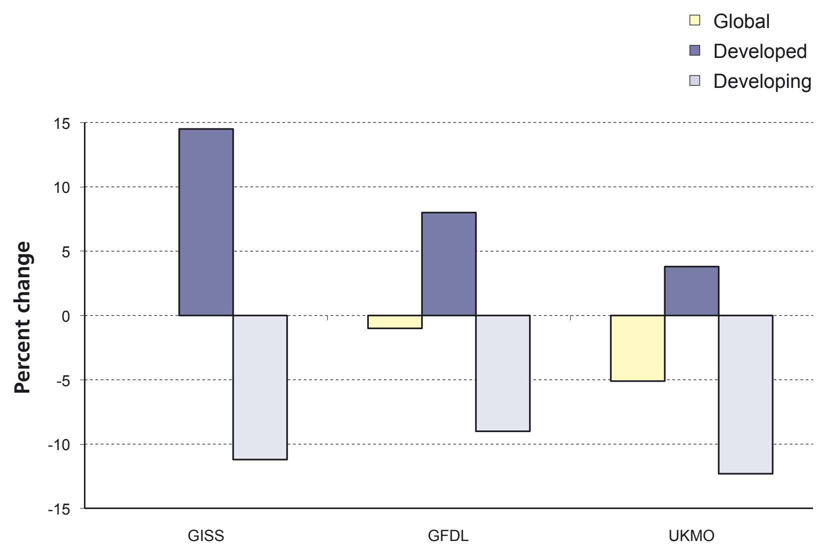
Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure TS.5. Cambridge University Press.

Rising temperature, rising potential evapotranspiration rates and declining rainfalls conspire to increase the severity, frequency and duration of droughts. Large-scale land-use change is expected on all continents. AR4 estimates that some 75 million ha of land that is currently suitable for rainfed agriculture, with a growing window of less than 120 days, will be lost by 2080 in sub-Saharan Africa (IPCC 2007). In rainfed systems, if potential evaporation rates increase, available root zone moisture content will be more rapidly depleted, requiring either shorter season crop varieties or acceptance of lower yields and more frequent crop failure.

Worldwide cereal yields are expected to decline by 5 percent for a 2 °C rise in temperature and by 10 percent for a rise of 4 °C. Grain yields should decline above certain temperature thresholds, with grain number in wheat falling in temperatures above 30 °C and flowering declining in groundnut when they are above 35 °C (Smith *et al.*, 2008). Yields are estimated to fall uniformly in the tropics due to temperature rise but higher productivity is expected in the higher latitudes with longer season growth, more optimal growing conditions, and the probable development of new lands. As temperature rises further at higher latitudes, productivity may then decrease in the longer term (USDA, 2008), and improved potential productivity may not be realized, as conditions for pests and diseases will become more favourable.

The mid-latitudes will suffer from declining yields because temperature change and areas will decline as a result of reduced water availability – for irrigation and rainfed farming in the Mediterranean, southern Europe, mid-west United States and the semi-arid to arid sub-tropics. These areas are close to the threshold temperatures for declining yield and so the yields of wheat and other staple crops in the Mediterranean, western Asia and Africa are expected to fall by 25–35 percent with weak CO_2 fertilisation and by 15–20 percent with strong CO_2 effect. The estimated balance of changes in cereal production modelled by Parry *et al.*, (2005) for a temperature rise of 3 °C and a doubling of atmospheric carbon dioxide concentration is shown in Figure 2.7.

FIGURE 2.7
Change in cereal production under three equilibrium climate change scenarios in 2060 assuming implementation of Adaptation Level 1 (AD1) (Parry *et al.*, 2005)



GISS: Goddart Institute for Space Studies; GFDL: Geophysical Fluid Dynamics Laboratory; UKMO: United Kingdom Meteorological Office

2.2.4. Broad regional impacts – food security and climate change

Although a great deal of analysis of potential regional impact was undertaken for AR4, its publication prompted a flurry of impact studies. There is a rising consensus of opinion that Africa and South Asia are the most susceptible and vulnerable to climate change; both have large populations of poor with meagre access to basic resources of water and productive land. AR4 reported the following broad regional impacts (IPCC SPM, 2007). Some further qualifications from other sources have been added as subsidiary points.

- In Africa, by 2020, between 75 and 250 million people will be exposed to increased water stress and in some countries, yields from rainfed agriculture could be reduced by 50 percent.
  - Significant reductions in runoff are forecast, with a 10 percent reduction in rainfall in the higher precipitation areas, translating into a 17 percent reduction in runoff. This compares with severe falls (30–50 percent) in the medium (500–600 mm) rainfall zones (de Wit and Stankiewicz, 2006).
  - However, there remains a high level of inconsistency between models across different macro-regions – western, eastern, and southern Africa in particular (SEI, 2008). There is urgent need for detailed predictive modelling across these extensive regions.
- In Asia, by the 2050s, freshwater availability in Central, South, East, and Southeast Asia, particularly in large river basins, will decrease. The heavily populated mega deltas in the South, East and Southeast will be at risk due to increased flooding from the sea and rivers.

- More recent downscaled hydrologic modelling (Gosain *et al.*, 2006) for the major river basins in India predicts that the most severe reduction in runoff will occur in the Krishna Basin (30-50 percent in response to a 20 percent decline in rainfall), a basin that is already highly stressed and subject to contentious inter-state competition for water. At the other end of the scale, the Mahanadi Basin will experience increased flooding due to increased peak runoff, with some potential benefits from a mild increase in base-flows.

➢ In Latin America, productivity of some important crops will decrease and livestock productivity will decline, with adverse consequences for food security.

Two and a half billion people relied on agriculture for their livelihoods in developing countries in 2005, while 75 percent of the world's poor lived in rural areas. Predictions of food security and livelihood are varied and reflect the underlying assumptions in modelling. Fischer *et al.*, (2005) estimated future per capita food availability for scenarios of no climate change (current development trajectory), and climate change with and without mitigation of carbon dioxide emissions by 2080 (Table 2.1) (Tubiello and Fischer 2007; Tubiello *et al.*, 2007). The assumptions on increasing productivity and area available for agriculture predict that the number of hungry in the world would be likely to fall without climate change, although in stark contrast, more than twice as many will be at risk in Africa. Even with climate change, the number of hungry people in the world is expected to be lower than in 2000, but will still more than double in Africa.

TABLE 2.1
Estimated numbers of people at risk of hunger in 2080 (Fischer *et al.*, 2005)

	Year 2000	A2r 2080 (No CC)	A2r 2080 (Had CM^3)	A2r 2080 (HadCM^3 mitigation)
Latin America	57	23	30	26
Sub-Saharan Africa	188	410	450	430
Southeast Asia	42	5	5	5
South Asia	312	43	45	44
East Asia	42	5	5	5
Developing countries	821	554	622	488

Note: A2r: revised version of scenario A2

A more recent analysis of future global security undertaken by IFPRI (Nelson *et al.*, 2009) foresees a grimmer world, and expects serious diminution of food security in South Asia as well as in Africa, due to progressive decline in crop productivity, in both rainfed and irrigated agriculture. As with Fischer's study, the real price for all food types is projected to rise, and average per capita kilocalorie intake is predicted to be lower in 2050 than in 2000. In contrast to the previous study's anticipation of small changes in global food security due to climate change, the IFPRI study predicts a 20 percent increase in child malnutrition compared with a world without climate change. It recommends large investments in enhancing agricultural productivity (US$7.1–7.3 billion a year) with 40 percent of the total required for Africa. It proposes increasing irrigation 'efficiency' in Asia, foresees a global increase in irrigated area of 25 percent and warns against investing in areas where water resources will decline.

A more optimistic study of 12 African regions, undertaken with an ensemble of 20 GCMs, identifies where adaptation needs to take place and prioritizes some suggestions – wheat, maize and sugar in southern Africa; yams and groundnut in West Africa; and wheat in the Sahel (Lobell *et al*., 2008).

The frequency of a 30-day delay in rainy-season rice planting in Java is likely to increase from 9–18 percent today to 30–40 percent by 2050; this is based on empirical downscaling of GCM ensembles (Battisti and Naylor, 2009). The delay has historical links to El Niño patterns, but these have weakened in recent decades. Water shortages are likely to be experienced in 15–20 million ha of rice by 2025, representing about 10 percent of the total planted area (Padgham, 2009).

2.2.5. The agricultural implications of the IPCC Working Group II report (Adaptation)

The anticipated impacts of climate change in terms of crop production are summarized in the IPCC AR4 WG2 (Ch. 5.4). These tend to focus mainly on agronomic impacts related to temperature rise and elevated CO_2. However, the balance of more recent experimental and modelling evidence since AR4 has downgraded the prospects for positive CO_2 fertilisation and is discussed in more detail in Chapter 4.

Adaptation options are defined by the context of farming system, existing water use, and weather impacts on crop production (temperature and evaporation). It has been noted that there is a rising tendency to claim climate change as a scapegoat for project failure and declining agricultural productivity, such as that resulting from withdrawal of fertilizer subsidies in the Machakos in Kenya, or the consequences of overgrazing by pastoralists (SEI, 2008). Recent reports on Africa (Barclays and the Met Office, 2009) and for United States (USDA, 2008) neatly summarize the agricultural risks of climate change that will require adaptation:

- Species viability is climate dependent. Changes in the climate may require changes in the cultivation of crops best suited to a particular location.
  - many crops have low tolerance to changes in temperature and water availability and yields fall once daily temperatures start to exceed certain thresholds. Although these thresholds are well-known in countries such as the United States, they are poorly defined for many important crops in Africa, and to a lesser extent in Asia;
  - increased variability in rainfall increases risk for dry-land farming;
  - the demand for irrigation will increase (in terms of area) and irrigation water use on existing crop areas will increase due to greater evaporative demand, even if growing seasons shorten.
- Water availability and quality, and timing of rains for initial sowing during the growth cycle and at harvesting can have significant impacts on yields.
  - the antecedent climate also affects catchment runoff and soil moisture availability;
  - changes in ozone and carbon dioxide impact crop growth rates and the use of water;
  - water resources available for irrigation will be more variable, and will decline in areas with declining rainfall (much of southern and western Africa).
- Precipitation and temperature extremes can increase vulnerability significantly, especially at fragile stages of crop growth.
- Changes in pests and disease burdens may have specific economic impacts on cash crops, livestock and orchards.

  - changing temperatures may impact habitats and breeding cycles for critical pollinators such as bees and other key species.
- The ability of livestock to survive and breed could be affected by climatic influences:
  - likely decrease in carrying capacity for extensive grazing;
  - possible increase in heat-stress related livestock mortalities;
- There are impacts on fisheries including those on breeding patterns from changes in water temperature and flow patterns.

A recent report on adaptation in agriculture by the World Bank notes that agricultural systems will shift at the margins of their current location and condition. This will result in loss of extensive rangeland; conversion of marginal arable land to rangeland; and a change to production systems with greater temperature or drought tolerance. For example, replacement of maize with sorghum and millet; and conversion of wet rice to dry-footed crops or upland rice in tropical areas impacted by declining water availability or increased evaporation (Padgham, 2009).

2.2.6. The agricultural implications of the IPCC Working Group III report (Mitigation)

The IPCC considers how agriculture can contribute to mitigation of global emissions of greenhouse gases, to help stabilize future carbon dioxide levels and restrain global warming. Agriculture contributes greenhouse gases and also cycles and stores carbon through the photosynthesis and biological accumulation of carbon in plant matter and soil organic matter. Agriculture contributes to greenhouse gas emissions through nitrogen fertilizer use, predominantly as nitrous oxide and through methane, from wet-rice production and at a larger scale, from enteric fermentation in ruminants (cows, sheep and goats).

Agriculture in industrial countries uses considerable amounts of fossil fuels in mechanisation, transport and processing whereas the fossil fuel inputs in developing country agriculture are modest. However, pumped irrigation, particularly for groundwater, is a major consumer of energy, notably in India and China where subsidized electricity has encouraged widespread development and competitive pumping from rapidly increasing depth.

The IPCC (2007) estimates that there is good potential in agriculture, particularly in the tropics, to mitigate greenhouse gas emissions. Chapter 6 of this document is devoted to mitigation of greenhouse gas accumulation through agriculture.

2.2.7. The Stern Review

The Stern Review (Stern, 2006) paid special attention to the economic impacts of climate change and to the consequences for developing countries. It presents a strong case for climate sensitive development and argues that the costs of immediate mitigation would be considerably lower than if delayed into the future. Although the Stern Review was published prior to AR4, it used a good portion of the material and scenario assessment that contributed to AR4 and can be thought of as being consistent in terms of science base.

The report makes it clear that developing countries are far more vulnerable than industrialized economies where more severe projected climate changes will impact weaker economies. Developing countries typically have greater economic reliance on agriculture and a significantly larger number of citizens engaged in agriculture. Their lack of broad economic strength, with weaker institutions and technology, hampers flexible adaptation.

Stern emphasizes that the primary economic impacts will occur through intensification of the hydrologic cycle, and that food production will be highly sensitive to climate change. The prospects for agriculture discussed in the Stern Review were strongly influenced by the then important debate on the balance of the detrimental effects of temperature and the beneficial ones of CO_2 enrichment. Increased temperature tends to decrease yield potential by accelerating growth rates and shortening the growing season, with a consequent reduction in assimilates in the plant. The Stern Review observes that predictions based on average changes do not properly account for the impacts of extreme events, and it provides some useful examples, such as an expected doubling of losses due to water logging in maize production in the United States by 2035, valued at around US$3 billion per annum.

From a water management perspective, two aspects of the Stern Review have been questioned. First, the assumption that all natural capital is 'substitutable' in economic terms is thought to gloss over limited options of economically substituting land and water resources that are suitable for agriculture (Neumayer, 2007; after Dubourg, 1998). Second, there has been considerable debate over the selection of a low discount rate chosen to value resource use in the future at levels similar to today's use (and that reflects some notion of inter-generational equity). In the water sector, higher discount rates are used for economic benefit-cost analysis of infrastructure investments in irrigation and water control (FAO, 2005). Thus there is an apparent inconsistency between valuing future impacts in a way that justifies immediate action and the more hard-headed approaches used to assessing the economic viability of specific investments. Even with the later assessments (Parry *et al.* 2009; World Bank, 2010) and the specific estimates of Fischer *et al.* (2007), irrigation infrastructure and agriculture costs cannot be neatly separated. However these studies clearly recommend avoiding to rush into expensive infrastructure adaptation without a good understanding of their impact.

2.3. AGRICULTURAL SYSTEMS DEPENDENT ON WATER MANAGEMENT

The basis for identifying agricultural systems at global scale is established from a combination of soil, terrain and climate properties, as expressed in the Global Agro-Ecological Zones (GAEZ) (FAO, 2000; IIASA/FAO, 2002; 2009). The socio-economic character of these zones is further developed as a set of regional farming systems (FAO/World Bank, 2001). This allows a global analysis of most agricultural systems – but not all. For instance, inland fisheries and aquaculture are not identified explicitly as a 'farming system'. The extents of irrigation in later GAEZ products (FAO/IIASA, 2007a; 2007b) are consistent with the known equipped areas established in the Global Map of Irrigation Areas (FAO, 2007c; Siebert *et al.,* 2007; Siebert *et al.* 2010). However, the global trend toward more intensive, precision based agriculture is striking. Table 2.2 shows that while the net increase in cultivated land since 1961 as exhibited modest annual growth, all of this net increase can be attributed to the application of irrigation.

2.3.1. Rainfed agriculture

Rainfed lands account for more than 80 percent of global crop area and 60 percent of global food output but are especially susceptible to the impacts of climate change, more so in the arid and semi-arid regions. In general, the productivity of rainfed

TABLE 2.2
Net changes in major land use (million ha)

	1961	2009	Net increase 1961-2009
Cultivated land	1 368	1 527	12%
• rainfed	1 229	1 226	- 0.2%
• irrigated	139	301	117%

Source: FAO. 2010. AQUASTAT database on http://www.fao.org/nr/aquastat
FAO. 2010. FAOSTAT database. http://faostat.fao.org

agriculture in developing countries is considerably lower than in more secure irrigated conditions, where the use of other factor inputs is generally higher. In the northern hemisphere intensive, mechanized and highly productive rainfed agriculture is the norm, benefiting from reliable and well-distributed rainfall. Cropping with variable rainfall can be intensive and highly productive where climatic risk is reduced by crop insurance (Australia, commercial farms in South Africa, the United States), or where supplemental irrigation can be provided in periods of low rainfall (Europe and the United States). Many sophisticated adaptations have been developed by farmers to allow cropping in precarious arid and semi-arid conditions, including mixed and companion cropping, floodwater spreading and runoff harvesting. Substantial literature exists on the likely impacts of climate change on rainfed agriculture, with only a skimpy outline given here. Rainfed and pastoral agriculture dominate land use in many countries and are therefore a major determinant of hydrology and runoff in a river basin.

African agriculture is predominantly rainfed, with low and erratic rainfalls over a large portion of the continent and is dominated by small subsistence farms. Urban migration is also proceeding apace, and it is likely that Africa will follow the same demographic pattern as the rest of the world. There is growing realisation that the subsistence model of small-holder development cannot power rapid economic growth in Africa and that it is unlikely to make the required difference to the lives of the poorest (Schmidhuber *et al*., 2009). Various forms of foreign direct investment in agriculture (including land purchase) have generated much debate and apprehension over the past five to ten years, but the development of an indigenous commercially based agricultural sector is limited. If African agriculture ‘converges’ with the rest of the world, there will be fewer farmers, larger urban and coastal populations as well as potential to increase labour productivity in agriculture and raise overall production. The transaction costs of raising the intensity of farming are lower in commercial farming than in subsistence production, indicating a window of opportunity for production growth in the continent (Collier and Dercon, 2009).

One of the main debates on how to feed the world’s growing population is the future balance between irrigated and rainfed agriculture. Higher productivity and relative security of irrigated agriculture is offset by the undesirable environmental consequences of diverting, storing and consuming stream flow and groundwater. This debate will be further complicated by the impacts of climate change on agriculture. Rainfed agriculture is reliable and productive at higher latitudes, and can be so in the humid tropics. However in the mid-latitudes (sub-humid tropics, seasonally arid, semi-arid and arid tropics), rainfed agriculture generally has low productivity and is prone to drought and crop failures. Rainfed staples (such as wheat, maize, sorghum and millet) are generally grown in conditions of deficient or sufficient rainfall. However, rice is naturally adapted to wet environments with excessive rainfall, requiring some measure of water control.

There is great potential to make global gains in food production through relatively modest (but large incremental) increases in rainfed production, because extensive areas have low productivity that can be increased significantly through a variety of low-cost and relatively simple means. In Niger, serious drought occurs about 3 in every 20 years. The staple food of millet is grown as a rainfed crop in river valleys and on less fertile plateaus. Market infrastructure is very limited and price variability is high so that prices rise through the year, especially during the 'hunger season' around June, but collapse rapidly in good and very good harvest years. Food aid intervention in poor (but not drought) years tends to depress prices and reduce farmers' incomes accordingly. Some level of nutrient input is required to maintain soil fertility and prevent long-term spiral of land degradation, as more traditional practices of manuring and fallowing are blunted by rising population pressure and sub-division of land holdings. Microdose fertilizer (NPK 8–25 kg/ha) has been widely used in some southern regions to stabilize production and slightly higher doses (NP to 65 kg/ha) can double yields in average to very good years, with similar increases in farm income. However, in poor and drought years, the benefits of micro dose fertilizer are marginal and result in reduced farm income (Abdoulaye and Sanders, 2006). The current challenge for supporting policy is to be able to distinguish between poor rainfall and drought years and improve the internal market for grains and processed millet products.

Nevertheless, a report by FAO (2002) concluded that although fertilizer inputs are singly important, the overwhelming evidence from developing countries being that better complementary benefits are derived from fertilizer and additional water, both in rainfed and formally irrigated conditions:

- the estimated average products of water and fertilizer increase with the volume of irrigation water applied, and the proportional gains in yield can exceed the proportional increases in applied water and the amount of fertilizer;
- while irrigation and fertilizer inputs can generate substantial increases in crop yields, above certain levels the law of diminishing marginal returns applies to input use;
- yield response to fertilizer varies with moisture conditions and sowing date;
- The water use efficiency of supplemental irrigation increases with increasing nitrogen;
- fertilizer use may tend to increase with the average number of irrigations;
- both moisture and fertility management contribute to higher yields but neither moisture nor fertilizer alone will generate maximum yield.

Water availability can be improved through a range of well-established conservation techniques that enhance storage of rainwater in the root zone, both directly and by collecting surface runoff from areas adjacent to crops. When water is less limiting, farmers find it less risky to apply fertilizers and other production inputs, to select higher yielding varieties, and spend more time on crop husbandry. Soil water conservation techniques, such as zero tillage, have clear benefits for rainfed crop production and are well-adapted to mechanized farms (as in Brazil), but further work is needed for smaller subsistence producers who rely on manual labour and animal power (Laxmi *et al*., 2007). Minimum tillage has direct benefits in reducing soil moisture loss associated with conventional ploughing, but may require chemical weed control and off-field disposal of straw. One of the most attractive benefits of zero tillage is that it requires less power and therefore less fuel and conventional cultivation. Other soil moisture conservation techniques include: mulching (using dust, crop residues (straw) or plastic sheet); occasional deep tillage to deepen the effective root zone and increase its porosity; strip planting; surface shaping to enhance retention and infiltration of rainfall and runoff; and the addition of soil amendments that improve structure and structural stability of the root zone.

The intensification of water capture in rainfed systems has inevitable consequences for hydrology and runoff. Large-scale water conservation activity in the upper catchments of Indian river basins has resulted in measurable depletion of runoff, sometimes to the detriment of established downstream users (Batchelor *et al*., 2005).

Rainfed cropping will remain inherently risky, more so with increasing temperature and declining, more variable rainfall. Soil moisture conservation will become an even more important adaptation, but if rains fail (and fail more frequently), crops will fail. The same is true if within season drought periods lengthen. Supplemental and full irrigation can mitigate longer within season and inter-annual drought, but under climate change, irrigation water supply will also be less secure.

The expansion of cropped area will also be necessary (MA, 2005; CA, 2007; FAO, 2007a), but has generally negative environmental consequences. The expansion of rainfed areas will come at the cost of the encroachment of forests while the expansion of irrigated areas further depletes water resources and encroaches on rainfed land (sometimes the most productive areas).

2.3.2. Irrigated agriculture

For more than 8000 years humans have turned to irrigation to improve food security, reduce volatility in production, add crop seasons and allow a diverse range of higher-value crops to be grown. The pace of irrigation development accelerated rapidly after the Second World War (1945) and reached a peak in the 1970s with heavy development financing (Figure 2.8). It has been credited with supporting the Green Revolution and propelling economic development in southern, eastern and Southeastern Asia but there has been very little impact in Africa. Irrigated yields in developing countries are in general, two to three times higher than those of rainfed yields (Ruane *et al*., 2008). Cropping intensity is on average more than 50 percent higher, and irrigation may support up to seven crops of rice in two years (115 percent cropping intensity) in the most intensively farmed parts of Southeast Asia (Vietnam and Indonesia).

Irrigation is the prime means of intensification and will remain a keystone of food security policies in the face of climatic variability. Despite under-performance and past over-investment with its environmental consequences, it is unlikely that the world can retreat from a production system that provides 40 percent of the world's food from just 20 percent of the cultivated area and underpins food supplies in populous countries such as Pakistan, China and India. Almost half of the total area under irrigation in the world is located in these three countries and covers 80, 35 and 34 percent of the cultivated area in Pakistan, China and India respectively (FAO, 2010). Just over 300 million ha of the world's agricultural land is equipped for irrigation (FAO, 2010). The distribution of land equipped for irrigated production is given in Figure 2.9 and a continental summary given in Table 2.3. Just under 40% of the global equipped area is now serviced by groundwater sources (Siebert *et al.*, 2010) illustrating the importance of local, privately accessed aquifers in buffering crop production.

FIGURE 2.8
Trends in irrigated areas, investments and food prices since 1960 (adapted from CA, 2007)

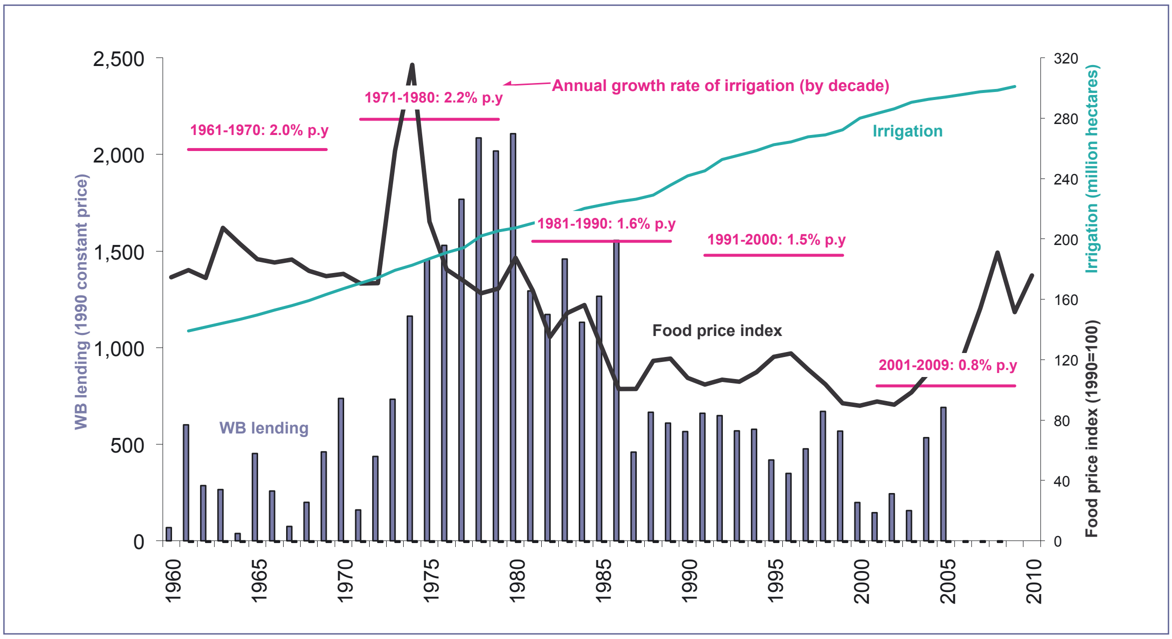
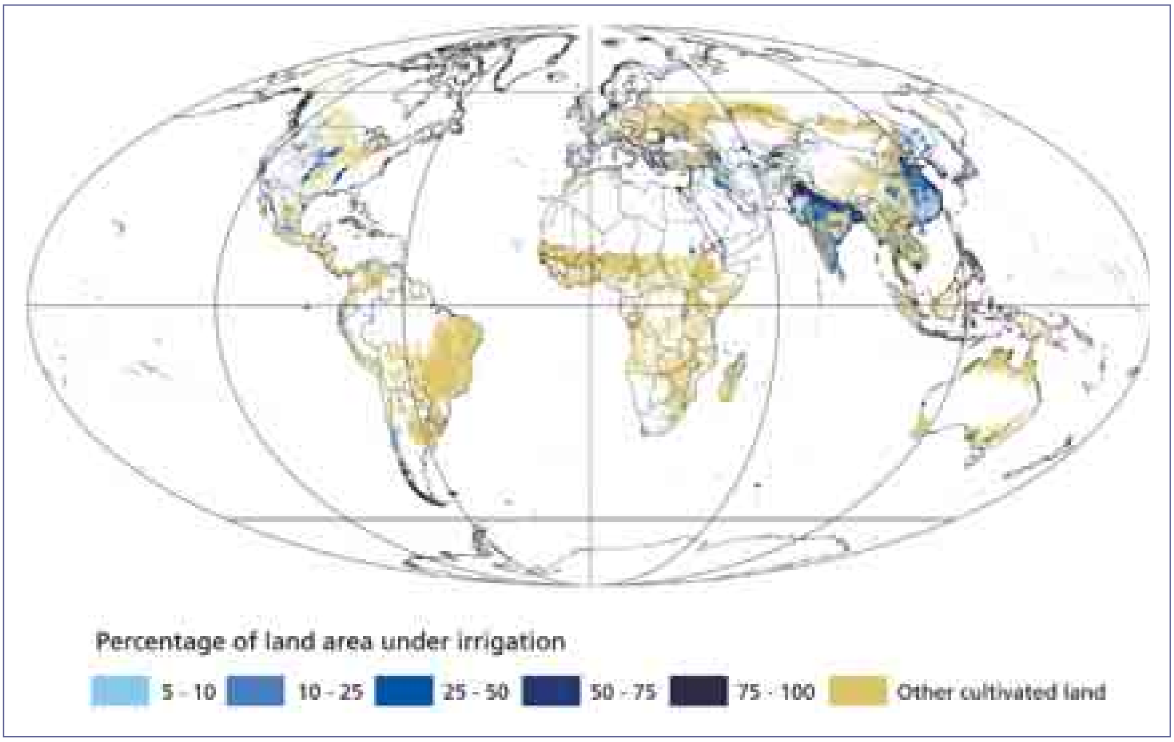


FIGURE 2.9
Distribution of area under irrigation in the world (FAO, 2010, Siebert *et al.*, 2007)



Future strategies of agricultural intensification and expansion depend on good quantification of existing and potential production from rainfed and irrigated agriculture. Improvements in both land and water are needed in the assessment of area, crop type and productivity. Similarly, prevailing climate and soil conditions need to be better defined so that climate change impacts can be more precisely understood, and appropriate adaptive responses developed. The mapping and characterisation of soils is perhaps the weakest element. Complementary understanding of existing ecosystem services is also necessary.

TABLE 2.3
Area equipped for irrigation, percentage of cultivated land and part irrigated groundwater

Continent / Region	Equipped area (million ha)		As % of cultivated land		Of which groundwater irrigation (2009)	
Year	1970	2009	1970	2009	Area equipped (million ha)	As % of total irrigated area
Africa	**8.4**	**13.6**	**4.7**	**5.4**	**2.5**	**18.5**
Northern Africa	*4.4*	*6.4*	*18.4*	*22.7*	*2.1*	*32.8*
Sub-Saharan Africa	*4.1*	*7.2*	*2.6*	*3.2*	*0.4*	*5.8*
Americas	**26.6**	**48.9**	**7.2**	**12.4**	**21.6**	**44.1**
Northern America	*20.0*	*35.5*	*7.5*	*14.0*	*19.1*	*54.0*
Central America and Caribbean	*0.9*	*1.9*	*7.8*	*12.5*	*0.7*	*36.3*
Southern America	*5.7*	*11.6*	*6.3*	*9.1*	*1.7*	*14.9*
Asia	**116.2**	**211.8**	**23.3**	**39.1**	**80.6**	**38.0**
Western Asia	*11.0*	*23.6*	*17.8*	*36.6*	*10.8*	*46.0*
Central Asia	*8.1*	*14.7*	*15.3*	*37.2*	*1.1*	*7.8*
South Asia	*45.0*	*85.1*	*22.8*	*41.7*	*48.3*	*56.7*
East Asia	*42.9*	*67.6*	*37.7*	*51.0*	*19.3*	*28.6*
Southeast Asia	*9.1*	*20.8*	*12.5*	*22.5*	*1.0*	*4.7*
Europe	**15.1**	**22.7**	**4.6**	**7.7**	**7.3**	**32.4**
Western and Central Europe	*10.8*	*17.8*	*7.4*	*14.2*	*6.9*	*38.6*
Eastern Europe and Russian Federation	*4.3*	*4.9*	*2.3*	*2.9*	*0.5*	*10.1*
Oceania	**1.6**	**4.0**	**3.5**	**8.7**	**0.9**	**23.9**
Australia and New Zealand	*1.6*	*4.0*	*3.5*	*8.8*	*0.9*	*24.0*
Pacific Islands	*0.001*	*0.004*	*0.2*	*0.6*	*0.0*	*18.7*
World	**167.9**	**300.9**	**11.8**	**19.7**	**112.9**	**37.5**

Source: FAO. 2010. AQUASTAT database. http://www.fao.org/nr/aquastat; FAO. 2010. FAOSTAT database. http://faostat.fao.org

from surrounding rainfed lands as they are greener and wetter but this distinction is less clear in sub-humid and tropical conditions, at least during the rainy season. However, irrigation tends to occupy specific topographic niches (flat, lower elevation).

2.3.3. Inland fisheries and aquaculture

It is estimated that one billion people depend upon freshwater fish as the prime source of protein (IRD, 2010). In many developing countries, it is frequently the case that most households in rural areas around lakes, rivers and wetlands are involved in fishing on at least a seasonal basis. Although the products from inland fisheries are mostly for home consumption, or sold at the local or nearest urban market, significant numbers of people are employed in processing, distribution and marketing of the products. Fish consumption makes a major contribution to nutrition, especially for the poorest (for example in Cambodia, Laos, and China). There is an extremely high degree of participation in inland fisheries and a considerable degree of dependency on aquatic resources.

Nevertheless, fishing has historically been neglected in terms of the management of water resources, especially for agriculture, with losses of habitat in streams, floodplains and deltas due to upstream development for irrigation (CA, 2007). The importance and value of inland fisheries has been underestimated in many countries, since it has not been taxed and therefore has not been reflected in national statistics. In broader terms, wetlands and their associated biodiversity are extremely valuable for sustaining rural livelihoods in many developing countries. Although farming tends to be the main occupation in these countries, aquatic resources play an essential role in providing proteins and minerals to diets that are otherwise dominated by starches.

However, irrigation and associated water storages may also provide new or alternative opportunities for both capture fisheries and agriculture. Irrigation supplies have long been used to manage water quality for high-value prawn production in brackish, coastal conditions.

Therefore, it is useful to look briefly at the conclusions of the IPCC AR4 on fisheries. Fisheries will come under pressure from increased temperature stress and rising pH associated with global warming. The frequency of extreme droughts and floods will have a disproportionate effect on fish habitat and populations, and the incidence of diseases is expected to rise. This will result in species extinctions at the margins of their current habitats (for example salmon and sturgeon), and fish yields in places like Lake Tanganyika are expected to fall by around 30 percent. Climate induced effects anticipated in the Mekong include a significant change in the food chain because of declining water quality, changed flow patterns, a changed pattern of vegetation and saltwater intrusion in the lower delta.

2.3.4. Livestock grazing and fodder production

Globally, livestock accounts for 40 percent of agricultural GDP and employs 1.3 billion people while supporting the livelihoods of one billion of the world's poor (FAO, 2007).

The world's consumption of meat is rising and intensifying, especially in rapidly developing economies (such as China). Extensive rangeland systems support livestock production where cropping is naturally precarious. More intensive livestock production systems are technically inefficient in terms of the water and feed resources consumed compared with what could be obtained from direct consumption of crop products. There is continuing heated debate on the advisability of using cropland to grow pasture or concentrated feeds (wheat, barley, maize, cassava) for livestock consumption. The debate has been slightly distorted by comparing the resources required to obtain 1 kg of meat, compared with 1 kg of grain (for example, rice or wheat), when a more correct comparison would be between 1 kg of animal protein against 1 kg of vegetable protein. Nevertheless, there are inevitable food conversion inefficiencies in animal production that bear an opportunity cost in the use of land and water resources in intensive farming systems.

In the semi-arid and arid rangelands, increased temperatures coupled with decreased and more variable rainfall will inevitably result in abandonment, especially at the margins. Productivity is likely to fall, and drought become more frequent. There is a high likelihood that existing cycles of natural resource degradation (declining rangeland quality, increased soil erosion, decreased livestock water availability and declining groundwater recharge) will be exacerbated in semi-arid rangelands, notably in southern Africa and Central Asia. Rangelands are the dominant land type in the Near East and, because of their extent, small changes in vegetation cover can significantly affect the organic carbon dynamics and storage in the ecosystem. The nomadic livestock system spreads over a wide area with low and erratic rainfall, extending from the dry and low-rainfall rangelands in the Near East and the Arabian Peninsula to the high-rainfall areas (above 1200 mm) in southwestern and southern Sudan. Further decline in available moisture is expected in this region, resulting in an overall decline in productivity. Livestock pest and disease distribution and their transmission patterns will be altered, with epidemics almost certain.

In areas where rainfall increases or irrigation is provided, the best rangelands will tend to be encroached by arable cropping. Upland rangelands that experience higher monsoon rains and higher temperatures may become more productive but remain less likely to be encroached by arable systems. In temperate areas, temperature increases may lead to an increase in pasture production in mid-latitudes, with corresponding increases in livestock production. In general, unhoused livestock are expected to benefit from warmer winters, particularly in the higher latitudes in the eastern Near East region and at higher elevations, with minor improvements in feed quality in temperate high-rainfall zones possible. However, greater summer heat stress is likely to occur with negative effects on animals.

In other settings, such as the dairy industry in Gujarat, the production of fodder for zero grazing of milk cows involves a total dependence on groundwater pumping. Such 'niche' agricultural systems will be sensitive to reduced recharge and to energy pricing initiatives undertaken to reduce carbon emissions from agriculture – if they do not run out of water first. In developed economies, the extent of irrigation for pasture and fodder production is likely to increase in the higher latitudes, with existing supplemental irrigated pasture requiring more consistent watering, and rainfed pastures making use of supplemental irrigation where water is available at an economically attractive price. In intensive dairy and meat farming systems elsewhere, the continued use of irrigation water will be driven by the net economic benefits of production.

2.3.5. Forested land

Forests cover 30 percent of the world's land surface, but distribution is very uneven ranging from as much as 90 percent of land cover in some very humid countries down to zero percent in very arid ones (FAOSTAT, 2008). Forests play key roles in both the global hydrologic cycle and in regulating runoff at basin scale. Trees can transpire water from considerable depths in the soil and thus play an important role in mediating surface runoff and groundwater recharge. New forest stands generally generate less runoff than agricultural land use or mature forest because of high rates of growth and accompanying high rates of transpiration (Calder, 2004; Brown *et al.*, 2005; Hofer and Messerli, 2006). At the same time, forests generally sustain higher levels of base flow, and preserve them for longer periods in the dry season when compared with other land use. This is the principle reason for forested catchments being preserved and managed for urban water supplies in many parts of the world, from New York to Melbourne.

Deforestation, regrowth and afforestation can have important impacts on catchment hydrology, and South Africa has taken a unique step in considering (commercial plantation) forestry as a water user (Dye and Versfeld, 2007). Long-term runoff patterns typically display an increase in flow after logging/clearance, followed by a substantial decrease during 25 to 50 years of regrowth, rising to a consistent long-term yield in mature forests. In semi-arid environments, such as southeastern and Western Australia, removal of tree cover has steadily contributed to increased rates of groundwater recharge, secondary salinization and water logging in lowland areas.

Forests contribute to local climate forcing through positive feedback on rainfall from high evapotranspiration fluxes. Forests will therefore play a key role in GHG mitigation strategies. Deforestation currently accounts for between 4 and 12 billion tonnes of CO_2 equivalent each year, or between 4 and 12 percent of global emissions, with an average estimate of around 9 percent, half of which is related to land clearance for agriculture. Afforestation is an important means of earning carbon credits and has been piloted with some success through the Clean Development Mechanism (CDM). This is yet another example of how land use and climate change adaptation and mitigation will be closely linked, and may have both reinforcing and conflicting rationales according to context.

2.4. ECONOMIC COMPETITION FOR WATER, CLIMATE CHANGE AND THE CHALLENGE FOR WATER ALLOCATION

In the absence of substantial claims for water from other sectors, and with little initial understanding of its environmental impacts, irrigated agriculture has been able to capture large volumes of freshwater. Today, it accounts for 69 percent of all water withdrawals in the world, and the proportion exceeds 90 percent in some situations – in arid countries where irrigation is very important or where other sectors such as water supply and sanitation or industry are less developed. However, agriculture offers the lowest economic return per unit of water.

The development of irrigation to satisfy food needs has intensified the consumptive use of water to the detriment of the goods and services provided by natural ecosystems. It is increasingly realized that water borrowed from natural terrestrial and aquatic ecosystems can eventually undermine the modified systems that have taken their place (MA, 2005; CA, 2007). More attention is presently being paid to understanding, valuing and preserving key ecosystem functions and services that in turn support sustainable long-term agriculture. The implications of environmental allocation for agriculture are significant, because the volumes involved are large. Where runoff is predicted to decline under climate change, allocation decisions and associated trade-offs between ecosystems and agriculture will become considerably more challenging than they are already today (UN-Water, 2007).

Agriculture is increasingly likely to become the residual user of water: it will access what remains after allocations have been secured for high-value uses – drinking water and sanitation, industry, navigation, amenity value – as well as for the other large-quantity user, the environment. In many different parts of the world, expanding cities have easily claimed water from agriculture by fair means or 'foul' (Molle and Berkoff, 2006). By 2030, over 60 percent of the world's population will live in urban areas, claiming an increasing share of water abstraction, from values of less than or equal to 5 percent to perhaps more than 40 percent of present water abstraction in parts of northern China, and typically more than 15 percent of demand in most developing countries. Although the volumes entailed are relatively small, the water needs to be supplied with 100 percent security. As populations increase, urbanisation progresses and climate change starts to bite, the volume of water diverted directly for agriculture will decline, and supply security for farming will become more erratic and variable as drought frequency and duration increase, with higher priority demands having to be met first.

Cities will generate increasingly large amounts of effluent that will be recycled for agriculture, subject to water quality and health and safety considerations. The use of untreated wastewater is already widespread (Scott *et al.*, 2004) with a variety of accompanying hazards to producers and consumers.

Cities will generate increasingly large amounts of effluent that will be recycled for agriculture, subject to water quality and health and safety considerations. The use of untreated wastewater is already widespread (Scott *et al*., 2004) with a variety of accompanying hazards to producers and consumers.

In most parts of the world, water accounting and allocation systems are rudimentary, and ill equipped to cope with the additional stresses of climate change. Inter-sectoral competition and environmental consciousness will be sharpened by climate change and will require much more sophisticated, detailed approaches to the specification and policing of water rights and allocations.

All decisions need to bear in mind the natural variability of hydrology; climate change introduces massive uncertainty into the existing canon of hydrological analysis. As Milly *et al*., (2008) famously wrote, 'Stationarity is Dead!' – shorthand for the conundrum that past hydrologic variability will be no guide to that of the future under climate change … a situation which undermines all existing analysis of water resource availability, supply security and thinking on allocation. Milly *et al*., (2008) call for a new thinking on water accounting and hydrology, but so far none has emerged, and will not anyway be a practical alternative until trends in hydrologic variability are better understood.

2.5. THE PACE OF AGRICULTURAL CHANGE AND CLIMATE CHANGE PROJECTIONS

Climate change is a long-term process. Some impacts, such as glacier-melt, are already evident, and their cumulative impacts are already evident in observed glacier retreat. Others, such as a 4 °C rise in global temperature, are forecast to occur towards 2100 if mitigation efforts do not work out. Adaptations to longer-term changes will emerge incrementally and over long periods.

Weather describes short-term variations in local climate, covering extremes of temperature and rainfall, manifested at their most extreme as drought, flooding, typhoons, heat waves and cold snaps. Agriculture is already well-adapted to the range of weather extremes that have been commonly experienced within living memory, but may be ill adapted to intensification of these extremes under climate change. Indeed, one of the crucial future adaptations will be in improving resilience to greater severity and higher frequency in what are now extreme and rare events. A significant portion of irrigation investment has been directed to mitigating recurrent drought and flood control programmes have been developed to maintain crop production systems in the wet tropics, as well as protect lives and property in settled areas.

Over the last 50 years, the pace of agricultural change has been fast, transforming some landscapes within a generation – a comparatively short time in comparison to climate change projections. Examples include the Green Revolution, the groundwater revolution in Asia, and at a local scale, mechanisation, consolidation and the construction of surface irrigation. It is less certain that further rapid changes will take place in the future, but it is possible that other factors in agriculture, such as rural-urban migration, will change the situation and context considerably by the time that climate change impacts really bite. The accommodation of extremes is always likely to seem more pressing and more dramatic than adapting to slow incremental change. It is therefore likely that adaptation of agricultural systems will occur incrementally in response to more frequent extreme events than to underlying long-term trends in temperature, evapotranspiration, rainfall and runoff.

They concluded:

> *"In summary, our simulation results suggest the following. First, globally the impacts of climate change on increasing irrigation water requirements could be nearly as large as the changes projected from socio-economic development in this century. Second, the effects of mitigation on irrigation water requirements can be significant in the coming decades, with large overall water savings, both globally and regionally. Third, however, some regions may be negatively affected by mitigation actions (i.e., become worse-off than under non-mitigated climate change) in the early decades, depending on specific combinations of CO_2 changes that affect crop water requirements and GCM-predicted precipitation and temperature changes."*

Although this assessment was conducted for FAO, its own analysis (2050 update of the Outlook for 2015/2030 (FAO, 2003)) remains based largely on the analysis of recent trends in production and consumption, and relies on the development of a new baseline for 2004. The AT2050 analysis for the Near East included a projection for changed climate conditions. Some observers note a mismatch between time frames for investment in day-to-day agricultural management (a less than 25-year horizon for farm machinery, land improvement and crop-breeding programmes) and large-scale adaptive infrastructure (storage dams with a discount life of 50 years). Although such complementary investments have often been made in the past, the uncertainty associated with future conditions poses unprecedented planning questions in the selection and financing of major long-term infrastructure projects.

Chapter 3
The baseline and trends in agricultural water demand

3.1. AGRICULTURAL PROJECTIONS TO 2030 AND THE ASSOCIATED DEMAND FOR WATER

3.1.1. Global analysis

This section briefly summarizes the challenges in food production without taking the added burden of climate change into account. Most global analysis of future food demand conducted prior to 2007 projected the needs for a world without climate change. Agricultural planning and associated water resources assessment in most developing countries has similarly turned a blind eye to climate change. The activities and investment associated with the 'no-change' perspective provides a convenient baseline for the analysis of the further impacts of climate change, using the projections of the IPCC Fourth Assessment (AR4) and subsequent analysis.

Current and projected trends in a) demand for food and b) agricultural production are given for 93 developing countries in FAO's world agriculture perspective study towards 2015/2030 (FAO, 2003). They are based on the United Nations (UN) Statistics Division medium population projection, the World Bank income growth projections and FAO's own estimates of future agricultural productivity. The pattern of this demand is analysed at country level and summarized at regional level in the report to give a global picture based on the analysis of national supply-utilization accounts (SUAs).

The total land area across the world amounts to around 13 billion ha, of which 1.5 billion ha is cultivated (12 percent) and a further 27 percent is managed as pastureland for livestock production. Between 1960 and 2000, the globe's cultivated area increased by 13 percent, while population more than doubled. Of the 510,000 km^3 of water that falls on the earth each year, only 110,000 km^3 occurs over land, generating a runoff of roughly 44,000 km^3 (40 percent). It is estimated that total water use in crop production (evapotranspiration) amounted to 7130 km^3 in 2000 and is likely to rise to between 12,000 and 13,500 km^3 by 2050 (de Fraiture *et al.*, 2005).

An overall expansion in cropped area of 29 percent is forecast to 2050, with rainfed areas increasing from 549.812 million in 1998 to 698.743 million ha (27 percent). Irrigated area is forecast to grow by 33 percent, from 242 182 million ha to 318 million ha over the same period (Bruinsma, 2009).

In this analysis, and in the calculation of associated water demand, it has been assumed that all minimum demands for potable water and daily kilocalorie intake have to be met. Demand for water (stream flow or groundwater) reflects irrigation needs, whereas water use in rainfed agriculture is considered only in terms of evapotranspiration of water from the available rainfall. Hydrological balances at regional scale are determined by land use and land-use change (notably afforestation and urbanisation), although rates of evapotranspiration from agricultural landscapes are effectively consistent in a given agro-ecological zone, regardless of the precise mix of crops.

Locally, climate variability has significant impacts on crop area and crop production, especially in periods of drought or flood. Since the 1970s, the extensive development of irrigation supplies and flood control has smoothed out the impacts of climate variability and, with the benefit of Green Revolution farming techniques, increased productivity to the point that commodity prices fell year on year in real terms until the early 2000s. During this period many countries maintained high carryover stocks of grains, but these have dwindled for various reasons, stimulating a corresponding increase in market demand and resulting in price increases, beginning in 2002 with Chinese buying (FAO, 2006 – SOCO).

In 2007, continued drought in Australia reduced the export pool of grains, sending supply shocks through the market at the same time as significant land areas were planted to biofuel crops in the United States. Commodity prices spiked in 2007, when global cereal import bills more than doubled (127 percent) in two years from 2005/6 to 2007/8 (Burke and Kuylenstierna, 2008). Although they have fallen since then, rising prices are expected in the medium to long term and global commodity markets have become more sensitive (FAO, Food Outlook, 2007a).

3.1.2. Regional analysis

The historical and anticipated growth in harvested irrigated areas projected to 2015 and 2030 is summarized from the original in Table 3.1 (Bruinsma, 2009).

TABLE 3.1
Expansion of harvested irrigated areas from 1961 to 1997 and predicted to 2050 (Bruinsma, 2009)

	1961/63	1989/91	2005/07	2030	2050	1961-05	1990-05	1996-05	2005-50
	million ha					annual growth (percent p.a.)			
Developing countries	103	178	219	242	251	1.76	1.05	0.63	0.31
idem, excl. China and India	47	84	97	111	117	1.91	106	0.89	0.42
sub-Saharan Africa	2.5	4.5	5.6	6.7	7.9	2.07	1.49	0.98	0.67
Latin America and Caribbean	8	17	18	22	24	2.05	0.62	0.27	0.72
Near East / North Africa	15	25	29	34	36	1.86	1.21	1.30	0.47
South Asia	37	67	81	84	86	1.98	1.10	0.28	0.14
East Asia	40	64	85	95	97	1.42	1.00	0.80	0.30
Developed countries	38	66	68	68	68	1.57	0.38	0.20	0.00
World	141	244	287	310	318	1.71	0.87	0.52	0.24

The current projected set of freshwater allocations to irrigated agriculture in the 93 developing countries are summarized in Table 4.10 of AT2030 (Table 3.2 below).

TABLE 3.2
Summary of annual renewable water resources and irrigation withdrawals, now and to 2050 (without climate change) (Bruinsma, 2009)

	Precipitation	Renewable water resources*	Water use efficiency ratio		Irrigation water withdrawal		Pressure on water resources due to irrigation	
			2005/07	2050	2005/07	2050	2005/07	2050
	mm p.a.	cubic km	percent		cubic km		percent	
Developing countries	990	28 000	44	47	2 115	2 413	8	9
sub-Saharan Africa	850	3 500	22	25	55	87	2	2
Latin America /Caribbean	1 530	13 500	35	35	181	253	1	2
Near East / North Africa	160	600	51	61	347	374	58	62
South Asia	1 050	2 300	54	57	819	906	36	39
East Asia	1 140	8 600	33	35	714	793	8	9
Developed countries	540	14 000	42	43	505	493	4	4
World	800	42 000	44	46	2 620	2 906	6	7

* includes at the regional level 'incoming flows'

The regional summary presented in Table 3.2 masks the higher levels of water withdrawals on an individual country basis. In general, agricultural growth is likely to be restrained when more than 40 percent of annual renewable water resources are depleted. The food production projections by FAO and others (CA, 2007; Rosegrant *et al*., 2002; 2001) anticipate further gains in land and water productivity that will reduce the total volume of future demand. Such gains are realistic and derive from the fact that current average levels of land and water productivity are considerably lower than attainable levels[1].

Many river basins around the world are either fully allocated or approaching full allocation. Almost without exception, these basins have extensive irrigation development; well-known examples include: the Indus in Pakistan; the Nile; the Jordan; the Syr Darya and Amu Darya basins in Central Asia; the Yellow River in China; and the peninsular rivers in southern India. Vietnam already has difficulty in meeting its Mekong Basin commitments as a result of the effective closure of the Srepok sub-basin while elsewhere in the same country, over or inflexible allocation of water in the economically crucial Dong Nai is constraining economic growth and paradoxically increasing flood damage. In many examples, the excessive water allocations have largely concerned cash crops, specifically cotton (in Central Asia) and coffee and sugarcane (in Vietnam).

Basins are also becoming stressed as a result of water allocation for subsistence agriculture or large-scale cereal production (Batchelor *et al*., 2003). The Rufiji and Pangani Basins in Tanzania for instance, are managed at their limit. Hydropower generation and pollution control are compromised and systemic integrity is threatened.

1 The gap between current and attainable yields is termed a 'Type II' yield gap by FAO. Attainable yields are based on what the better farmers can already achieve now, as opposed to theoretical potentials that require all conditions and factor inputs to be perfectly managed.

If the Rufiji Delta were to dry up, (it is suggested that) the marine fisheries between Mogadishu and Durban would fail because of breakdown of the vital relationship between river flooding and turbidity cycles and marine food chains/spawning processes that begin in delta regions (Hirji *et al*., (ed.) 1994). Equally, the coastal (prawn) fisheries in Mozambique and eastern South Africa are already suffering because the small coastal basins are drying out, largely because of withdrawals for cooling water and irrigated sugar cane (Maputo Basin) and the impacts of rainfed sugar cane production in KwaZulu-Natal Province.

Agro-chemical pollution of surface and groundwater places further constraints on water availability for agriculture, and more importantly for human and animal consumption. Nitrate runoff and pesticide accumulation can compromise groundwater, and phosphates are strongly implicated in algal blooms in rivers and lakes.

The Near East region faces considerable challenges in meeting future food and water needs, and will be further troubled by likely reductions in rainfall and increases in temperature due to climate change. More recent agricultural projections (to 2050) for the Near East and North Africa (FAO/NERC, 2008) are presented in Table 3.3 below:

TABLE 3.3
Crop production and land use in the Near East region*

		Rainfed land			Irrigated land			Total land		
		Area	Yield	Production	Area	Yield	Production	Area	Yield	Production
		Million ha	t / ha	Million t	Million ha	t / ha	Million t	Million ha	t / ha	Million t
Cereals (incl. rice paddy)	2005	24.6	0.96	23.6	10.6	4.64	49.0	35.2	2.06	72.6
	2030	27.9	1.09	30.4	14.7	5.13	75.4	42.6	2.48	105.8
	2050	30.0	1.23	36.9	17.1	5.51	94.4	47.1	2.79	131.3
Oil crops	2005	5.0	0.66	3.3	1.0	2.01	2.0	6.0	0.89	5.3
	2030	7.9	0.81	6.4	1.7	2.75	4.7	9.7	1.16	11.2
	2050	9.5	0.98	9.3	2.1	3.08	6.5	11.6	1.36	15.8
Vegetables, citrus and fruits	2005	0.8	8.31	6.9	4.6	18.37	83.6	5.4	16.83	90.5
	2030	1.2	9.41	11.2	6.7	19.87	132.5	7.9	18.25	143.7
	2050	1.4	10.82	15.2	7.4	22.03	163.7	8.9	20.18	178.9
Pulses	2005	1.3	0.65	0.9	1.1	1.60	1.7	2.4	1.07	2.6
	2030	1.4	0.89	1.3	1.1	2.13	2.4	2.6	1.43	3.7
	2050	1.6	0.97	1.6	1.2	2.36	2.9	2.8	1.58	4.5
Total harvested land	2005	33.8			22.4			56.2		
	2030	40.6			30.3			70.8		
	2050	44.7			34.3			79.0		
Cropping intensity (%)	2005	65			99			75		
	2030	77			117			90		
	2050	84			120			96		
Arable land	2005	51.9			22.5			74.5		
	2030	52.6			25.8			78.7		
	2050	53.4			28.6			82.6		
Potential land		152			35			171**		
excl. Sudan		59			33			77**		
Arable land as % of potential	2005	34			64			43		
	2030	35			73			46		
	2050	35			81			48		

* including 'old' data and projections for Iraq
** total potential land is not equal to the sum of rainfed and irrigable potential land since part of the latter is on rainfed land

Source: FAO, 2003; FAOSTAT

The associated water demands and proportions of renewable water resources used under climate change scenario SRES B1 are summarized in Table 3.4. Clearly, where stress is already evident and problematic, the impacts of climate change will be more severe.

TABLE 3.4
Annual renewable water resources (RWR) and irrigation water requirements for Near East and North Africa (FAO, 2007a)

Region		North East Africa	West Asia	North Africa	Arabian Peninsula	Total Region
		Water availability				
Precipitation	mm	308	225	102	78	177
Internal RWR	km^3	37.8	176.2	48.1	6.5	268.5
Net incoming flows	km^3	108.7	28.3	11	0	148
Total RWR	km^3	146.5	204.5	59.1	6.5	416.5
		Irrigation water withdrawal				
2003/05						
Water requirement ratio	%	57	48	55	50	52
Irrigation water withdrawal	km^3	98.4	126.2	22.2	21.7	268.5
idem as percent of RWR	%	67	62	38	334	64
2030						
Water requirement ratio	%	62	57	60	58	59
Irrigation water withdrawal	km^3	125.1	160.1	29.1	21.5	338.6
idem as percent of RWR	%	85	78	49	331	81
2050						
Water requirement ratio	%	69	65	64	64	66
Irrigation water withdrawal	km^3	130.2	164.7	30.1	21.7	346.2
idem as percent of RWR	%	89	81	51	334	83
2050 with climate change*						
Precipitation	mm	330	221	92	78	179
Total RWR	km^3	147.5	195.7	47.5	6.6	397.3
Water requirement ratio	%	71	67	64	65	68
Irrigation water withdrawal	km^3	137.5	174.1	33.8	22.6	365.8
idem as percent of RWR	%	93	89	71	343	92

*Under the assumptions of the International Panel for Climate Change (IPCC) Special Report on Emissions Scenarios, Scenario 'SRES B2'

Note: The water requirement ratio is defined as the ratio between irrigation water requirements for optimal crop growth and water withdrawn for irrigation.

Sources: FAO, 2003; FAOSTAT; IPCC, 2001c.

Countries:
North Africa: Algeria, Libya, Mauritania, Morocco, Tunisia;
West Asia: Iran, Iraq, Jordan, Lebanon, Syria;
North East Africa: Egypt, Somalia, Sudan;
Arabian Peninsula: Saudi Arabia, Yemen.

Elsewhere (Northern Europe and Latin America), the AT 2015/2030 projections may underestimate the shift to irrigation and subsequent expansion of areas equipped for irrigation. A systematic update of the 1997/99 baseline is long overdue.

The environmental and economic impacts of existing development are becoming rapidly apparent, and climate change stresses will magnify the challenges. Climate change will, in most irrigation regions, decrease runoff, increase evaporative demand due to higher temperature, and increase the frequency of droughts and floods. Rainfed crop production in the most heavily impacted regions will be proportionately more severely affected. The current debate over the Murray-Darling Basin in Australia, which is facing contraction in agriculture as well as prolonged and unprecedented drought, can be seen as an exemplary warning for many other over-allocated river basins. Some of the earliest lessons of climate change will emerge from this region during the next decade.

Australia already has, by world standards, a very sophisticated water accounting and allocation system, based on volumetric measurement and water charging. Its water rights system internalizes natural hydrologic variability, but even without over-allocation of licenses, the system would be under severe stress from climate change, with an average reduction in runoff of 20 percent forecast for 2080. If emerging theories of a step change in climate in southeastern Australia prove correct, future runoff will be 40 percent less than the historical average. The implications for future allocation are stark – especially the balance between agriculture and environmental use – and involve awkward political and economic decisions.

In countries with less sophisticated water rights and water allocation mechanisms, as well as poor water accounting, it is evident that considerable effort is required to both understand and adapt to climate change impacts on water resources and agricultural water use. Even where water productivity and irrigation system/basin efficiency is low, the rapid development of effective and equitable water allocation and water rights systems should be a priority. Improving water productivity and realizing real water savings in poorly performing irrigation systems is an integral part of efforts to bridge the gap between present day and attainable yields (FAO, 2007b). The extent to which climate change impacts attainable, as opposed to theoretical, yields will receive plenty of attention in the coming years.

3.2. EMERGING TRENDS IN AGRICULTURAL WATER MANAGEMENT

The key trends in agricultural water management, identified prior to the IPCC AR4 are discussed in this section, which is based on the work of the Comprehensive Assessment of Water Management in Agriculture (CA, 2007: Ch. 3 Trends and Ch. 9 Irrigation) and others (Meinzen-Dick, 2007).

The major emerging water issue concerns water allocation, particularly in stressed basins, where there are strong political imperatives to continue water development, even after full allocation (India, Northern China, Pakistan).

Highly productive delta systems are under pressure from increasing population pressure and upstream flow variability, resulting from land-use change and upstream water developments. In many cases (Mekong, Hai He) increasing use of groundwater exacerbates saline intrusion to coastal aquifers and along rivers.

International concern and pressure to maintain and enhance productive environmental services (aquaculture, biodiversity) (MA, 2005) is increasingly being echoed at national level in non-government sectors and in official policy (for example efforts in China to address industrial pollution of major rivers).

Since the heyday of irrigation development in the 1970s, there has been a dramatic decline in public and international development assistance to the irrigation sector, as well as in the agriculture sector more generally. Irrigation development and expansion has however, not stood still, as there has been massive and extensive private investment in groundwater development throughout Asia. In India, the area serviced by private groundwater development significantly exceeds (doubles) the area of canal irrigation developed and managed by the state. The rapid expansion of groundwater has been aided by low or subsidized energy costs. The decline in public investment and the rise in private investment have mirrored continually declining real commodity prices over more than 20 years from 1978 to 2002. However, despite declining investment, there has been minimal cost recovery in public systems and widespread continuation of subsidies in their operation and occasional 'rehabilitation'.

Although it was expected that declining public investment in irrigation development would also stimulate increased emphasis and capacity in irrigation system management and the development of more service-oriented approaches, this has not happened to any real extent. Consequently, poor technical performance of surface irrigation systems in Asia has continued to be a concern – with equity, water use efficiency, salinization, and degradation of capital works being major issues.

The rate of increase in land and water productivity for staple crops in developing countries began to decline in the 1990s as the main benefits of the Green Revolution were realized and more incremental improvements in breeding, input use and support services took hold. Average yields in OECD countries have risen close to potential under subsidized production regimes, eventually necessitating the imposition of quotas and other restrictions on production in the European Economic Community. More than 70 percent of European grain farmers are reported to currently achieve wheat yields approaching 10 t/ha, compared with only 10 percent 20 years ago.

Strong donor interest has re-emerged in improving rainfed agriculture and in trying to establish better soil moisture conservation through a range of different techniques; this is focused on 1) greater equity in poverty alleviation and 2) significant theoretical potential to increase production. In practice, progress has been constrained by poor capital availability, poor design and construction of soil and water conservation programmes and continuing risk-averse behaviour by farmers.

Irrigation still mainly supports the production of low-value staple crops (wheat, rice, maize, pulses and oil seeds). However, there have been some remarkable diversifications, for example the rapid and massive expansion of horticulture in China since 1990 and the development of floriculture in East Africa. However, the distributional impacts of such development are limited.

Raising water productivity

Water productivity is mentioned frequently in this document. There are high expectations that raising crop water productivity will offset increased water demand from crops that will result from increases in atmospheric temperatures. However, interest in water productivity is not a new concern, and much has been written in the past ten years in relation to managing increasing inter-sectoral competition for water, and in reducing agricultural water use in fully allocated river basins (CA, 2007 Ch. 7). Water use efficiency has long been a concern of crop physiologists and breeders; the surge of interest in the 1960s and 1970s was largely a performance measure for improved crop performance (Salter and Goode, 1967), where the main focus was on enhancing harvestable yield (land productivity). Water productivity is now considered in a wider landscape context, where both land and water resources are limiting (Molden *et al.*, 2010).

Physical water productivity is defined as the ratio of (useful) crop output (for instance one kilogram of grain) to the volume of water used to produce it (m^3/kg or mm/ha/kg). As water becomes more scarce, the traditional metric of yield (production per unit of land area) has been augmented by water productivity. Economic water productivity assesses the value of output per unit of water used and reflects crop choice, market conditions and the effectiveness of water management. Physical water productivity can be measured with reference to applied water or to transpired water and the difference between the two can be seen as a measure of both water management effectiveness and husbandry. The specific water use per unit of food produced (the inverse of water productivity) is presented for the main crop types in Table 3.5 in terms of both kilograms of production and a more uniform measure – per 1 000 kcal of energy contained in that food (Rockström *et al*., 2007). This latter measure is less ambiguous than measurements per kilogram, even when adjusted to consistent moisture content. However, products that are high in protein, vitamins, fats or oils, which are also nutritionally important, are not properly evaluated in this sort of tabulation. Similar metrics of water use per unit of protein would give a more balanced and practically useful view and avoid the simplistic conclusion that all meat products would be more efficiently substituted by crops.

TABLE 3.5
Specific water use for crops, meat and dairy products (Rockström *et al.*, 2007), per kilogram output and energy value

Food type	m^3/kg	m^3/1 000 kcal
Cereals	1.5	0.47
Starchy roots	0.7	0.78
Sugar crops	0.15	0.49
Pulses	1.9	0.55
Oil crops	2	0.73
Vegetable oils	2	0.23
Vegetables	0.5	2.07
Meat		4
Dairy products		>6

No single indicator of water productivity carries great significance in terms of developing a strategy to improve farm-level management and adaptation, although it is less ambiguous at irrigation system and basin scale. Improving application efficiency in one part of a basin or system may improve water productivity, or it may actually reduce it, depending on what happens to the water savings and total water use throughout the basin. In the Murray-Darling Basin in Australia, application efficiency is important because any accessions below the root zone exacerbate water-table rise, secondary salinity and water logging.

As the efficiency of all biological processes declines asymptotically with satisfaction of each limiting factor, there is more scope to increase water productivity efficiently and effectively when it is low. Thus the addition of a small increment of water or fertilizer, or both, makes a large percentage change (but not necessarily such a great absolute change) in total product. This understanding supports a logic that there is considerable potential to raise the land and water productivity of rainfed crops, at least those grown in sub-optimal conditions, by improving soil-moisture status through better soil water conservation and harvesting technologies, or by providing supplemental irrigation where possible. A major reasoning behind widespread efforts to re-invigorate rainfed farming in this way is that it will allow for mitigation of damage to natural ecosystems from 1) abstraction of water for formal irrigation and 2) expansion of rainfed areas at the cost of forest and other natural ecosystems (Rockström *et al*., 2001). However, farmers are traditionally risk-averse and will not overinvest (in fertilizer or time, for example), where they assess the risk of failure to be high. Water harvesting technologies can help in dry periods, but provide less insurance against drought (seasonal and annual). Both the conditions for rainfed cropping, and the hydrology of rainwater harvesting and conservation will deteriorate in the tropics and semi-arid tropics under climate change. Further investigation of these factors is due and will be timely in assessing future mixes of options between rainfed and irrigated agricultural development and intensification.

Interestingly, the breeding of high-yielding varieties has historically increased water-use efficiency by: shortening season length and dwarfing and improving harvest index, resulting in lower seasonal transpiration as well as greater harvestable production. There are many factors of yield that contribute to water-use efficiency. Where the management of inputs is poor or unbalanced, water productivity may be low due to depressed yield for reasons other than water supply. Nitrogen responsiveness has contributed to increased biomass accumulation (in a shorter season with a shorter plant) and has encouraged better early crop establishment, which (in rainfed, and possibly in irrigated conditions) results in less direct evaporation loss. Much of the gap between yield potential and actual yields (and hence water productivity) is due to poor husbandry and sub-optimal management of inputs – especially in irrigated agriculture. The corollary to this is that inputs are often in short supply in water-short, rainfed conditions.

Current controversy in the potential for further improvement of water use efficiency (WUE) percentage and of acquisition of drought-tolerance (Rebetzke *et al*., 2008) centres on whether single-gene expressions can be found to confer drought tolerance or increased water productivity as have been found for genetically modified crops that are resistant to pesticides and herbicides such as BT Cotton. The opposing argument is that water productivity (and yield) are the expressions of complex genotype (with multiple genes) – phenotype – environment interactions that are better addressed by conventional plant breeding and cultivar selection methods. Secondary traits that are often identified as desirable, such as low specific leaf area to achieve a higher assimilate to transpiration ratio, may also be linked to other expressions, in this case low harvest index.

However, recent marker assisted wheat-breeding research indicates that there remains considerable potential to improve in areas such as transpiration efficiency, early season development, emergence in rainfed wheat in Australia (Rebetzke *et al*., 2008). In other crops, like legumes and beans, (which are generally less bred and less researched), the dominant reason for variation in water use efficiency in screening trials is the relation between stomatal conductance and assimilation/transpiration (A/T) – so there is potential to screen and select when the gene pool is large and use marker technology to avoid linked but undesirable traits. Indeed one strategy to improve water use efficiency in wheat is to enlarge the gene pool from which selections can be made, and this means that the preservation of wild and old strains is very important.

Improving yield and water use efficiency in irrigated and rainfed agriculture follow different pathways. In rainfed cultivation, the focus is on increasing yield through good husbandry, best use of rainwater through soil moisture management and by the provision of more nutrients. In irrigated agriculture, the availability of water will dictate whether to focus more on yields (when irrigation is unconstrained by water availability) or on water productivity (when water is scarce), resulting in different combinations of area and water use for an optimum level of production.

3.3. ANTICIPATED TRENDS IN AGRICULTURAL WATER MANAGEMENT

3.3.1 Trends without climate change

A number of recent reports have summarized the main trends and drivers in agricultural water management that mainly respond to economic factors relating to rising water scarcity (FAO, 2003; FAO, 2007a; CA, 2007). All have assumed that past hydrology is a good guide to hydrology in the future, and they have (with the exception of FAO/NERC analysis (2008)) not quantitatively factored climate-change impacts on crop-water demand and on water availability into their analysis. Box 3.1 summarizes the main findings of the Comprehensive assessment of water management in agriculture about the future of irrigation (CA, 2007, Faurès *et al.*, 2007).

Many recent reports on adaptation to climate change (Fischer *et al.,* 2007; Nelson *et al.,* 2009; Climate Adaptation Working Group, 2009; Padgham, 2009) anticipate a substantial increase in irrigated area in response to global temperature rise, higher rates of crop water use, and declining and more variable rainfalls. The foregoing indicates, at least for many developing countries, that the options are limited and will need careful scrutiny.

BOX 3.1

Prospects for irrigation (adapted from Faurès *et al.*, 2007)

- The conditions that led to large public investment in irrigation in the past have changed radically and today's circumstances demand substantial shifts in irrigation strategies. Irrigation and drainage will still expand on to new land, but at a much slower pace. New investment will focus much more on enhancing the productivity of existing systems through upgrading infrastructure and reforming management processes. Large surface irrigation systems will need to incorporate improvements in water control and delivery, automation and measurement, and training staff and water users to better respond to farmers' needs. Conjunctive use of canal water and groundwater will remain an attractive option to enhance flexibility and reliability in water service provision.

- More farmers around the world will integrate into a global market, which will dictate their choices and behaviour. The changing demand for agricultural products and the increasing understanding of possible impacts of climate change on agriculture and the water cycle will also influence future investment in irrigation and water control. Rapidly rising incomes and urbanization in many developing countries are shifting demand from staples to fruits or vegetables, which typically require irrigation technologies that improve reliability, raise yields, and improve product quality.

- Irrigation will increasingly be under pressure to release water for higher value uses. Environmental water allocations will steadily increase and present a much greater challenge to irrigation than will cities and industries, because the volumes at stake are likely to be larger. Transfers of water from irrigation to higher value uses will occur and require oversight to ensure that they are transparent and equitable. Water measurement, assessment, and accounting will likely gain in importance, and water rights will need to be formalized, especially to protect the interests of marginal and traditional water users.

BOX 3.1 *(CONTINUED)*
Prospects for irrigation (adapted from Faurès *et al.*, 2007)

- Irrigation and drainage performance will increasingly be assessed against the full range of their benefits and costs, not only against commodity production. The success of irrigation has often come at the environment's expense, degrading ecosystems and reducing water supplies to wetlands. It has also had mixed impacts on human health.
- Governance will need to adapt, and the recent trend to devolve the responsibility for irrigation management to local institutions, with more direct involvement of farmers, is likely to intensify while bulk water supply infrastructure, because of its multiple functions and strategic value, will usually remain in the hands of the state. Governments will need to develop compensating regulatory capacities to oversee service provision and protect public interests.

3.3.2 Analysis of economic drivers and future investments

Agricultural production patterns are determined largely by market demand and governing agroclimatic conditions in a particular region. It is anticipated that trade policies and subsidy programmes will exert greater influence on crop production patterns in the short term (5–15 years) than climate change. Irrigation is historically used as a system of political patronage and may be politically important in maintaining rural employment and national food security (particularly with urbanizing populations) even if it is not performing in response to market signals. In the longer term, climate change and its large uncertainties poses potentially serious threats to agricultural water management, hitting hardest in poor, semi-arid areas that already suffer from erratic water variability.

Future investment needs in irrigation have been examined in several studies (CA, 2007; Faures *et al.*, 2007; Turral *et al*., 2009). The summary provided in Table 3.6 is taken from these publications, and examines investment in relation to a simple typology of the dominant 'irrigated production systems' set in a broad economic context that is defined by contribution of agriculture to GDP and also reflects the level of economic competition for water (bottom row). Countries with a less than 9 percent contribution from agriculture may still have large rural populations, but have more diversified sources of income and are generally wealthier. Farming remains the backbone of the economy in countries where it accounts for more than 30 percent of GDP, although the number of countries in this category is rapidly diminishing. The potential impacts of different developments on aquatic ecosystems are indicated in the right-hand column. The table includes a number of other classifying factors, such as the state of competition for water and the level of environmental management, which in turn indicate further investment costs.

This investment typology has some commonality with the typology for climate change impacts and adaptation that are proposed later in this document. It can be adjusted to assess investment needs for adaptation and development responses to climate change in the future. It is, however, focused primarily on development options. There is some potential for confusion in meeting both development and adaptive investment needs; the two need to be integrated as far as is possible; a real and practical challenge in future years.

TABLE 3.6
Typology of irrigation contexts, conditions and sources for future investment

Financing	Agriculture > 30% GDP	Countries in transition	Agriculture < 9% GDP	PNIAE
Large public schemes in arid areas				
International	Large dams, drainage, Formation of WUAs	Large scale irrigation system control and operation, selective IMT/joint management of irrigation schemes	Environmental flow management	Scale: regional Q & q
National	Small dams, irrigation staff training, run-off river gravity supply	Large and small dams, rural electrification, drainage, bulk water allocation, staff training	Automation and SCADA, water quality monitoring, recycling return flow, IMT, environmental management plan and operation, sub-division to multiple autonomous management units, water conservation	
Cost recovery			Service provision, information systems	
Local / Farmer		Farm layout and land forming in surface irrigation, conjunctive use of surface water and groundwater		
Large public schemes in humid areas (rice)				
International	Formation of WUAs	Selective IMT/joint management, system control and operation	Environmental flow management	Scale: regional Q & q
National	Conjunctive use systems based on run of river diversion, irrigation staff training, run-off river gravity supply	Rural electrification, bulk water allocation, staff training, (dams)	Selective canal lining, IMT, Automation and SCADA, Environment management plans and operation, sub-division to multiple autonomous management units, water conservation	
Cost recovery			Information systems, service provision	
Local / Farmer		Conjunctive use of SW and GW		
Small scale community managed				
International	WUA formation, monitoring & support			Scale: local, depends on density of development Groundwater quality and depletion
National	Run of river - weirs, diversions	Local storages and small dams, improved water distribution infrastructure, recognition and formalization of water rights and bulk allocation, rural infrastructure, credit, market opening	Re-engineering and modernizaton - including pipe distribution systems, land consolidation, measurement and monitoring, information systems, regional water management	
Local / Farmer	Shallow GW within irrigation systems, riparian zones and deltas	Mechanized and deeper groundwater		

TABLE 3.6 *(CONTINUED)*
Typology of irrigation contexts, conditions and sources for future investment

System Type	Agriculture > 30% GDP	Countries in transition	Agriculture < 9% GDP	PNIAE
Medium scale commercial and private				
National	Export markets	Market chain, regulation and monitoring	Regulation and monitoring, export markets	Water quality
Local / Farmer	Pumped irrigation - surface and groundwater, on-farm mechanized systems, overhead irrigation (sprinkler and micro-irrigation technologies)	Precision farming - pivots, lateral moves, land forming, micro-irrigation, runoff recycling, automation of water supply	Irrigation scheduling and soil moisture monitoring, precision farming and fertigation, piped distribution systems	
Farm scale systems				
International	Low cost technologies - drip kits etc.			Water quality
National	Wastewater re-use - engineer supplies, market and infrastructure development, credit	Mechanized groundwater use, wastewater treatment and management	Water measurement and control, farm consolidation, water user and marketing groups	
Cost recovery		Rural electrification / Energy pricing (targeted subsidies)	Sprinkler and micro-irrigation for horticulture	
Local / Farmer	Low cost shallow groundwater & small pumps for surface water			

Note: GW: groundwater; IMT: Irrigation management transfer; PNIAE: Potential to negatively impact on aquatic ecosystems; Q&q: Quantity and quality; SCADA: Supervisory control and data acquisition; WUA: Water Users Association.

Chapter 4
Specific climate change impacts related to agricultural water management

4.1. INTRODUCTION

Climate change impacts are secondary drivers of agricultural water demand, which is responsive to a broad range of economic factors outlined in Chapter 3. At a global scale, it is possible, likely even, that further climatic stress on water-short river basins will be offset by higher rainfall in temperate zones. Conversely, it is possible that higher intensity rainfall events over temperate cereal production regions, coupled to more severe outbreaks of pests and diseases, will result in widespread crop damage, thus worsening the global supply shock arising from water scarcity.

Agricultural trend analyses prior to AR4 have arguably under-estimated the potential additional impacts of climate change in their projections (FAO, 2003). Equally, attempts to explain likely trends from the perspective of the SRES alone (Parry *et al*., 2005; Fischer *et al.,* 2005) have had their own methodological limitations in dealing with complexity of farming systems. While the modelling in relation to irrigation water requirements is becoming more specific and robust, as Fischer *et al*., (2007) acknowledge, the body of work is still small when compared with that dedicated to analysis of global crop production.

It should also be made clear that the emission 'scenarios' used by the IPCC to drive crop modelling are very distinct from the non-replicable expert projections made for the FAO agricultural trends analysis (FAO, 2003; FAO, 2007a). To date there has been no formal resolution of the two approaches, and work continues to match these two perspectives. In the meantime, a number of assessments based on SRES scenarios have presented a more alarming picture (Nelson *et al*., 2009).

4.1.1. Predictive modeling and its limitations in determining agricultural impact

Climate change effects on crop production are more complex than those related to changes in average temperature and rainfall: combinations of stress are common and important. Therefore effects of variability, frequency of extreme events and combinations of stresses should be specifically addressed in modelling scenarios (Porter and Semenov, 2005). Overall seasonal precipitation determines the yield over large areas, but stress and dry spells threaten productivity (even a few hours at critical growth stages) (Huntingford *et al*., 2005). Thus the factors affecting crop productivity are predominantly weather based, rather than determined by long-term climate:

- changes in mean weather (temperature and rainfall);
- changes in variability or distribution of weather;
- combinations of changes in the mean and changes in its variability.

A simulation study coupling a stochastic weather generator to GCM predictions for wheat in Spain and the United Kingdom examined these weather combinations and demonstrated grave consequences of increased variability with marginal decreases in yield for increased temperature in Spain but a 50 percent chance of much lower yields with increased variance, mostly due to longer dry spells over the vegetative growth period, in both countries. Longer periods of dry weather with the same total precipitation increased simulated variability in yield and quality by 70–80 percent compared with baseline (Porter and Semenov, 2005).

Porter and Semenov (2005) conclude that yield-damaging weather signals for cereals are in the form of absolute temperature thresholds; these are linked to particular developmental stages and are effective over short time periods. Therefore global analyses based on annual and seasonal crop patterns may be wide of the mark: crop-climate models need to be able to work at a temporal resolution of a few days.

In addition to poor spatial representation of existing rainfall patterns, the current generation of models distribute monthly rainfalls uniformly for each day (IPCC, 2007). As with temperature, this smoothing must underestimate the impacts of within-season drought periods between rain events. Similarly, it is likely to underestimate runoff and overestimate infiltration, especially in flashy catchment settings.

Huntingford *et al.*, (2005) also identified other limitations in using GCMs to evaluate agricultural impacts. Ocean–atmosphere coupled models cannot duplicate the North African drought from 1971–1989, although (strangely) atmospheric only types can. Current thinking is that such weather patterns are driven more by local forcings rather than global climate changes. Although GCMs cannot currently reliably replicate cyclic weather patterns such as ENSO, modelling does suggest ENSO cycle periodicity could reduce from 5 to 3 years under CO_2 doubling in 2050.

4.1.2. Impacts on nations or river basins?

Patterns of production are currently confused by the actual impact of price signals on agricultural production (including biofuels) (Rosegrant *et al.,* 2006); these indicate the ability for rapid and sudden change in production patterns and the knock-on effects for the whole sector (Ch. 3). Although rapid improvements are being made in land-use classification from remote sensing, obtaining an accurate assessment of rainfed and irrigated areas and production will remain a continual challenge resulting from the relatively rapid short-term market-driven responses in crop choice.

In the end, an analysis of the sensitivity of agriculture water management to climate change only makes sense within a systemic context – the river basin and its related aquifers. For this reason, this section concentrates on the impacts across hydrological units. Despite the fact that adaptation and mitigation policies and strategies will be framed at national level, largely in response to macro-economic analysis, such a systemic approach will remain valid. National production in semi-arid countries, such as Morocco and Yemen, is an aggregate of harvests in individual river basin and aquifer systems. Further, many of the large basins and aquifers that support productive agriculture, such as the Aral Sea basin, Indus, Nile and Mekong, cross one or more national boundaries. Thus impacts on agriculture and hydrology and potential solutions have to be examined at levels broader than national interest; the river basin will remain an important arena (Svensen, 2008).

4.2. PRINCIPAL CLIMATE CHANGE DRIVERS IN AGRICULTURE

Five main climate change-related drivers will affect the agriculture sector in ways that will vary in intensity and importance across the regions. They are: temperature rise; precipitation patterns, including rainfall and snow; the incidence of extreme events (floods and droughts); sea-level rise; and the atmospheric carbon dioxide content. Impact pathways on food production are summarized in Figure 4.1.

There are clear differences in the statistical variability of climate and hydrology between continents (Peel *et al*., 2001), which are as yet not well modelled by GCMs. Although there is as yet only limited literature available on the prospective impacts of climate change on water balance and implications for irrigation, the impacts of these drivers are likely to include the following:

- reduction in crop yield and agricultural productivity where temperature constrains crop development (changes in diurnal fluctuation are as important as overall trends);
- reduced availability of water in regions affected by falling annual or seasonal precipitation (including southern Africa and the Mediterranean region);
- exacerbation of climate variability in places where it is already highest (Peel *et al.*, 2004 and 2004a);
- reduced storage of precipitation as snow, and earlier melting of winter snow, leading to shifts in peak runoff away from the summer season where demand is high (Barnett *et al.*, 2005);
- inundation and increased damage in low-lying coastal areas affected by sea-level rise, with storm surges and increased saline intrusion into vulnerable freshwater aquifers;
- generally increased evaporative demand from crops as a result of higher temperature.

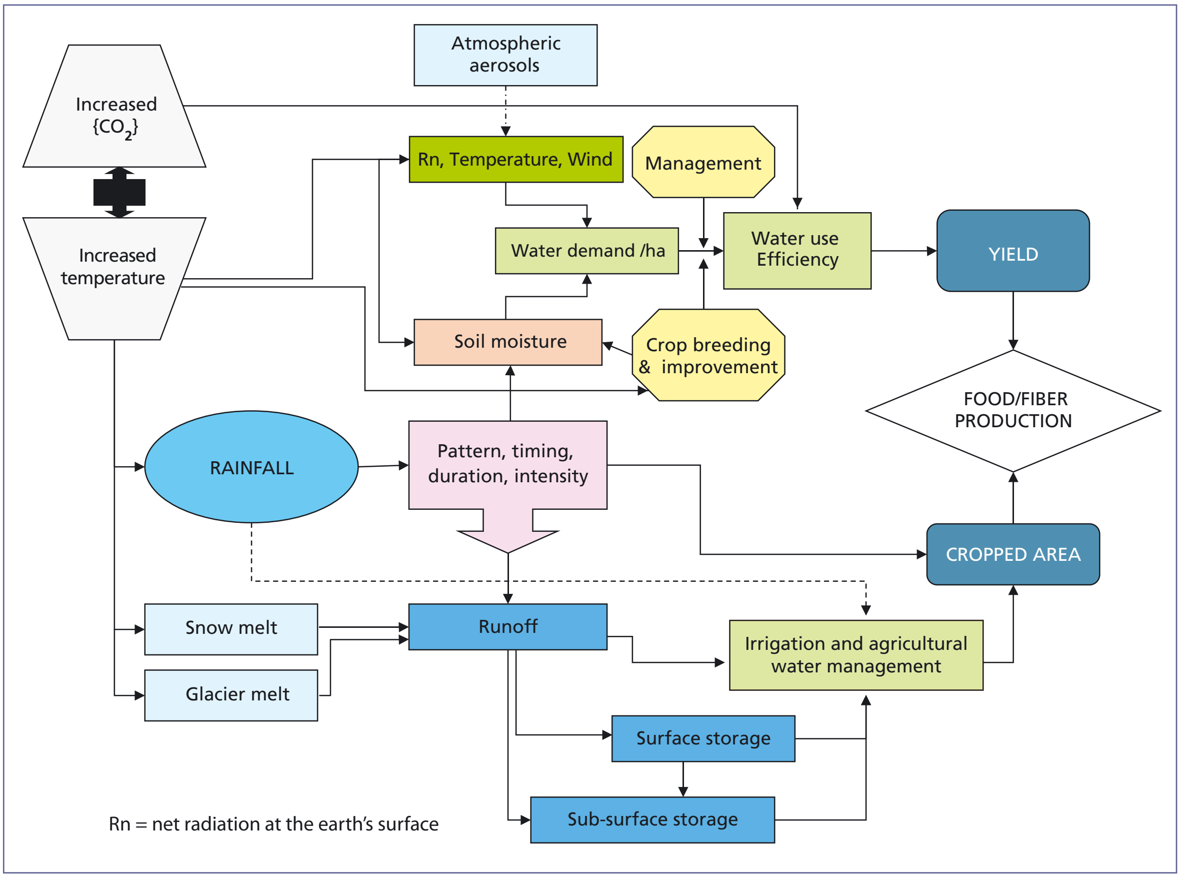
4.3. OVERALL IMPACTS ON CROP PRODUCTION

4.3.1. Direct effects of temperature and changes in precipitation

The writings connected to the IPCC, Stern Review and climate change literature are pessimistic about the impacts of climate change on agricultural production compared with recent analyses conducted by FAO and the Comprehensive Assessment of Water Management for Agriculture (CA, 2007). These analyses have focused on the future food and water demands up to 2050 and have stated that, with conservative assumptions about improvements in both land and water productivity, most regions and countries will be able to meet these needs.

These studies have factored in very limited climate change impacts, and do not include the detail that became available in AR4, which was published later. To some extent, the modelling exercises associated with climate change look at the reduction in potential productivity, whereas the development literature looks at possible improvements over current productivity, which are generally significantly below potential, or even achievable levels in most developing countries (China excepted). It is quite possible that both approaches are valid, but this discrepancy clearly needs to be better resolved.

FIGURE 4.1
The agricultural production cycle, as impacted by climate change



In brief summary, at high latitudes crop yields are expected to rise with temperature increases of 1–3 °C, but fall, due to declining crop health, once 3 °C is exceeded. At lower latitudes, crop yields are expected to decline with temperature rises as little as 1–2 °C.

Overall, the benefits of carbon dioxide enrichment on photosynthesis are likely to be outweighed by increased temperature and lower rainfall (Long *et al.*, 2005; Smith *et al.*, 2008, section 4.3.1). It is expected that agriculture (without any further adaptation), especially in the dry and wet tropics, will be more affected by an increased frequency of extreme events, rather than the mean change in climate (Porter and Semenov, 2005). Additionally, there is anticipation of greater fire risk and incidence of pests and diseases.

Growing season temperatures in the tropics and sub-tropics by the end of the twenty-first century are highly likely to exceed the most extreme seasonal temperatures recorded from 1900 to 2006 (Battisti and Naylor, 2009). These authors note that losses in French and Italian maize grain and fodder harvests were great in the hottest year on record (during the European heat waves of 2003), with 30 percent reductions; they note that there are many historical examples where high seasonal heat has had severe consequences, which resulted in price hikes. The tropics currently experience less summer season temperature variation than found in temperate areas, but this will change dramatically with climate change and this area will be the first to experience severe impacts.

Cereals incur major physiological damage when average season (92 days) temperature reaches 33 °C (Huntingford *et al.*, 2005). The effects of a modest, 2 °C, rise in temperature are likely to decimate the tea industry in Kenya, and coupled with declining rainfall, significantly reduce the productivity of cocoa in Ghana (Barclays and Met Office, 2009).

Global annual irrigation water water withdrawals are estimated at 2 710 km^3 (FAO, 2010) or about 70 percent of the total water withdrawals of 3 862 km^3 per year (FAO, 2010). Estimates of future irrigated areas are highly dependent on estimates of water use 'efficiency' – the ratio of crop water requirements to water withdrawals. This, in turn, depends on the interaction between negative effects caused by rising temperature (increasing evaporative demand and night-time respiration, resulting in declining potential net primary production) and CO_2 enhancements (increased photosynthetic efficiency, reduced water use and reduced respiration rates).

Average global irrigation demand is expected to increase by between 5 and 20 percent (Fischer *et al.*, 2007; Nelson *et al.*, 2009) as a result of rising temperature – somewhat lower than earlier estimates by Döll (2002). However, it has been observed that canopy and air temperatures over land irrigated in semi-arid conditions can be as much as 10 °C below ambient without irrigation (USDA, 2008). This has some important, and not fully explored, implications for the productivity of irrigated areas. A more bottom-up assessment conducted across the United States concludes that irrigation water requirements will increase by 64 percent by 2030, or 35 percent with CO_2 fertilisation effects (derived from FACE estimates) (USDA, 2008).

IIASA's baseline scenario (without climate change) projected a 45 percent increase in irrigated land to 393 million ha in southern Asia, Latin America and Africa in order to meet future food demands (Fischer *et al.*, 2007). This translated into a 66 percent increase in water requirement over present use when climate change was taken into consideration. Two thirds of the increase was attributed to temperature rise and rainfall changes and one third to extended crop calendars. It was estimated that only 50 percent of the water supplied to crops transpired in 2000; in other words, average global irrigation efficiency is 50 percent. The modelling scenarios allowed for modest increases in global irrigation efficiency to 60 percent in 2030 and to 70 percent in 2080. The broad distribution of future water stress is predicted to closely match that presently being seen. FAO had previously estimated that an extra irrigated area of 40 million ha will be needed to meet global food security needs in 2030 (FAO, 2002); this is substantially less, pro rata, than the 122 million ha increase estimated by IIASA for 2080. The broad conclusion is that the additional water required because of climate change will be nearly as great as the net increase in demand from present day to 2080 to meet additional food and other needs.

An implicit assumption in the IIASA study is that potential water productivity does not decline *per se*: although water demand will increase because of temperature effects, it is assumed that the underlying physiology will be maintained. The International Food Policy Research Institute (IFPRI) study is based on Decision Support System for Agrotechnology Transfer (DSSAT) crop modelling of four main representative crop types, with less delineation of global agro-ecological zones. The physiological processes represented in the crop model respond to temperature and evaporative demand, but the underlying efficiency of photosynthetic and respiration processes is not changed. A sophisticated study of irrigated production under climate change undertaken for Morocco (Gommes *et al.*, 2009) used a simpler modelling framework (FAO's Crop Specific Soil Water Balance Model) that is linked to downscaled climate prediction to derive complex multi-factor yield functions with up to 43 variables in the multiple linear regression. It assumes that present crop response functions will be unchanged in the future, and that future irrigation supply will satisfy all crop water demands. Crop physiologists would disagree with this assumption, but it seems likely that considerable further work needs to be done to develop integrated crop models that take all climate change effects fully into account. The study predicts net positive yield response to climate change and indicates that continued irrigation will isolate cropping from the broader impacts of climate change. Like all modelling, this result derives from its assumptions and does not address the impacts of climate change and variability on irrigation water availability and the consequent effect on production.

The increased frequency of extreme events may lower crop yields beyond the impacts of mean climate change. Impacts of climate change on irrigation water requirements will therefore be 'large' and countries with greater wealth and natural resource endowments can adapt more efficiently than those where water is already scarce.

There remains much to be done to improve and standardize on methodologies to assess future production potential at local, regional and global scales: a broader range of economically important crops and locally adapted varietal characteristics is required. The modelling should link future climate change patterns to more detailed and downscaled weather based models; it should account for short term (daily) and averaged effects of increased temperature and to extremes and variability in temperature and rainfall as much as to long-term trends. Such work is better undertaken at a local scale, by researchers who are strongly connected to the subtle detail of specific systems. More effective global assessment is likely to result from continued development and refinement of governing GCMs and RCMs, and the integration and amalgamation of more specific and detailed local assessments in different agro-ecological zones and regions around the world. Where irrigated agriculture is concerned, it is important to integrate the hydrology of water supply with the direct effects on crop growth.

4.3.2. Carbon dioxide 'fertilization' of crops

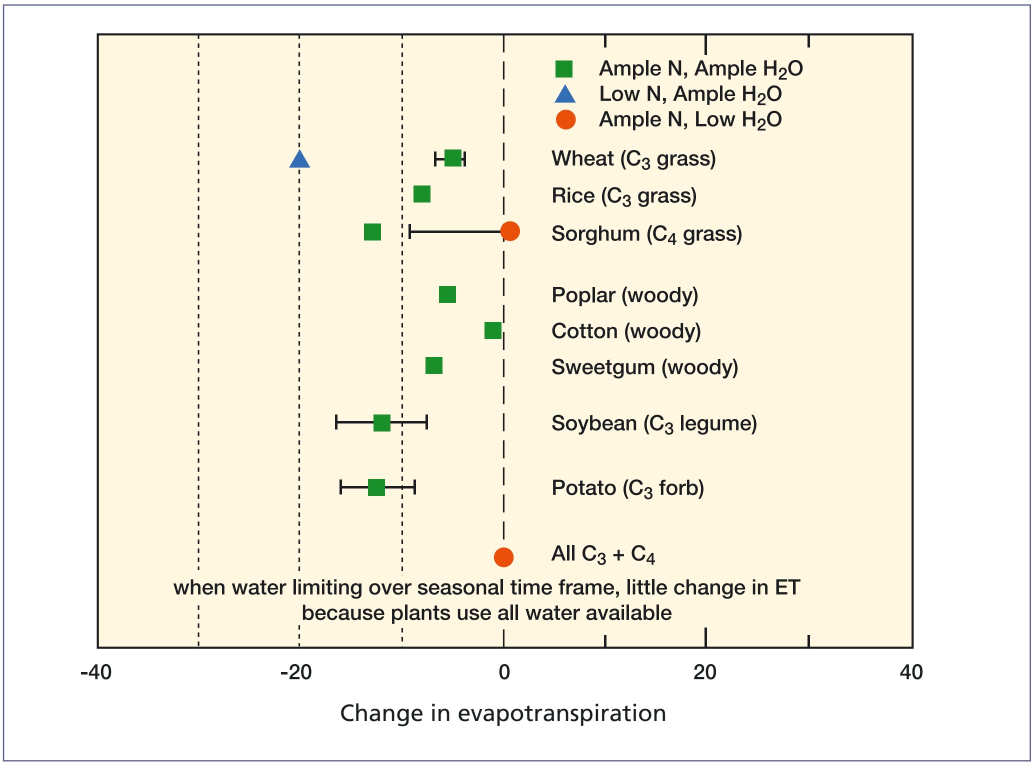
Higher atmospheric concentration of CO_2 stimulates yield by decreasing photorespiration in C3 crops and transpiration in all crops. However, the initial expectations of increased productivity from enhanced atmospheric CO_2 have been downgraded, because the very local scale of experimental measurement (point and leaf scale in chambers) tended to exaggerate field and larger-scale responses.

In general, plant response to elevated CO_2 alone, without climate change, is positive and may be relatively greater for crops under moisture stress compared with well-watered crops (IPCC, 2007). The effects on plant growth and yield depend on photosynthetic pathway, species, growth stage and management regime, including the application of water and nitrogen (N). On average, across several species and under unstressed conditions compared with current atmospheric CO_2 concentrations, crop yields in growth chambers increase at 550 ppm CO_2 in the range of 10–20 percent for C3 crops and 0–10 percent for C4 crops. However, the effects of elevated CO_2 are inevitably limited by other agronomic factors at field scale, including pests, weeds, soil and soil-moisture availability (Fuhrer, 2003). In addition, modelling studies suggest crop yield losses with minimal warming in the tropics and predict that mid- to high-latitude crops will benefit from a small amount of warming (about +2 °C), although plant health declines as temperatures rise.

Free-Air Concentration Enrichment (FACE) technology allows investigation of the effects of rising CO_2 concentration and ozone on field crops under open-air conditions at a field scale. Experiments with rice, wheat, maize and soybean show smaller increases in yield than anticipated from studies in chambers. More worryingly, experiments with increased ozone show large yield losses (~20 percent), which are not yet accounted for in projections of global food security (Long *et al.*, 2005). C4 crops are generally much less sensitive to ozone, but impacts derived from soy (C3) experiments across the United States showed an average 34 percent reduction in biomass, accompanied by a 24 percent reduction in grain yield, but only a 20 percent fall in the rate of photosynthesis. Ozone is already thought to be limiting present yields and will impair them further as levels rise.

Much of the work elaborating positive CO_2 responses has been undertaken in the United States, and USDA (2008) maintains that responses from FACE experiments broadly corroborate growing chamber experiments. Rates of evapotranspiration at an atmospheric CO_2 concentration of 550 ppm are reduced by around 10 percent for well-watered crops with adequate access to nitrogen (see Figure 4.2), a situation that is increasingly unlikely to prevail for rainfed crops. One consequence of stomatal closure is reduced evaporative cooling, so crop canopy temperature has been observed to rise, thus increasing rates of respiration.

FIGURE 4.2
Summary of evapotranspiration effects of elevated CO_2 concentration, for different categories of limiting conditions under current temperature conditions – determined in FACE experiments in the United States (USDA, 2008)



Current thinking in the United States is that the net reduction in evapotranspiration at 440 ppm (2030) will be negligible and growth improvement could be as much as 10 percent (on projections of 30 percent increase for C3 plants to 700 ppm), depending on whether growing season temperature is more or less favourable. The assessment of temperature limits for different crops in the United States is quite elaborate, based on extensive experimental evidence at all stages of growth, and further supported by crop modelling studies. Temperatures over the southern, central and western United States will generally become sub-optimal. Overall, potential yield is generally expected to decline as a result of rising temperature, with only limited mitigation or mild improvement with CO_2. By the time CO_2 levels reach the more stimulating 2x level (700 ppm around 2050 without mitigation), the rise in atmospheric temperature will have negated its positive contributions to net yield.

High temperature during flowering may lower positive effects of CO_2 by reducing grain number, size and quality. Increased temperatures may also reduce CO_2 effects indirectly, by increasing water demand (IPCC (WG2, AR4), 2007). Larger-scale experimentation continues, but most extrapolation has been undertaken using models that have been modified to include carbon dioxide concentration effects on photosynthetic efficiency. It is now thought that the best responses are obtained when other factor inputs (water, nitrogen etc.) are not limiting. C3 crops have been shown to be more responsive with increases in water use efficiency of up to 30 percent at a CO_2 concentration of 550 ppm, compared with half that for C4 crops, which already have more efficient photosynthetic processes.

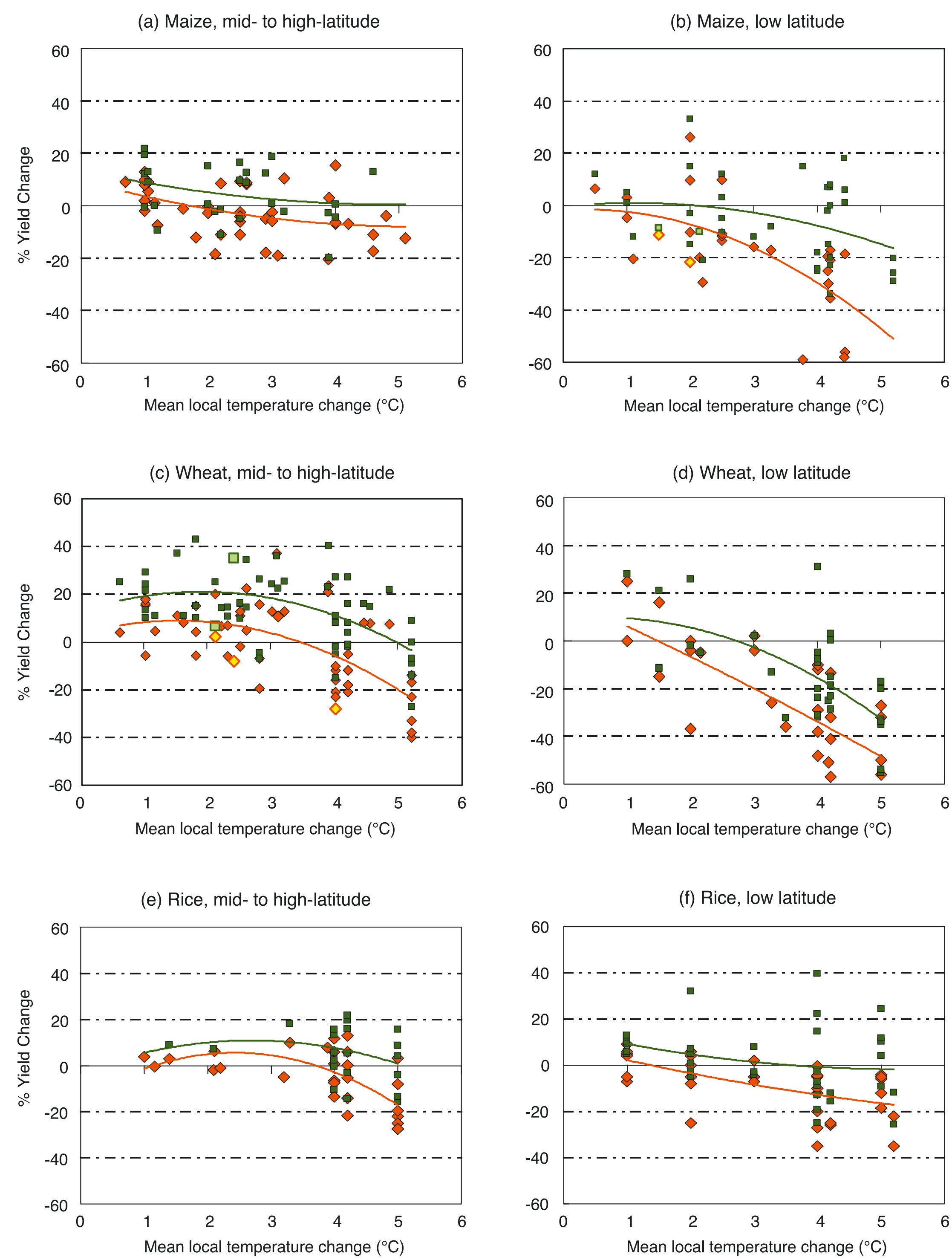
Climate impacts on crops may significantly depend on the precipitation scenario considered. Detailed crop modelling studies in Australia indicate that the likely reductions in water supply (lower rainfall and increased evapotranspiration) will more than offset CO_2 enhancement to production; the result being an overall decline in productivity (CSIRO, 2007).

Expected yield trends for rice wheat and maize at low altitude, derived from modelling over a range of temperatures and carbon dioxide concentrations, are shown in Figure 4.3 (IPCC, 2007). The orange markers indicate performance without adaptation and the green assume a variety of adaptations, including irrigation. The lighter coloured markers indicate rainfed crops with lower rainfall. The trends are predominantly downwards with outliers indicating more positive possible responses with adaptation. These are aggregated results, and more local variation is expected in specific conditions and locations.

Most recent detailed Australian analyses show that, despite adaptation, production and productivity will fall, mainly because of reductions in water availability. This will be broadly true of other variable semi-arid and arid climates. Scientific commentary in Australia seems less concerned with temperature effects than the IPCC and Stern literature, possibly because of the high ranges of temperature already experienced in the main agricultural areas.

The consequences of rising temperatures have focused attention on loss of agricultural and natural habitat, and this is echoed in the Australian horticultural industry, where temperature regimes are optimized to 1 °C. It also has great resonance to Europeans and North Americans, because of the vernalization requirement for wheat, but for C4 crops and pulses, legumes and tropical crops, temperature adaptability must be much greater than is being credited by the pundits. The key issue is unnaturally hot dry years with longer high temperature spells. Understanding the probability and sequencing of these seems to be important, and is one reason that climate prediction/forecasting is seen to be a major tool in adaptation strategies.

FIGURE 4.3
Projected changes in yield for major cereal crops at different levels of global warming (IPCC, AR4, WG2, 2007)



Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 5.2. Cambridge University Press.

4.3.3. Pests and diseases

The following points on pests and diseases are summarized from the recent World Bank publication on adaptation to climate change in agriculture (Padgham, 2009):

- Climate change is likely to increase pest pressure on agriculture. Changes in temperature and precipitation, increases in extreme events, and loss of ecosystem integrity could increase pest reproductive rates and virulence, shift the distribution and range size of pests, and lead to greater frequency of new emerging diseases and invasive alien species.
- Current evidence of range expansion linked to higher minimum temperatures, new pest outbreaks, or more intensive infestations linked to El Niño episodes, presage an increase in biotic stress to agriculture from climate change.
- Climate change has the potential to reduce the effectiveness of current pest management strategies, requiring the dedication of additional resources for developing new knowledge systems and appropriate measures to counter new pests or the intensification of existing pests. A narrowing of pest management options could potentially occur with management strategies that rely on host resistance breeding, use of biological control, and pesticides.
- Adaptation to heightened biotic stress from climate change will require significant investments in enhancing national pest management surveillance, diagnostic and management capacity, and knowledge systems, in terms of local and traditional pest management knowledge, as well as training in molecular methods for characterization of pest populations and breeding.
- Better institutional coordination, information sharing, and public awareness are needed to counter the threat from invasive alien species.

4.4. IMPACTS ON WATER SUPPLY AND DEMAND – A GLOBAL PICTURE

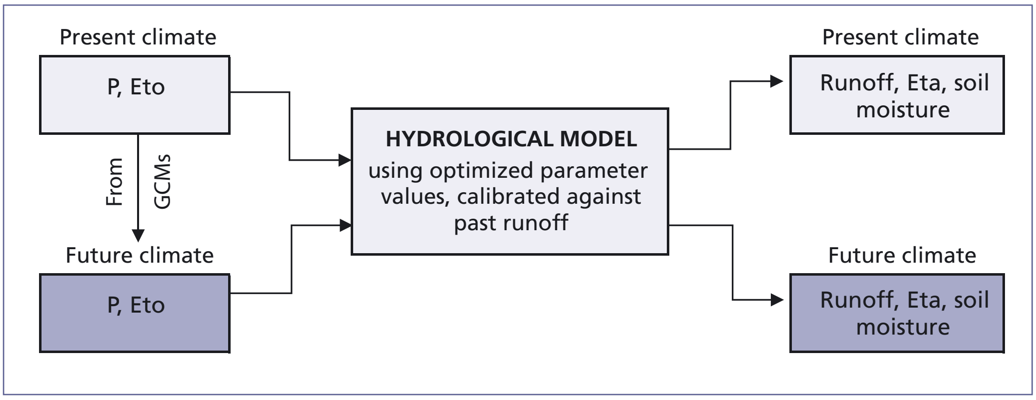
4.4.1. Overall water supply impacts

Rainfall is the key climatic variable for agriculture but the prediction of rainfall by GCM simulation is not as accurate as that for temperature and pressure. GCM resolution is at a larger scale than that at which weather processes are driven (Huntingford *et al*., 2005). In AR4, there is some indication that the uncertainty associated with rainfall has been increased further by the incorporation of atmospheric-ocean interaction. Studies in many countries use Regional Climate Models at finer resolution, but nested within GCMs, to provide more detailed predictions of weather change, particularly in terms of the spatial and temporal variability of rainfall. It would be fair to say that the calibration of RCMs is still a challenge and that additional methods of downscaling are required to assess water resources impacts.

The prediction of runoff is based on projected patterns of rainfall. Hydrologic models are parameterized against recent conditions, and these parameters are usually 're-used' to predict future flows (see Figure 4.4 (Chiew *et al*., 2003)). The uncertainity associated with the combination of downscaling methods and rainfall-runoff models has been illustrated by Chiew *et al*. (2010). Two systematic sources of uncertainty arise: 1) due to the assumption of consistent rainfall variability on the input side and, 2) the assumption of no change in hydrological model parameters. The former can be addressed by stochastic variation of the input rainfall series as a form of sensitivity analysis.

Rising temperatures result in the melting and shrinkage of glacier and snow storage, which is particularly important in mountainous areas that are the source of surface flows and groundwater recharge that sustain irrigation, such as the sub-Himalaya. This is perhaps the most immediate cause for concern within the international irrigation community.

FIGURE 4.4
Prediction of runoff under climate change (adapted from Chiew *et al.*, 2003)



4.4.2. Groundwater

Aquifers have an important strategic value as accessible over-year stores of water in a relatively stable condition without evaporation losses. In addition, percolating water is naturally de-contaminated along diffuse recharge and circulation pathways. The development of groundwater has therefore been an important structural adaptation to drought and is likely to be more so in the future. Clearly this character of groundwater is of more strategic importance to potable water supply than agriculture since agriculture is generally indifferent to the quality of most freshwater stored in accessible aquifers. However, agriculture has been quick to exploit groundwater circulation and now accounts for over 80 percent of all groundwater withdrawals (Siebert *et al.*, 2010).

Patterns of groundwater recharge drive groundwater circulation and are determined both by rainfall (direct recharge) and transmission losses along watercourses (indirect recharge) (Döll and Fiedler, 2008). When localized alluvial aquifers are annually replenished, they have good connection to surface flows and are dependent on stream flow (duration and stage) and surface water bodies for recharge. Groundwater in such systems serves to buffer annual and seasonal variations in rainfall and runoff, and will require increasingly careful management for sustainable use. The influence of land use on groundwater recharge is generally well documented in post-industrial economies where groundwater is an important component of potable supply. However, it will be important to understand the relative importance of base flow versus flood events in long-term recharge of alluvial aquifers. The role of forests in raising base flow, even while reducing overall runoff, needs more understanding.

A good and clear understanding of the likely impacts of climate change on groundwater circulation is therefore very valuable, but is unfortunately bedevilled by the general uncertainty surrounding the prediction of rainfall and runoff under current conditions (Scanlon *et al.*, 2006; Döll and Fiedler, 2008; Döll, 2009) . The sustainability of groundwater use is determined by the rates of abstraction and recharge, and also quality of the recharge water. In broad terms, recharge is expected to be high where rainfall is high and vice versa (Dragoni and Sukija, 2008). Recharge will also increase where permafrost thaws and may increase when runoff increases, particularly if over-bank flood events occur more frequently. Although there is a broad correlation between recharge rate and rainfall, replenishment in a specific aquifer is further governed by geology, topography and land use. Forested catchments tend to have lower rates of aquifer recharge than agricultural and cleared catchments, and afforestation, although desirable to sequester CO_2, will probably reduce recharge; this would require compensation if groundwater resources are to be maintained.

Obvious climate-related impacts, in general terms, are:

- If flooding increases (frequency and extent), aquifer recharge will increase, except in continental outcrop areas. A significant part of aquifer recharge happens during overland flooding in climatic contexts as different as Australia and Bangladesh.
- If drought frequency, duration and severity increase, the cycle time will lengthen and abstraction will require better balance, with less in sequences of wet years and more in dry years. There is greater potential for banking groundwater for use in extended droughts as a first line of reserve, although there are considerable challenges to the governance of such regimes in terms of the transaction costs of monitoring and compliance, and in the communication and institutional arrangements required for implementation.
- If snowmelt increases, aquifer recharge rates should increase but this is dependent on permafrost behaviour and recharge patterns, which remain largely in the realm of unknown science.

The vulnerability of groundwater systems across different continents has recently been assessed (World Bank, 2009b) in relation to existing utilization, the effects of climate change on recharge and sea-level rise, and wealth; this is summarized in Table 4.1.

As aquifers in humid and even semi-arid zones are intimately connected to streams and other water bodies, changes in aquifer level can lead to changes in network behaviour, such as the reversal from recharge from a river to discharge into it and vice versa. The dynamics of many aquifers are complicated, and the transit time for recharge may be very long indeed. Changes in runoff and rainfall may be amplified in the groundwater response, and in arid and semi-arid conditions, falling rainfall and runoff are accompanied by proportionately greater reductions in aquifer recharge.

TABLE 4.1
Vulnerability of groundwater to climate change (World Bank, 2009b)

	Sensitivity	Exposure		Adaptive capacity	
World Bank region	**Utilization of groundwater**	**Climate change impact on recharge**	**SLR[1] & storm surge exposure**	**Per capita income**	**Vulnerability**
East Asia & Pacific	Moderate	Increase	Medium	Moderate	Moderate
Europe & Central Asia	Low	Increase	Low	High	Low
Latin America & Caribbean	Moderate	Reduction	Medium	Moderate	Moderate
Middle East & North Africa	High	Uncertain	Low	Moderate	Moderate
South Asia	Moderate	Negligible	High	Low	High
Africa	Moderate	Reduction	Low	Low	High

Abstraction over recharge rates results in aquifer depletion and increased abstraction costs but can also induce water quality changes as saline groundwater and other natural mineral contaminants such as Arsenic and Fluoride are mobilized. Longer periods of drought in arid conditions will result in greater build-up of solutes in the soil and increase the frequency of saline flushes to groundwater following rainfall events.

Throughout much of the world, even in countries with strong water management systems, groundwater remains poorly understood. The increasing realisation of its strategic importance has prompted a wave of activity in trying to understand surface water - groundwater interactions better and to monitor and study systems accordingly. The literature on climate change impacts on groundwater remains thin, and modelling is often the only way to assess a possible future. Groundwater modelling is constrained not only by uncertainty in climate change hydrology but also by the coarse description and understanding of many aquifer systems.

Private groundwater development has propelled a massive increase in irrigation areas since the introduction of the mechanized borehole, and aquifers are being depleted rapidly in many parts of the world, from California to Gujarat. The on-demand, just-in-time availability of groundwater has made its exploitation difficult to resist, even in surface irrigation commands (Shah, 2009). Despite this, the literature dealing specifically with groundwater impacts is limited and often general. In dry zones, groundwater recharge is only a fraction of rainfall, most of it being lost in evaporation, and is difficult to assess accurately. The estimation of groundwater trends under climate change is further complicated by its place in the hydrological cycle and the relative difficulty of measuring and modelling its dynamics, and by current uncertainty in the prediction of rainfall and the impacts of future land use.

A sophisticated analysis, incorporating land-use interactions with crop selection driven by profit maximizing, was undertaken for the eastern United Kingdom (Holman, 2006), where low-lying areas will also be more frequently inundated with rising rainfalls and sea levels. The nested modelling study concluded that climate induced changes in precipitation dominated socio-economic and temperature effects in governing distributed groundwater recharge. In contrast, an aquifer dominated by flood plain recharge in Canada will experience increased annual recharge from increased rainfall and runoff, but there will be little impact on maximum groundwater level because of changes in timing and volume of peak flows (Scibek *et al*., 2007); this points to the inherent damping in groundwater systems. In the arid San Pedro Basin that flows from Arizona (United States) to the Sonora (Mexico), the principle source of groundwater recharge is over-bank flooding. Despite more frequent high-intensity storms, climate change models predicted a 21 percent decline in annual recharge as a result of a general decline in rainfall and runoff (Serrat-Capdevila, 2007). The work also predicted a decline of 31 percent in riparian vegetation, which might normally moderate over-bank recharge rates. The implication from these studies, though far from universal, is that semi-arid and arid groundwater systems will be highly susceptible to further reductions in rainfall.

4.4.3. Implications for water institutions

The institutional arrangements for water resources management, and particularly for irrigation provision, have been subject to intense scrutiny for their cumulative shortfalls in providing adequate service to users and in safeguarding the sustainability of water resources and environmental values. Climate change will exacerbate water scarcity in existing and newly stressed locations and add additional complexity to already tough issues that traverse large and far-flung communities as well as multiple sectoral interests. As the constraints and requirements in water allocation and the management of water distribution, flood prevention and drought management become sharper, there will be ever greater impetus to find effective answers to institutional problems that have been treated with token and prescriptive 'solutions' to date. Practical and effective communication, representation, delegation and responsibility will be sought and the likelihood that cross-sectoral integration will lead to bureaucratic inertia should be circumvented. Institutional reforms, though widely aired and promoted, take a long time to implement and are closely bound to the prevailing views and understanding of society at large. They need to be flexible, logical and strategic, but water is a highly political subject and it is common for short-term political imperatives and realities to stymie longer-term goals.

A cogent review by Meinzen-Dick (2007) observes that different panaceas for better institutional arrangements have been promoted over the past 30 years to largely reflect the predispositions of their promoters: 1) state intervention and control; 2) user participation and control; and 3) market solutions. Elements of all three approaches are commonly required, defined by different social, economic and political settings that include the resources system and resource unit; the governance system; the users and uses. Rather than base reforms on any one agenda, there is emerging consensus on the need for effectiveness of partnerships between the state, the civil society and the market. In relation to climate change, Meinzen-Dick notes that water scarcity tends to promote better management, but that this rapidly breaks down with more severe scarcity and competition, and can quickly result in organisational breakdown. Robust functional institutions will rely on the continued existence of a viable and manageable resource base in the future.

4.5. REGIONAL IMPACTS

The impacts of climate change on agricultural production and water resources remain highly uncertain, with potentially great spatial variation. Semi-arid and subtropical areas in the Mediterranean, the Near East, sub-Saharan Africa, and Latin America are likely to be affected most through higher temperatures, more rainfall variability, and greater frequency of extreme events (IPPC, 2007; Kurukulasuriya *et al.*, 2003).

The predicted temperature increases are very likely to lead to reductions in crop yields, particularly in C4 crops, and it would be unwise to expect any net positive effects from higher atmospheric CO_2. Farmers might be able to adapt to temperature increases by changing planting dates, using different varieties, or switching to different crops (Aerts and Droogers, 2004; Droogers and Aerts, 2005). This might generate substantial transaction costs when institutional infrastructure is geared toward one primary traded crop, such as coffee in Uganda (Maslin, 2004). The same applies to arguments for irrigation systems and management, including institutional adaptation geared towards service to a particular cropping system.

While future regional temperatures are relatively certain, future precipitation rates and patterns within regions are not. Most climate models agree on a global average precipitation increase during the twenty-first century but they do not agree on the spatial patterns of changes in precipitation (Alcamo *et al.*, 2005), and some forecast a trend of declining soil moisture (Dai *et al.*, 2003).

Most climate change models indicate a strengthening of the summer monsoon. In Asia this might increase rainfall by 10 to 20 percent, but more importantly will be accompanied by a dramatic increase in inter-annual variability (Kumar *et al.*, 2006). For paddy farmers this might imply less water scarcity (and more erratic dry season flows), but more damage from flooding and greater fluctuations in crop production. Some arid areas will become even drier, including the Near East, parts of China, the Mediterranean Basin (southern Europe and North Africa), northeastern Brazil, and west of the Andes in southern South America, West Africa and southern Africa. According to most climate models, the absolute amount of rainfall in Africa will decrease while variability will increase. In semi-arid areas where rainfall is already unreliable, this might have severe impacts on crop production (Kurukulasuriya *et al*., 2003) and the economy (Brown and Lall, 2006). Irrigation might help smooth out variability, but is only useful if the total amount of manageable precipitation remains sufficient to meet crop water demands.

Subsistence sectors are threatened (notably Africa, parts of Asia) by 2080, by which time some 75 percent of the population could be at risk of hunger in Africa (FAO, 2003). Since Africa presents the greatest cause for concern, and because its limited economic development increases its vulnerability and limits its adaptive capacity, it is useful to elaborate further. In North Africa and along the Sahel margin, rainfalls and runoff are expected to decline, with some dramatic changes in land use (increased desertification or encroachment) and reduced growth potential by 2050. Further south, in West Africa, agriculture GDP is expected to decline between 2 and 4 percent, and coastal settlements, which are currently home to the majority of the population, are expected to be affected by sea-level rise and flooding. In East Africa and its heartland in the Ethiopian highlands, rainfall and runoff are expected to increase, with risks of more extensive and severe flooding. However, it is possible that rainfed agriculture could become both more reliable and more productive at altitude and the potential for water storage and local use in the Blue Nile Basin could be realized without seriously compromising existing downstream commitments to Egypt. The risk of malaria and other water-related diseases is expected to increase in a more humid, warmer climate.

In southern Africa, increased moisture stress is anticipated in the wake of lower rainfall, higher potential evapotranspiration and higher temperatures. Crop yields in rainfed systems are expected to fall, and food security will decline. Vulnerability is high as a result of factors such as poor governance and high incidence of HIV/AIDS.

In Asia, water stress will increase, particularly in areas currently supplied with water from Himalayan snow and ice which are expected to witness accellerated mass losses from glaciers and reduction in snow cover. In addition, irrigation demand is expected to increase by 10 percent for every degree rise in temperature in arid and semi-arid East Asia, bringing water scarcity to between 0.12 and 1.2 billion people by 2050. Crop yields are predicted to rise by up to 20 percent in eastern and Southeast Asia, but expected to fall by 30 percent and become more variable in central and southern Asia. Sea-level rise will threaten farming in the major deltas, affecting 3.5–5 million people. The IPCC estimates that a 1 m rise in sea level will result in the flooding of 15-20 000 km^2 in the Mekong delta alone.

The major issues identified for South America are a loss of crop and livestock productivity, accompanied by a loss of biodiversity in all major ecotomes – notably the Andes and the Amazon. Water stress will increase in the already-dry areas (Savannah, southern latitudes, desert and desert fringe areas) that are dotted across the continent. In addition to human impacts, rising temperature and reduced rainfall will see a natural conversion of jungle to savannah and valuable niches for coffee production will decline.

It is expected that temperature rise will be more pronounced at higher latitudes (IPCC, 2007). This means that crop production will be possible at higher latitudes than is currently the case because of lengthening of possible growing seasons, although this opportunity could be somewhat compromised by decreasing vernalisation, especially in parts of Canada and Russia.

All this has several strategic implications for climate change adaptation that can be summarized as follows:

- Cereal production is expected to fall by between 9 and 11 percent in the developing country regions and Australia/New Zealand, but it is expected to increase by as much as 11 percent in the developed countries, including Russia, thereby reinforcing existing disparities in food production.
- However, the temperature increases that open up ‘new’ growing seasons for cereals in the higher latitudes and the associated increases in evapotranspiration rates will increase the demand for irrigation.
- Where irrigation is already commonplace and rainfall declines, such as in southern Europe, crop water productivity will have to increase or crop areas will contract.

The arid and semi-arid regions (mid-latitudes) face the double burden of declining and more erratic rainfall, and increases in temperature that surpass the threshold limits for major stable crops. At the margins, land will be retired from agriculture, and elsewhere cropping will be increasingly precarious, even in irrigated areas. National food policy will face tough choices, such as deciding whether to maintain irrigation (and subsidies) to secure subsistence farmers and traditional crops from perennial drought, whether to make better economic use of limited water supplies in reallocating irrigation supply to more secure, and higher potential areas, or to grow high-value (export earning) crops. Many solutions will be possible and all will have particular benefits and downsides.

Elsewhere, in tropical and sub-tropical regions where more rainfall and run-off is expected (southeastern South America, east Africa and Southeast Asia), it will be possible to expand irrigated production, but greater rainfall variability suggests additional water storage facilities will be necessary. If food security is less pressing in these areas, increased water availability may justify and facilitate diversification into cash cropping.

Other parts of the tropics, including places where wetland rice is commonly grown, are expected to become drier (e.g. Gulf of Guinea, Central America, northeastern Brazil). Trends used in AT2015/2030 (FAO, 2003) indicate that the area of wetland rice in these areas would expand (in a constant climate), and if this is to happen under climate change, less water intensive forms of rice irrigation will be needed (alternate wetting and drying or aerobic rice).

Small islands are threatened by climatic and sea-level rise impacts, which are likely to affect most of their inhabitants. Although island populations are small compared with those of the Asian sub-continent, agriculture is important and sustains livelihoods and food supplies; freshwater is sourced from rain, shallow groundwater and freshwater lenses in the surrounding sea. Some 295 Atolls with freshwater lenses have been identified as highly vulnerable and likely to disappear. Agricultural land will also be lost along the coastline, and economic costs without adaptation are predicted to reach 17–18 percent of GNP by 2050 for SRES scenarios B2 and A2 (IPCC, 2007).

Countries with a variety of climates and agro-ecological zones may have the option of relocating agriculture from highly impacted areas, to higher potential areas, providing that there are sufficient land and water resources available.

The variety of situations and the generalization of this section suggest a need to consider impacts and adaptive strategies on a more detailed and local basis.

4.6. IMPACTS AT RIVER BASIN LEVEL: SYSTEMIC CONSIDERATIONS

4.6.1. Introduction

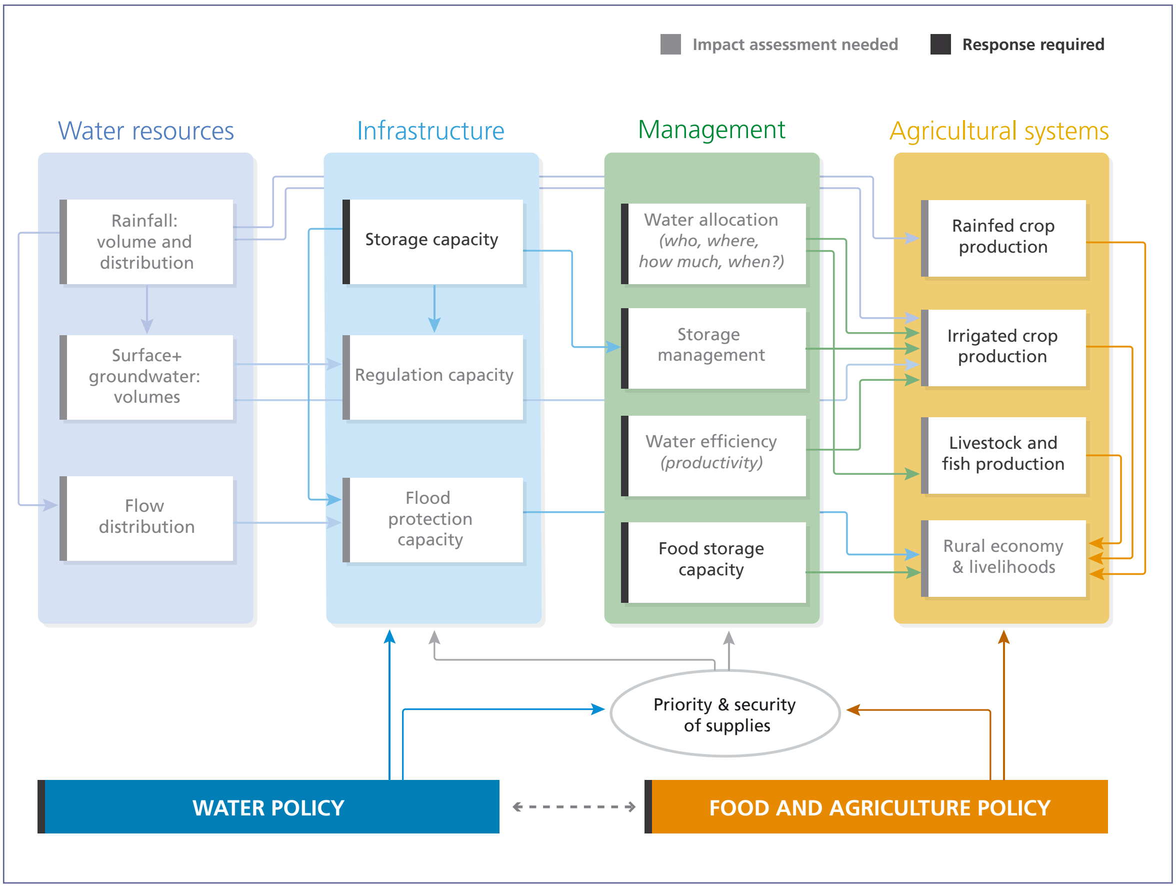
A water management perspective is essential to the analysis and management of the impacts of global warming on agriculture and agricultural water management. Climate change impacts at basin level will integrate considerable spatial variability in all the variables affected by global warming – temperatures, evaporation, rainfall, runoff, and at the river mouth – sea-level rise. The effects in any one place will be moderated by land use and by the hydrological pathways taken through surface and groundwater. The challenges of river basin management will remain essentially as they are now, although the impacts and vulnerabilities of different land units may change, as may the priorities in managing them.

In the United States there are at least five macro regions with substantially different climatic conditions, ranging from the semi-arid west and south-west to the cool temperate east coast. Nationally, precipitation and stream flow will increase from 2050 to 2100 and drought frequency will decline (USDA, 2008). At regional level, runoff will increase in the eastern region, and decline substantially in the interior of the west (Colorado and Great Basin): in between (Missouri and Mississippi), little change is expected. At the same time, the mountain snowpack will continue to melt and decline, with earlier spring snow-melt and associated changes in flow regime. More severe droughts have occurred in the past 2000 years than have been observed in the instrumental record, indicating past variability that exceeds predictions of future systematic change. Some river basins cross the boundaries of these macro-regions. The availability of publicly funded data collected in the United States is extensive, much of it managed by the USGS. It covers an impressive range of situations, and supports and is fed by local intelligence in many different departments. For many developing countries, collecting data is one thing, but making it available to researchers, managers, and policy advisers is another. Data is subjected to close scrutiny when made available to the broad public, and as the connection between cause and effect becomes ever more complex, more sophisticated statistical and analytical techniques will be brought in to play, requiring ever better data quality.

In a long, slow and adaptive process, it will be beneficial if river basin managers can distinguish between ‘natural’ variability and progressive change. Since many other factors (not least land-use change) will be impacting basin hydrology, it will be difficult to determine cause and effect, and at times problematic even to determine trends in data. In many parts of the world, data collection has been one of the first casualties of tighter budgets, and (short-sightedly) of sector reforms. Adaptive management is an intuitive idea, but it is harder to determine practically what to adapt and why, at the appropriate time. Where bureaucratic inertia and conservatism are too entrenched, the time for adaptation may be missed, but over-hasty corrective action is equally likely to have unwanted consequences. Understanding climate change will require not just restoration of data collection but also considerable expansion of spatial and temporal coverage, and also of the types of data to be monitored.

Climate change will impact food production through distinct but linked effects on agriculture and on hydrology, which are summarized in Figure 4.5. Each component implies data collection and analysis. It is important for managers and users to understand the likely changes over space and time at a level where the expected range of change and current levels of variability are better matched. Two tools that help considerably are spatial and temporal disaggregation the use of higher resolution models and statistical downscaling (Zorita and von Storch, 1999) coupled to scenario analysis that is complemented by risk assessment.

FIGURE 4.5
Elements of water and natural resources management that should be put in place in order to 1) assess climate change impact on agriculture and 2) develop adaptive strategies



There are a number of points that arise from Figure 4.5:

1. Water and food policy have implicit linkages at present, which need to be made more explicit in the context of competing demands for water and rising needs to maintain or restore environmental water allocation.
2. Strategic alternatives between food storage and water storage will be one of the key links between agricultural and water resources policy in the future.
3. A system of water accounting (and the supporting hydrology) should be in place to monitor and predict change and additional stress. Water allocation

systems in most developing countries are very ad hoc, which needs attention to detail.

4. Improvement of service delivery has been seen as increasingly important in all aspects of water management in both developed and developing countries for the last 15–20 years. With the additional stress of climate change, larger-scale water resources management will be increasingly important in determining both macro and within-system options to adapt agriculture and agricultural water management, and this will increasingly be mediated by better and more specialist service delivery.
5. The increasing importance of establishing effective institutional arrangements for water management, allocation and response thus becomes evident. Such processes take a long time to evolve, and cannot be created overnight.

4.6.2. Glaciers and runoff

The most immediate and large-scale impacts on runoff are likely to be due to reductions in snowmelt and retreat of glaciers (Barnett *et al.*, 2005). Worldwide, measurements have shown glaciers to have been in retreat since 1850, and there are some Chinese historical records indicating that certain areas started to decline some 150 years before (WWF, 2005).

In the Himalaya, summer accumulation glaciers depend on high monsoon precipitation and cool temperatures; the annual mass balance equates to summer mass balance (WWF, 2005). The estimated area of glaciers in the Himalaya in 1978 was 33 200 km^2, equivalent to 17 percent per cent of the total mountain area, with a further 30–40 percent having seasonal snow cover. Surprisingly, the overall contribution to total runoff was estimated to be only 5 percent (WWF, 2005), but winter season low flows are crucially maintained. A longitudinal study using remote sensing and old survey data has recently quantified glacier loss in three large Himalayan River Basins - Chenab, Parbati and Baspa (Kulkarni *et al.*, 2007). Between 1961 and 2007, the total area of 466 glaciers reduced from 2 077 to 1 628 km^2. Using simple relationships between landform and depth, volume was estimated with an estimated error of 15–20 percent, with the estimated loss in volume of 21 percent in 46 years. Small fragmented glaciers are more sensitive to warming, and contributed 38 percent of the volume lost compared with 12 percent from large ones, which are also becoming fragmented.

The science behind glacier melting will receive much attention in the coming years. Glaciers contribute 60 percent of the sediment load from the Karakorum but only 35 percent of mean annual flow at the head of the upper Indus Basin is contributed from glaciers, which cover 17 percent of the mountains (Collins and Hasnain, 1995). Later work has divided the Upper Indus Basin into three zones: the high zone generates temperature-controlled glacial runoff, which is stored and lagged in winter accumulation in the mid-altitude zones, and instantaneous runoff is generated by rainfall in the lower zones. Summer temperatures have been cooling, possibly due to an increase in cloudiness, with broader and more complex interactions between East (ENSO) and West (NAO) climate signals having been identified – the strong relationship between ENSO and the Indian monsoon has been weakening, and it is hypothesized that the Upper Indus Basin is responding to effects of the northern jet stream; NAO is an indicator of this (Fowler and Archer, 2005).

Three runoff-producing regions have been defined for the whole Himalaya (Hannah *et al.*, 2005):

- Low runoff. July–August peak regimes in the central to eastern High Mountains and High Himalaya and the eastern Middle Mountains, where the summer monsoon arrives earliest. Melt water contributes to runoff but topography limits the amount of precipitation.
- Low–intermediate runoff. August–September peak regimes dominate the central Middle Mountains as the result of an extended summer monsoon and substantial groundwater contributions.
- Intermediate–high runoff. Occurs along the Middle Mountain–High Mountain boundary with July–August peaks in western–central areas and marked August peaks at higher elevations in eastern–central and eastern Nepal, reflecting differences in summer monsoon penetration.

A period of low snowfall and rainfall in the Himalaya from 1999 to 2004 resulted in the lowest Indus flows on record with water allocations of around 40 percent of long-term mean in the Punjab in Pakistan. There is clear evidence of an average warming of 4 °C (1980–2005) and loss of 7 percent of glacier area in the headwaters of the Yellow and Yangtze rivers in the Qing Hai Plateau in China (Institute of Tibetan Plateau Research, web reference, and personal communication, 2004). Low headwater flows have been attributed to the associated decline in glacier area (YRCC, personal communication, 2004).

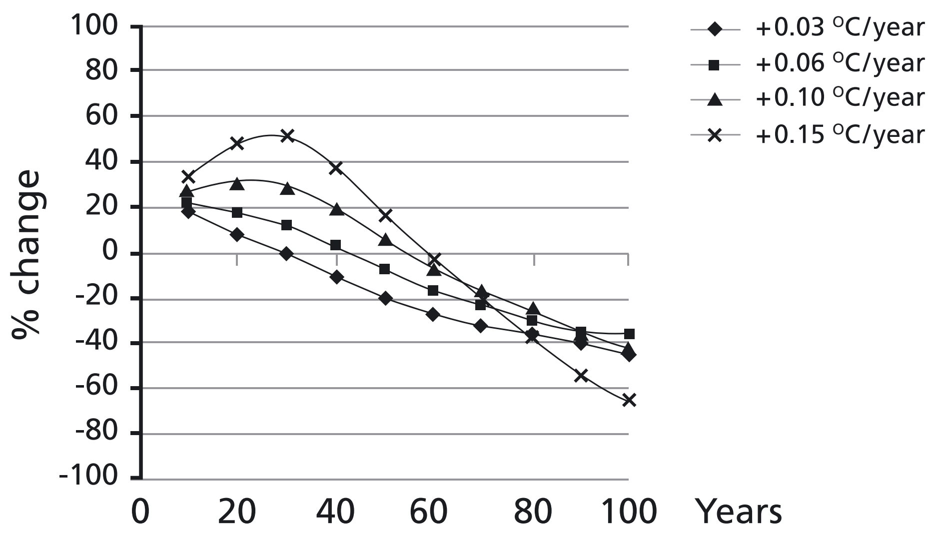
However, the science and understanding behind these changes remains contradictory and is not yet resolved. WWF (2002) contentiously suggested that a global temperature rise of 4 °C would cause melting of all glaciers in the Himalaya, resulting in a long-term decline of 65 percent of mid-summer flows (June-September), and affecting up to 500 million people in the mid and lower Ganges. A later, and more scientific review (WWF, 2005), has estimated that by 2100, runoff from Chinese glaciers will contribute between 1 and 10 10^9 m^3 per year, which is about 0.45 percent of estimated future total runoff.

Forward predictions, as shown in Figure 4.6, should see a mid-term increase in annual average runoff (consistent with mass balance) and/or an increase in groundwater recharge (Rees and Collins, 2006). However, it is not clearly documented yet and the fact of declining flows in major rivers is counter-intuitive. In Central Asia, there is emerging evidence in the Fergana system in the form of increased mudflows from the Tien Shan Mountains and new periods of late season melt and mudflows (Raivodhkhoz, Osh, Kyrgizstan, personal communication, 2007).

Given the importance of snowmelt to irrigation supplies throughout the sub-Himalaya (India, Pakistan, Bangladesh, Vietnam and China) and other mountainous regions in the United States (Rocky Mountains) (USDA, 2008), the Andes and Central Asia (Tien Shan), further analysis and research is required. A key issue is to improve the monitoring of flows and their variability and the closure of snowmelt water balances. Remote sensing (especially synthetic aperture radar) offers effective, frequent and relatively cheap means of monitoring glacier area and snow cover, but better temperature, precipitation and flow data will be needed to help understand the processes involved, especially in flow paths between glaciers, rivers and aquifers. The main puzzle for Chinese scientists investigating the Qing Hai source flows is the hydrological behaviour of the frozen ground in the plateau.

As far as snowmelt is concerned, changes in the amount of precipitation tend to affect the volume of runoff while temperature mostly changes the timing of the runoff (Barnett *et al.,* 2005). Increasing temperatures lead to earlier runoff in the spring or

FIGURE 4.6
Predicted patterns of Indus flows above Tarbela with changes in snow-melt patterns and volume under climate change (World Bank Pakistan Country Water Assistance Strategy, 2005, quoting Rees and Collins, 2006)



winter and reduced flows in summer and autumn. Furthermore, where temperatures rise such that the melt quantities exceed precipitation, ice deposits will decline both spatially and in terms of their ability to supply downstream needs. This is already happening, with glacial retreat in evidence almost everywhere. The knock-on effect is already apparent in large river systems and is expected to affect more, especially the large Asian drainage basins that depend on the Himalayan Ice, and in which much of the world's large-scale irrigation is situated. Runoff does indeed occur earlier in the season and peak earlier, requiring a gradual shift in the cropping season. In some places this may be beneficial, if supplies peak ahead of monsoon rains, supply may in fact be more consistent, although it will encourage use when crop water demands are highest and possibly least efficiently used. Barnett (2005) suggests that one sixth of the world's population lives in areas that are or will be affected by declining snowmelt and changing hydrographs; one quarter of global GDP is generated in these areas, which include much of North America.

4.6.3. Arid basins

Where water is available – usually in great rivers or in groundwater – irrigation development has been the major structural innovation to securing crop production in arid and semi-arid conditions – notably in China, northern India and Pakistan, Central Asia, western United States and Australia. It is likely that runoff in arid and semi-arid areas will decline, and that groundwater recharge will do likewise. Thus, massive investments made to secure livelihoods and food production will be more vulnerable than at present and require correspondingly better management.

Salinity is a major constraint to cropping in the arid and semi-arid tropics, where rates of evapotranspiration exceed precipitation. Decreasing runoff will have a variety of effects on salinity: dilution flows will reduce, but so may the mobilisation of salt from flows through saline zones. Groundwater recharge may decrease with declining surface flows, which may lower saline water tables in arid situations such as Pakistan, northern India and Australia. However, any declining salt mobilisation will be offset by more limited leaching resulting from lower rainfall and reduced surface water availability. Reduced river outflows to the sea will encourage further saline intrusion and contamination of near coastal aquifers (as seen due to upstream abstractions in the Krishna Delta in India (Venot *et al.*, 2008).

Conjunctive use of surface and groundwater will be particularly relevant on alluvial fans and coastal delta systems where groundwater is easily accessible. In the case of the coastal deltas however, abstraction of groundwater can result in saline intrusion, which would require leaching and therefore additional water. However, this may be a practical solution where sufficient water is available on a seasonal basis – another change in demand.

The risk of saline intrusion will also increase as runoff decreases and evapotranspiration increases. Again, it may be possible to deal with this either by means of salt-tolerant trees and crops, or where there are marked flood seasons, by growing wetland rice as a means to keep the saline front at bay (as in the case of the coastal margins of the Nile Delta) or to leach out salt accumulated during dry season cropping.

As is now the case, detailed salt balance and dynamic modelling will be required to assess the actual impacts of salinity, which will also be governed by land-use change and patterns of water use and abstraction in the basin. To date, there has been limited assessment of salinity effects resulting from climate change and this has been based on scenario analysis coupled to soil-crop-water modelling in countries such as Iran.

Current variability in stream flows spans a greater range than the predicted future median change. At one level this implies that adaptation to new median conditions can be understood in terms of current responses to more extreme events (in terms of floods and droughts). However, even with no change in variability, the frequency of what are currently extreme events will increase dramatically (IPCC, 2007) and the resilience of systems (economic, social and biological) is bound to be blunted. If the variability of future hydrology also becomes greater, resilience could be much further impaired in vulnerable eco-regions.

Sub-Saharan Africa and parts of Central and southern Asia are expected to be impacted by declining runoff. In Africa, this will limit options for irrigation as a solution to declining rainfed areas. Africa, generally does not have the luxury of a 'reliable and steady' Himalayan type of water source – that which buffers against inter-annual variability in rainfall, and one of the factors that has limited irrigation development to date. Even if monsoon rainfall increases in the Indian sub-continent, declining snowmelt will have major consequences on water supply for agriculture in the Indus and Ganges Basins, largely for the enormous number of people already dependent on irrigation, and more so for the food surplus currently generated in Punjab and Haryana. Without additional storage to capture increased summer runoff, much water will flow 'unused' to the ocean, leading to water scarcity in the drier months (Barnett *et al*., 2005; Wescoat and White 2003; Rees and Collins, 2006; Dinar and Xepapadeas, 1998).

Changing rainfall patterns affect both the seasonal availability and the manageability of water. By 2070 there will be less water available in Central America, southwestern South America, northeastern Brazil, the Eastern United States, West Africa, southern Africa, South Europe and the Mediterranean Basin, the Near East and Australia. Furthermore, supplies everywhere will vary more greatly than at present. Even in some of the areas where climate change is expected to result in greater run-off (much of the Amazon Basin, central and eastern United States, central and East Africa, South Asia, parts of Central Asia and Australia (Milly *et al.,* 2005), the intensity of specific events as well as overall variability in the seasonal distribution of rainfall means that additional storage is necessary to smooth out supplies to match the seasonal crop water requirements. Where especially high intensity (extreme) events are likely, it may not be possible to capture adequate proportions of the peak flows with infrastructure that is affordable in social, economic or environmental terms; hence the paradoxical situation that an increase in water supply can result in reduced availability.

There are several options available for addressing food security or other factors that result in reduced or unmanageable supplies, or changed patterns of supply. If demand cannot be restrained, supply-side options include surface or aquifer storage or afforestation and forest management to stabilize more limited supplies.

Several challenges are associated with surface storage, the most obvious being that many of the 'easy' dam sites have already been taken. New sites will be increasingly expensive, involve difficult ground conditions and have steep stage-discharge characteristics and therefore high evaporation and seepage losses. The use of multiple storage structures across large basins as opposed to single large dams may offer alternative benefits and distribution of risk, but when taken to scale, for example, the tank systems in Peninsular India, the aggregate impact can still bring a system to its hydrological limit (Batchelor *et al.,* 2005).

Another challenge associated with surface storage concerns the need for increasingly sophisticated spillways, probably with variable capacity and elevation, in order to deal with increasingly intense storm events. Modern technology, such as remote sensing, gives greater flexibility in storage management, providing timely and quantitative information on: 1) how much water flow there is in the river basin; 2) the probability attached to that flow; and 3) when it will arrive at its destination. Overall, conjunctive management of dam storage and the use of near-real-time flow data can improve flood attenuation and optimize release rules to benefit hydropower generation and downstream agricultural uses.

Finally, where water rights are in operation, there is the possibility of establishing water banks such as those pioneered by sugar growers in KwaZulu-Natal in South Africa. There, rights-in-use that are not required at a certain time can be kept for later use by the rights holder (seasonal or trans-seasonal use). Such facilities are small, generally community driven and may find good application where water management is decentralized. The use of 'carryover' is also practised in large systems in Australia. Carryover volumes are typically restricted to between 10 and 25 percent of entitlement and are reset to zero if the dam either fills or empties. A more ambitious method, known as continuous accounting, is practiced in the Namoi River valley – where the entitlement is managed as a share of storage by the rights holder and released 'whenever' they request, allowing full carryover if so desired.

Aquifers are potentially a water resources safety valve against scarcity but need to be properly managed for long term, high security and because in the future, groundwater will, arguably, be too valuable to use for cultivation of staple crops; the aquifers should also be organized so as to manage the risks of high input/high output farming. In this respect, well-managed groundwater is especially useful as a risk management option when used conjunctively with groundwater or supplementary irrigation where the recurring costs of groundwater abstraction are economically more favourable than the total costs of a surface irrigation system that is only partially utilized.

4.6.4. Recycling water

Supply-side problems can also be partially addressed by greater reuse of agricultural run-off, or by the use of urban wastewater. In the Nile River system, field irrigation efficiencies are low, particularly in the delta, but return flows and drainage are substantially reused, resulting in high efficiency of water use at the basin scale. One of the major challenges for water managers in many developing country basins lies in accounting properly for existing levels of recycling between upstream and downstream use.

An informal water market operates along the Jatilahur River in Indonesia, where savings from group rights-in-use are left in the river for high-value potable water supplies further downstream, while facilitating an increase in capture fishery yield along the way. Risk of accumulating agrochemicals must be managed: chemical treatment would be excessively expensive, whereas artificial wetlands could do the job effectively, if at the cost of some extra evaporation loss.

The continued migration from rural areas to the cities and their own internal growth will generate much larger quantities of wastewater than are available to farmers at present. Since potable and sanitation water supplies will have highest priority, urban wastewater will become a highly reliable secondary source of irrigation, whether treated or not. The Werribee Irrigation District, a horticultural area southwest of Melbourne in Australia, has experienced nearly 11 years of drought. During this time, groundwater use was initially increased and then banned as saline intrusion further degraded the declining coastal aquifer. Channel water has been very limited and its salinity has steadily increased to the point where almost no surface water is supplied from local sources. This has been substituted by treated urban wastewater (90 percent of total supply) from Melbourne, purchased on a rolling two-year contract. Interestingly it has a much higher level of supply security than the historical average for the surface water it replaces (Southern Rural Water, 2009).

Urban wastewater by definition also needs to be treated before it can be used for irrigation. Usually, local standards specify the level of purification according to the type of crops to be irrigated. Thus water intended for tree crops, cut flowers or fodders, does not need to be treated to the same level as water applied to salad greens or root vegetables. The decision is usually made on economic grounds, although in many parts of the world, wastewater is used without even primary treatment (settling). Urban wastewater, including storm run-off, will be more widely used for peri-urban irrigation, for mostly high-value fruits and vegetables. Future developments in wastewater treatment will require adapting to provide adequately treated and affordable wastewater for agricultural use.

4.6.5. Land-use change in river basins – afforestation and sediment management

Global land use has changed rapidly since 1950, and further changes are expected. Despite major efforts to replant forests in China, India, the United States and other countries, net forest area continues to decline alarmingly (at a rate of more than 50 000 km^2/year). Deforestation rates are highest in South America and Africa, mostly to clear land for grazing and cropping. Land use and topography are important factors governing evaporative loss, runoff, groundwater recharge and water quality.

Under global warming, land-use change is likely to be significant, as the boundaries and nature of agro-ecological zones differentiate and systems morph at the margins (see Ch. 5). Crop patterns will be adapted to changing conditions and, where land pressure is high (probably a large area), growers will try to extract livelihoods from marginal and fragile lands both in the wetter tropics and in the semi-arid and arid zones.

Afforestation has the potential to not only attenuate flood peaks and maintain base flows but also sequester carbon while contributing to or maintaining biodiversity. However, well-established tree stands mobilize soil moisture from deeper soil horizons and the hydrological impact of afforestation can also include significant reductions of base flow (Calder, 2004), even as they stabilise it. In some cases, the many benefits of afforestation (which also include the reduction of advective energy and hence of potential evapotranspiration in and around the forests) may be considered to outweigh the disadvantages. Reservoirs, which may be the direct beneficiaries of upstream deforestation, also lose water, either to seepage (which can often be recaptured as groundwater) or to evaporation. Reservoirs may contribute to GHG emissions as a result of the decomposition of inundated biomass, where forests mitigate the effects of GHG.

Linked to landscape stability and hydrological response is the issue of sediment yield. The effective life of many storage and distribution structures is severely compromised by accumulation of sediment, for example, the Tarbela Dam on the Indus in Pakistan and the Aswan Dam on the Nile. Sediment loads further upstream on the Blue Nile are impacting the operation of large irrigation schemes in Sudan. Long-term land-use management strategies will be more complex, with multiple objectives in mitigating greenhouse gas emissions and maintaining productive agriculture, healthy ecosystems and in moderating runoff. Land-use management will be closely linked to water storage strategies, both for surface and groundwater, and in protecting existing infrastructure investment from sedimentation.

4.6.6. Basins with increasing runoff – managing deltas

Increased annual runoff is predicted in the higher latitudes and in the tropics, and will be accompanied by larger and more frequent flood flows in both areas of increasing and decreasing rainfall. Deltas and alluvial plains have long been the sites of massive human drama – the Yellow River, the Yangtze Delta and Bangladesh are prime examples. Millions have died or been displaced, and flood defence has been the major priority in water management in China and northern Vietnam through millennia (Malano *et al*., 1999). Structural measures, such as diking and dam construction, have been widely used, sometimes at high human and financial cost, to protect agriculture and habitation. As physical measures are still susceptible to events of probability lower than used in the design, the consequences of failure can be costly and extreme. The expected shifts in rainfall patterns will challenge these structural measures, and if accompanied by increased variability, the risk will be further exaggerated.

Non-structural measures, such as land zoning and insurance, have been increasingly promoted in developed countries and in Bangladesh. Under most flood management systems, there are reserved areas which are preferentially flooded should cities or other sites of high economic value be threatened: this is mostly agricultural land with relatively low population density, although populations tend to rise rapidly in flood plains protected by structural measures (Red River and Yangtze Deltas, Yellow River, and the Mississippi, for example).

With increasing flood frequency and severity, these two broad trends are likely to continue, especially in transition countries with rapidly developing high capital value infrastructure. At the same time, the need to protect agriculture from floods, especially less severe ones, will become increasingly important to maintaining levels of food production, not least in irrigated systems within the humid tropics and deltas.

4.6.7. The susceptibility of wetlands to climate change

For people living in sensitive wetland areas, food security depends on the dynamic relationship between social and environmental variables beyond their control. Inland fisheries are notoriously vulnerable to environmental changes and show dramatic declines in both productivity and the underlying biodiversity as a response to habitat alterations and losses of ecosystem integrity caused by anthropogenic pressures, including climate change. The crucial role played by part-time activities such as inland fisheries that provide food and jobs during harsh times of unemployment, or when crops fail, has been neglected too often in upstream water management.

Irrigation and associated water storages may provide additional opportunities for both capture fisheries and aquaculture, but these alternatives are often poor substitutes for the loss of environmental services in natural wetlands.

The lifecycles of fish and other aquatic organisms are closely adapted to the rhythmic rise and fall of water level and changes to this pattern may disrupt many species. Dams on rivers and streams interrupt migration routes, and changes in flooding patterns may lead the fish to spawn at the wrong time of the year, resulting in the loss of eggs and fry. Flash floods may wash juvenile fish and eggs out of their normal habitats, thereby increasing chances of starvation or predation. Prolonged periods of drought will reduce available fish habitat, especially during the dry season.

Although rising water temperatures may benefit the farming of tropical species in colder climates, capture fisheries will experience stress from increased temperature and rising pH associated with global warming. This will result in species extinctions at the margins of their current habitats, and fish yields in places like Lake Tanganyika are expected to fall by around 30 percent (Reilly, 2003). In the Mekong, home to the most significant inland fisheries in the world, significant changes in the food chain may result from declining water quality, changed vegetation patterns and salt-water intrusion in the delta.

4.6.8. A basin example

To round out the discussion on macro-level considerations, let us consider the well-known Murray-Darling Basin (MDB), in Australia, which has been over-allocated despite having one of the best water accounting systems in the world. It is predicted that climate change will have a high impact in semi-arid and arid Australia. Reduced rainfall and higher evapotranspiration rates are likely to cause dramatic reductions in runoff by 2070 – 20 percent overall in the basin (CSIRO, 2007) and up to 40 percent in some sub-basins, such as those in NW Victoria (DSE, 2006). In such circumstances, the additional impacts of climate change are sharpened and will press for even tougher decisions on water use and trade-offs between agricultural and environmental water allocation. A brief score card for the MDB is presented in Box 4.1.

4.7. FOOD SECURITY AND ENVIRONMENT LINKAGES

Taken together, the anticipated impacts of climate change on water management will affect food security in many parts of the world (Schmidhuber and Tubiello, 2007). Underlying these macro considerations are a set of impacts and externalities that will not be equally distributed. In the coming years, the farms and regions most at risk are likely to be those:

- that currently lie at the edge of their climate tolerance and where that tolerance will be further eroded;

BOX 4.1
Climate change in the Murray-Darling Basin

Exposure: The Murray–Darling Basin (MDB) is likely to experience reduced annual average rainfall and increased temperatures leading to an overall drying trend. More frequent and severe drought is also possible.

Sensitivity: Sensitivity is high. Water is already over–allocated and climate change impacts will exacerbate the difficulties associated with managing demand and water quality. Agriculture, biodiversity, natural systems and the quality of water for towns and cities are likely to be significantly affected.

Adaptive capacity: Adaptive capacity of the agricultural systems is high, although it will take planning and some time to realise. There is considerable scope to adapt to reduced run–off through measures already under investigation, such as changes to the allocation of water (including trading and price mechanisms) and water conservation measures.

Adverse implications: The MDB accounts for about 40 percent of Australia's agricultural production. Adelaide draws a significant proportion of its drinking water from the Murray. There are an estimated 30 000 wetlands in the MDB supporting important populations of migratory birds.

Source: The Allen Consulting Group, 2005

- that are already stressed as a result of economic, social or biophysical condition (e.g. threatened by salinization or labour availability);
- where large and long-lived investments are being made — such as in dedicated irrigation systems, slow growing vulnerable plantation species and processing facilities (Allen Consulting Group, 2005).

Allocating water for productive use, including agriculture and hydropower, will compromise the integrity of aquatic ecosystems and associated biodiversity, which sometimes has profound economic implications. It is clear that excessive abstractions impact biodiversity associated with natural flow regimes, including economically important capture-fisheries. Less obvious and often ignored is the risk that stored water will be released and appear as dry season flows when local eco-systems have adapted to dry riverbeds and wetlands. Such flow reversal is one of the main negative in-stream impacts along the tributaries of the Murray-Darling System.

While increasing attention is being paid to the maintenance of environmental stream flows, or reserve flows as they are called under South African Water Law, the importance of flood peaks is ignored. Storage facilities that capture or over-attenuate low and medium return period flood peaks can seriously disrupt food chains, especially important marine food chains that depend on reliable annual flood peaks to bring fresh sediment into the brackish habitats in estuaries and along the coastline. Interestingly, many dams do little to attenuate extreme floods and so the environmental values derived from them are often preserved. In addition, dams capture crucial sediments, thereby reducing the seasonal nutritional value of the overall river regime in sediment-dependent aquatic/marine ecosystems.

Elsewhere, the sustainability of other kinds of ecosystem depends on sediment-free waters, including coastal reefs, sometimes called nowadays 'the rainforests of the seas'.

Poor land preparation practices in newly developed or intensively irrigated areas increases turbidity to levels that are unsustainable, with dreadful consequences for complex and often economically significant ecosystems. Australia's Great Barrier Reef is suffering from the combined effects of agricultural runoff (N and P fertilizer) from irrigated and rainfed farming, in addition to suspended matter from rainfed agriculture (WWF, 2001).

All these risks can be expected to both expand and intensify as new irrigation and storage facilities are built in response to climate change.

4.8. CLIMATE CHANGE IMPACT TYPOLOGY

Following on from the impact pathways outlined in Figure 4.1, a coarse typology of irrigation and agricultural water management situations has been prepared to further tease out where and in what way these different impact pathways will play out (Table 4.2). We propose a number of situations based largely on agro-ecological and climate impact factors. This typology is different from the one proposed for irrigation investment in the Comprehensive Assessment (Table 3.6), which emphasizes scale, economic setting and socio-technical considerations. Scale remains important, especially in terms of institutional arrangements, but has been bypassed here as it can be dealt with at a second level of regional and local analysis.

The typology could be refined in a number of ways, and it makes sense to do so when considering specific locations within a country or region. Since any specific location will likely fall within one agro-ecological zone, the most obvious candidates for refining the typology are the extent and nature of water resources development. The existing level of water development is an important factor that could be represented in a second level of the typology. The current literature on adaptation contains many references to the benefits of increasing irrigation efficiency (usually not defined) as a means of saving water, with little or no reference to basin-level water use and the possibility of making real net water savings at basin level.

A third level of the typology could (in nearly all categories) be extended to groundwater resource characteristics and use. Groundwater becomes an increasingly attractive mode of storage under climate change scenarios – to minimize infrastructure costs, maximize flexibility, and manage both short- and long-term variability in surface water supplies.

Examples of where groundwater system characteristics are distinct include the dominant processes of recharge, for example whether from flooding, seasonal saturation in rainfall periods, or from snowmelt. In arid areas groundwater recharge is often dominated by river flows or recharge from lakes or other forms of surface-groundwater interaction with complex shallow to deep groundwater connection and disconnection (as in the Murray-Darling Basin). In Deltas, net behaviour is dependent in the balance of inflow patterns, sea-level variation, and water abstraction patterns from the shallow 'groundwater' and from stream flow. The geology and parent material in different locations tends to determine whether recharge and groundwater cycling is 'fast' or slow, which also has major implications for management, restoration and adaptation.

The typology somewhat neglects small-scale and traditional systems within humid, arid and semi-arid conditions. Eight hundred million people are estimated to be involved in urban and peri-urban agriculture with 200 million producing vegetables,

TABLE 4.2

Typology of climate change impacts on water management in major agricultural systems

System	Current status	Climate change drivers	Vulnerability	Adaptability	Response options
1 Snowmelt 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)	
Northern 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	Minimize 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 snowmelt / limited groundwater					
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	

TABLE 4.2 (*CONTINUED*)
Typology of climate change impacts on water management in major agricultural systems

System	Current status	Climate change drivers	Vulnerability	Adaptability	Response options
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	
Rice: Southern China	Conjunctive use of surface water and groundwater. Low output compared to northern China		High	Medium	Increased storage for second and third season; Drought and flood insurances; crop diversification
Rice: Northern Australia	Fragile ecology		Low	High	
Non-rice - surface or groundwater irrigation			Medium	Medium	
5 Temperate areas					
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	Reduced runoff, increased water stress	Medium	Medium	Increased productivity and outputs; Limited options 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	High water scarcity		High	Low	Localised irrigation, supplementary irrigation
West Asia	Fertile crescent, increasing water scarcity	Loss of groundwater reserves	Low	Low	Integrated water resources management
7 Small islands					
Small islands	Fragile ecosystems; groundwater depletion	Sea water rise; saltwater intrusion; increased requency of cyclones and hurricanes	High	Variable	Groundwater depletion control; Water demand management

fruit, meat, dairy and fish for market (Padgham, 2009). In particular contexts, more attention could be paid to the following niches that occur within the broader categories:

1. **Garden irrigation systems:** for fruits, vegetables and (possibly) fodders. These are ubiquitous in Southeast, East and Central Asia, and are common in many parts of India. They are perhaps the most important irrigation niche in Africa. Generally they are 'off the radar' in terms of public policy and monitoring. In many countries they are part of an informal economy.

2. **Peri-urban and urban irrigation systems** (more formal than gardens); using fresh water or urban wastewater. They have worldwide importance, acknowledged economic and nutritional benefits, and are potential (often cited) public health hazards.
3. **Wetland agriculture:** significant in Africa and the poorest countries in Asia (Laos, Cambodia).
4. **Intensive horticulture:** shade-house and greenhouse production systems; orchards and vineyards. These tend to be at the forefront of technology, where the value of production and associated risk justify higher levels of investment in technologies such as drip irrigation, fertigation, and automatic control of watering based on soil moisture and plant leaf potentials. However, their significance in terms of potential impacts in reducing water use and mitigating GHGs are limited by their small scale and small proportion of total agricultural water use.

All four niches require reliable water supplies: gardens, peri-urban systems and intensive horticulture tend to be market oriented, providing high-value crops with relatively high levels in investment in capital, inputs and/or labour. Although they will be especially sensitive to the hydrological impacts of climate change, they are also likely to witness early innovation and adaptation, and growers have strong motivation to secure scarce water supplies, through a variety of means. Wetland agriculture has typically been undervalued and ignored in the development and management of river basins, often resulting in a loss or diminution in the livelihoods of the poorest. The amplifying effect of climate change in water-scarce areas will pose higher levels of risk to this group. Groundwater use is already high in many of these niches and continued development will exert considerable and difficult-to-govern pressure on aquifers. The institutional, monitoring and compliance issues related to water allocation and management will typically be complex and challenging to administer.

4.9. SUMMARY: THE COMBINED IMPACTS – POSITIVE AND NEGATIVE

The smoothing of short-term climate variability provided by irrigation is threatened by long-term shifts in climate resulting from human-induced global warming. One consequence of warming is an increase in the variability of precipitation, which together with the loss of mountain snow packs, decreases the security provided by irrigation (IPCC, 2001a). Intensifying changes in long-term climate provide a dynamic backdrop to the forces driving reallocation of water to 'higher value' uses. Climate change will increasingly be entwined with complex choices and trade-offs, in particular between irrigation and ecosystem health.

Although there is now considerable interest in raising the productivity of rainfed agriculture, and in shifting more public investment to that sub-sector, it is the storage of water, either behind dams or underground, that enables cropping in droughts and in dry seasons. Although it is certainly possible to enhance rainfed production in 'normal' seasons (Rockström *et al*., 2001), if there is no rain, then there can be no agriculture, thus bringing us back to the importance of irrigation.

Climate change impacts will further increase risk in rainfed farming systems (MA, 2005) and may exaggerate current risk-hedging behaviour by small farmers. By contrast it has been assumed that because productivity is higher in irrigation, the potential marginal gains of further improving land and water productivity are more limited. However, yields and water productivity are well below potential in many regions, notably the Indian sub-continent; significant productivity increases can be expected in both yield and water use efficiency by better management of all farm inputs and with optimal use of nitrogen fertilizer (Nangia *et al*., 2008). Irrigated agriculture, even with declining water availability, generally offers a more secure risk environment for more intensive management.

Projections developed in the Comprehensive Assessment (CA, 2007, Ch. 3) on the basis of IPFRI macro-economic modelling show that, without substantial improvement in the productivity of rainfed agriculture, and despite a considerable expansion of cropped area, irrigated area would have to increase to close to 500 million ha globally to meet expected food demand, entailing a doubling of water use. It is unlikely that either adequate land or water is available to allow this, even without likely transfers of irrigation water to other uses. Thus, raising the productivity of irrigated agriculture (especially its water productivity) will be a key target of investment and management, and one that will, in public investment terms, be balanced with strategies to enhance the productivity of rainfed agriculture.

One critical impact on hydrology is temperature-related, as rising temperatures push mountain snowlines higher and cause more precipitation to fall as rain rather than as snow at higher elevations. This effect is already causing peak runoff to occur earlier in the year in snow-fed rivers such as the Columbia in the western United States and is reducing summertime flows, when demand for irrigation is the greatest. This loss of natural storage has powerful negative implications for extensive irrigated areas that depend on snow and glacier-fed rivers for their water supply, such as the vast Indo-Gangetic Plain and large areas of northern China. At the same time, evaporation losses from reservoirs will increase, reducing their useful supply, while more intense rainfall events may increase reservoir sedimentation rates.

Irrigation plays a multi-faceted role in relation to climate change. On the one hand, it contributes to the problem through methane emitted during rice production, use of petroleum-based nitrogen fertilizers, and the use of fossil fuels in cultivation and in transporting inputs and outputs. On the other hand, by adopting improved cultural practices such as low-tillage agriculture, it can help remove carbon from the atmosphere and store it in the soil, thus helping to mitigate the impacts of fossil fuel combustion elsewhere in the world economy. Irrigation also has the potential to buffer agriculture against increased variability in rainfall and higher crop water requirements, while itself being vulnerable to warming-induced changes in its water supply. The Himalayan sub-region is a case in point, as a large share of the world's irrigation depends on water descending from its shrinking snowfields and glaciers. Increased artificial storage to compensate for the loss of this natural storage will be a huge and necessary investment requirement, whether above- or below-ground. Food storage strategies and crop insurance schemes are another possible response, but one which only buffers against variability in output and not against secular declines in production. Investments in wastewater treatment and reuse and inter-regional water transfers will also be prominent. Whether the greatest productivity is achieved through concentrated management or diffuse, low intensity investment, needs to be determined: 1) for specific locations, 2) with techniques that increase certainty in the predicted impacts, and 3) with good consideration of the environmental externalities created by each option.

Chapter 5
Prospects for adaptation

5.1. INTRODUCTION

In the previous sections, this paper has argued for the estimation of climate change impacts from an integrated perspective that considers direct impacts on cropping and indirect effects on the hydrological system, in a river basin setting. This section reviews the possible adaptive responses in a more hierarchical fashion, starting at farm level and scaling up to basin and national level policy, assuming that most adaptive strategies will be set at national level and implemented through regional economic initiatives.

Climate change impacts will come into play above many other pressures, and the formulation of adaptive responses and ability to respond will be governed by a complex mix of factors. Adaptation strategies will be continuously changing and will create feedbacks among themselves. It is important to gain understanding early and, just as importantly, to know whether such feedbacks are positive or negative.

The IPCC make a distinction between autonomous adaptations, which respond to changing conditions but are not designed specifically for climate, and planned adaptations, which deliberately take climate change into account. In relation to water use, agricultural adaptation will comprise a mix of the two.

Some adaptations, such as biological and market adjustments, will be incremental, autonomous and 'unnoticed'. Adjusted cropping patterns, changing crop types, land use and even adjusting diets are examples of autonomous change. Many such adaptations can be implemented quickly and easily with good communications and social marketing campaigns.

Other changes, such as designing water control structures to cope with a higher frequency of extreme events, will involve proactive planning on the basis of economic appraisal; this will be based on the assumption that timely investments can lead to reduced uncertainty in the long term and improved benefits in the short term. However, such macro-planning requires broad inter-sectoral coordination, with implications for dams, levees, and flood detention areas arising from increased frequency and severity of flood, which in turn impact human settlement, including farming.

Given the trends in agricultural demand for water – as driven by population, income growth and changing diets – a recurring challenge for agricultural water management is the question of how to do more with less. Competition for bulk water is already driving this autonomous adaptation, but climate change is expected to sharpen the points of competition and give added impetus to water management adaptation, to reduce demand and to rearrange supply or extend it through recycling.

Adaptation is ultimately about maximizing welfare over time. In the context of agriculture and climate change, taking advantage of any potential benefits can be handled largely by application of available technologies from existing agroclimatic systems. Where the impacts are negative, they occur because the conditions will have become worse, leading to the possibility of using (sub-optimal) technologies and solutions from today's more marginal systems (or better adaptations of them) in even more hostile or uncertain conditions. The Stern Review and more recent publications (World Bank, 2009b; Nelson *et al*,. 2009), have emphasized the strong economic linkages and potential synergy between **development** and climate change **adaptation** and **mitigation** (see Annex 1). The financial requirements for adaptation and mitigation are enormous and, where both economic development and climate change objectives can be met at the same time, the potential for efficient and effective investment is much enhanced.

Humans are conditioned to respond naturally to immediate threats but are not so alert to longer term or indirect threats and impacts (World Bank, 2009a). Some commentators are now beginning to question whether traditional coping strategies for climate variability can actually deal with climate change; they propose approaches that 'avoid the avoidable' and cope with or manage the unavoidable. This simple idea has great resonance when considering climate sensitive development to incorporate adaptation and mitigation measures where possible; there is focus on 'no-regrets' policies and actions – measures that have benefit regardless of whether certain predicted climate change impacts are realized. Three additional ideas have been added in the recent World Development Report for 2010 (World Bank, 2009a): firstly, that there is inertia in the responses made from present day into the future – particularly in terms of lumpy capital investments that take time to complete and sometimes longer to prove effective, if at all. Assessment of the consequences of this inertia is closely tied to the certainty of a particular climate impact. Secondly, that equity in response and benefit is fundamental to success in terms of implementation of overall climate adaptation and mitigation, and in terms of benefit (or prevention of loss) to the poorest. Thirdly, ingenuity is required at all levels of adaptive effort – it is difficult to imagine options that are not already familiar, and many of the possibilities discussed in this paper are indeed tied to present knowledge and experience. Ingenious solutions, ideas and options will emerge; these need to be welcomed, evaluated and tested.

Adaptation takes place on farm level and at system/catchment and basin levels. Trade-offs and constraints at basin scale determine what farmers on the land can and will do in response. Adaptations can be private or public, planned or autonomous. There is a great deal of room for all, but both private and autonomous adaptation will occur largely in terms of what can be achieved in practice at the farmgate. In the absence of planned and public strategies, farmers may find themselves in an age-old situation of some familiarity – fending for themselves. Most wealthy country governments clearly take the view that coordinated and planned responses are required, even as they dodge the issues of responsibility and mitigation. Poorer countries are likely to do the same, but have much weaker economic foundations supporting them.

In situations where climate change will have adverse impacts – principally in terms of reduced productive capacity owing to declining water resources availability and poorer agroclimatic conditions for crop growth, the **broad adaptive capacities and options** can be summarized as follows (after Allen Consulting, 2005):

- Bear the loss – accept reductions in area or productivity.
- Share the loss – distribute the impacts of reduced water resources to share reductions in area and productivity – a more managed approach involving a re-allocation of water use rights, for instance.
- Modify the threat – at an individual level, expand farm size and benefit from economies of scale; improve water use efficiency through better technology and management, where real water savings can be made.

- Prevent the effects – for example increase water and input use (perhaps the former is not a good example and is anyway a rare opportunity for many countries) – though it may work in cases where more favourable eco-regions emerge, as expected in northern China, possibly (and contentiously) in northern Australia, in northern America and in northern Europe.
- Change use – crop change, land-use change, mix of rainfed and irrigated production change on farm (if a farmer has sufficient land to make a choice).
- Change location – farming regions (see fourth bullet point above).
- Research to find adaptations – improve crop productivity in higher temperatures and with greater moisture stress.
- Educate for behavioural change.

Before looking at adaptation options in more detail, it is useful to summarize the broad choices that exist at strategic, system and farm levels. In physical terms, the river basin is the logical strategic planning level that integrates hydrology, farming systems, and infrastructure. However, markets, politics and public administration are rarely defined at basin scale, and national perspectives and imperatives will usually transcend those apparent there. Thus the physical focus of **strategic adaptation** policy may often be on the basin, although much analysis and policy development will be at national scale and will concentrate on:

- choices between expansion of irrigated or rainfed area;
- intensification of agriculture;
- supporting policies and incentives;
- (agricultural) research priorities and management;
- development of infrastructure, especially large-scale surface and underground water storage;
- accompanying water accounting and allocation policy;
- inclusion of crop storage and trade strategy.

In certain conditions, the strategic choices available may be limited: for example, where crop productivity (yield and water use efficiency) is already high (for example, California), one of the costs of maintaining high levels of yield under more hostile climate conditions is likely to be a substantial loss in water use efficiency. Higher overall water productivity (and production) might however be achieved by expanding area and sharing water supplies sub-optimally across old and new areas. In this example, expansion might be preferable to intensification, subject to the other externality impacts of expanding irrigated area.

The **system** level incorporates catchments and groundwater districts as well as irrigation networks, and adaptation will revolve around:

- managing infrastructure and associated services effectively:
  - irrigation systems;
  - groundwater districts;
  - dams and storages (rural energy from water systems – hydro-electricity, hydro-pumps).

- achieving cost-effective real water savings;
- supporting farmers in increasing yield and water productivity;
- providing early warning for drought and managing drought cycles through improved storage management and irrigation scheduling;
- managing secondary impacts:
  - salinity and drainage;
  - flood management: warning and protection;
  - safeguarding natural ecosystems.

At the **farm level**, the main thrust will concern the application and management of technologies that improve actual yield and water productivity in response to higher temperatures and more uncertain water supply, while:

- reliably satisfying household food and nutrition needs;
- generating producer surplus and income;
- mitigating GHG emissions where possible.

It almost goes without saying that there are strong relationships between system and farm level responses. System level activities intended to meet strategic targets may require support and incentives to farmers to enable them to adapt in harmony. However, farmer innovation is more likely to lead than lag system level initiatives, and will require that system management be in harmony with effective and replicable on-farm adaptations. Service provision is still a fairly sketchy idea for many irrigation system managers, but understanding service requirements will increasingly require an open and inquiring mind-set, with a commitment to observe and learn from farmers and work much more closely with them than in the past.

Farm size and farm energy use, the cost and availability of well-adapted crops and the existing level of water resources development will all influence the trajectory of system and on-farm adaptations.

Further fragmentation or, conversely, consolidation of land holdings creates constraints and opportunities for technology choice, acceptable capital and recurrent investment, and labour needs. The evolution of farm size is proceeding in greatly different directions, and in different contexts (for example consolidation in rural China, to increasing fragmentation in much of India and Africa). The trajectory depends on:

1. Rural population dynamics, and the size of the active farming population in response to:
   a. Continued population growth
   b. Urban migration.

2. Land ownership patterns following urban migration: in many countries, the rates of urban migration or urban population growth exceed national average population growth. In general, under these conditions, rural populations may stabilize or shrink substantially in the near term (20 years), depending on the balance between birth rates in rural and urban areas, and the continued attractiveness and capacity of over-stretched cities to absorb newcomers.

In China and Iran, for example, many urban migrants maintain ownership of their land, but rent it out to those who stay behind. Where rural birth rates remain high, and are significantly higher than in the cities, rural populations will continue to grow, despite out-migration.

3. Profitability of agriculture compared with 1) off-farm earnings in rural and urban settings and 2) the extent of financial flows from urban migrants back to their ‘homelands’.
4. The impact of climate change on urban migration rates and the relative attractiveness of living in a city compared with rural areas.

Since agriculture contributes about 14 percent of greenhouse gas emissions, and a further 7 percent through deforestation for development of arable land, there will be considerable pressure to both reduce GHG emissions from farming and also to mitigate emissions. In irrigated agriculture, farm energy use is significant for:

1. groundwater pumping: requires considerable energy, dependent on depth of pumping and discharge rate. Irrigation pumping, especially to upland communities, can also be energy intensive, although low head pumping at farm level may use more modest amounts of energy;
2. farm mechanization (in response to declining availability of labour, or increasing area of land-holding);
3. manufacturing (nitrogen) fertilizers;
4. transport of inputs and products.

Alternative energy sources, such as wind power and photo-voltaic arrays are capital intensive and may struggle to provide sufficient power density, especially for water pumping. Biofuels can be grown for farm use on larger properties, but are unlikely to find justification on small subsistence holdings. Biogas generated from plant and animal wastes could find a niche, although manure has many other calls on its benefits as a fertilizer; it is a cooking fuel in its own right, and also a building material.

Precision agriculture is often put forward to integrate efficiency gains as an effective way of adapting to climate change, through dealing with mitigation (for example reduced GHG emissions and energy use arising from smaller applications and higher efficiency of nitrogen fertilizer use). However precision agriculture presumes energy sources on farm for machines and the availability of technological systems, such as GPS and GIS, which are supported by specialized agronomists and other farm advisers. It would be instructive to consider the likely GHG costs incurred on the way to developing the required level of on-farm energy availability in developing countries. Adaptation in small-holder agriculture will happen by finding proxies for good ideas, such as precision agriculture, and enabling farmers to carry them out within the constraints and context of their world. This implies the need for continued effort in agricultural extension and advice, delivered to larger groups of small farmers, but at a much higher technical level and with more detailed focus than has been typical in the past.

The adaptations required at farm and system levels obviously stem from the existing socio-economic conditions at household level and the prevailing agro-ecological conditions that have governed crop choice and farming system in the locality. Broadly, **the transitions in climate** that are relevant to farming systems can be categorized in the following table:

TABLE 5.1
Transitions in agro-ecology under climate change

	Current condition	Changing to…	Temperature	Rainfall	Adaptation required to…
1	Tropical humid	More humid tropics	Up	Up + variable	Floods, within season drought periods, temperature
2	Tropical humid	Drier and semi-arid	Up	Down+ variable	Higher canopy temperature & evaporative demand, drought periods, seasonal (irrigation) water shortage
3	Semi-arid tropics	Arid zone	Up +	Down -	Temperatures that reach limits of crop suitability and require crop substitution, or irrigation
4	Arid zone	Tending to marginal	Up ++	Down -	Persistent drought: requires continued irrigation or conversion to pastoral land or fallowing (abandonment)
5	Temperate, humid	More productive temperate	Up	Up + variable	Take advantage of better growing conditions
6	Temperate, dry	Seasonally to annually dry	Up not limiting	Down	High E-R, requiring irrigation or soil and water conservation improvements
7	Montaine, quasi temperate	Drier – to semi-arid	Up ++	Up / down variable	Higher temperatures, evaporation rates, and shorter seasons

This table is far from exhaustive, but is illustrative of the main situations. In contrast to the majority of shifts shown here, some climate predictions indicate a possible greening of the Sahel, with higher rainfall over the currently arid area, following more severe predicted collapse of rainfall systems over adjacent parts of West Africa.

A positive observation from this table is that, apart from the case of the Arid zone, there are 'pre-packaged' farming systems already in existence that can be 'transferred' and adapted from places that are currently dry and hot to those that will become more so. This includes irrigation systems, although it is also worth reiterating that irrigation has been the default agricultural adaptation to semi-arid and arid conditions as well as to those regions with high seasonal variability in precipitation and risk of droughts.

The prospects for irrigation as a continuing default solution are far less clear, given:

1. the impact of declining water resources availability on the existing stock of irrigation;
2. the extensive development of existing water resources in places with large areas under irrigation, with correspondingly little additional water to allocate to agriculture;
3. the impact of increased hydrologic variability on water storage capacity (needs to increase), and the financial and environmental costs that follow;
4. increased crop water demand as the result of rising temperature;
5. increased risks of salinity associated with irrigation in a drying climate;
6. limits to the expansion of irrigated area because of:
    a. suitability of soils and terrain;
    b. water availability and access;
    c. encroachment of existing and potential lands by urban development, sea-level rise and increased extents of flood-prone areas;

d. cost;

e. possibly marginal benefit compared with improving rainfed agriculture.

5.2. ON-FARM ADAPTATION

Malcolm (2000) wryly observes that: "a glance through history suggests that in the most important ways, the fundamental elements of managing a farm have altered little". Successful farm management in a commercial context will continue to depend on good decisions about the farm's enterprise mix, machinery replacement, land leasing or purchase, labour hiring and off-farm investments. For subsistence farmers, the same is basically true, save perhaps the question of machinery, but in an increasingly large number of Asian countries, this is also a consideration (FAO, 2002). Much can be made of the differences between commercial and subsistence farming in terms of scale, technology and capital deployment, but the fundamental decision and management processes of how to produce more, and more reliably for the inputs made, are remarkably similar.

Farm size and access to capital set the limits for the scope and extent of adaptation and change at farm level. Larger farms have more scope for changing and adapting enterprise mix (Nix, 2009): where conditions allow, the balance of irrigated and rainfed production can be changed on an annual basis, as in the irrigation areas of New South Wales in Australia. Larger farms can concentrate their water allocations on smaller areas, and (providing the supply is assured) move to higher value production, such as horticulture. Capital is still required to intensify, even at subsistence scale. Large farmers, such as commercial dry-land farmers in South Africa, can afford capital equipment for timely operations, and can insure their crops against failure.

There is much discussion of extending crop insurance to developing country agriculture; at this stage there is little progress in Africa and Asia, but there is emerging progress in South America (Cook *et al*., 2006). The total annual agricultural and forestry insurance premiums, worldwide, in 2001 amounted to some US$6.5 billion and 70 percent of this was for crop and forest products. This sum must be compared with the estimated total farmgate value of agricultural production globally, which is US$1 400 billion. In this case, the insurance premiums paid represent just 0.4 percent of this total. Geographically these insurance premiums are concentrated in developed regions, i.e. in North America (55 percent), Western Europe (29 percent), Australia and New Zealand (3 percent). Latin America and Asia account for 4 percent each, Central/Eastern Europe 3 percent and Africa just 2 percent (Roberts, 2005). Roberts (2005) identifies a need to smooth tensions between insurance run as a business in the private sector, and food security and livelihoods being in the strategic national interest, and suggests the following: insurance companies need to be sound and well backed; international re-insurance can back-stop emerging national companies as well as international insurers entering a more uncertain arena; national governments play an important role in facilitating and promoting crop insurance and if it is managed as a form of subsidy, extra precautions are needed to avoid rent-seeking and ensure continuity.

Farm financing is also a major constraint on the adoption of better technologies and changes in practice. The first constraint is a lack of collateral for small subsistence farmers. Microcredit schemes have variable success (Mishra and Nayak, 2004, on India), and subsidies are often implicit, even in low-cost technologies, such as 'drip-kits' in Africa (Keller and Keller, 2003). Where there is consolidation of farming, if not in ownership then in management (through rental), economies of scale may become more favourable. The declining real-price of food products over the last 20 years has placed increasing pressure on 'profit margins', and it is not uncommon to find subsistence producers cross-subsidising their own food production from other sources in countries like Indonesia and Vietnam (ACIAR, 2004). Whether the 2007 turnaround in crop and commodity prices will be sustained remains to be seen. Any impact of price on small farmer investment in technology and ultimately the ability to adapt to the pressures of climate change, will need to be closely monitored.

Aerts and Droogers (2004) identify two main groups of adaptation at farm level: 1) improved farm management; and 2) crop production technology; to which could be added non-structural measures such as insurance, withdrawal (finding alternative income strategies and renting out land), or diversification into specialist livestock production (as with pig rearing in China). Clearly different sub-sectors have different structural and capital bases with differing constraints and abilities to adapt.

Looking at irrigated agriculture in more detail, the options for adaptation to climate change at farm level can be considered in the following terms:

1. manipulation of crop selection and cropping calendar;
2. better management of factor inputs – nitrogen and agricultural chemicals;
3. improved water management technologies and techniques for cropping.

The key starting point for farmer adaptation is once again that increased temperature results in increased evaporative demand and shorter growing seasons. Without adaptive breeding, this will reduce potential yield and associated water productivity as more water is used to satisfy evaporative demand, coupled with lower harvestable yield. Materially, it seems less likely that CO_2 fertilization will change this equation for developing country farmers (Long *et al*., 2005, and others) as a doubling of CO_2 concentration is likely to be accompanied by temperature rises of 4 °C, which will more than offset any benefits. In more arid areas, where C4 crops are already widely planted, the potential CO_2 response is much more muted, especially if temperatures potentially reach limiting thresholds (USDA, 2008).

In practice, most farmers in developing countries obtain yields that are considerably below potential for a number of reasons that include: existing water supply sufficiency and reliability; nutrient (and micronutrient) status and availability of (synthetic and organic) nutrient inputs; incidence of pests, diseases and weeds, and the ability to control them; soil structure, aeration and drainage; timing of operations (farm management); seed quality and viability; availability and preference for high-yielding varieties and assessment of any associated risks in satisfying household food needs. The immediate challenge for many farmers may therefore not be in dealing with observable declines in yield, but rather in how to raise actual productivity in more difficult conditions than they face at the moment.

Clearly where productivity is already high (as in European and North American agriculture), options to enhance yields and water productivity are slim, and trying to maintain unit area production will come at the cost of lower water productivity and higher use of other factor inputs. It is likely that real reductions in yield will be observed where climate change introduces less favourable conditions; and increased production will result from the expansion of cropped area at the expense of lower land productivity.

All farm management and agronomic practices that currently contribute to increased yield and water productivity will continue to be effective in relative terms in the future under climate change conditions, and will remain valid practices for maintaining and enhancing crop production.

5.2.1. Crop selection and crop calendar

Adaptation strategies related to crop pattern can be summarized as follows (adapted from Aerts and Droogers, 2004):

1. Change crop to one with greater resilience or value.
2. Change planting dates for a better match with season length and productivity in relation to temperature, water availability and rainfall.
3. Use better-adapted varieties for the same season, or for a shifted season.
4. Increase on-farm diversity of cropping/enterprise mix, with or without livestock.
5. Change (increase) cropping intensity, where possible.
6. Expand area and irrigate sub-optimally – increase total production and returns to water with lower yield – but this is only possible if land surplus is available.

Increasing cropping intensity either requires more water from rainfall or a reliable source of irrigation, or the sharing of water over two crop seasons instead of one with sub-optimal or deficit irrigation in each one. Deficit irrigation has an attractive aura, but it requires excellent availability and control of water as the margin for error is rather limited, especially in high-value deficit irrigation of stone fruits (Boland *et al*., 2000). The effectiveness of deficit irrigation strategies under global warming has not been investigated, and needs to be validated before large-scale application (Padgham, 2009).

Farmers can adapt to increasing temperature, shorter seasons, more erratic rainfall and water supply by changing crop variety, crop species and by changing the planting dates to match season conditions to crop characteristics. Usually planting will occur earlier to reduce average season temperature, take advantage of better early season moisture conditions and minimize drought risk periods during grain fill. However, later planting may make more effective use of rainfall and stored soil moisture: soaking seeds to enhance germination has been shown to improve establishment and vigour and allow later planting when rains have fallen, rather than multiple sowings in advance of the expected wet season (Harris, 2006). In the monsoon period in India, later planting may also reduce season average temperature, since peak temperatures occur May and June, prior to the rains.

Changing crop type may allow adaptation through deeper or more aggressive rooting habit, which better exploits available soil moisture and allows greater soil moisture storage under irrigation. Substitute crops may have lower water demands and shorter seasons, but may also yield less, or have lower value (for example millet and sorghum are often grown in Indian canal systems when water supply is insufficient for rice, generating both lower yield and lower value), resulting in significantly lower farm income (Venot *et al*., 2008; Gaur *et al.,* 2008).

Some examples of possible shifts in cropping pattern in response to changed temperature and rainfall are presented in Table 5.2. Where one or two crops are grown per year, it is possible to substitute loss of yield in a single season with an additional season's cropping (1 to 2; 2 to 3), if temperature and rainfall or water supply conditions allow. Irrigation has historically served to stabilize and enhance yield in first-season crops, and increase annual production by adding a second season – for example Rice–Wheat, Rice–Pulse and Rice–Maize systems in formally irrigated areas in India. The recent groundwater 'revolution' in Asia has allowed triple cropping as well as year round production of perennials, sugar cane and other high-value crops. Provision of new irrigation (where feasible) or revised allocation and scheduling within and between seasons may allow similar intensification in crop patterns to offset the effects of shorter crop seasons and lower potential productivity.

TABLE 5.2
Examples of crop pattern changes in response to climate change

#	Initial cropping pattern	Temperature	Rainfall	Alternative cropping pattern, mostly with irrigation
1	WR-F-F (RF or I) Tropical	Up	High Up	WR-WR-F
2	WR-WR-F (I) Tropical to semi-arid	Up	High / Down	WR-WR-DL (wet paddy areas) WR-UC-F (limited irrigation) UC-UC-F (upland soils) UC-UC-UC (GW/SW with long-term storage)
3	UC-F-F (RF) Tropical to semi-arid	Up	Down	UC-UC-F (I) – shorter season UC-UC-F (supplemental irrigation) UC-F-F (RF) SWC
4	UC (W, M) Temperate	Up	Up	UC – longer season UC-UC – short season, 2 crop
5	M –UC-Pulse Semi-arid	Up	Down	S-UC/Pulse-F (low irrigation reliability) M-UC-Pulse (higher irrigation reliability)
6	W (I) Semi-arid	Up	Down	B (I/RF) Drought resistant W (I/RF)
7	S/Mi or W, Arid Extensive irrigation	Up	Down	S/Mi or W– extensive irrigation Extensive pastoral land Retirement

Key: B: barley; DL: dry footed crops; DR: upland rice; F: fallow; I: irrigated; M: maize; Mi: millet; RF: rainfed; SWC: soil and water conservation; UC: upland (dry footed) crop such as maize, sorghum, pulses; W: wheat; WR: wet rice.

Table 5.2 is focused on irrigation in Asian, American, Mediterranean and South African farming systems. It has little to say about wetter farming systems and staples found in other parts of Africa (for example those based on yams or sweet potato).

Strategically, it may be preferable to accept lower production in a single shorter cropping season but then increase production by growing a second crop. This is because the crop responses to all factor inputs are asymptotic (they decline with each extra unit of input above a certain threshold). Thus an additional crop that may perform similarly to the first season planting should generate more efficient and larger total annual production from the same input resources that would maximize output from a single season. The same logic prevails for 2–3 season cropping. It is also the rationale underlying the potential to increase the land and water productivity of rainfed agriculture (Rockström *et al.*, 2001), providing sufficient, but relatively low levels if factor inputs (mostly water and nitrogen) can be supplied.

Rainfed production in the wetter semi-arid tropics (annual rainfall 600–1 000 mm) is so far below optimum that small improvements in input can yield relatively large benefits. The same is theoretically true in lower rainfall conditions (400–600 mm p.a.), but few soil–water conservation and water harvesting technologies compare favourably with irrigation in assuring a minimum increase in quantity and security of water supply throughout the growing season.

Statistically, the larger proportion of irrigators produce staple crops of relatively low value, and the strategic interest of many governments in food security is based on the stable provision of coarse grains – rice, wheat, maize, sorghum and millet. Small subsistence farmers growing low-value staples have limited costs, but limited returns. Many true subsistence farmers may have no disposable surplus, but it is common for irrigators to have excess production to sell. Larger-scale cultivators of staple crops or small-scale producers of higher value field crops lie somewhere in between. Fodder producers for livestock cover the range from extremely vulnerable and poor to highly profitable, for example peri-urban maize producers near Karachi, who grow five crops of fodder maize in a year to sell to stall-fed buffalo-milk producers in the city.

Traditional forms of risk hedging through planting mixes of crops with varying susceptibilities to drought and water logging may become more popular. Examples of such risk management measures are found in the rice/maize systems in southeastern Tanzania, where the two crops are planted in alternative rows on heavy, black cotton soils. If there is flooding, the rice survives, whereas under drier conditions the maize is harvested. A similar adaptation is found on poorly drained 'tegal' land (upland red luvisols) in the monsoon season in Indonesia. On the shores of Lake Poyang in China, farmers mix wheat and rice, but this time on sandy soils. Grain production is typically low, although the 'failing' crop is a good source of animal fodder.

Adoption of enhanced crop varieties

The availability of drought-tolerant crop varieties may allow continuation of the same cropping system, with similar or even improved output. Research on the development of drought-tolerant and higher water-use efficiency cultivars of wheat, maize and rice is on-going, accompanied by considerable debate on the relative merits of enhanced conventional breeding (using Gene Marker techniques) and transgenic manipulation based on single genes.

There are plans to release a drought-resistant corn in the United States that should out-yield current varieties in clement conditions (Monsanto, 2009), and efforts are on-going to develop climate adapted GM maize technology for Africa. The technology is likely to be based on five years of research on drought-tolerant maize for the commercial sector in the Americas, and it will take at least eight years before such technology reaches farmers' fields.

Meanwhile, many crop breeders note that drought resistance is not conferred by a single gene, but rather as the expression of multiple genes interacting with a variety of stimuli. Genes that confer drought resistance are sometimes linked to those for low harvest index. Breeders seem to agree that genetic technology applied to conventional breeding offers the prospect of more rapid cross-breeding, testing and replication. GM crops may also 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 is small and limited to those with significant commercial value in the west.

Research on wheat in Australia has shown that it is possible to improve drought resistance through selection for emergence and more aggressive rooting to increase water use at early growth stages, and confer higher yields despite water shortage in the less sensitive grain-fill stage. Associated research has also shown that it is possible to improve harvest index, and that it may be possible to improve the transpiration efficiency of wheat through marker assisted conventional selection and breeding (Rebetzke *et al*., 2008).

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 the time frame for them to occur must probably be counted in decades. In climate science, a decade represents about two generations of thinking and analysis (as measured by IPCC Assessments). In any case, improved varieties will not be a 'silver bullet' in their own right, and will require concomitant farm management as with the short-strawed, nitrogen responsive cereals of the 'Green Revolution'.

Perceptions of water productivity

Water intensive crops are often associated with low water productivity. Rice and sugar cane are often considered as wasteful water-intensive crops that could be replaced by more 'efficient' cultivation. There are two important considerations from a farmer's perspective: 1) rice and sugar cane are profitable crops with higher economic (dollar value) water productivity than many 'less water intensive' crops, and 2) rice is a wetland crop. It is interesting that economic commentators describe crops that use large amounts of water (volume per unit area per season) as wasteful, without considering the production and value generated per unit of water consumed.

The natural habitat for rice is in flooded areas, which do not drain naturally and remain waterlogged through all or most of the growing season. For sure, rice cultivation has spread far beyond its natural niche, and onto ill-suited soils that require a continuous supply of irrigation water. Upland and dryland rice has been developed that does not require constant inundation (Pinheiro *et al*., 2006; Tuong and Boumann ed., 2003), but this cannot be substituted in wet-rice habitats to save water, nor does it reduce methane emissions from perennially saturated soils. Thus, estimates of the potential water saving and mitigation of GHG emissions in rice requires stricter attention to soil and topographic conditions which determine the fundamental suitability of wet and upland rice culture. There is considerable potential to reduce irrigation applications during the rainy season and to hold water over to the second cropping season if appropriate storage is available.

Agroforestry systems

There is increasing interest in mixed agroforestry systems that both sequester carbon and also offer adaptive benefits, such as shade (reduced temperature, and possibly reduced evaporative load), wind protection, and provision of out of season animal fodder. There are many existing examples of mixed agroforestry systems in the seasonally dry humid tropics (Leucaena and horticulture in Indonesia, for example), and some systematic evaluation has taken place of the potential of agroforestry systems from both productive and climate change adaptation and mitigation perspectives

(Verchot *et al.*, 2005). Agroforestry introduces compromises in terms of more intensive management requirements; competition for soil water and nutrients; and challenges in managing the right balance between tree leaf cover and cropped area. Crop yields in agroforestry systems tend to be lower than in broad-acre agriculture for these reasons, but the situation might improve in relative terms under climate change stresses. The total benefit budgets of agroforestry systems need to be carefully evaluated and considered from a farmer's perspective. It is relatively rare to find examples of mixed agroforestry within irrigation systems, although bund planting of poplars in Punjab and Haryana may qualify and has been shown to increase net farm income substantially (Zomer *et al*., 2007).

Diversification into high-value crop production

There is an almost automatic response to the problem of increasing water scarcity; this contends that the problem is best addressed through market-like mechanisms that can value a good solution effectively and thus apportion resources efficiently. An interim step is often made, suggesting that because water is scarce, then higher value products such as fruits, vegetables, grapes and spices should be grown. It is true that in commercial farming economies, such as in Australia, this is one of the main (but still niche) adaptations to rising water scarcity and recurrent or prolonged drought. A recent re-specification of water entitlements in Victoria (Australia), known locally as unbundling, resulted in farmers effectively accepting a cap on maximum allocation in return for a higher average level security of supply. The prime motivation for this has been unprecedented low levels of water allocation following more than five years of continuous drought. There will be general market pressure on the irrigation sector to provide more horticultural products in the future, and there will be strong financial incentives that drive a relatively larger share of irrigation to high-value products.

Irrigated horticulture (which is probably most of horticulture in developing countries) often services tight marketing niches. With increasing involvement of supermarkets, and demand for year-round supplies, lettuce varieties may be optimized to match 1 °C changes in ambient temperature over each growing period (HWI, 2006). Vegetables, fruits and vines are all more sensitive to temperature change and water stress than staple commodities, but their better-endowed capital base gives them more options for adaptation in the medium and long term. Short-term climatic variation and uncertainty are readily addressed by better technology and a higher security in water supply.

At global scale, there are a number of important caveats for diversification into higher value cash crops, especially in recognition of the likely impacts of climate change.

1. The bulk of future global food demand will continue to be for grains, whether for direct consumption or for livestock rearing. Although direct consumption of rice and wheat has fallen in economies such as China, the total demand for grain has increased considerably to supply feed for meat production (USDA, 2008; FAO, 2007). The reasons are simple: humans and animals need relatively large quantities of starchy energy-packed foods compared with those furnishing proteins, vitamins and trace elements.
2. The market for higher value products is relatively small and is easily saturated, leading to price collapse in the market and at the farmgate. Over-supplying the market can be punishing and salutary examples of price collapse include: coffee in the wake of Vietnamese entry into the global market; orange production and the price of concentrate juice Brazil; chillies and tobacco seasonally within Indonesia;

tomatoes as a hedge against drought in Andra Pradesh in 2004/5 (contributing to the fall of the State government that promoted the adaptation).

3. Cultivation of higher value products requires higher levels of input than for the production of staples, incurs much higher production costs, and therefore entails greater risk to the producer. Without effective mitigation measures in transport and fertilizer manufacture, the carbon footprint of greater diversification into high-value crops would likely increase.

4. A highly reliable water supply is required to minimize the investment and production risks in high-value cropping: there is a trade-off between the provision of high reliability water and the general security of water supply to all other agricultural users. In countries such as Australia, high-value producers pay considerably more for water than field croppers and dairy producers. As climate change bites, and water systems become less reliable, these trade-offs will come into sharper focus. Private groundwater perhaps offers the highest security and most flexible supply, where aquifers are well managed. However, if groundwater abstraction becomes a 'race to the bottom' (Shah, 2009), such benefits are quickly lost.

5. In a more variable climate with heat waves, higher temperatures, and more intense storms, high-value cropping systems will tend to need more protective measures, such as shading, through natural (agroforestry and shade tree approaches) and engineered (shade house/net house) solutions. The risks and costs of production will rise accordingly, and the risks and consequences of failure will become more severe.

Nevertheless, it is likely that irrigation will become more commercially oriented in response to opportunities created by urbanization and changing food preferences (see Ch. 3), coupled with relatively higher security of production and compared with rainfed production systems. From a policy point of view, this will have to be balanced with the assurance of adequate high reliability supply of staple foods to contend with droughts.

5.2.2. Farm and crop management – fertilizer management

The two most researched and most important limiting factors of crop production are water and nitrogen. The global efficiency of nitrogen fertilizer use is reported to be as low as 30-40 percent, implying that 60 percent of the mostly synthetic fertilizer applied is returned to aquatic systems and to the atmosphere, where N_2O plays a significant, if short term, role in atmospheric warming (FAO, 2002a).

To ensure higher levels of production (yield and water productivity), it has been estimated that global fertilizer demand will increase by 60 percent by 2025 (Padgham, 2009). Improving fertilizer use efficiency and benefit will become increasingly important to the mitigation of GHG emissions, directly by reducing N_2O emissions and indirectly in terms of the energy consumed in its manufacture (World Bank, 2009a). The effectiveness of small doses of fertilizer will be improved if efficiency of uptake can be improved, and is a good example of a 'no-regrets' adaptation measure that has clear mitigation, adaptation and production benefits, some of which will accrue directly to an individual farmer.

Fertilizer efficiency can be improved through:

- better timing and control of application, especially with respect to irrigation scheduling;
- better uniformity of application and where possible targeted application according to need/deficiency based on soil and plant status (precision farming approach);
- split dressings at appropriate growth stages;

- placement within the soil;
- potential for fertigation in simple as well as technical irrigation (drip and microsprinkler) systems;
- use of slow-release granules.

Improved nutrient status occurs with higher levels of soil organic carbon (SOC) (organic matter content). Raising SOC is an emerging priority for carbon sequestration and mitigation (see section 6.2.1) and is another example of a practical ‘no-regrets’ policy. However, it is far from clear how easy it will be to raise SOC to the desired levels. If anything, soil organic matter contents have been declining worldwide, part of the available soil carbon storage potential created effectively contributed to past agricultural GHG emissions, and the balance needs to be restored. The mitigation potential of soil carbon sequestration should be assessed in terms of the carbon storage, over and above the restoration of recent historical loss.

One notable example of large-scale technology adoption that may be raising soil carbon levels is the work of the Rice-Wheat Consortium in India, and there is companion work in Australia and Brazil on zero tillage and other soil and water conservation technologies. Zero tillage allows retention of more organic matter in irrigated and rainfed soils than under conventional ploughing, and much has been claimed, for instance in the rice-wheat Systems of the Indus and Ganges basins in northern India and Pakistan (Humpherys *et al.*, 2007). Secondary analysis has indicated that the major benefits derived from zero tillage are in reduced input costs (tractor fuel) and marginal increases in wheat yields; actual water savings have not matched earlier claims (Ahmad *et al.*, 2006). Additionally, productive soil conditions for wheat (deep aerated soils) do not match those for wet rice (restricted drainage and saturation). Incorporation of straw in rice systems remains problematic, especially when paddies are wet, with straw and stubble retention depressing germination of the subsequent crop; a problem that has yet to be completely solved. Zero tillage is (ironically) more feasible in mechanized agriculture, and adopters in the rice–wheat systems have mostly been wealthier farmers on larger farms. In the near term, innovations such as zero tillage, which can enhance SOC, should be more objectively evaluated, and then adapted for use by less well-off small holders.

5.2.3. Water management on farm

Farmers have two sets of complementary options when managing water on farm: irrigation management and soil moisture conservation. Enhancing soil moisture retention and storage can allow crops to perform well through drought periods between rains, or between irrigations, and in the latter stages of rainfed crop growth when there is no rainfall (typically in current temperate northern European cereal production). Drought adaptation in rainfed crops will require enhanced soil moisture conservation at a minimum, and in many cases will require supplemental irrigation. At the same time, as the reliability of some irrigation systems decreases under climate change, soil-moisture conservation techniques will assume increasing importance for managing short-term moisture stress. The options in improved water management include:

1. more efficient irrigation technologies that reduce unproductive evaporation losses:
    a. sprinkler and drip methods of water application;
    b. direct seeding/dry seeding in rice (Boumann *et al.* in CA, 2007);

   c. Soil moisture retention through conservation tillage (zero tillage, direct seeding etc. (Ahmad, 2006)).

2. deficit irrigation – to reduce actual evapotranspiration, while maintaining (cereal) or even enhancing (fruit) yields (Boland *et al.*, 2000);
3. reduction in local (on farm) storage losses due to evaporation;
4. better spatial uniformity of irrigation to minimize accessions to saline water table in areas where saline groundwater table is a problem (many surface irrigation areas in the arid and semi-arid tropics);
5. reduction in evaporation losses from bare soils (organic and plastic mulching; dust mulching);
6. dynamic and changing balance of irrigation and rainfed production from year to year;
7. adoption of irrigation or water harvesting practices where conditions allow;
8. improved management - intensification of use of other factor input such as fertilizers, pesticides, soil amendments, better timing of operations;
9. improved drainage.

Enhancing root zone moisture storage

The benefit of irrigation can be enhanced by retaining as much of the applied water as possible in the root zone. The depth of the root zone can be enhanced (deepened or made more porous) through planting more deeply rooted (0.8–1.5 m) or more aggressive rooting crops (see crop section). At the extreme, agroforestry systems can capture deep percolation below the crop root zone as tree roots extend from 2 to 4 m and beyond. In mechanized farming systems, soil water retention capacity and effective rooting depth can be increased by deep tillage and breaking up of compacted layers (pans) in the soil. Whether this will continue to be a viable option in a climate changed world is more doubtful, but zero and minimum tillage systems avoid the creation of compacted layers in many (not all) cases.

As noted above, higher organic matter contents also increase available water capacity in the soil. Other soil amendments have been used or researched to achieve the same result, such as marling (the mixing of clay into sandy soils in medieval Europe) and the addition of polyelectrolytes (such as poly-vinyl-acrylate – PVA).

Reducing unproductive evaporation

Some literature claims that as much as 50 percent of water use in rainfed crops is lost as unproductive evaporation, through bare soil evaporation and transpiration by weeds (Rockström, 2004). In principle, unproductive evaporation and transpiration are minimized by rapid development of vegetative soil cover, which in turn depends on rapid and even germination, strong establishment vigour and early growth to cover bare soil (Leaf Area Index (LAI) is approximately 1.2 to 1.5) and subsequently intercept all incoming radiation (LAI > 3).

In practice, most unproductive evaporative loss occurs in the crop establishment period, or with heavy weed infestation. As minimum night temperatures rise, so do respiration rates, which will also effectively increase unproductive evaporative loss slightly, while having a greater effect on plant productivity through increased metabolism of stored photosynthetic product.

Potential bare soil evaporation is higher for row crops, although soil texture and structure can play a part in restricting bare soil evaporation. 'Capping' loam soils, for example, creates a thin sealing layer of fine (silt) particles that can completely stop evaporation. Flood farming systems in Baluchistan (Pakistan) are adapted to this phenomenon, which enables planting of mustard to be delayed from the post-rain period in late August-September to December-January, with minimal loss of stored soil moisture and the benefit of cooler atmospheric temperatures. Engineered and traditional floodwater spreading systems are designed to take advantage of such favourable soil conditions. Strip tillage was much researched for sorghum and maize production in southern Africa (Botswana and Zimbabwe) to enhance rainfall runoff from the uncultivated area between rows into the tilled strips (Willcocks, 1981). Strips are tilled to a greater depth than in conventional cultivation (for example, 60–100 cm, depending on farm power available) to increase soil porosity and hence water retention.

Within irrigated agriculture, plastic mulching has emerged as a widespread technology for row crops, such as irrigated maize, in northern China (3H basins) and mechanized variants have been tested and used in Israel and California. Covering the raised bed area with a plastic sheet immediately after sowing, or subsequently hand sowing (dibbing) seed into plastic sheeting, allows almost complete control of weeds and prevention of bare soil evaporation. The furrows between raised beds cannot be lined, as irrigation water must infiltrate from them into the body of the raised bed, some evaporation loss occurs during and after irrigation, and weeds may also grow in the furrow. However, with quick crop establishment, weeds may not survive very long.

Clearly, effective chemical and mechanical weed control also reduces pre-sowing and post-emergence evaporation losses, but mostly have higher GHG 'costs' than agronomic and bed-system approaches. Plastic sheet used for mulching also has a GHG cost. Some further detailed work on the comparative GHG emission and energy efficiency of alternative approaches to minimizing evaporation losses in irrigated agriculture would be useful.

Improving irrigation management and flexibility on farm

The subject of farm level water efficiency has been researched and debated extensively over time. Improving application efficiency through technological or management innovation attempts to increase the proportion of water applied to a crop that is transpired (used productively), which is mostly dependent on soil characteristics and crop root depth. Increased application efficiency can be achieved by matching soil moisture storage capacity with the soil's ability to absorb water (infiltration characteristics) and the application rate of water supply. Thus deep, well-structured soils with moderate intake rates can be irrigated infrequently with large application depths (75–150 mm water). On the other hand, highly porous soils, such as sands, poorly structured or low-intake soils can be watered 'little and often'.

5.2.4. Irrigation technologies on farm

Irrigation technologies have been developed and adapted to match different combinations of soil condition and crop choice. Surface irrigation techniques have been widely adopted, but in general have lower application efficiencies than overhead sprinkler and micro-irrigation methods because of relatively poor uniformity of application, in addition to drainage losses below the root-zone that arise from attempts to improve uniformity of irrigation over the whole field. Techniques (such as furrow and bed irrigation, surge flow, and cutback) have been developed to reduce the time taken for water to cover the field from top to bottom, and thus improve uniformity and reduce deep drainage. Management needs to be correspondingly better to avoid generating large amounts of tail water runoff, which in turn can be lost to evaporation or infiltration. Application efficiency and uniformity of surface irrigation (graded basins and borders) can be very high in certain conditions – where soils have high clay contents (such as vertisols) or where a restrictive layer impedes drainage. Such soils may also have low intake rates, with the result that the residence time of bare water surfaces can be high, with a corresponding loss to direct evaporation during pre-sowing and early establishment stages.

Application efficiency of pressurized systems (sprinklers, rain-guns, centre pivots and linear move sprinklers) can be high when properly designed and well managed to ensure that application rates are less than the intake rate (to minimize runoff) and that application time is sufficient to recharge the soil moisture deficit. Sprinkler systems become inefficient in strong wind, which distorts the application pattern and reduces uniformity. Application pattern and uniformity are dependent on supply pressure, which is in turn a function of design and energy use. Low energy systems (LEPA: Low energy and pressure application) have been developed for use with lateral move and centre pivot systems, both to reduce pumping costs (and energy consumption) and to minimize wind effects on application uniformity.

Micro-irrigation systems deliver controlled amounts of water through drippers, drip-tape or microsprinklers to supply daily water needs without permanently saturating the root zone or compromising aeration and root health and development. Micro systems require extensive piping and are generally best suited to high-value crops because of the capital and operating costs involved. However, cheaper systems such as disposable and re-usable sub-surface drip tape have been developed for higher value field crops such as maize (as sweet corn), but with limited large-scale commercial adoption.

Fertigation can be achieved using any of the surface and overhead/micro-irrigation techniques, but is easier to manage in pressurized systems, especially micro-irrigation and LEPA sprinkler systems.

5.2.5. Depletion accounting

Two important aspects of farm level irrigation efficiency need to be stated and understood (Seckler *et al.*, 2003). The first is that the achievement of real savings in water at system and basin level is highly dependent on the fate of water that is 'lost' at field level. Any unproductive evaporation losses are clearly real losses, and if reduced, will either enhance productive growth or use less water application in field. Deep drainage below the root zone or surface drainage off the field may constitute real losses if evaporation occurs or a sink is reached (such as contaminated or saline groundwater). If, on the other hand, water returns to the aquifer or to the river as stream flow, that water is potentially available for use elsewhere. It is therefore important to realize whether or not improved application efficiency results in real water savings; in-depth understanding of water depletion at field, farm, system and basin scales is required (Molden, 1997).

The second point is that increasing efficiency of application may result in the use of more water in one location upstream in a basin than was used previously. It may simply mean that more water is transpired from the existing cropping system, with resulting increase in production, but it is also possible that growers may use those local savings to expand their cropped area or intensify their irrigation. In such cases, the total production of an irrigation system and basin may increase, but downstream users may lose some portion of supply that they had earlier benefitted from.

In contrast to a blanket recommendation that 'the efficiency of agricultural water use be improved', careful consideration is required of the nested levels of efficiency; potential downstream impacts; and of the equity between winners and losers. The potential for tangible water savings is complicated by hydrology, agro-ecological conditions, equity and existing water rights or established/customary use. This is especially true of basins that are either fully allocated or approaching full allocation.

The adoption of a 'better' technology does not guarantee a saving of water. A wide range of international experience shows that effective management of water saving technologies is crucial to success. A recent study of the adoption of micro-irrigation in Andhra Pradesh revealed that water usage actually increased through larger unit delivery and an expansion of intensively irrigated area; this was driven by profitability of crops and technology as well as limited costs and concerns for water conservation (Batchelor *et al.*, 2005).

At field and farm level it is important to match the suitability of technology choice and its management to soil, crop, cost-benefit and investment constraints. For example basin irrigation on vertisols, that is designed and managed well, can achieve high technical application efficiency of around 80 percent, and therefore changing to overhead systems would be counterproductive and uneconomic for most (if not all) field crops.

Who benefits from 'efficiency gains'

Smallholding farmers will tend to have limited land and water resources, and where possible will try to maximize yield (total production from their land) in preference to maximizing water productivity. Farmers with larger holdings may find water supply to be more limiting, total production and net farm income can be maximized by increasing water productivity at the expense of yield. Maximizing production through different combinations of yield and area for the same amount of water supply has been hotly debated since the early days of formal irrigation development. In what is now Pakistan and northern India, 'protective' irrigation systems were designed to share sub-optimal amounts of water between as many users as possible, whereas at the same time, 'productive' systems were built with limited water resources and/or access allowed by relatively few land holders. Over time, access to groundwater in many of the protective systems has resulted in their becoming locally, or entirely, 'productive systems'. Under climate change, with potential reductions in surface water availability and lower rates of groundwater recharge, they may well revert to being more protective in nature.

In wet-rice culture, labour shortages have made direct seeding an increasingly attractive alternative for transplanting. This has some potential benefits in real water savings, as the land soaking and land preparation requirements (which often require around 300 mm of water) can be substituted by lighter land preparation watering (100–150 mm). However, it is not always easy to puddle wet rice effectively under this regime, and there can be corresponding increase in daily percolation rates, with little net seasonal benefit. Likewise, cultivation on highly porous and unsuitable soils with large water requirements needs to be discouraged.

Land zoning can help with the identfying of suitable areas and minimizing groundwater percolation from rice fields. In the Murray-Darling Basin, successively more demanding limits have been imposed on the application of water in rice paddies; zoning here is policed by an annual aerial photographic survey, with limits set at 1 400 to 1 200 mm per crop (165-170 day season). In other situations where groundwater quality is good and recharge is required, it might be desirable to grow rice on more porous soils in summer to ensure effective annual recharge.

The point of this discussion is to emphasize that on-farm adaptation in irrigation technology and management is highly dependent on a complex set of biophysical and socio-economic factors. Although manipulated and changed in the past, they require detailed and contextual understanding for further development and adaptation in the future. It is therefore worthless making general recommendations on the improvement of irrigation efficiency: efficiency needs to be improved where losses 1) are real; 2) are recoverable; and 3) can be explicitly re-allocated as desired. The devil is in the detail. The analytic tools, knowledge and options are available. The challenge is in applying them to obtain the best balance of adaptive benefit between individuals and the society at broader basin and economic levels.

5.2.6. Flood protection and erosion

The literature sometimes conflates irrigation with erosion hazard, although in practice most irrigation occurs in relatively flat and structured land forms that are marked out by field bunds (banks), channels, and furrows, and makes limited contribution to river loads. Dry soils are more erodible than wet types, but excessive irrigation flow rates, especially in furrow irrigation, may result in localized erosion and sediment transport. Again, this is rare in common practice, and in general, field irrigation suffers from inflow rates that are too low and preferably need to be increased to improve uniformity and efficiency.

Agriculture can both mitigate and exacerbate flooding. Many flood-control systems in China and Vietnam are designed to divert problematic peak flows out of the river network and through agricultural areas, but can have catastrophic results for rural people and their crops if poorly managed. In perennially flooded or flood-prone areas, rice agriculture may be adapted, following a sequence from no cropping in high-risk and longest-duration flooded areas; to flood rice, deep-water rice, and more tolerant short-strawed varieties of rice in successively lower-risk areas (as traditionally practiced in Laos and Cambodia along the Mekong River).

Other floodwater adaptations have been traditionally practised in lowland parts of the wet tropics. Similar systems of rice or dry crops (including fruit tree cultivation) with reserved pond storage were originally common in northern and central Vietnam and are presently making a comeback in Southeast Asia (Vietnam and Indonesia). In Java, heavy rice soils are formed into exaggerated raised beds with surrounding furrows, creating islands of land out of flooded and deepened ‘trenches’ or *Sorjan*. Tree crops and dry-land crops are grown on the raised beds, and rice is planted in the trenches during low flood periods. Alternatively, rice can be grown on the beds during flood periods, but only if the soils can be wet up sufficiently by the surrounding comeback as an alternative to expensive and ineffective pumped drainage systems within polders.

Under climate change, the risks of soil erosion and flooding are likely to change for a number of reasons:

1. expansion of irrigated and rainfed area to more marginal areas in terms of slope and soil type;

2. increase in intensity of rainfall and frequency of high intensity storms;
3. increased likelihood of dry-surface soil conditions prior to a storm;
4. greater net runoff rates from expanded irrigated areas following long storms.

Flood control and management will become a more taxing problem, especially in the humid tropics where rainfall increases and becomes more variable. Areas that have been converted to wet rice culture along the flood plain are likely to be converted to a more varied and less risky level of intensity, with further adaptation of deep-water rice systems and adaptation, modernisation and expansion of traditional measures such as *Sorjan*. It is also likely that erosion control within irrigation systems will require more attention in future, if only because of increased rainfall intensities under climate change.

5.2.7. Commercial agriculture

A summary of the adaptive capacity of the more commercial Australian agricultural sector to climate change found that most potential adaptation options for Australian agriculture were extensions or enhancements of existing activities for managing current climate variability (Kingwell, 2006). In broad-acre farming a range of coping and adaptation options are either available or in need of development. An incomplete list of activities was derived from a variety of sources by Kingwell (2006), but is more specific than the preceding text:

1. Development of varietal portfolios suited to greater weather–year variation. In particular, developing varieties with greater drought tolerance, heat-shock tolerance, resistance to flower abortion in hot/windy conditions, and resistance to new or more virulent pests and diseases;
2. Reduction of downside risk of crop production (e.g. staggered planting times, erosion control infrastructure, minimum soil disturbance at crop establishment, crop residue retention, varietal portfolios);
3. Further facilitation of crop operations (e.g. seeding, spraying, swathing and harvesting) by improvement in skill of weather forecasting;
4. Further facilitation of decisions about crop type, variety selection and crop input levels by improvement in skill of seasonal forecasting;
5. Greater opportunism in planting rules and planting decisions (e.g. time of sowing, seeding rates, row spacing, tactical applications of nitrogenous fertilizers);
6. Improved pasture and crop management decision support systems based on satellite imagery technology and advisory services drawing on expert systems;
7. Further facilitation of decisions about stocking and de-stocking through improved climate prediction systems that more accurately forecast the extent and duration of drought;
8. Alteration of mating time or mating populations based on seasonal conditions and forecasts;
9. Development of water use efficiency strategies to manage potentially lower irrigation water availabilities;
10. Assessment of genetic variation across and within livestock breeds regarding their production response to extreme heat, so that more productive animal systems can be developed;

11. Development of low-cost surface sealants on farm dam catchments to allow runoff from small rainfall events;
12. Development of low-cost desalination plants to use saline groundwater to supply water to stock or irrigated crops;
13. Utilization of research findings on the effect of prolonged dry conditions and extreme heat on weed and pest ecology, especially weed seed survival;
14. Re-design of farm housing, building, machinery and outdoor clothing to accommodate extreme heat;
15. Development of profitable crops or tree species that include returns as renewable energy or carbon sinks.

5.3. ADAPTATION AT IRRIGATION SYSTEM LEVEL

5.3.1. Introduction

Irrigation will remain very attractive as an adaptation to further water scarcity and variability, especially where seasonal and inter-annual storage (in reservoirs or groundwater) is involved. At the same time, irrigation itself becomes less effective as an insurance as water availability decreases, unit demands increase, higher value uses draw water away from farmers to cities and industry and variability increases. As we learn how to better value and conserve aquatic ecosystems that support livelihoods and even agriculture as a system, the stress on irrigation will further increase. Other important agricultural water management practices are drainage, flood control, and water conservation agriculture in rainfed systems.

It is unfortunately true, that if irrigation is vulnerable to climate change, then all shorter-term strategies aimed at conserving and optimising the use of rainwater stored in the soil are more vulnerable. In areas where cropping is almost fully dependent on irrigation, such as Pakistan, that dependence will remain, and at the same time will be exposed to greater demands and conflicting stresses. However, there may be more irrigation where water supplies have been sufficient but climatic variability has increased sufficiently to require it (northern Europe, for example).

Perhaps the major challenge facing irrigation managers in the future will be the declining volume and security of supplies. Some structural measures may be effective (see strategic discussion) through the construction of additional supply storage in the form of dams or via groundwater. However, it is likely that even in river basins experiencing an increase in rainfall and runoff, the security of supply will diminish as the storage management required to cope with greater variability becomes more complex and confounding.

In parts of the Murray-Darling Basin (Australia), recent detailed and downscaled modelling indicates that annual runoff could decrease by as much as 40 percent by 2050 (DSE, 2007; CSIRO, 2008) in some sub-basins. This has enormous implications for agricultural users and for environmental allocation. The current allocation rules already sit over a stretched and over-allocated water resource, and some form of reallocation is inevitable in the future – both to effectively share a diminished resource among farmers, and to accommodate environmental flow needs for the preservation of certain parts of the ecosystem. Wherever there is presently tension between agricultural and environmental allocation, it will be sharper and tougher in the future. This will be broadly true of all irrigated systems where rainfall and runoff are predicted to decline.

Less water can be applied per unit area, but usually with a consequent reduction in yield. Improved water use efficiency may offset this or even increase production while depleting less water, but this in turn depends on many factors, including breeding through management and the use of other factor inputs of production. The balance of production of high- and low-value commodities may change, and the overriding factor will be national government policy for food security and subsistence livelihoods at one end of the spectrum (for example, India) to economic efficiency at the other (for example, Australia).

5.3.2. Water allocation

The options for adaptation by water managers include better and more sophisticated water allocation and its corollary, better service delivery (Aerts and Droogers, 2004). More sophisticated water allocation provides different users and uses with differentiated products, usually at differing prices. In Australia, high-security water supply for rural towns, permanent plantings (orchards) and high-value vines and horticulture costs considerably more than general security allocation. Improved allocation requires information for water users to assess and base decisions on – for example, how much area to plant and suitability of crop. Water allocations need to be set on the basis of a good understanding of long-term hydrological variability, frequency distribution of flows and of drought sequences. As more information becomes available about trends in means and variability of rainfall, runoff and recharge, these allocation procedures can be updated and managed accordingly.

Regularly updated allocation announcements are helpful, more so if they indicate different levels of probability; allowing farmers to make their own assessment of risk. Better allocation may use weather and climate forecasting tools, such as ENSO and stream persistence (Panta *et al*., 1999). Clearly this level of sophistication is better tailored to smaller numbers of larger farms. Different approaches to improving allocation, mostly through better bulk allocation to groups of users, are more appropriate where there are large numbers of poor, small farmers. Allocations could be redefined across the spectrum of surface water, groundwater and conjunctive use and almost uniformly need to be designed in such a way that farmers are able to internalize natural hydrologic variability. Once this is in place, the mechanics of dealing with more variable water availability due to climate change impacts (and re-allocation to other uses) becomes more comfortable and familiar. Even sophisticated allocation systems can still witness zero allocations in protracted drought, but drought risk can be delayed and sometimes offset if users are allowed to manage their allocations across successive water years. This is necessary if they are to adopt productivity strategies that spread water use across seasons and years. Of course, storage management and storage losses may have an impact on the benefits of such strategies.

5.3.3. System performance

Where real water savings are possible, they can be achieved through minimising return flows from the channel network and reducing net diversions within a system using in-line and off-line storage. Seepage losses can be reduced by canal lining (where appropriate), or improved water control to manage water levels to minimize pressure head and seepage. Appropriate modernisation of flow control requires redesign and construction regulators and offtakes, supported by adequate instrumentation and automation (SCADA). More ambitious remodelling of existing canal networks can be undertaken to reduce the total distance of delivery channels to the farmgate., and to increase flows and reduce seepage and leakage as a proportion of flow. For example, the proposed ‘Connections’ programme of the ‘Food Bowl’, a Victorian Government programme to connect farms directly to higher capacity (upstream) channels, and allowing ‘on demand’ access (DSE, 2007a).

Leakage losses can be identified through better monitoring and evaluation, leading to better maintenance and management. Evaporation losses can be reduced, where feasible and economical, by covering channels or by piping supplies. The substitution of open surface-water storage by groundwater storage may also be effective.

Enhancing the performance of irrigation systems through modernization of institutions and technology to be more responsive and flexible as supply allocations become more volatile will continue to be the main systemic means of adaptation (FAO, 2007b). Water efficiency and agricultural productivity gains can result if improved management can be effective across the whole scheme – including the scavenging of drainage and prevention of water logging and salinity build up.

Irrigation service providers are now under pressure to become more reliable, transparent and equitable in their delivery to farmers, while infrastructure and equipment improvements are sought to facilitate greater physical efficiency and flexibility at user/scheme level. Irrigation on demand has the potential to be more productive and economical in water use, but evidence is very variable in practice. In the Red River Delta in Vietnam, on-demand users abstract less than when supplies are available only on a rotational basis (Fontanelle *et al.,* 2007) although this may be related to differences in supply between pumped and gravity flow within polders. Contrary evidence is seen in the well-known ‘Block H’ experiment with on-demand supply in the Mahaweli in Sri Lanka, which is now defunct. It is also evidenced in the Upper Swat Canal following modification of the lower reach to on-demand supply after the construction of the Pehur High Level link canal in Pakistan. Even with volumetric pricing and measurement of farm inflows in Australia, it is not clear that on-demand access necessarily results in optimal use.

However, the nature of water use efficiency has an important element of scale. Increased physical efficiency at user/scheme level only translates into increased water productivity (or economic efficiency) if there are mechanisms to reallocate the saved water elsewhere in the water economy of the basin (this may or may not involve irrigation). In Egypt for instance, the physical efficiency of irrigation water use in field is low at around 30 percent, whereas basin level efficiency is more than 95 percent. Progressive salinity build-up in the cycling of drainage water clearly limits this process. Therefore adaptation measures to cope with increased water scarcity need to be accompanied by accompanying measures that reallocate the savings in a way that maximizes overall system and basin benefits.

5.3.4. Cropping patterns and calendars

The scope for planned large-scale changes in cropping calendars and crop types, in line with reduced or more volatile water supply, is harder to orchestrate and will still be constrained by market conditions, which will determine whether the product is sold at an acceptable price level at the time of harvest. Agriculture policy has to beware adverse impacts such as the risk that, when lower value staples are irrigated, the price may undercut those of rainfed production with undesirable consequences on rural incomes and equity. It is nevertheless likely that many countries will seek to promote changes in cropping pattern in order to meet multiple objectives of mitigating carbon emissions, optimising production, obtaining the highest economic benefit from expensive irrigation infrastructure and enhancing rural incomes.

Broad shifts in cropping pattern will occur in response to different combinations of climate change, market demand, technological innovation and targeted policies and support measures. Spontaneous broad-scale adjustment of cropping calendars is already noted through MODIS (Moderate Resolution Imaging Spectroradiometer) imagery analysis for the Nile basin (FAO, in press), which may be indicative of an adaptive shift, although it is less easy to define what the drivers are at present.

An example cropping calendar for irrigated production in Morocco (Box 5.1) illustrates what is possible in a country where agriculture is already operating beyond the limit of its renewable water resources. Despite a distinct climatic advantage in relation to European markets, cropping intensities on land equipped for irrigation are still only in the order of 100 percent. The AR4 projections for the Mediterranean Basin predict considerable warming and drying with substantial reductions in surface runoff, which make it unlikely that cropping intensity can be increased in this system in the future.

BOX 5.1

Irrigated production cropping calendar for Morocco (FAO, 2003)

Crop under Irrigation	Irrigated area ('000 ha)	Crop area as share (percentage) of the total area equipped for irrigation by month											
		J	F	M	A	M	J	J	A	S	O	N	D
Wheat	592	47	47	47	47						47	47	47
Maize	156			12	12	12	12	12					
Potatoes	62					5	5	5	5	5			
Beet	34				3	3	3	3	3	3			
Cane	15	1	1	1	1	1	1	1	1	1	1	1	1
Vegetables	156					12	12	12	12	12			
Citrus	79	6	6	6	6	6	6	6	6	6	6	6	6
Fruit	88	7	7	7	7	7	7	7	7	7	7	7	7
Groundnut	10					1	1	1	1	1			
Fodder	100	8	8							8	8	8	8
All crops	1 305	70	69	74	77	49	49	49	36	44	70	70	70
Equipped for irrigation	1 258												
Total cropping intensity	104%												

5.3.5. Conjunctive use of surface water and groundwater

Conjunctive use of surface and groundwater is widespread in large surface irrigation systems, throughout Pakistan, northern India and northern China. Increasingly, this is an autonomous and privately financed adaptation to poor service and restricted water availability in surface irrigation systems. A major attraction of conjunctive use is the flexibility it confers on users and system managers as it allows the satisfaction of varying demands (between high- and low-value users, for example) and allows on-demand supply of water where needed. In situations where surface water is rationed, this flexibility will be increasingly important in tiding farmers through drought conditions arising from surface water shortages.

There is considerable scope for improving the management of conjunctive use of ground and surface water, in maintaining effective recharge, managing salinity and improving the productivity of water use. Conjunctive use may offer a cost-effective adaptation to the storage problem associated with glacier-melt systems – runoff patterns will change, median flows reduce and peak flows will increase in the sub-Himalaya. Enhanced ability to store and manage these flows as groundwater is inherently attractive, subject to satisfying other competing and in-stream needs. There are significant policy and water management dimensions inherent in moving from conjunctive use to management, and the state has a key role in the assessment, promotion and facilitation of local institutions of management, sensitizing its irrigation bureaucracies and evolving locally based, economically effective compliance networks.

There is a useful potential trade-off between using groundwater to improve drought proofing at the expense of maximum annual production, by selectively abstracting only in drought years. Although this makes great strategic sense, it is hard to implement and police. Many governments are under extreme pressure to provide short-term solutions, even at the cost of more severe long-term impacts.

The last observation related to groundwater is that, in general, we lack insight and knowledge about the extent of the resource, the modes and effectiveness of recharge, and the true extent and pattern of abstraction. Given that groundwater, and improved groundwater management, will be key to successful and economically attractive adaptive strategies, major effort is required to improve the science and socio-ecological base of groundwater use and potential.

The mitigation of salinity on farm will become a more challenging task in areas with lower and more variable rainfall. Mitigating soil salinity, while having lower water availability, will often presage abandonment of the farm, as has happened under structural adjustment programmes in northwestern Victoria, Australia. Strategically, if alternative lands are available, and compensation can be made to failing producers, it makes sense to reallocate water to areas with fewer or no salinity problems. Maintaining irrigation supplies in saline areas inevitably results in lower water productivity than if the water was allocated elsewhere. The water market in Australia was further enabled when water entitlement was detached from land title. One of the main reasons for this was to enable sales of permanent water right as compensation for farmers leaving saline and other unproductive areas (Turral *et al.*, 2005). Water markets have evinced great international interest, but most developing countries do not have sufficient institutional and water accounting capacity in place for equitable and effective implementation (ibid).

5.3.6. Irrigation policy measures

In many wet rice irrigation systems in Southeast Asia, substantial amounts of water may be supplied during the monsoon season, even when not needed, and not actually used. It is likely that, where feasible, more monsoon supply will be stored for use with a second or third crop, and irrigation within the wet season reduced. In all systems, there will be substantial moves toward making more effective use of rainfall, and using predictive techniques (such as short and medium range weather forecasting) to aid scheduling and demand management. More targeted irrigation scheduling and delivery would require higher capacity canals and structures, and good water level control.

The management requirements would be correspondingly more demanding, including likely difficulties in ensuring that supplies are not diverted upstream of their intended delivery point. Although hostage to unsanctioned capture of supply, system-wide deficit irrigation strategies may be practicable, if demanding, to implement.

Water pricing continues to be advocated as a tool for limiting demand and shifting production to higher values (Aerts and Droogers, 2004). Some authors doubt the ability of water pricing to control demand, since most irrigation fees do not even cover the operational costs of irrigation service (Molle and Berkoff, 2007), and resource pricing therefore remains an unattainable objective. Certainly many countries are reluctant to charge fully or even at all for irrigation service, while others have quite rigorous systems (a long-held tradition, but recently over-turned, in Vietnam, and emerging in volumetric pricing in China). Water markets have too often been promoted with little acknowledgment of the institutional, technical and information impediments. In Australia, a country with an established and active water market, an analysis by Beare and Heaney (2002) of the potential for either increased water use efficiency or water markets to mitigate economic losses in the irrigation sector arising from climate change, finds in favour of water markets. Certainly such findings are highly dependent on the assumptions used in the modelling and the institutional settings are insufficiently developed in most countries for this to be an option for the foreseeable future.

Adoption of differentiated supply policies and security between high and low-value producers is also likely to emerge, and would be facilitated by clear water allocation and water rights policies that include differential payments for high and low security water. The service offered and the flexibility of operation will probably need to improve, as allocation and distribution is adjusted to both satisfy a relatively small number of high-value growers and a large number of field croppers. Groundwater will play a key role in providing different securities of supply to different types of customer, as now.

A very likely autonomous response to climate change will be the further, extensive development of groundwater. In the policy dimension, this might be viewed as 'mission impossible', and it will be important to avoid the trap that many states in India have currently fallen into. Although the provision of subsidies to locate and drill wells has largely been restrained, it continues to prove politically impossible to back away from the provision of partial and full electricity subsidies to irrigation pumpers. This is resulting in many negative impacts arising from falling water table and competitive deepening of wells, including failure of domestic water supplies and associated fluoride contamination. Initiatives in Andhra Pradesh (www.apfamgs.org) are attempting to reverse resource depletion and degradation through programmes of self-monitoring in an effort to improve the management of groundwater resources and reduce agricultural risk. At the same time the financial cost of free agricultural power supply is a heavy burden on state finances, with imminent (yet so far never realized) financial collapse of state power authorities (Shah, 2006).

Although extremely challenging, establishing good groundwater governance is therefore a key part of the policy matrix of climate change adaptation. In developing countries, with large numbers of small users (famously 20 million in India), the transaction costs of licensing, fee collection and auditing are very high. Rational energy pricing, even at flat tariffs, may not completely restrain groundwater abstraction to sustainable levels, but should go a long way to avoiding short-term loss of the resource. This will prove to be an increasingly political problem as governments try to juggle rural livelihoods with sustainable development.

Increased flexibility in system operation can be obtained when farmers build on-farm storage, as in Zhang He Irrigation system in Hubei, China, where farmers have had to adapt to reduced rural supply in the face of overwhelming and profitable urban and industrial demand (Roost *et al.*, 2008a, b). Significant on-farm storage has long been popular in 'frontier irrigation areas' of the Murray-Darling Basin in Australia to store erratic surface water supply and divertible flood flows. It is now being widely considered and spontaneously developed in response to drought in previously well-supplied irrigation areas. In the long term, its popularity will increase as an adaptation to declining water availability and is likely to be built into operating policies in some river systems (UN-Water, 2007). It is also likely that policies to incentivize on-farm storage will become popular.

Many of these options are highly dependent on the understanding and acceptance of the farming community, and are challenging to police when customer numbers are high and their holdings small. This implies increased demands on monitoring and evaluation and instrumentation. There will be an increasing role for remote sensing in monitoring cropping activity, assessing water demand, and monitoring system performance. GIS will provide the backbone of many surface and groundwater irrigation management systems. Although GIS is in widespread use in irrigation systems in the United States, Australia, France and Spain (for example), the systems are much less widespread and less sophisticated in most developing countries. Current irrigation management innovations, such as asset management, automatic control, arranged demand scheduling, sophisticated irrigation scheduling and soil moisture monitoring will all contribute in their own fashion.

The more general literature notes institutional bottlenecks between irrigation system managers and users (Turral, 1995; Bruns and Meinzen-Dick, 2000; Garces Restrepo *et al.*, 2007), with continued calls for greater user participation and representation (ECA, 2009; Padgham, 2009). The record of user participation effectiveness in much of the world's irrigated area is poor to say the least. Programmes to develop water user associations have been ineffective and uninspiring. The challenges of working with hundreds of thousands of small farmers pose enormous logistical problems, and approaches that require individual participation and mobilization are likely to be troubled. Alternative models of ensuring self-interested and beneficial participation or 'voice' through adequate and equitable representation are needed, but candidates appear to be thin on the ground. There have long been calls for irrigation professionals to become more service oriented and open to meaningful co-management of systems with users. A climate-changed world will stimulate renewed capital spending in the irrigation sector in the construction of storages, remodelling and modernization of existing systems and construction of new systems. If the irrigation profession is allowed, collectively, to return to past preferences for construction over management and service, the task of meaningfully adapting to climate change will be all the harder for the farming community. This will be doubly true if we return to past levels of rent seeking and pork-barrel profiteering in contracts for construction of public irrigation infrastructure.

Groundwater users and developers have rarely felt the need to participate with anyone, but as a consequence, unconstrained and self-interested groundwater development has created common property access and benefit problems in much of India and China (Giordano and Villholth, 2006).

Some of the more difficult choices at irrigation system level will include selective land retirement or retirement of parts of the distribution system, especially those in more marginal areas or those that are not cost-effective to run. This may include heavily salinized areas or areas where other negative environmental externalities impose larger downstream costs. The equation of cost-effectiveness will be governed increasingly by the productivity of water use across a given system, balanced against socio-economic needs and justification to support livelihoods and subsistence.

5.4. ADAPTATION AT RIVER BASIN AND NATIONAL LEVELS

5.4.1. Irrigation sector policy

Important choices will have to be made at national and sector levels for how best to guide and assist adaptation at system and farm levels. Simulation with regionally downscaled models is likely to play an important role in assessing the options in detail. A predicted increase in the frequency of delays in onset of the monsoon in Indonesia (Naylor *et al.*, 2007) will require import and grain storage policies to be adapted in order to bridge the resulting production loss and stabilize market supplies. Where feasible, greater water storage should be constructed to balance lower rainfall in July–September: with higher precipitation predicted earlier in the year (April–June) this could, in the longer term, be complemented by increasing the drought tolerance of rice production systems through diversification into aerobic rice. Alternatively, there could be more elaborate crop diversification into other crops which better match modified climate and water availability (with additional implications for rice supply, storage and import).

Some sensible generic recommendations for the irrigation sector are suggested in the recent World Bank report on adaptation in agriculture (Padgham, 2009), which can be summarized briefly:

- Prioritize drought-sensitive farming and ecosystems for irrigation investment and facilitate groundwater development where abstraction and capital costs are low.
- Reduce rice production on highly permeable soils to conserve water and minimize salinity, preferably through reasonable incentives and removal of perverse incentives.
- Redirect subsidies from energy use to water conservation.
- Build capacity to integrate climate change scenarios in water resources policy planning.
- Develop policies to externalize poor water and fertilizer use and achieve synergy in mitigation and production efficiency.

Interesting innovations have been suggested for directly addressing the downstream impacts of upstream water harvesting on catchment yield; these ideas include the possibility of encouraging upstream farmers to conserve more winter runoff with the intention of improving dry season flows downstream. The merits will depend on many factors, not least soils, slopes and patterns of rainfall, and the use of payments for environmental services to develop balanced adaptation strategies at basin level is clearly a practical and potentially useful tool.

A recent, interview-based analysis of climate change adaptation and preparedness in Africa (SEI, 2008) identified a widespread lack of climate awareness in most national development agencies and the authors recommended:

- improving and expanding climate change projection data in Africa;
- bringing data producers and data users together;

- improving capacity to interpret and apply climate data;
- moving from awareness raising to 'proof of concept';
- establishing platforms as the backbone for collaborative action and information sharing;
- focused donor funding;
- placing climate change within the broader African development context.

Writings on adaptation portray optimism for the potential benefits of forecasting of drought, floods, water availability and so on. The science of forecasting is still emerging, with great progress already made in the understanding of long-term cycles and the attendant predictive ability of such signals (ENSO, NAO, SAM). However, the real-world application of forecasting has not yet met expectations in Africa (Padgham, 2009) because:

- Forecasts are not sufficiently specific – spatial and temporally.
- Coordination between forecasters and end-users is inadequate – communication and language translation.
- Poor interpretation and communication of forecasts leads to mistrust and low overall dissemination (difficulties with probabilistic forecasts).
- Farmers are unable to act on forecasts.
- Efforts to enhance access can lead to greater social inequality by (unintentionally) targeting those with greater resources.

These points are worth remembering when considering more specific adaptation measures, elaborated at farm and field scale and at strategic and planning levels. The ability to forecast weather patterns varies across the globe, and the strength of relationships varies and is changing over time. It is not yet known what effects climate change will have on strong relationships such as ENSO. The analysis is becoming progressively more difficult for even the scientifically aware layman to understand. Complex statistical analysis of Pressure, Temperature and Rainfall (PTQ) fields was recently conducted for the winter season in the United States, using monthly data spanning 50 to 90 years (Kumar and Duffy, 2009). The results showed that climatic forcing is modified by landform and human activity (including the construction of dams) and that analysis can ascribe hydrologic changes to physiographic, climate and human forcings. However, the study also showed that forecasting tools perform poorly for temperature and very poorly for precipitation aside from years with a strong El Niño or La Niña signature. This means that prediction is strong for the peaks and troughs of climatic cycles but not over the relatively longer periods in between.

5.4.2. Coping with droughts

The regional response to drought within river basins has been continual preoccupation with agricultural water resource management (FAO, 2004c). Drought response over much of the world has tended to be reactive, and even after the advent of sophisticated monitoring and warning systems, such as FEWS (Famine Early Warning System), responses have been focused on immediate food aid, rather than on longer-term structural preparation. With respect to the prospect of increased severity and frequency of drought under climate change, the state of affairs is somewhat depressing. Low-input agriculture is no longer capable of meeting the livelihood demands of rising populations in the fragile dry-land environments prone to recurrent drought. A major, multi-country study of the Limpopo basin and response to drought in southern Africa by FAO provided a strong assessment of the physical, economic and climatic conditions, but came short of providing practical responses (FAO, 2004c).

The objectives of drought relief are stark and simple. Drought response and management typically has three components:

1) **Drought relief** to minimize loss of life and assets (mostly livestock) provision of general food aid to the most-affected households, with supplementary nutrition for the most vulnerable – children (especially under five years old), pregnant and nursing mothers, and the elderly and disabled; provision of emergency water supplies for people and animals, including assistance in reducing livestock numbers; and provision of income through work programmes.

2) **Drought rehabilitation** to get people back on their feet once drought has passed through re-establishing agricultural and pastoral livelihoods, including: seed-pack and fertilizer distribution; ploughing services and row-planting grants; livestock programme provision of free vaccinations in certain drought-related conditions, an expanded livestock water development programme, the facilitation of supplies of livestock feeds and requisites, and, where feasible, incentives for an increased livestock offtake; garden projects aimed at enhancing nutrition; and disbursement of general subsidies and loans.

3) Longer-term structural measures to **mitigate the impact of drought** through dam construction; soil water management including water harvesting and conservation, and improved development and management of fragile catchment areas; small-scale irrigation schemes; agroforestry programmes and other participatory measures to limit desertification; rangeland and stock improvement; and food storage chains.

5.4.3. Coping with flooding; structural and non-structural interventions

Structural solutions to flooding often shift the impacts downstream or restrict the passage of the flood itself. For example, draining land is immediately affected by flooding, which simply increases downstream flow, sometimes catastrophically, as evidenced by recent events in the Danube and Rhine Basins. Containing floods within the natural drainage system by means of levees has the same effect and also disrupts normal flood plain functions and ecology, often resulting in damage to biodiversity. The genetic diversity of native fish deteriorates due to fragmentation of water bodies, with consequent loss of capture fisheries that typically benefit the poorest.

Nevertheless, flood management for human benefit and safety requires that flows are attenuated, which in turn requires some form of storage. Although functioning flood plains are naturally adapted to this purpose, they have become heavily settled and densely farmed. The main means of substitution has been in the use of an adequately-sized water body, natural or human-induced, which has suitable stage storage and outflow characteristics to attenuate floods of expected magnitude (FAO/RAP, 1999).

Structural methods can be part of an integrated drought management plan that is focused mostly on non-structural measures, and may include gates preventing back up of high flood waters; reservoirs and retention dikes to protect urban areas and agricultural lands; widening and deepening of tributaries and natural drains; diversion channels; and retention ponds and retarding basins. When structural measures fail, the consequences are usually severe in terms of loss of life and damage to property and infrastructure. Flood detention areas are designed to divert and store large volumes (often within the natural flood plain), where agricultural damage is considerably less costly than loss of human life and urban infrastructure. Flood detention and diversion areas are common in diked or poldered deltas in China and Southeast Asia.(Red River in Vietnam, Yellow River in China, but not the Mekong River).

Non-structural methods have become increasingly popular to avoid the high costs of structural approaches, and also to try to escape the penalties of failure of structural solutions when floods are greater than design values. The flood plain is naturally capable of dissipating most floods, and non-structural methods seek to preserve this capacity, despite settlement and economic activity. Land zoning, based on the assessment and classification of areas affected by regular flooding, limits habitation and high-value economic use, according to risk. Flood insurance can be obtained in more wealthy countries, and will reflect land zoning in its premiums: however much domestic and agricultural insurance does not include flood in the standard terms.

Traditional farming systems along the Mekong in Thailand, Cambodia and Laos are both adapted to flood risk and to take active advantage of floodwater by spreading it and diverting it to rice paddies. Different forms of rice, from floating, deep-water varieties through to higher-yielding types are grown in catenas, which reflect expected risk (and reliability) of flooding.

More modern adaptations to farming in flood areas revolve around the development of irrigated cropping in the dry season, and possible abandonment of cropping in the monsoon season in the most risky areas. Shallow groundwater is usually available in the flood plain and in flood zones where portable pumps and low-cost wells minimize the need for risk prone infrastructure. Low cost, treadle pumps widen access to the poorest.

Recent advances in flow monitoring and detailed survey of riparian corridors (with DGPS and GIS) have much improved the practice of using hydrodynamic models to assess flood risk. Levels of risk can be further assessed and managed by retrospective analysis of large historical floods and the actual extents of present and future floods can be easily measured from satellite radar sensors. Coupled with remote sensing to estimate the extents and patterns of rainfall, sophisticated and effective flood estimation and warning is 'routine' in many river basins. The effectiveness of flood forecasting can be dampened by land-use change and other human activity that impacts floods; constant updating is needed. It is not uncommon to see settlements spring up within both natural and constructed drainage channels in many parts of Southeast Asia! Appropriate building methods can be specified in building codes, although traditional housing in many parts of Southeast Asia is already adapted to life with floods – in many parts of Vietnam and Thailand, people don't live on the ground floor, and houses may be built on stilts.

Long-range forecasting (such as El Niño cycles) may in due course improve flood preparedness and could be used to mitigate risk in crop choice and the extent of planting in detention areas. As with flood early warning, it is vital to inform people living in the flood path in a timely way and have well-understood and well-communicated procedures for evacuation, provision of shelter, water and food. Often, the weakest link in flood management is in timely communication, although amazing feats of impromptu human organization have been witnessed in efforts of defense such as sandbagging embankments.

Storage trading is one way to improve the effectiveness of existing river infrastructure, for example where operating rules of hydropower dams can be ‘relaxed’ as a result of indemnification against production losses by those at risk downstream. Alternatively, effective flood warning procedures, based on remote sensing and extensive flow measurement, could reduce the need to keep the dams empty and enhance effective annual storage. Another activity that falls between structural and non-structural approaches is the control of sediment levels in natural waterways, diked and modified channels and impoundments, especially dams, in order to maintain flow capacity.

Examples of adaptation include the Lower Nile Valley where communities have learned to adapt to annual flooding, or in Bangladesh, where the annual flood plays a vital role in the agricultural economy by: 1) bringing fertilizing silt; 2) replenishing the groundwater supplies on which a significant amount of the irrigated agriculture is dependent; and 3) maintaining the connectivity of water bodies, thereby maintaining biodiversity in capture fisheries.

Floods in deltas are likely to become more severe in future. Higher inflows will result from more extreme patterns of rainfall and increased annual precipitation, while drainage will be restricted by effects related to sea-level rise – such as storm surges.

5.4.4. Managing aquifer recharge

The role of aquifers and recharge processes in buffering climatic shock and offering on-demand, just-in-time water services to irrigated agriculture has been outlined in Chapter 4. But despite the growing reliance on groundwater resources for municipal and agricultural services changing styles of aquifer recharge are one of the least explored aspects of climate change impacts – due in part to the difficulty in determining recharge processes and aquifer storage renewal and the more fundamental problem of predicting the spatial and temporal patterns of rainfall and runoff (Jones, 2008). Some ‘open’ aquifers such as the dolomite blocks in the Zambian Copper Belt, can fill to the point of discharging within a few days of intense rainfall. But determining the rates of recharge from contemporary rainfall in stratiform aquifers of the Middle East are fraught with the interpretation of detailed chloride balances and isotopic analysis (Scanlon *et al.*, 2006).

Globally there is limited but growing experience of managed aquifer recharge for agricultural use. One of the longest established is in the Burdekin Irrigation District in coastal Queensland, Australia, where the Burdekin Dam maintains recharge through a large part of the coastal plain: sugarcane is irrigated from shallow groundwater, with control of the saline/freshwater interface critical to the sustainability of production. A review of managed aquifer recharge techniques and approaches (Jones, 2008) has shown mixed results with attempts at emplacing naturally available runoff conditioned by the geological ‘openness’ of receiving aquifers.

Various methods of managed aquifer recharge are possible and include:

- spreading methods – such as infiltration ponds, soil-aquifer treatment, in which overland flows are dispersed to encourage groundwater recharge;
- in-channel modifications – such as percolation ponds, sand storage dams, underground dams, leaky dams and recharge releases, in which direct river channel modifications are made to increase recharge;
- well, shaft and borehole recharge – in which infrastructure is developed to pump water to an aquifer to recharge it and then either withdraw it at the same or nearby location (e.g. aquifer storage and recovery, ASR);

- induced bank infiltration – in which groundwater is withdrawn at one location to create or enhance a hydraulic gradient that will lead to increased recharge (e.g. bank filtration, dune filtration);
- rainwater harvesting – in which rainfall onto hard surfaces (e.g. building roofs, paved car parks) is captured in above- or below-ground tanks and then allowed to slowly infiltrate the soil.

Despite these caveats noted by Jones (2008), adaptation measures in groundwater use and management can be expected to focus on managing the quantity and quality of recharge combined with aquifer storage and recovery, particularly with high value uses. While managing recharge processes has proved cost-effective as an alternative to surface water storage (Pyne, 2005), it incurs costs in injection and pumping back to the surface (recovery) that generally make controlled aquifer storage and recovery (ASR) viable for potable use (Gale, 2005). Only in the case of recycling urban waste-water through ASR or the large scale management of flows in alluvial aquifers linked to high value agriculture is such recharge management relevant to agriculture. However, while localized management of recharge for agricultural use through checkdams and gravity 'injection' has been attempted in many rural settings as part of 'watershed management' projects, the evidence for the demonstrated emplacement of groundwater over and above natural recharge processes is not forthcoming.

The relative merits of surface and groundwater storage are presented in Table 5.3, taken from recent work by Shah (2009b) to illustrate an initiative by the Central Groundwater Board in India which has recently set a strategic climate adaptation objective of stabilising groundwater at a depth of 3 m below ground surface over as large an area of India as is feasible.

TABLE 5.3
Relative merits of surface and groundwater storage in India under climate change (Shah, 2009b)

		Small surface storages	Large surface reservoirs	Aquifer storage (BAU)	Managed aquifer storage
1	Makes water available where needed (space utility)	↑↑↑	↑↑	↑↑↑↑	↑↑↑↑↑
2	Makes water available when needed (time utility)	↑	↑↑	↑↑↑↑	↑↑↑↑↑
3	Level of water control offered (form utility)	↑	↑↑	↑↑↑↑	↑↑↑↑↑
4	Non-beneficial evaporation from storage	↓↓	↓↓	↓	↓
5	Non-beneficial evaporation from transport	↓↓	↓↓↓	↓	↓
6	Protection against mid-monsoon dry spell (2–8 weeks)	↑↑	↑↑↑	↑↑↑↑↑	↑↑↑↑↑
7	Protection against a single annual drought	↑	↑	↑↑↑	↑↑↑↑↑
8	Protection against two successive annual droughts	↑	↑	↑↑	↑↑↑↑
9	Ease of storage recovery during a good monsoon	↑↑↑↑↑	↑↑↑↑	↑↑	↑↑↑
10	Social capital cost of water storage and transport and retrieval structures	↓↓	↓↓↓↓↓	↓↓	↓↓↓
11	Operation and maintenance social costs of storage, transport and retrieval structures	↓	↓↓	↓↓↓↓↓	↓↓↓
12	Carbon footprint of agricultural water use	↓	↓↓	↓↓↓↓↓	↓↓↓

Note: BAU: Business as usual

The benefits in allowing broad access of groundwater (Shah, 2006; 2009a and b) will need to be tempered against: 1) the difficulties and transaction costs of regulation and control over abstraction; 2) avoidance of pumping subsidies which promote over-abstraction; 3) water quality problems associated with groundwater use, including salinisation, fluoride mobilisation and elevated arsenic content; and 4) the promotion of increased fossil fuel use in agriculture as a contributor to greenhouse gas emissions. There has been some recent research in technologies and strategies for groundwater recharge in Australia, the United States and Central Asia, but more is needed. A good understanding of surface and groundwater interactions is becoming increasingly important. Whatever potential storage technologies and strategies offer, groundwater management will assume increasing importance and complexity. It will require good information and data to facilitate more precise water accounting and conjunctive management of recharge and depletion cycles. These could be better-tailored to meet inter-annual variability in recharge and optimize use between average and dry years.

The eventual selection of appropriate methods depends on water availability, feasibility (geology and soils) and cost. Operational experience indicates that management issues, encompassing water quality, monitoring, ownership and stakeholder communications are equally important.

5.4.5. Assessment of adaptation options to ensure irrigation supply security

The identification of adaptation options requires a context (climatic conditions and changes coupled to a production system, such as defined in the typology shown in Table 4.2). It also requires an analysis of the cost-effectiveness and sustainability of different options with, preferably, a selection of options that mitigate rather than exacerbate GHG emissions. An example of the alternatives and combinations of options to enhance irrigation supply security to existing irrigation or expand area under irrigation is given below:

1. Augment supply storage to secure supplies
    a. Increase surface water storage capacity AND/OR
        i. Construct new dams and /or
            - Sites, costs, environmental impacts
            - Embodied energy cost considerations
            - Multiple functions – including flood detention and electricity generation
        ii. Modify operations of existing dams to increase annual useable storage and /or
            - Pump out of dead storage
            - Upgrade spillway capacity to pass revised Probable Maximum Flood for climate change enhanced runoff to enable higher levels of retained storage
        iii. Raise dam height
    b. Increase groundwater storage
        i. Consider target water levels, costs of abstraction, water quality issues, governance and access

ii. Passive groundwater recharge and /or
   - From surface canal networks (as Indus System)
   - At alluvial fans (determined by scale, snowmelt runoff, surface to groundwater connectivity and other hydrologic and engineering considerations)
   - In partially constructed recharge basins at natural recharge sites

iii. Active groundwater recharge
   - Delay or recharge dams
   - Direct injection

2. Increase within system storage (for example for run-of-river systems)
   a. Construct Balancing storages AND/OR
   b. Increase on-farm storage
      i. Incentive policy
         - Design and site investigation assistance and grants
         - Construction grants for farm dams
3. Reduce transmission losses in water distribution (where not required for groundwater recharge)
   a. Loss accounting programme AND/OR
   b. Selective lining to reduce channel seepage AND/OR
   c. Selective covering or piping to reduce evaporation losses AND/OR
   d. System reconfiguration or modernization to:
      i. Improve hydraulic control and distribution or
      ii. Enable on-demand supply or
      iii. Ration supplies.

Each thread has subsidiary options or implications related to economic cost, cost benefit, environmental impact, embodied energy use and GHG contribution/mitigation value as briefly elaborated for 1a. Similar logics can be developed for options in flood control for agriculture and especially irrigated agriculture; salinity management strategy; and for incorporation of energy generation within suitable irrigation systems to provide GHG mitigating rural energy supply.

5.5. ADAPTIVE CAPACITY IN AGRICULTURAL WATER MANAGEMENT– POLICIES, INSTITUTIONS AND THE STRUCTURE OF THE SUB-SECTOR

5.5.1. Mechanisms for allocation

Under conditions of scarcity and competition, the fundamental issue of water allocation – who gets what – can be expected to be prominent in public debate. Allocation systems have to smooth out short-term variability in supply and meet longer-term development objectives. A challenge in water allocation and hydrology is to understand the nature and partitioning of return flows between uses and users or different parts of a landscape (from up-stream to downstream in a basin). It will be necessary to separate regulatory authority from supply functions, and develop transparent, well-enforced regulations, rules and procedures for accounting, allocation and monitoring of all bulk water use. This in turn may require a reconciliation of economic efficiency and equity in relation to water and will place new demands on the institutional landscape. In order to manage and allocate water as a scarce resource, the ability to monitor flows and distribute them accurately and reliably will become increasingly important. This will require appropriate new infrastructure and the institutional capacity to operate it.

Reconciliation of growing demands with declared environmental preferences further complicates the issue of allocation. It is clear that maintaining the highest possible levels of biodiversity is a sensible adaptation measure to climate change, if only to preserve genetic variety that might allow adaptation in the future. With a wide biodiversity base, aquatic ecosystems stand the best chance of being able to adapt to incipient and future changes. Climate change is also increasing awareness of the crucial role of the services that wetlands provide, for example in the sustained delivery of freshwater, nutrient recycling and the mitigation of extreme rainfall events (both droughts and floods), as well as the role of healthy coastal wetlands in mitigating the damage caused by extreme storms. Using nature's ability to cope with change is a sensible and cost-effective response option to climate change and in this process considerable benefits will also accrue to biodiversity and the fisheries reliant upon it.

5.5.2. National food policy issues

With increasing global temperature, agriculture may adapt progressively to new conditions, resulting in incremental changes in cropping patterns. In more extreme or rapid scenarios, large areas of staple food production would be affected, and when combined with rising demand from transition economies, buffer or carry-over stocks will be depleted and food prices could be expected to rise.

Challenges to world agricultural trade emerge from a slowing of agricultural productivity growth across most of the world leading to greater vulnerability for the least developed countries. Climate change impacts are likely to worsen their plight and the prospect of future food crises suggests the need for new international rules on agricultural trade (Sarris, 2009). Although many of the popular attributions of the 2007 'food crisis' have been debunked, oil prices have been identified as a major factor influencing commodity price volatility, and it is expected that the long-term trends in petroleum prices will influence commodity price volatility which is anyway expected to rise and impact agriculture through greater cultivation of biofuel crops, especially in developed countries. Although price volatility is now expected to be relatively high, it is likely that the general downward trend in commodity prices will continue (Sarris, 2009).

Agriculture-based livelihoods are likely to be impacted most by climate change, and Africa is likely to be the most adversely affected continent (Stern, 2006). The most vulnerable people are the poor, landless and marginal farmers in rural areas dependent on isolated rainfed agricultural systems in humid, semi-arid and arid regions; small changes in rainfall can result in locally significant changes in surface water and groundwater resource availability in the semi-arid and arid regions. Further compensatory irrigation development will be necessary in these regions, both in areas where it already exists, and to supplement rainfed areas. Necessary changes to fixed capital associated with irrigation may represent one of the largest costs associated with climate change adaptation, and this will present considerable challenges to the poorest farmers (Quiggin and Horowitz, 1999; 2003). The overall outlook for Africa is not encouraging as food imports are expected to grow, while the inability to pay for them will be increasingly evident (Sarris, 2009).

Populous and poor countries have tended to place a high premium on self-sufficiency in food, and are reluctant to rely on trade. China, with the backing of enormous industrial wealth, has relaxed slightly in its attitude to importing food, but continues to place great emphasis on maintaining self-sufficiency (Solot, 2006). The existence of significant food stocks does not necessarily ensure food security, as witnessed by a number of localized famines in India in 2003, at the same time that central food stocks were at an all-time high around 60 million tonnes, a proportion of which was rotting due to low turnover. Nevertheless, there is clear possibility of substituting water storage with inter-annual grain storage, providing the dynamics of surplus and deficit years can be determined, and the necessary distribution infrastructure put in place to provide food where it is most needed. Clearly it is possible to buffer inter-annual and seasonal variation in food supply through storage. This has been a central pillar of food policy in many countries (with dedicated and powerful agencies, such as BULOG in Indonesia). Indeed, recent analysis suggests that the low ratio of stocks to total production seen before 2007 was an anomaly and that stock levels will get closer to historical norms over the medium term (Sarris, 2009).

5.6. INSTITUTIONS

Building resilience among affected populations can be achieved through a mix of rural development strategies in which all forms of agriculture and water management, not only irrigation, will contribute to food and livelihood security. Possible changes include crop diversification, less water intensive varieties of crop, or increasing irrigation water use efficiency. While some farming communities prove resistant to change, particularly if incentive arrangements such as credit facilities or hedging mechanisms are not aligned, the Comprehensive Assessment (CA, 2007) foresees a general 'industrialisation' and high-value orientation of irrigated production, with the caveat that staples will remain the bulk of demand. This trend is emerging with aggregation of farm holdings (not necessarily ownership) and declining proportion in populations engaged in agriculture.

At national level, there are a number of options to adjust the focus and balance of agricultural water management. Investment and subsidies can follow shifts in agro-ecological zones, and can focus on areas that continue to have comparative advantage. This approach makes sense in terms of food security but is less likely to deal with problems of social and livelihood equity. Subject to water resources availability, and the economics of management, storage and construction, irrigation can be 'relocated' to less impacted or more productive areas. Alternatively, new irrigation systems can be constructed, or governments can create incentives for private development (mostly in groundwater).

Governments will also play a key role in policies and incentives that define the balance of irrigated and rainfed agriculture in different river basins. Different approaches will be required depending on preferences and careful scrutiny of rural benefits. The trade-offs in water scarce basins will be between the value of a reliable – if also more variable – irrigated production base, and a larger area of rainfed production, which will be increasingly vulnerable to climatic extremes. Governments will also have to factor in GHG mitigation strategies through agriculture, both via the substitution of fossil fuels with bio-energy and the sequestration of carbon in vegetation and soils. Again, such considerations and complexity argue for more detailed and localized analysis of impacts and adaptive strategies.

National government will, as now, play a strong role in protecting agriculture from flooding and water logging as a matter of public interest. This will be through structural measures, and increasingly, through non-structural approaches. Approaches to drainage that involve the generation of greenhouse gases, such as pumping, will increasingly come under review, and more attention will be paid to the carbon accounting in the protection of agricultural crops from flood hazard.

Wastewater re-use from cities offers an increasingly reliable flow of water for agriculture, albeit with vary variable and often hazardous quality. Untreated wastewater is used widely, often without government sanction and without appropriate public health safeguards (Scott *et al*., 2004). Although industrial use is rising dramatically, the total volume available is a fraction of agricultural water use (about 5–15 percent of total abstractions, potentially rising to 30–35 percent in some parts of China and India) (Van Rooijen *et al*., 2005; 2007). Increasingly a large proportion of urban water use will be sourced from agriculture (Molle and Berkoff, 2006) and will contribute to a reshaping of the irrigated landscape. Governments will become more directly involved in managing and safeguarding this resource.

Finally, governments can and will underwrite the research into adaptation of crop patterns and the adoption of on-farm technologies and management responses, and can also motivate these through market levers or subsidy programmes. Public education, especially through the school curriculum, has proved to be an effective way to raise awareness and preparedness to deal with issues of sustainability and environmental management in countries such as Australia and could be emulated usefully elsewhere.

5.7. LONG-TERM INVESTMENT IMPLICATIONS FOR AGRICULTURAL WATER MANAGEMENT

Estimates of sector investment needs have been given for both agriculture and water supply by the United Nations Framework Convention on Climate Change (UNFCC, 2007). The water demand estimates are derived from Kirshen (2007), based on partial baseline data and generalized modelling assumptions. The quantity of investment in well-adapted agricultural water management is perhaps less important than its quality.

Adapting to climate can be seen as an opportunity for change, particularly if seen in combination with other socio-economic shocks, including managing transitions to higher value crops or even transitions out of agriculture. With respect to large-scale investments in irrigation systems and associated flood protection structures, there is little point in capital expenditure that is compromised by climate change before the end of its economic life – this is an important conclusion of the Stern Review, but it does involve a debate over the use of appropriate discount rates and the extent to which some natural resources can be considered to be economic substitutes (Neumayer, 2007). Overall, irrigation costs will increase, primarily through re-adjusted operation costs and subsequent capital costs. Even without investments in additional inter-annual storage, the operational costs of re-designing and re-scheduling irrigation on the basis of more extreme or more frequent hydrological events are not negligible.

Two positive outcomes can be anticipated: first that adaptation may involve regional concentration of irrigation where domestic resource:cost ratios are low in a particular crop sector and natural resources are less constrained (e.g. gravity schemes such as Office du Niger in Mali). Under suitable trade agreements, there may be good economic and resource management reasons for establishing regional production centres in food staples and thereby relieve pressure on domestic production where climate variability is expected to worsen. Second, the prospect of change may present an opportunity to re-tune investment approaches, for example with more emphasis on early warning systems and demand management rather than direct structural investment.

It is not possible at this stage to determine the incremental costs of climate change adaptation in terms of water management alone. This can be done only on the basis of national analysis of the water economy. However it is possible to indicate what the scope of that investment could be – assuming a national consensus on the urgency of implementing an adaptation strategy has been reached. A recent example from Australia is presented in Box 5.2.

BOX 5.2
Investment choices in Australia

The broad pattern of hydrological impacts of climate change for Southeastern Australia has been confirmed by detailed regional climate modelling and the use of statistical downscaling with expected reductions of stream-flow of -40 percent by 2070 in northeastern Victoria (DSE, Victoria, 2007) and -20 to -30 percent in the Murrumbidgee and Macqarrie Valleys in New South Wales (CSIRO, 2007).

The biggest implication of reduced runoff is that expected water allocations for irrigation, and water availability for environmental flows will both decline, as is the case for the Murray-Darling Basin. An immediate consequence of reduced surface water availability is that the trade-off between environmental and agricultural water use will come into sharper focus.

There are a number of important aspects to the changes in runoff: where yields are expected to decline, we can cautiously assume a reduction in groundwater recharge, but this may not always be the case. An expected increase in the frequency of larger rainfall events is likely to cause increases in peak runoff rate and probable maximum flood. This has implications for storage management in that the proportion of currently available storage will decrease unless peak flows can be captured and stored. Where runoff declines and the proportion of large events increases, we can expect lower median annual storage volumes and supply security. At the same time, spillway sizes will have to be increased to pass larger probable maximum floods, especially if more dams are designed or modified to harvest peak flows and carry storage from year to year. Thus the costs of surface water storage can be expected to increase, especially in terms of unit costs of median annual volume stored. In Australia, there has been a revision of estimated Probable Maximum floods (Australian Rainfall and Runoff, 1999) and a revision of spillway capacity, overseen by the Australian National Committee on Large Dams (ANCOLD)(CSIRO, 2007). If this logic is correct, then there will be considerable interest in enhancing groundwater recharge as an alternative and possibly cheaper means of storage.

An immediate adaptation that would have impact at scale is the adjustment operational rules for multi-purpose dams and large-scale irrigation schemes. Such operational fine-tuning of existing assets can extend to the point of delivery and would quickly necessitate an overhaul of service delivery organisations, coupled with significant efforts to improve farmer awareness.

Policies that encourage sustainable use of shallow groundwater to buffer inter-annual droughts and supply shortages will offer the most scope for autonomous adaptation, but pose some major challenges in the design of regulatory and incentive structures that ensure equity and long-term resilience. In the short to medium term, modernisation strategies for irrigation systems should aim to minimize capital investments, and seek the most cost-effective options in water control.

The uncertainty associated with climate change suggests that large, long-term capital projects should be avoided if their discount life is long. Medium to long-term investment in dams and large water storages will need careful scrutiny as the most economic sites have already been developed and the marginal cost of increasing irrigated areas will be significantly higher, necessitate higher factors of safety for dams or involve substantial energized pumping from groundwater storage. The determination of acceptable environmental trade-offs will be noticeably challenging and more contentious than they are today, and compliance will probably add significantly to capital costs.

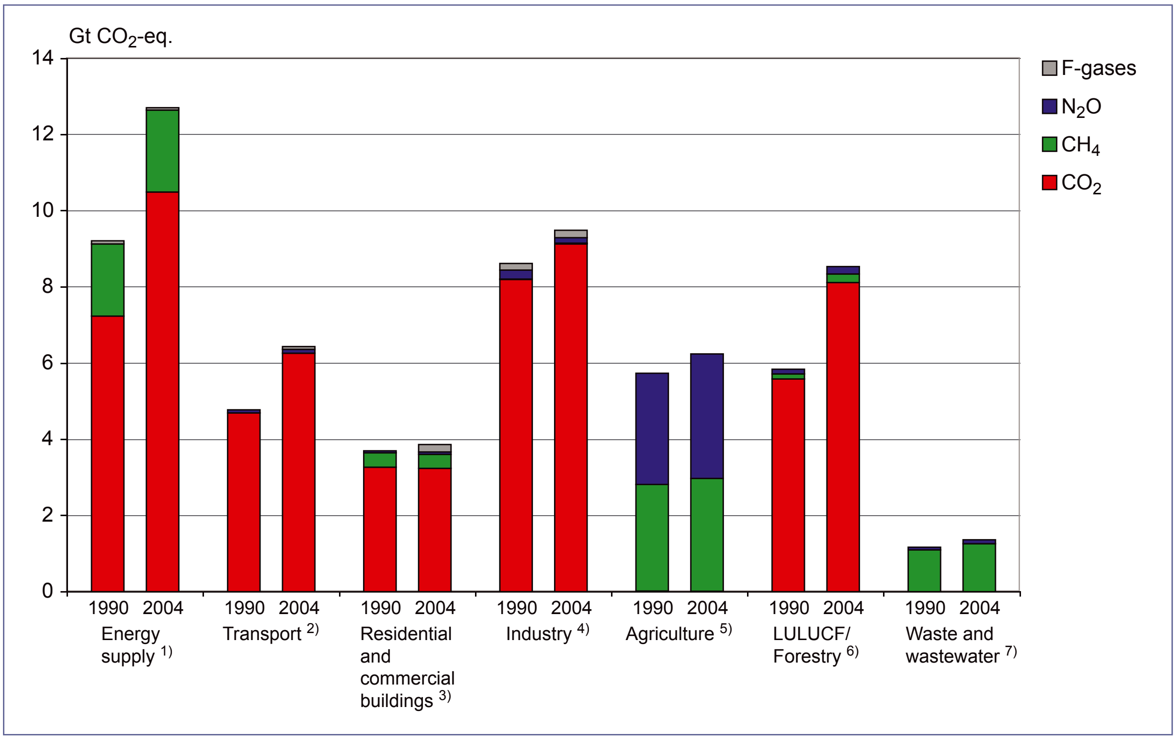
Chapter 6
Prospects for mitigation

6.1. THE GREENHOUSE GAS EMISSION CONTEXT

Globally, agriculture directly contributes almost 14 percent of total GHG emissions and indirectly accounts for a further 7 percent incurred by the conversion of forests to agriculture (mostly conversion to rangeland in the Amazon), currently at the rate of 7.3 million ha/year (Figure 6.1). CO_2 emissions from agriculture (<2 Gt/year) equate to about 9 percent of the global total of anthropogenic emissions, with the rest contributed by methane (2.5 Gt CO_2e per year) and nitrous oxide (2.7 Gt CO_2e per year). Agriculture's relative contribution to methane and nitrous oxide is large at 35 percent and 65 percent of total anthropogenic emissions, respectively.

This review of mitigation prospects takes a less hierarchical approach than that used for the adaptation (above). It focuses on specific aspects of agriculture and agricultural water management that contribute to greenhouse gas emissions and offer prospects for mitigation. In addition to the impacts of cycles of wetting and drying, the concentration of inorganic and organic fertilizer on land with some form of water management means that the practice of irrigation has scope to mitigate GHG emissions.

FIGURE 6.1
Contributions to global greenhouse gas emissions (CO_2 equivalent) by sector and gas in 2004 (IPCC, 2007)



Climate Change 2007: Mitigation of Climate Change. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure TS.2a. Cambridge University Press.

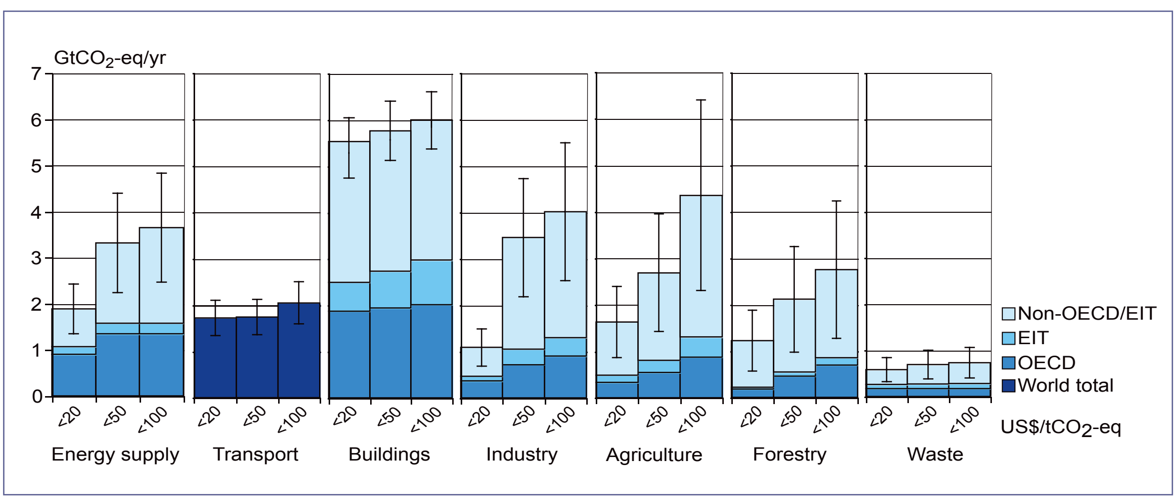
Globally, there was a 70 percent increase in GHG emissions between 1970 and 2004, with a reported increase in emissions of 27 percent in agriculture from 1970 to 1990 (Niggli *et al.*, 2009). Figure 6.1 indicates that most of this increase is in the form of N_20, attributed to increased and inefficient use of artificial fertilizer. Asia currently accounts for 50 percent of global nitrogen use, which is predicted to double by 2030 (Padgham, 2009).

Fossil energy use in US maize production as far back as 1994 was reported to equate to 400 gallons of oil equivalent per capita per year (McLaughlin *et al.*, 2000) with a percentage breakdown as follows:

- 31 percent for the manufacture of inorganic fertilizer
- 19 percent for the operation of field machinery
- 16 percent for transportation
- 13 percent for irrigation
- 8 percent for raising livestock (not including livestock feed)
- 5 percent for crop drying
- 5 percent for pesticide production
- 3 percent miscellaneous.

The Stern Review (2006) noted that prospects for stabilizing greenhouse gas concentrations will be determined by the price attached to carbon equivalent in the future. At three levels of price, the potential for stabilizing carbon at between 445 and 710 ppm in 2030 are summarized in Figure 6.2. In agriculture, the highest price would mitigate approximately 75 percent of current agricultural net emissions.

FIGURE 6.2
Potential for GHG mitigation by sector, in 2030, based on three costs (US$ per tonne CO_2 equivalent) (IPCC, 2007)



Climate Change 2007: Mitigation of Climate Change. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.6. Cambridge University Press.

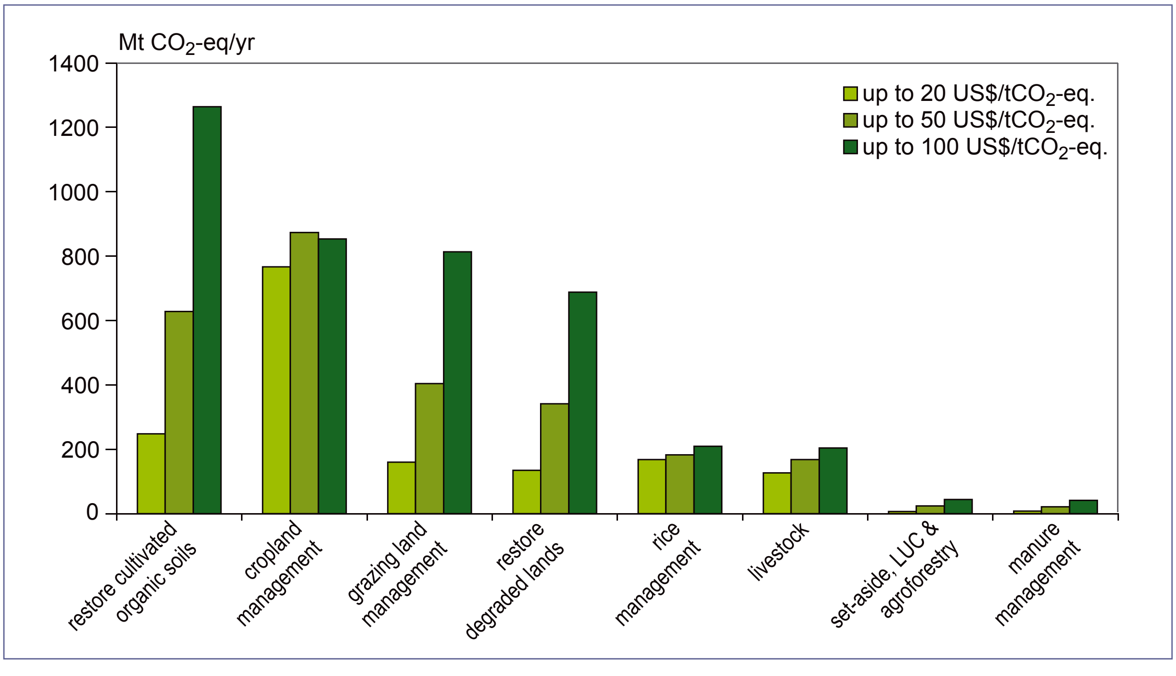
Agricultural lands occupy 37 percent of the world's surface and have a potential sequestration in excess of agricultural fossil fuel use estimated to be 5.5-6 Gt/year CO_2e in 2030, compared with a reference global output of 29 Gt/year CO_2e (Smith *et al.*, 2008). The prospects for mitigation are thought to be relatively high in non-OECD country agriculture and forestry, but with high levels of uncertainty. Global emissions of nitrous oxide and methane are predicted to continue rising to 8 Gt CO_2e by 2020, or about 60 percent more than in 1990. Minor decreases in Europe and a very minor increase in North America will be overtaken by major increases projected in sub-Saharan Africa, South and East Asia and in South America (FAO, 2007). FAO (2007) estimates that 65 percent of the potential for mitigation lies in developing countries, and that 50 percent of the total could arise from limiting deforestation.

The options and their potential for mitigation within agriculture are based on three different prices for one tonne of carbon dioxide; these are summarized in Figure 6.3 (Smith, 2008). Cropland management has highest potential, whereas water management has rather low potential, as the costs per tonne of mitigated CO_2 are very high. There is also great potential to reduce (by 30 percent) the carbon footprint of transport and mechanisation used in agriculture by adopting existing technologies (World Bank, 2009a).

Although livestock and rice are leading contributors of GHGs, the main potential for mitigation is thought to lie in the restoration of cultivated organic soils (predominantly peat lands in the tropics) and associated measures to increase or restore the carbon content of depleted and degraded soils. Even a 1 percent increase in carbon content in the top 10 cm of a soil translates into significant amounts over large areas – for example an increase of 1 percent carbon in the top 10 cm of a typical soil with a bulk density of 1.5 t/m^3 is equivalent to 15 tonnes of carbon per ha. Taking the irrigated area of the world (300 million ha), the theoretical potential to a level approaching 4 Gt is evident.

Improved agronomic practices that increase yields and generate higher inputs of carbon residue can lead to increased soil carbon storage (Follett *et al.*, 2001). Examples of such practices include: using improved crop varieties; extending crop rotations, notably those with perennial crops that allocate more carbon below ground; and avoiding or reducing use of bare (unplanted) fallow (West and Post, 2002; Smith, 2004a, b; Lal, 2004a; 2004b; Freibauer *et al.*, 2004). Key questions are for how long carbon is sequestered and whether water management makes adoption of such practices easier or harder.

FIGURE 6.3
Potential for GHG mitigation through different agricultural activities (IPCC, 2007)



Climate Change 2007: Mitigation of Climate Change. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure TS.20. Cambridge University Press.

6.2. AGRICULTURAL WATER MANAGEMENT AND GREENHOUSE GAS EMISSIONS

It is essential to know how carbon is cycled and distributed on the landscape. Only then can a cost/benefit analysis be applied to carbon sequestration as a potential land-use management tool for mitigation of GHG emissions (Markevich and Buell, 2002). Work by the USGS has used soils databases at national (STATSGO) and state (SSURGO) levels to map carbon inventory and identify high potential sequestration sites. Such innovations point the way for other countries, although much has to be done to improve the detail of soils mapping. Such analyses use simple regressions between soil type and soil-carbon capacity, based on current understanding. Simulation modelling to investigate the effects of climate change on sequestration capacity (Thornley and Cannel, 2001) suggests that warming will increase the rate of physico-chemical processes that transfer organic material to protected and more stable carbon pools. The modelling shows that equilibrium soil carbon increases when the sensitivity of transfer reactions is 50 percent or greater than that of soil respiration.

Irrigated agriculture accounts for only 20 percent of the area of global agriculture, but is more intensively managed, and on average uses greater amounts of inorganic fertilizer (NPK) and other agrochemicals to protect its relatively higher value production. Where groundwater is used for irrigation, the fossil energy costs of supply may be high. Lemons *et al.,* (1998) report that US wheat and maize production uses 4.2 and 3 times more energy respectively under irrigation compared with rainfed production and its combined effects of nutrient input, direct fossil fuel use and water pumping.

Comparisons between the direct fossil energy use in mostly small-scale developing country irrigation and rainfed farming (which, globally, is more mechanized) are harder to make. The greatest proportion of irrigated area lies in developing countries, with China and India together accounting for almost 50 percent of the total. In developing country irrigation, direct fossil fuel and fertilizer usage are relatively modest (Nangia *et al.*, 2008) but are likely to rise if productivity and water use efficiencies are to be raised in the wake of more variable and restricted rainfall and runoff.

Energy consumption for groundwater irrigation is regionally important and is significant in India and China, accounting for 16–25 million tonnes of carbon emissions in India, 4–6 percent of the national total (Shah, 2009). It is harder to estimate the contribution of <u>net</u> CO_2 emissions from irrigated farming or determine how significant they are: the figures probably vary considerably case by case, and need further detailed elaboration and investigation. One concrete example is that, in Australia, agriculture is the second-largest emitter of carbon and other greenhouse gases (17 percent) and larger than transport, due to 1) fertilizer production related emissions; and 2) fossil fuel use in cultivation, storage and cooling, and transport costs (Australian Govt. Dept. Climate Change, 2009). This is partially related to the extensive and highly mechanized nature of rainfed agricultural production. There are presently no published figures for the contribution of irrigated agriculture to national GHG output.

The options for direct mitigation through irrigation, on balance, are those of agriculture as a whole, with likely greater potential in certain specific contexts (intensive groundwater irrigation in the US for example). The possibilities are governed mostly by the increased intensity of irrigation, allowing greater potential for carbon sequestration in tropical conditions and greater productivity, offset by more intensive use of inputs.

6.2.1. Organic and zero emissions agriculture

Organic and zero-emissions agriculture are periodically put forward as solutions to resource depletion, land degradation and more recently climate change (Niggli *et al.*, 2009). The merits of organic farming lie in recycling wastes as nutrients, using nitrogen fixing plants in rotational farming systems that include livestock and do not over-work and degrade soils through year-on-year mono-culture. Livestock integration extends to the use of natural pastures and fallows, without the use of purchased feed concentrates. Organic producers avoid the use of synthetic pesticides and fertilizer, thus reducing fossil fuel use. It is suggested that conversion to organic pastures and agriculture could mitigate 40 percent of agriculture's GHG emissions, rising to 65 percent when combined with zero tillage and that organic farming could reduce irrigation needs by 30-50 percent (Niggli *et al.*, 2009).

There is clearly a need for detailed work to properly quantify trade-offs, costs and benefits and long-term prospects of organic farming in a range of climatic and socio-economic settings. There is no doubt that there is scope for less wasteful, more resource-efficient agriculture in many cases. However, claims that organic agriculture could replace current practices have no agronomic or physiological basis and clearly should be treated with caution: there are physical limits to the adoption of organic methods, and nutrient depletion needs to be compensated in one way or another: organic agriculture cannot satisfy current let alone future food production needs. There is clearly a problem of declining nutrient status in many African soils that are the result of insufficient nutrient supply that can not be addressed using organically based approaches only. The World Bank (2009a) indicated that global production might fall by 30–40 percent below current levels if all land was farmed organically.

6.2.2. Irrigation and the carbon balance

FAO (2010) estimates that about 20 percent of the world's croplands now receive supplementary water through irrigation, but there are claims that this total could be higher when considering informal, mostly groundwater-based irrigation (Thenkabail *et al.,* 2006). Irrigation can enhance carbon storage in soils through enhanced yields and residue returns (Follett *et al.,* 2001; Lal, 2004a). However, some of the gains from irrigation may be offset by CO_2 emissions resulting from energy used to deliver the water (Schlesinger 1999; Mosier *et al.,* 2005) or from N_2O emissions from higher moisture and higher rate of fertilizer inputs (Liebig *et al.,* 2005). The latter effect has not been widely measured.

Irrigators in many countries are seeking ways for improving returns to land, capital and labour, including plantation and boundary plantings of fast-growing trees, such as poplars, in the states of Haryana and Himachal Pradesh in northern India with clear potential to earn carbon credits under the Clean Development Mechanism (Zomer *et al*., 2007), and generate higher returns for small holders than those of agricultural field crops. Other variants of agroforestry may become increasingly popular. Fruit trees can presumably also claim carbon credits, but the potential area is more constrained by the high capital costs of production, sensitivity to climatic variation, the need for high security irrigation supply, and by fairly narrow markets, in comparison even with vegetables.

A second important aspect of carbon mitigation directly related to irrigation in the tropics concerns the drainage of peat soils. Famously, peat soils in Kalimantan and Sumatra have been drained for both irrigation development and plantation crop production with large releases of organic carbon, compounded by forest burning. Organic or peaty soils contain high densities of carbon accumulated over many centuries because decomposition is suppressed by absence of oxygen under flooded conditions. To be used for agriculture, these soils are drained, thus aerating the soil, favouring decomposition and resulting in high CO_2 and N_2O fluxes. Methane emissions are usually suppressed after drainage, but this effect is far outweighed by pronounced increases in N_2O and CO_2 (Kasimir-Klemedtsson *et al.,* 1997). Emissions from drained organic soils can be reduced to some extent by practices such as avoiding row crops and tubers, avoiding deep ploughing, and maintaining a shallow water table. But the most important mitigation practice is avoiding the drainage of these soils in the first place or re-establishing a high water table (Freibauer *et al.,* 2004).

Lastly, irrigation may be needed in the production of biofuels. In India, de Fraiture *et al*., (2008) note that 100 million tonnes of sugar cane would be required to meet the biofuel demand, requiring an additional 30 km^3 of water per year; this would either be at the expense of environmental allocation of water or existing food crops would have to be imported (ibid). Maize demand in China is modelled to rise to 195 million tonnes in 2030 (up by 70 percent from 2000), mainly because of growth in per capita meat consumption as a result of income growth. Part of the additional demand can be met through productivity growth and slight increase in area, but even under optimistic yield growth assumptions, imports will have to reach 20 million tonnes compared with 2 million tonnes in 2004. Under such a scenario, it is quite unlikely that the additional maize demand for biofuel can be met without further degrading water resources or inducing major shifts of cropping pattern at the expense of other crops. More likely, under an aggressive biofuel programme, China would have to import more maize (or the crop displaced by maize), which would undermine one of its primary objectives, i.e. curbing import dependency.

6.2.3. Carbon sequestration in irrigated soils

Although it is widely accepted that the largest pool of terrestrial carbon lies in the soil, the literature on carbon sequestration in irrigated soils is rather limited (Swift, 2001). Worldwide, the conversion of native soils to agriculture has resulted in a significant loss of soil carbon (Davidson and Ackerman, 1993). Globally, the amount of carbon stored in cultivated shallow, saline, sodic and arid soils is lower than in native types (Paustian *et al*., 1998). However, carefully managed soils can sequester organic carbon (SOC) in a number of ways:

- humification of organic matter;
- formation of organo-mineral aggregates;
- incorporation of organic matter below the plough zone;
- addition of deep root residues.

Irrigation can affect soil-forming processes in contrasting ways: the humidification of soils through irrigation and crop cultivation can increase soil organic matter through the incorporation of crop residues, root matter and applied organic material. In contrast, land levelling and tillage can deplete surface soil organic matter content through oxidization and microbial activity. Rates of organic decomposition increase across the board with increased temperature, but irrigation may play a role in reducing soil temperature for considerable times during the year. At the same time, irrigation is most-needed in arid and semi-arid conditions where temperatures are already high.

Thus, in general, dryland conditions do not appear to have useful potential for carbon sequestration (Markevich and Buell, 2002).

The literature (see summary in Wu *et al*., 2008) reports both losses and gains in soil carbon following the development of irrigation. A general pattern of short-term decline (0–25 years), stabilization (25–50 years) and long-term gain (> 50 years) in soil carbon has been observed following conversion of native land to agriculture (Paustian *et al.,* 1998; Swift, 2001). This pattern has been confirmed and elaborated for two irrigated soils in California: in the San Joaquin Valley (loam, irrigated with fresh well water) and Imperial Valley (silty clay–silty clay loam, irrigated with Colorado River water with a relatively high electrical conductivity) (Wu *et al*., 2008). The study used historical and recent measurements of both SOC and SIC at different depths within the soil, finding that native contents were much higher in the Imperial Valley. In the San Joaquin case, there was no significant reduction in SOC up to 45 years, followed by a significant increase, but this was accompanied by a significant decrease in SIC. At the Imperial Valley site, both SOC and SIC were significantly higher at 85 years after conversion, with the greatest contribution from accumulating SIC (carbonate deposition, in and below the root zone). The greatest rate of SOC increase was observed at a depth of 25–60 cm, almost doubling native contents, although the highest concentration occurred at the surface. Since bulk density plays an important role in determining actual carbon content, this high concentration does not translate into highest content. Nevertheless, sequestration in the tillage layer ranged from 16 to 33 percent greater than in native soils at 55 and 85 years respectively for the San Joaquin and Imperial sites.

Soil texture, permeability and structure play important roles in carbon storage, and Wu *et al.,* (2008) derived a strong correlation between clay fraction (<0.02 mm) and soil carbon content, to a depth of 100 cm. High calcium contents of irrigation water in the Imperial Valley site encouraged the sequestration of SIC as carbonate in the soil, effectively absorbing breakdown products from organic carbon decomposition. Artiola *et al.,* (2009) report that both high sodium content irrigation water and rainwater encourage release of soil organic carbon, but that high-calcium waters encourage accumulation of carbonates in and below the root zone. Eshel *et al*., (2009) hypothesize that irrigation water with elevated organic matter content (such as effluents) will encourage accumulation of SIC below the root zone in arid and semi-arid soils, and have encouraging preliminary results.

Wu's study concluded that preferred sites for carbon sequestration under irrigation in arid and semi-arid conditions are those with higher clay fractions (greater than 30 percent). They and others (Entry, *et al*., 2004 a, b; Artiola *et al*., 2009) note that irrigation water chemistry plays a significant role in carbon sequestration in carbonaceous soils.

There remains a great deal of work to be done to understand the potential for carbon sequestration in other irrigated soils in currently temperate and wet tropical conditions. Intuitively, soil carbon accumulation in inundated (wetland) rice soils runs the risk of exacerbating methane emissions, although incorporation of crop residues during dry periods has been shown to reduce net methane emissions (Yan *et al*., 2009). The practical application of residue incorporation is highly dependent on soil drainage characteristics, rainfall timing and cropping intensity in wet rice systems.

6.2.4. Managing methane emissions from agriculture

Cultivated wetland rice soils emit significant quantities of methane: 25.6 Mt per year from rice, at 95 percent uncertainty, covering a range from 14.8 to 41.7 Mt/year

(Yan *et al.*, 2009). Other estimates of global rice-derived methane contributions are as much as 92 Mt in 2005 and predicted to rise to 131 Mt in 2025. It is estimated that 19 Mt is emitted from irrigated and 6.5 from rainfed lands (Table 6.1, after Yan *et al.,* 2009). Emissions during the growing season can be reduced by various practices (Yagi *et al.,* 1997; Wassmann *et al.,* 2000; Aulakh *et al.,* 2001), such as aerobic rice and alternate wetting and drying where conditions allow. Thirty percent less methane is emitted when a paddy field is drained and rice straw is incorporated into the soil (World Bank, 2009a). This is difficult to do in practice in poorly drained natural rice soils, and straw often needs to be disposed of quickly, especially when double and triple crops are grown with tight harvest to replanting periods. However, draining once per year could reduce methane emissions by 4.1 Mt/year rising to 7.6 Mt/year if combined with straw incorporation (Padgham, 2009).

Intuitively a shift to aerobic conditions should reduce methane emission, but reductions in methane are offset by increases in nitrous oxide emissions in cyclic wetting of rice soils (World Bank, 2009a).

TABLE 6.1
Summary of methane emissions from rice (Mt/year) (Yan et al., 2009)

Region/Country	Irrigated Rice	Rainfed + Deep water rice	Total
China	7.41	0.00	7.41
India	3.99	2.09	6.08
Bangladesh	0.47	1.19	1.66
Indonesia	1.28	0.38	1.65
Vietnam	1.26	0.39	1.65
Myanmar	0.80	0.36	1.17
Thailand	0.18	0.91	1.09
Other monsoon Asia	2.32	0.67	2.99
Rest of World	1.20	0.49	1.70

The natural habitat for rice is flooded land and much of the area grown is naturally flooded, often seasonally, in the monsoon. The natural wetland area around the globe (900-1200 million ha) is more than 10 times that of wet rice, and according to EPA, rice in the United States contributes 6-9 Mt carbon every year, compared with 190 Mt/yr from natural wetlands, which account 75 percent of total US methane emissions (http://www.epa.gov/methane/sources.html). A more recent estimate of global methane generation by wetlands is 67-236 Mt/year (Yan, 2009). The actual accounting of the net contribution of methane from irrigated rice over and above emissions from seasonal and permanent natural wetland is not yet very refined, with recent projects initiated to assess the global area of rice using remote sensing (Xiao *et al.*, 2006). Estimates need to be refined by soil type and information on whether the land is irrigated, naturally flooded or rainfed. An initial estimate can be made by estimating areas of rice where second and third crops are produced under conditions that would normally be aerobic but are saturated through irrigation: at a very rough estimate of 100 million ha of irrigated rice, with a cropping intensity of 1.5 on average, around 33 million ha might represent the upper limit of potential for conversion to aerobic rice. Currently, true aerobic rice yields tend to be poor (less than 2 t/ha) and this in itself remains a strong disincentive to adoption even in situations where natural drainage conditions allow (Boumann *et al.*, in CA, 2007).

Many claims have been made for technologies such as the system of rice intensification (SRI) in reducing the extent of water use and its potential to reduce GHG production, but SRI is certainly not aerobic rice production and well-quantified data on reductions in methane emission are not available.

Irrigated pastures are important in some areas of the world (Australia and California). Livestock methane emissions can be reduced by 30 percent reduction by better pasture management (Smith *et al*., 2008). Similar reductions can be achieved through use of feed additives that suppress methane fermentation of ruminants.

6.3. THE HYDROLOGICAL IMPLICATIONS OF FOREST-RELATED MITIGATION

Deforestation and afforestation are important elements of land use change and have hydrological implications. There has been some controversy over the consequences of afforestation (Calder, 2000; 2004) and it is increasingly realized that the hydrological consequences of upper catchment afforestation need to be understood and taken in to account so that existing downstream users are not compromised. Trees generally consume more water than shorter stature vegetation growing under the same environmental conditions. Largely as a result of being perennial and deep rooted, trees can exploit a larger volume of soil to extract moisture and increase rainfall interception. Jackson *et al*., (2005) found that plantations decreased stream flow by 227 mm per year (52 percent), with 13 percent of streams drying completely for at least one year. A review of catchment experiments (Bosch and Hewlett, 1982) found that with respect to grassland, on average, pine and eucalypt plantations cause a 40 mm decrease in runoff for a 10 percent increase of forest cover. The equivalent responses of deciduous hardwood and shrubs are 25 and 10 mm decreases in runoff, respectively.

Zomer *et al*., (2007) noted that under irrigated conditions, water requirements for poplar at boundary or block plantings covering no more than 10 percent of farm area in Haryana consumed only about 1 percent (statistically insignificant) more water than under full cropping.

Larger forests also reduce advective energy locally, so although the catchment yield can be further reduced by new plantings, gross demand may not vary much. Using a global water balance model, Zomer *et al*., (2006) also report on the potential increase in water use on land suitable for afforestation under the Clean Development Mechanism (CDM). As part of the Environment and Community based framework for designing afforestation, reforestation and revegetation projects in the CDM (ENCOFOR) project, they modelled reductions in runoff ranging from 50 to 400 mm across all continents, with greatest reductions in South America and sub-Saharan Africa in absolute terms, but with much higher percentage reductions relative to total runoff in South Asia and Southeast Asia.

At global scale, more than 50 percent of the suitable area would experience a less than 60 percent reduction in runoff, meaning that there are significant implications of CDM plantings (affecting less than 1 percent of global carbon credits) and there is a strong need to factor this in to land-use change and catchment management in developing countries. More detailed studies on four catchments in South America revealed similar findings.

6.4. THE CONTRIBUTION OF AGRICULTURAL WATER MANAGEMENT TO HYDROPOWER GENERATION

The difficulties in optimising productivity of water in both hydropower and agriculture in the same basin are well known. Demand for hydropower varies in a characteristic daily pattern and is consistent, whereas agricultural water demands change systematically over a season according to aggregate stage of crop growth. Hydropower is non-consumptive, and where electricity can be generated before flow for agriculture, both benefits are obtained. However when the release required for one use does not match the other, it is usually hydropower that takes precedence because of its higher economic value. Conflicting demands can be expected to increase where crop seasons are re-sequenced to avoid peak temperatures, especially when optimal cropping times may require hydropower dams to be drawn down to levels that seriously compromise power generation.

Improved monitoring of upstream flows and rainfall, using both terrestrial instrumentation and satellite remote sensing, can be used to improve the benefits derived from both hydropower and agriculture. If flows arrive that will replenish agricultural withdrawals, then the dam operator can make ‘unscheduled’ releases (if needed and if they will be beneficial). For example, updating old operating rules and adoption of better flow prediction would allow soybean irrigation at crucial growth stages for hydropower dams in Madhya Pradesh in India.

In conclusion, it seems that there is good potential to mitigate GHG emissions, both directly and indirectly in irrigated agriculture, but that much more work needs to be done to quantify likely benefits and then pilot and test appropriate modifications to practice and management at field and system scales. The quickest benefits would come from appropriate incentive policies to minimize energy use (in pumping) and to maximize fertilizer efficiency, both good examples of ‘no-regrets’ policies. Longer-term benefits of carbon sequestration in irrigated fields are tied to the longevity of irrigation itself in addition to continued good stewardship and husbandry.

Chapter 7
Conclusions and recommendations

Chiew *et al*., (2003) provide a relevant quote from Roger Pielke's testimony to the US Senate:

> *"Policy response to climate variability and change should be flexible and sensible. The difficulty of prediction and the impossibility of verification of predictions decades into the future are important factors that allow for competing views of long-term climate future. Therefore policies related to long-term climate should not be based on particular predictions, but instead should focus on policy alternatives that make sense for a wide range of plausible climatic conditions. Climate is always changing on a variety of time scales and being prepared for the consequences of this variability is a wise policy".*

A counter argument is that better modelling of impacts is needed in order to better define and assure investment in particular adaptive strategies. Improved rainfall prediction is the key target for agricultural and hydrologic assessment. Science is heading in the right direction in understanding the processes and linkages necessary for incorporation into simulation modelling. Science, data, trend analysis and simulation power will continually improve, but wise policy will indeed focus on 'no-regrets' policies where benefits will be realized from normal economic development as well as have the potential to adapt to or mitigate climate change.

Climate change will have far-reaching effects on water management in agriculture, even if adaptive capacity is relatively strong. In developing countries, the impacts will vary considerably from location to location, but will arise through a combination of less favourable conditions for plant growth, such as more variable rainfall, lower water availability for irrigation and higher crop water demands. These stresses will be additional to the pressures to produce more food, with less water and less land degradation in the face of rising global population and changing food preferences.

Climate change will have its greatest impact on agricultural water management in further sharpening the trade-offs between conservation and protection of natural ecosystems, which ultimately support agriculture, and the allocation of land and water to sustain productive agriculture. The choices will be toughest in terms of surface and groundwater allocation where selections must be made between productive and environmental needs, as these are the two high-volume but low-value uses. Higher-value, low-volume allocations to cities, industry, rural water supply and sanitation are unlikely to be materially affected by climate change (even if the demanded volume rises slightly), but collectively these demands will reduce the volume of water for allocation to agriculture and environment.

A lesson emerging from Australia is that consultation is a crucial aspect of vulnerability assessment and in the development and understanding of feasible adaptation strategies. In this conclusion we argue for a more detailed and regionally/nationally focused assessment of climate change impacts on agriculture in developing countries, with appropriate stakeholder participation is part of this process.

7.1. INVESTMENT AND COSTS IN CLIMATE CHANGE RELATED WATER MANAGEMENT – IRRIGATION DEVELOPMENT, ADAPTATION MEASURES AND MITIGATION

The calculation of investment costs is a sure way of improving the focus and detail of strategies and actions to adapt to climate change or to mitigate its impacts. Investment is considered here because it integrates points from Chapters 4, 5 and 6, such as the typology of impacts on agricultural water management and the possible contextual responses. Some of the tensions between development and mitigation can be overcome by seeking climate sensitive or 'climate smart' development (World Bank, 2009a; 2010). Future agricultural development, (intensification, expansion, diversification) will have to balance environmental consequences with equity of opportunity to all. Early action will be required, with difficult decisions about how to share the burden and finance needed investments, and the current debates at the UNFCCC-COP show how difficult this is. As science improves, the predictability of climate outcomes will become more certain, but the development process will continue to behave less predictably and where funds for both activities are provided externally, there will be tension around conditionality and ownership.

Recent studies have tried to prioritize responses by applying a cost:benefit discipline to packages of alternative investments, and to identify where the earliest and largest gains can be obtained (ECA, 2009; Barclays and Met Office, 2009). A clear price per tonne of carbon defines a marginal abatement curve (MAC) for different types, scales and combinations of investments. Improved efficiency in the agricultural sector will generate benefit and mitigate climate impacts, and the potential for this is estimated to be highest in Asia and Europe (ECA, 2009).

The choice of investment is connected closely to assumptions about the present and future values of capital, and is underwritten by an assumption that world wealth will continue to grow in the future. The selection of discount rate is based on three factors: 1) the weight assigned to future benefits; 2) the growth rate in per capita consumption (future level of wealth), and 3) how steeply the marginal utility of consumption decreases as wealth rises (ECA, 2009). Comparisons are made between today's situation and moderate and high change scenarios in the future, identification of changes that have the highest potential economic impact (storms, cyclones, drought etc.). A cost:benefit approach focuses on losses averted and has two components – 1) evaluating and 2) implementing measures. The process followed by the ECA includes the following steps:

1. Establish comprehensive scope and objectives.
2. Prioritize hazards and locations.
3. Recognize uncertainty of future climate, but to not be frozen by it.
4. Define current and target penetration for cost-effective adaptation measures (integrated with development measures). Needs explicit definition of development goals and target benefits.
5. Focus on addressing traditional implementation bottlenecks.
6. Encourage sufficient funding from the international community.
7. Recognize, facilitate and mobilize different roles for each stakeholder.

Prioritization, especially in agricultural water management, requires an extra step to refine local climate change predictions, especially for rainfall, to minimize the range and sign of predicted outcomes, as outlined later in this chapter. The Barclays and ECA studies both identify irrigation as being a cost effective and priority adaptation with strong development attributes, but in all cases the economic focus of the analysis has ignored the impacts of climate change on water resources availability and relied on third-party assessments that have not taken these factors properly into account (see sections on Maharashtraya in India, Kenya, Ghana and Burkina Faso).

Three limitations to the cost:benefit approach have been elaborated:

- First, it can accommodate only discrete adaptation options rather than the full spectrum (for example, it does not work well to assess dykes in a wide variety of different heights, or all possible crop rotations).
- Second, it must be explicitly modified to take into account synergies or redundancy between different measures (for example, building a very high seawall against flooding and relocating all houses further back from the flooding zone are mutually redundant measures).
- Third, it represents a necessarily static view – it is based on assumptions about the price of the identified measures, economic growth, and other metrics.

Current finance to developing countries for climate change adaptation and mitigation is about US$10 10^9/year compared with projected needs of US$75 10^9/year in 2030 and US$400 10^9/yr for mitigation (World Bank, 2009a). Development assistance amounts to roughly US$100 10^9/yr at present, and so the potential for synergistic development and mitigation is both inviting and plausible. The authors of the ECA study (ECA, 2009) argue that:

- Society has sufficient information to build plausible climate scenarios on which to base decision-making.
- Significant economic value is at risk: the locations studied by the ECA will lose between 1 and 12 percent of GDP as a result of existing climate patterns, with low income populations such as small-scale farmers in India and Mali losing an even greater proportion of their income.
- A portfolio of cost-effective measures can be put together to address a large part of the identified risk. In principle, between 40 and 68 percent of the potential loss expected to 2030 in the study locations – under severe climate change scenarios – could be averted through adaptation measures whose economic benefits outweigh their costs.
- The studies reinforced the view that adaptation measures are in many cases also effective steps to strengthen economic development – especially in developing countries.
- Even in locations where climate and economic data is sparse – as is often the case in the least developed countries – it is possible to develop a robust climate loss model and quantify the economic costs and benefits of a wide range of adaptation measures.

It is suggested that the methodological approaches outlined here are useful and worth undertaking for irrigation and agricultural water management investments, provided that more detailed analysis is undertaken to define likely climate impacts in specific locations, and to properly factor in environmental costs and trade-offs in prioritising actions.

In contrast to the above, a recent preliminary analysis for groundwater management suggests a number of factors to be considered in assessing adaptation and investment options (World Bank, 2009a):

- effectiveness
- flexibility
- institutional compatibility
- farmer implementability
- independent benefits.

As the financial resources required to mitigate climate change are large, scaling up financing from its current levels will challenge public and private conduits. Pilot mechanisms, such as the Clean Development Mechanism (CDM) source their funds from a levy on trading of carbon offsets brokered by the fund. However, it has been criticized as being too fussy and too slow in disbursing funds; CDM disbursement has mostly benefited emerging industrial nations rather than provided assistance to the poorest countries: 75 percent of the revenues from sales of offsets from CDM have accrued to China, India and Brazil.

Soil carbon sequestration appears to hold some promise in mitigating GHG emissions, but broad implementation will depend on widespread adoption of practices by small farmers, mostly in developing countries. The potential transaction costs need to be fully considered in relation to the individual benefits and similar attention should be paid to understanding what those benefits are to small subsistence farmers. They are 'paid in perpetuity' for a one time lock-up of carbon, which must then be maintained safely for the future. Compliance and incentives to maintain soil carbon stocks imply further costs and thus diminution of real benefits.

The search for effective ways of scaling up finances for adaptation and mitigation covers a broad range of mechanisms, which are favoured by different camps and interests. In the industrialized countries the debate centres on whether carbon taxes are more effective and efficient than cap-and-trade mechanisms. If damages are fairly constant per marginal tonne added, then a tax is simple and efficient. Cap and trade may lead to increased certainty about emissions but to less certainty about price, and price volatility makes it hard to plan abatement. Politics underwrites much of the debate: no one likes taxes but cap-and-trade approaches require effective, well regulated and transparent markets, and are subject to rent seeking and price fixing. In practice, cap and trade initiatives have been plagued by requests for allocation of free permits, which should in theory be auctioned. Taxes on fuels (and possibly fertilizers and agrochemicals) are relatively easy to levy because of existing arrangements but are argued to be unfair by some pressure groups, such as motoring organisations.

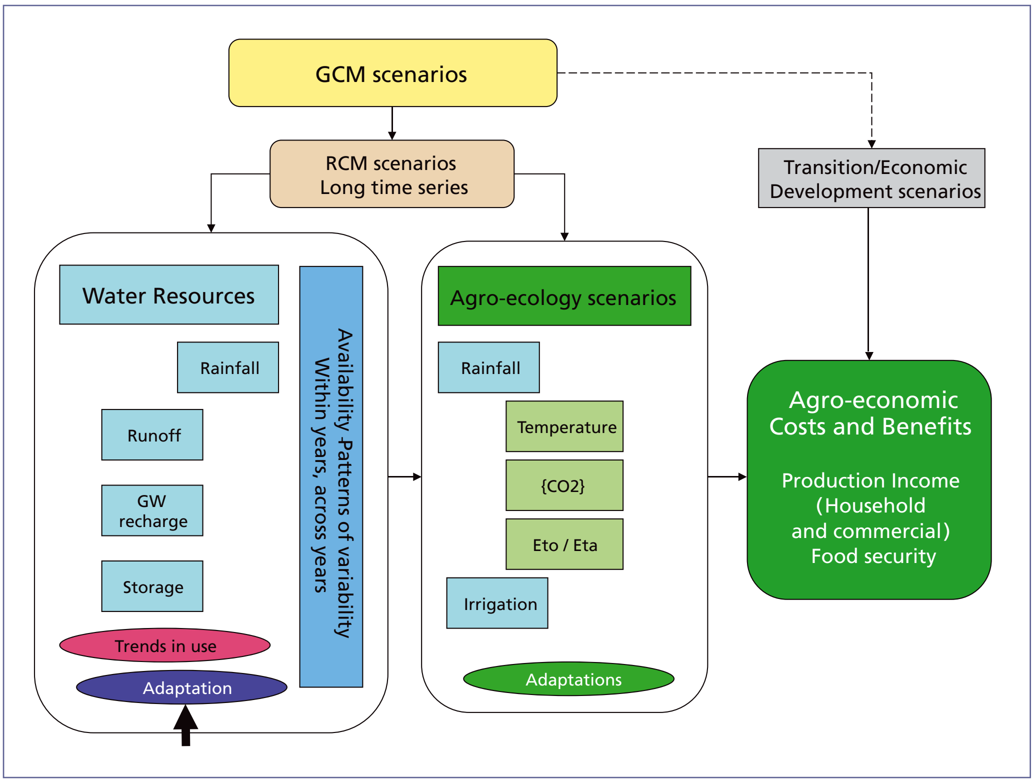
Insurance has been much touted as a response to climate change. It is worth remembering that insurance classically works to mitigate the impacts of rare events, with high risk. What are now rare events will (actuarially) fall outside of the category of rare or extreme events in the future. Therefore insurance will do little in practice to mitigate the impacts of systematic changes in climate. Insurance is also a business, and whether underwritten by private finance or by the state, insurers have to earn more than they pay out. It is possible for governments to underwrite crop insurance as a form of subsidy, but the economics of doing so will need careful assessment.

7.2. IMPROVING UNDERSTANDING OF IMPACTS AND ADAPTATION STRATEGIES IN DEVELOPING COUNTRIES

There remains considerable uncertainty about the long-term changes in temperature and precipitation resulting from greenhouse gas accumulation. The uncertainty lies in the degree of outcome and its spatial and temporal pattern. This uncertainty does not diminish the severity of the challenge nor the need for adaptation (and mitigation), but requires such strategies to be formed and prioritized in a flexible and probabilistic way. Elaboration of multiple and competing projections, especially when further expressed in probabilistic terms, is hard to communicate to achieve a common understanding about what to do in response.

There is a need to promote, assist and facilitate a broad programme of regional and national analysis to identify hot spots and priority areas for coordinated national and regional response. It is suggested here that greater precision and focus is needed in the understanding of the nature, scope and location of climate change impacts in developing country water resources management for agriculture. A generic approach is outlined in Figure 7.1 that could be elaborated to assist countries in the preparation of adaptive strategies for agriculture and water management, relying on national and regional capacities for the development and calibration of regional climate models.

FIGURE 7.1
Generic approach to determining climate change impacts and agricultural adaptation strategies
Source: this study



Recent literature (World Bank, 2009a and Nelson *et al.*, 2009) has consolidated behind one of the central arguments of the Stern Review – that adaptation and mitigation measures be integrated within development policy and programmes. A more detailed logic to support this conclusion in relation to agriculture and water management is presented in Annex 1. The complementary way of expressing this is to say that development should be climate sensitive and adopt adaptive and mitigation measures wherever possible. Since the climate change and development communities are currently rather distinct, the two ways of stating the same idea are more than just nuance. The idea of 'no-regrets' policies and actions fits very well into the promotion of climate change sensitive development.

Although some examples of 'no-regrets' policies may be obvious (for example improving fertilizer use efficiency), others may require considerable rethinking of strategic and policy options. The combined targets are challenging:

- satisfaction of food demand (household, rural and urban);
- assurance of improved nutrition;
- generation of livelihoods through agricultural activities;
- minimum degradation of ecosystems, and where possible their enhancement;
- resilience and improved productivity of farming systems in spite of climate change effects;
- mitigation of sectoral and global emissions.

There are important institutional implications arising from the logic of integrating adaptation and mitigation into development policy. Many of the present institutional deficiencies in natural resources management (including irrigation service provision) will assume an even greater importance in the future and therefore need to be addressed now. New institutional challenges arise from the complexity of climate change impacts on all sectors of the economy, with the resulting need for **stronger coordination between sectors** and the need for a lead (non-sectoral) agency, such as the Ministry of Finance, to coordinate, balance and prioritize investments:

- Specific areas requiring development are the coordination of development, adaptation and mitigation strategies in agriculture.
- More effective management and regulation is required in agriculture-environment policy and trade-offs.
- The scale of the climate challenge is such that private, public and public-private partnerships will all be essential to mobilizing capital for adaptation and mitigation. Stronger but strategic links between government and private sector will require effort in many developing countries.
- Many aspects of climate adaptation and mitigation to be put in place through intelligent incentive structures will require low transaction costs if they are to be effective.
- The removal of perverse incentives, such as subsidized energy for irrigation pumping (which contributes to GHG emissions while encouraging over-abstraction of a scarce and strategic resource), will be high on a rational agenda for reform. However, the political willpower and the institutional capacity to execute potentially unpopular policy changes will require considerable reinforcement and a deft approach.

Although there is much discussion of integrated water resources management (IWRM), from principles through recipes to practice, most developing countries still have very limited capacity in water accounting, and rarely have well-specified water allocation frameworks and rules (Turral *et al.*, 2005). It is widely recognized that this situation needs to be addressed to manage inter-sectoral competition and looming water scarcity more equitably, especially in fully allocated river basins (Molle and Wester, 2009). The rationale for effective and up-to-date water accounting is strongly reinforced by the pressures of climate change. The earlier this capacity can be practically and effectively implemented, the better. Strong institutions are required for groundwater management, which assumes an ever-increasing importance in adaptation to drought and to more variable and often declining runoff.

Transboundary and trans-national water management is especially likely to cause concern as climate change impacts on water availability, water quality and flooding begin to bite. Establishing effective transboundary water management prior to the development of serious climate-change-related conflicts is therefore a priority (Timmerman, 2008).

The coverage, continuity and range of climate and natural resources systems monitoring data will need considerable enhancement to provide a sound basis for impact assessment, monitoring change, and informing adaptation and mitigation activities (World Bank, 2009a). Such data will have to be well managed and be freely available to public and private users. This, of itself, will require some concentrated and careful institutional development.

Many countries have yet to acquire strong capabilities in climate change science, especially in modelling and scenario assessment (The Working Group on Climate Change and Development, 2006). The logic presented earlier argues strongly for a detailed and local focus in forecasting impacts and guiding adaptation and mitigation. A strong local capacity is therefore needed to understand climate change science, draw up appropriate scenarios, and above all, communicate the results to government and to the general public.

There is also a need to promote and assist in the development of adaptive capacity. Initially, this could focus on promotion and capacity building in water resources accounting, assessment and planning, with a view to helping clients establish formal water allocation systems, and to develop sufficient diagnostic capacity and context to understand the detailed likely impacts of climate change.

A Historical Climatology Network (HCDN) has been established as a subset to existing meteorological and hydrological stations across the United States (USDA, 2008). Biases and errors arising from changes in instrumentation and adjacent conditions have been removed. Currently there is major investment to extend and adapt the monitoring network for climate change applications, incorporating snow hydrology through SNOTEL (snow telemetry), and creating the Ameriflux network (200 Eddy correlation stations across the country). The Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture in Soil Climate Analysis Network (SCAN) proposal seeks to establish soil moisture measurement at 1 000 sites, partly to improve terrestrial feedback information for GCM modelling. While it is not possible for many countries to afford or perhaps even staff similar networks, some serious consideration should be given to ways of emulating this initiative, for instance across the breadth of Africa.

A small but useful task would be to popularize useful newer metrics for estimating the impacts of climate change. There are many options, but two examples related to glacier impacts include the 'centre of volume of runoff metric' (USDA, 2008) to examine shifts in snowmelt sourced flows and the snow-to-precipitation ratio. Broader use of both metrics will require better measurement in mountain areas elsewhere in the world.

As considerable hydrologic input will also be needed, partnerships will be required with national and international bodies, in particular those associated with the International Hydrology Programme of UNESCO, by ensuring the practical relevance of outputs and findings for irrigated agriculture. Serious consideration needs to be given to the collection of data and to the substitution of historical data in many regions. One way to help stimulate this might be in assistance to establishing and maintaining regional networks, in collaboration with the development banks.

There is therefore a need to establish a broader base of support for impact analysis and adaptive strategy formulation, through the development and provision of tools in addition to the analytical framework suggested above. This could include more detailed modelling strategies, risk analysis and prioritisation, and development and promotion of climate forecasting tools for different regions. At the crop and field scale, better calibration, development and adaptation of crop models are used to assess future productivity under climate change scenarios. A particular focus would be on major developing country crops that are not well described in the current literature and databases.

7.3. IMPROVING FOCUS - A REGIONAL AND NATIONAL APPROACH

It is important that the spatial and temporal trajectories of climate change impacts be more tightly bounded at regional and national scales. There is increasing consensus that the climate models themselves are doing a more reliable and effective job of predicting real historical climate, and that spatial resolution can be improved through a variety of approaches, using both regional climate models and statistical downscaling (Baron et al., 2005). The breadth of outcomes under different forcing scenarios may remain broad, but if the spatial patterns at regional scale are better differentiated, then it becomes possible to assess relative risk, and to prioritize different areas for investigation and adaptation.

Therefore, mapping vulnerability becomes a key task at national and regional levels. Some countries, such as the United States, Australia, and northern European countries, have been doing this for the past ten years, but although there have been a few externally funded investigations, such as the ADAPT project of the short-lived Dialogue on Water and Climate Change (2001-2005), there has been little done within developing countries themselves.

Irrigation in particular and agricultural water management in general, are highly impacted by temperature change and changes in the water cycle. These changes will be profound and negative in the areas already most under stress. Current predictions of future food production and security are undermined by the likely extent of reduction in utilisable water resources, as predicted, and seemingly emerging in Australia, a dry continent with the greatest variability in climate and hydrology in the world.

The key drivers of water and food stress remain population growth and changed food preferences, with a consequent greater demand for water – in terms of rainfall on catchments, runoff diverted from rivers and captured in dams, and groundwater.

There are many areas of the world that will not suffer increased stress, and may even have short- and long-term benefits in agro-ecology and growing conditions. However, climate change applies significant additional stress in precise locations, which need to be identified and characterized more specifically, especially in the more vulnerable developing world. From an agricultural perspective, and especially in irrigation or water management terms, these comprise:

1. Large surface irrigation systems fed by glaciers and snowmelt (most notably northern India and China);
2. Large deltas, which may be submerged by sea-level rise, 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, which are seasonal storage systems in the monsoon regions, and where the 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.

Better analysis of climate change impacts on these food production systems needs to be focused on precise regions and localities, where it is possible to predict with some certainty the combined effects of increased temperature, changed precipitation and water resources availability, and nature and frequency of extreme events (droughts and floods). Figure 7.1 presents an overall process based on regional climate modelling, and other downscaling techniques, to better predict likely climatic changes in specific locations and their impacts. The main objective of this intensive approach is to reduce the uncertainty in rainfall prediction derived from GCM modelling.

With respect to irrigation, climate impact analysis should be set in the context of other demographic, social, economic and water resources management situations at an appropriate scale. Careful regional analysis should be undertaken, preferably using regional scale climate models (50–75 km grids or finer) and the best statistical methods for downscaling spatial data. A clearly identifiable challenge is to improve the coverage, availability and quality of data required to do so.

From this point on, a probabilistic analysis should identify the areas most at risk climatically, and this should be coupled with other indicators of stress and adaptability to identify and prioritize areas and communities at greatest risk over different time horizons. In developed countries, great emphasis has been placed on stakeholder consultation and mobilisation in understanding vulnerability, risk and potential adaptive strategies. The Stern Review commends this approach to developing countries too.

Since AR4, there has been some work on ensemble RCM modelling nested within ensembles of GCM simulations (Kumar *et al*., 2006). A more in-depth review of this work is necessary, following the approaches taken by Naylor *et al*., for monsoon change in Indonesia (2007), the regional analysis across the United States (USDA, 2008) and the Murray-Darling Basin Sustainable Yields Project (CSIRO, 2008). It would be useful to focus the lessons (in terms of benefit, effort and cost) on strategic locations, for example rivers sourcing water for irrigation from the Himalaya and conduct much more detailed analysis, including the impacts on glaciers and groundwater.

The selection of appropriate strategies can become complex, not least because of the trade-offs in costs and benefits within different options as discussed earlier. A more formal approach to evaluating options within a given context is presented in outline in

Annex 2, making use of decision trees which can be constructed and reconfigured for different contexts.

7.4. INTERNATIONAL SUPPORT TO ADAPTIVE STRATEGIES

This document has identified weaknesses in the existing information bases, the institutional arrangements to oversee water resources management and the sustainable provision of water to agriculture. Existing information and knowledge programmes, including such products as FAO's AQUASTAT can help to provide a footing for much-needed institutional development in water management. AQUASTAT itself can be expanded to include groundwater information and can provide assistance in establishing frameworks for rational water accounting (both use and resource availability) in many client countries. At scheme operational level there is broad scope to apply management software to: 1) calculate water requirements (for example, FAO's CROPWAT system and its successor AQUACROP) and 2) diagnose performance for modernisation of canal systems (for example, the MASSCOTE/RAP assessment tools).

International specialist agencies can promote better understanding of the water resources and agriculture implications of climate change and assist developing countries to improve regional and local projections of impacts in order to develop planned adaptive strategies. The international community can act as a 'clearing house' to include climate change science and projections into its scenarios and support for global food security and similar national programmes. Since climate change impacts may be difficult to internalize in some countries, given the host of other pressures on water resources and agriculture, there is need for a broad level of advocacy.

Advocacy would lead on the integration of climate science with agricultural water management and include a strong focus on the preservation and enhancement of natural ecosystems, which are tightly bound to the development and management of irrigated agriculture. This will see further development of an integrated perspective at river basin level, and also across a spectrum of irrigated and rainfed agriculture.

Two fundamental issues to resolve are how yields and production are likely to change in the future, and how best to provide concrete examples for the extent to which crop adaptation to higher temperatures is possible. The international climate change literature is pessimistic, predicting significant reductions in yield and production, even with adaptation strategies. Recent modelling on global food security without climate change by FAO, CA, IFPRI and others assumes continued possible improvements in land and water productivity, from a performance base that is well below potential in developing countries at present. It will be important to resolve the potential for increases in productivity against a declining potential due to climate change. A separate strand of effort could therefore be directed to the establishment of a public access database on climate adapted crop varieties. Some considerable thought and preparation would need to go into the structure of such a database, and into an easy and accessible means of abstracting relevant data. It would be very useful if the database were validated by some testing and evaluation of the field performance of adapted varieties, directly or from secondary data.

There is need for a number of high impact and strategically chosen pilot projects to improve institutional capacity for climate change adaptation. These would have to be well-resourced, long term and have high-level buy-in from the partner country. It seems clear that climate change adaptation and mitigation will be conducted most effectively if fully internalized by individual countries, rather than being an imposed, short-term funded agenda conducted largely by outside parties.

7.4.1. Planning adaptation strategies

Irrigation sits in a strategic planning context that must consider risk; food security; food type; industry type; balance of water demands and environmental impacts; substitutability with rainfed agriculture and associated environmental trade-offs. It is clear that a differentiated and detailed regional analysis is needed between areas emerging with a need for more irrigation, and those parts of the world where there is already a heavy reliance on irrigation and which will become more vulnerable or risky in their own right.

It is timely to re-evaluate the strategic role of irrigation in:

- drought proofing of staple crops;
- high-value agriculture, with particular consideration of urban demand and changing food preferences;
- high nutrition value agriculture targeted at subsistence farmers and the poor;
- export earnings versus import substitution;
- minimizing forest loss and other ecological and climate change sensitive impacts.

The contexts for analysis and development of balanced adaptive strategies are identified in the typology given in Table 4.2 and can be further elaborated by the existing level of water resources development and the nature of groundwater resources and use. The target is to develop an appropriate investment plan for climate sensitive development that is based on future agricultural performance and the probable availability of water resources (in the form of rain, stream flow, surface water and groundwater storage).

More focused regional and local analysis can be undertaken to better understand adaptation and mitigation options, as well as supporting strategic planning options. The analysis is complex, but increasingly in reach with continual improvement of simulation models in terms of calibration; incorporation of processes (such as land surface: atmosphere interactions); and resolution. Ensemble modelling with both GCMs (as drivers) and RCMs (as better predictors of spatial pattern) can lead to more focused and constrained prediction of impacts. The most important of these is the prediction of amount and distribution of rainfall, through better coupling of GCMs to RCM and other downscaled analysis using crop models.

The importance of glaciers for the water resources available for irrigation cannot be understated, albeit with large regional variations: it is becoming clear that the contributions of snowmelt to river flows vary from small (less than 5 percent of mean annual flow) to significant. Precipitation changes are likely to occur in glaciated areas, which may moderate or exaggerate future stream flow patterns. Our understanding of hydrology in mountain and glaciated areas remains crude, and further work is needed in understanding process, spatial distribution of process and sources of stream flow. These are probably long-term challenges.

Simulation of impacts should take better account for landscape level effects on runoff (water availability) and groundwater recharge. Landscape effects incorporate associated socio-economic choices that can be effectively captured in existing catchment simulation models, resulting in better risk assessment in determining a desirable and effective balance between irrigated and rainfed agriculture.

At field level, we require better prediction of temperature and evaporation effects on crop yield limits and failure rates, to better assess likely net improvements or losses in production and water productivity within irrigation systems. This analysis has to be conducted over a long time series to elaborate the impacts of increased climate variability on the reliability of production and the frequency of failure, due to likely combinations of erratic water supply and heat waves. For example, will irrigated microclimates be cooler than predicted by GCMs and therefore maintain current levels of productivity as assumed in the recent World Bank Morocco study?

The impacts of climate change on rice production will affect the lives of millions of farmers and consumers. Some of the considerations for adapting rice production systems and incorporating mitigation are listed below:

- Assess reduction likely in paddy area due to reduced runoff or increased flooding, as a function of enhanced monsoon effects;
- Determine core wet paddy areas under climate change scenarios;
- Assess areas that will remain under rice in the wet monsoon season, but be planted to dry crops outside of it;
- Develop methodologies to assess consequent likely reduction in methane emissions and, where possible, incorporate soils information into remote-sensing-based estimates of rice area;
- Assess areas where N^2O output is likely to increase, and quantify trade-off between managing for methane (CH_4) reduction and N^2O reduction;
- Differentiate yield impacts across a new rice landscape;
- Assess prospects to enhance soil carbon storage in wet and dry rice systems, and look at risks in terms of net GHG emission;
- Determine rice irrigation strategies and crop diversification strategies to suit.

Any changes from rice dominated surface irrigation systems will require considerable re-engineering for dry footed crops to: increase canal density and extent; add sufficient cross drainage works to maintain channel integrity; and ease transport and traffic management. Such system remodelling presents opportunities for land consolidation and mechanization.

Development planning for specific region should also attempt better quantification of how mitigation can be achieved in irrigated agriculture through minimal input use (mostly N-fertilizer) and fossil fuel use. Innovative thinking is required to encourage integrated farming systems that combine irrigation with rainfed production with livestock rearing and associated nutrient cycling. While this is easy to conceive for large farms, such as are found in northern Europe and the United States, it will require a nuanced and clever approach in situations where there are large numbers of smallholders. The feasibility and productivity of organic farming approaches in irrigated systems merits considerable further research in Asia and Africa, and should be complemented by similar work to improve carbon sequestration on irrigated land.

It is important that planners in developing countries develop the capacity and have access to the tools to undertake this analysis, and to shore up the information base for decisions – particularly with respect to actual water use and current resource availability. Various adaptation scenarios can then be investigated in relation to 1) likely runoff, 2) likely demand for evapotranspiration, and 3) groundwater availability and use. Crop model-based scenarios of production can be nested over this analysis to evolve the production outcomes and the values of that production, in addition to the likely range of impacts on the farming community. Various adaptation strategies and their outcomes can then be investigated across different scenarios of water availability through changed storage and operational regimes, coupled to changed crop selection and seasonality. Such scenarios need to be assessed against the existing range of climatic variability applied to changed climate, and complemented by stochastically generated changes in expected climate variability.

Where there is evidence or a likelihood of a step-change in climate, more drastic scenarios should be added – which will be as much about significant change in variability as in median and mean water availability. International effort to assist developing countries with assessing climate change impacts on agriculture should work more closely with environmental agencies to foresee and shape future trade-offs between environmental and agricultural water allocation.

7.4.2. Farmers' perspectives in adapting to climate change

This review has stressed the importance of links between strategic, system and farm level development. Although farmers will intuitively adapt to climate trends and more extreme variability, traditional knowledge that has served well for centuries may lose its edge. Amid the scientific excitement of climate change, we should not forget farmers' daily realities and points of view.

As water becomes increasingly scarce, and more expensive, it would be logical to specialize and intensify production to increase returns ($ productivity), although at the cost of greater year-to-year risk and higher capital investment. Further, the long-term risk associated with capital investment will also increase. Insurance can hedge risks against extreme failures, but is less likely to protect farmers from a generally more extreme climate. Engineered approaches to limiting crop water demand and heat stress (such as shade houses) will only be afforded by the better-off and more commercially oriented farmers. Those who do intensify are likely to require more secure water supplies, and will need some form of high security water right or access (groundwater). Few irrigation systems have explicit allocation rules, or differentiate between high and low security water supplies, let alone have different tariffs charged for them. Absenting reforms in water pricing and water rights, we can expect that farmers will evolve other means for securing water supply for higher risk ventures.

Higher commodity prices may improve the terms of trade for farmers and provide incentives to intensify and invest, but recent experience (2007) has not been encouraging in that farmgate prices did not rise in many parts of the world, even when prices of commodities doubled. The increasing dominance of supermarket chains in setting prices to farmers and consumers will have to be monitored carefully.

Livestock production has always been integral to subsistence and commercial farming within irrigation systems. Farmers will rightly continue to value livestock as a high-value product, a source of protein and a hedge against short-term drought and crop price fluctuations. The imperatives to increase productivity of land and water, and to minimize the greenhouse footprint of agriculture, should not become obsessed with cropping and forget the importance of livestock in the livelihoods of the poor.

The poorest subsistence farmers will face tough pressures to produce more, in more adverse conditions, with limited capital resources. At the same time, they will be expected to manage their production in a more environmentally sensitive way. Widespread and sustained adoption of drought tolerant and other improved crop varieties will be enhanced if farmers are able to provide their own seeds, and not become locked into buying seeds every season. Dry-land farmers and irrigators will require better use of rainfall and access to better information to adjust seasons and planting dates. Similarly, they will benefit from effective forecasting of storms and floods, and the seasonal likelihoods of the sum of all possible catastrophic events – drought, cyclone and flood.

For example, ENSO and other hydrological analysis increasingly allow useful prediction of drought and higher rainfall years (although this is less certain between extremes). In Australia, commercial services providing good-decision support to farmers have been available for more than ten years, but are used by only a small proportion of them. Reviews of FEWS and other regional climate forecasting efforts in Africa have noted shortcomings in the use and usefulness of forecasting. ENSO-related signals have progressively weakened in Indonesia over the last 30 years, but still provide a good guide to the start dates of the monsoon (Naylor *et al.,* 2007). Developing countries should be supported in assisting with the development of farmer-oriented programmes, which in this case might include:

- explaining El Niño and predictive methods to farmers;
- gaining trust in predictive ability, and in associated advice;
- making the right decisions in response to warnings;
- improving the timing of warnings.

It may be possible to reduce crop water demand by adopting mixed agroforestry systems with shade trees to reduce crop canopy temperatures, but farmers will need good advice on which shade trees give good protection, transpire modest amounts of water, and do not compete with the crop to the point that net benefits are fewer than those for open cropping.

The potential for carbon sequestration in soils has been noted, but successful global mitigation will depend on widespread adoption of good practices that reverse current trends in nutrient and organic matter depletion in agriculture. It is widely recognized that the transaction costs of monitoring small-scale projects and subsistence farmers exceed the value of benefits, so good incentives for subsistence farmers will be required.

There will be strong pressures for individual farmers to harvest more water by planting deeper rooting crops, intercepting and storing more runoff. This should happen spontaneously but will also be promoted through soil and water conservation (watershed development) programmes. There will be costs in terms of reduced downstream flows (catchment yield) in both surface and groundwater, and these apply to more distant farmers. Land use will play an even greater role in river basin management in the future; balancing the equity of water use among established users will take on a new twist and imply new challenges for participatory management.

Adaptation strategies need to be thought through to very practical levels of detail, and therefore close consultation and collaborative development with farmers will be essential to achieving successful and balanced outcomes.

7.5. ADDRESSING IDENTIFIED KNOWLEDGE GAPS

The uneven availability of long-term climate and hydrological data contributes to a major knowledge gap. It is much harder to address, as new monitoring will help establish trends and the characteristics of climate change, but without a baseline. Monitoring networks can increasingly be automated and data downloaded remotely. The cost of doing so is rapidly becoming cheaper, although the security of remote and automated stations can be precarious, and remote data transmission is sometimes viewed with distrust by national and local governments. There remains good scope to further operationalize remote sensing as a monitoring and prediction tool in many developing countries, and some notable initiatives, such as the European Space Agency (ESA) TIGER SHIP programme, are working in this direction.

The allocation and accounting of water resources in many countries could be usefully improved. FAO periodically convenes expert consultations on various aspects of agricultural water management, and could justifiably do so for water allocation and accounting.

In agriculture, forestry and fisheries, a need for a comprehensive assessment of climate change impacts on agriculture and food security was identified, resulting in the elaboration of adaptive strategies, for different scales and scenarios. In tandem, there needs to be better identification of highly vulnerable micro-environments and households, and enumeration of well-tailored and practical coping strategies, across a range of economic and agronomic perspectives. Existing work on poverty mapping and alleviation should be very useful in this regard.

Crop science needs to investigate the response to enhanced CO_2 of other important developing-country crops such as millet, roots and tubers. Similarly, further work is needed on the impacts of CO_2 enrichment on the nature and dynamics of pests, weeds and diseases for a large range of crops. It is suggested that there should be a comparison study of crop models, but this stops short of the suggestions made above. If the studies on developing-country staple crops are advanced accordingly, it would be possible to combine some model improvement directly with this research.

Fundamental and applied research is required to develop effective practices for carbon sequestration in tropical and other high turnover soils, and in irrigated soils. Globally, the delineation of soil types and properties is poor and coarse, and better mapping is required for many reasons, not only in identifying soil carbon sequestration potential. FAO's strong capacity in soils mapping could be used in assisting its member countries in improving their inventories and approaches.

Another natural resource that is rarely well mapped and characterized is groundwater. Aquifer connections are often complex, and defining and understanding surface-groundwater interactions may require considerable effort. Improvements are needed in order to assess available resources and manage use, or at least understand the water balance in areas of significant use. Groundwater is an important strategic resource that will require careful management under climate change, and in turn will require much improved institutional mechanisms for sustainable management. These in turn will require that all users have a clear understanding of the nature and state of the resource.

In certain instances, in situ adaptation will not be possible, and farmers will eventually relocate from salinizing, desertifying or flood-prone areas, or from deltas that are encroached by sea-level rise. This requires investigation, quantification and forward planning. Similar ground-preparing efforts will be needed to examine tough trade-offs between water allocation to agriculture and the environment under climate change, and to more fully understand the relative costs and benefits of enhanced water storage in groundwater and surface water.

Finally, the impact of climate change on biofuel crops and better assessment of their carbon balances in different situations would help in planning mitigation and adaptation strategies and in finding an appropriate, productive and economically optimal balance. The goal of synergy between adaptation, mitigation and sustainable development strategies requires an analytical framework with a sound economic basis.

7.6. MITIGATION OF GREENHOUSE GAS PRODUCTION THROUGH AGRICULTURAL WATER MANAGEMENT

Two areas in which work could commence immediately are identified.

Work could begin by completion of a GIS-based inventory of the locations where different types of mitigation activity are possible (methane reduction in paddy production, improved plant and soil sequestration in irrigated agriculture). Carbon balances could be derived from this, but better information on the actual performance and potential of different initiatives is probably required, especially with regard to the restoration of carbon contents in irrigated tropical soils.

It would be useful to convene a series of policy workshops that bring attention to the production, and hydrological trade-offs of different mitigation strategies at river basin scale, accounting for GHG benefits, hydrological changes and the consequences for agricultural production. Scenarios could include the planting of biofuel crops. The mitigation and production aspects can be consolidated under an economic analysis that values all components, and in terms of food self-sufficiency at household and national scales – in order to elaborate the trade-offs, and understand the broader consequences in terms of trade and other parameters of political feasibility.

7.7. COOPERATION BETWEEN INTERNATIONAL ORGANIZATIONS AND DEVELOPMENT PARTNERS

A number of policy clusters present opportunities for collaboration and concerted development in relation to climate change: food security, poverty alleviation and economic transitions. The challenge will be to make development assistance climate smart across such clusters as well as a wide range of interested parties, who may often have more time-bound agendas. Aid coordination has often proved to be a chimera, and the added nuances of climate change adaptation will certainly pose additional challenges to this desirable goal.

Some key questions to answer include:

- What do these policy clusters mean in terms of climate change in a given context? (It will be helpful to be very concrete.)
- What sort of non-traditional new partnerships are possible?
- What do different key organisations have to offer and what can they bring to the table for mutual benefit, with minimal competition and duplication of effort:
    1) statistics;
    2) analytical capacity for global trends, data, trade;
    3) convener or provider of scientific expertise (expert consultations, technical cooperation, research) at a range of levels from action through to policy;

4) practical forecasting capacity;
5) country office networks;
6) past staff and collaborators;
7) implementation capacity on the ground;
8) funds.

There is clear need for the international community to focus on the two most climatically vulnerable regions – Africa and South Asia. The established scientific capacity in South Asia is broader than in Africa and has stronger working links with academia in the OECD countries. This argues for a primary focus on Africa with a secondary one on South Asia. Whatever the level of established capacity and resources available, it will be vital to strengthen local capacity as rapidly as possible. In Africa, significant use of western 'contractors' (universities, etc.) is not ideal and those in South Africa are probably stretched already. Innovative funding mechanisms could be developed to retain and employ the myriad graduates and post-graduates trained elsewhere.

General capacity development in analysis, forecasting and provision of generic solutions could be developed on the basis of existing projects and initiatives, including:

- cooperation in forecasting (FEWS: USGS and NASA);
- pilot projects to implement the methodologies outlined in this publication in selected locations. It would be sensible to regionalize efforts by type of impacts. An example for Africa could include a focus on:
  - Eastern Africa - Ethiopian Highlands;
  - Southern Africa - Zambia based on existing work in Kafue or other longer-term integrated projects looking at water, agriculture and environment;
  - West Africa – Burkina/Ghana/Niger/Mali, where considerable research has been conducted in climate related science (such as the Global change and the hydrological cycle (GLOWA) Volta Project by ZEF);
  - North Africa – Morocco or Algeria.

Practical research on agricultural adaptation through cropping systems research and through crop breeding and testing is required, as are partnerships between the CGIAR centres and research units with established capacity in global and regional climate modelling to evaluate and test resource constraints and options. Physical testing may be possible in agro-ecological conditions similar to those likely to be encountered in the future. Such research support and capacity building should be aimed at mainstreaming climate-smart development into local agencies and policy.

The establishment of monitoring networks for climate and hydrology across sparsely covered continental areas would need to include considerably more detailed mapping of groundwater and associated geology, as well as establishment of robust hydrometric networks. There is great potential to enhance and infill these networks using state of the art remote sensing technologies, where NASA, USGS and the ESA are already playing key roles in the development and application of science.

In addition to recent advances in digital mapping of soils (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008) soils maps lack detail in some regions the physical and chemical characteristics that are important for agriculture. There is again great potential to combine modern remote sensing technology with well-established survey and interpretation of aerial photography. A coordinated effort is required to prioritize soil survey in relation to agricultural development and adaptation to climate change, to organize ground campaigns and to develop and enhance databases. At the same time, it would be useful to assess their potential for carbon sequestration and identify locations where pilot sequestration projects can be tested. In the fullness of time, this could lead to pilot projects to sequester carbon on a large scale, encompassing the required institutional development and payment/compensation mechanisms, in conjunction with a revised focus of the Clean Development Mechanism and its successors.

Although these suggestions have a scientific and informational bias, considerable effort will be required in making data available and useful, and a good place to start would be on existing drought and flood forecasting initiatives across the continent. The recent Barclays/UK Met Office publication 'Storm Shelter' (2009) points the way for interesting partnerships and approaches to climate-smart development in Africa, even if there are technical questions concerning the evaluation of some of the agricultural and irrigation-related measures proposed.

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Annex 1

Overall logic for assessing development, adaptation and mitigation options in agricultural water management and irrigation, in response to climate change

The pressure and rationale for economic development to benefit the world's poor will remain a major goal for mankind as populations continue to rise. The provision of adequate food, water and sanitation is one of the most basic aspects of continued economic development. Coupled with changing dietary preferences, it is estimated that world food production will have to double by 2050 to meet likely future demands (FAO, 2007; CA, 2007 (Ch. 2); Nelson *et al*., 2009).

This calculus does not factor in climate change, which introduces further pressures and constraints. The satisfaction of future needs, even without consideration of climate change impacts, has major implications of its own for land use, water use, expansion of irrigated and rainfed crop areas, and their corollary impacts on forest and rangeland areas (MA, 2005; CA, 2007):

1. Sustainable use of increasingly pressured natural resources (land and water) requires careful consideration of competing socio-economic uses and values, and of the trade-offs (short- and long-term benefits: financial costs; and environmental costs) between different mixes of land and water development and the intensification of production on existing lands.
2. Agricultural development that relies on intensification through the use of fossil energy (transport, traction, production of fertilizers (N) and agricultural chemicals) will, in turn, contribute further to climate change forcing through emissions of CO_2, CH_4 and N_2O.
3. Further expansion and intensification of agricultural production has the potential to continue existing trends in the degradation of soils and their long-term productivity (increase of salinity and acidity; loss of nutrients; and loss of soil carbon).
4. In contrast, there are significant hopes that soil carbon storage can be enhanced to minimize net agricultural emissions and possibly to mitigate emissions from other sources (industry, transport and energy for the built environment) (Smith *et al*., 2008; USGS, 2002; USDA, 2008).

Climate change impacts on agriculture will include:

1. Rising **temperatures** that will result in higher evaporation rates; shorter crop seasons in mid and low latitudes, but longer crop seasons in the higher latitudes. There will be potential to increase the number of cropped seasons per year at all latitudes, where sufficient rainfall or water resources permit, although yield

potentials for most crops in the mid and low latitudes will decline due to shorter seasons, higher respiration rates, and increased evaporative demand. There will be corresponding declines in potential water productivity, with and without CO_2 fertilization, for which the prospects of mitigating loss of yield potential seem to be diminishing (Long *et al.*, 2005; USDA, 2008).

2. Less clearly understood and more spatially variable **changes in precipitation**: The general trends in precipitation predicted by AR4 modelling exercises are gradually being corroborated by analysis of trends in some areas (declines in northern Africa and southern Europe, for example (Allison *et al*., 2009)). However, there remains strong disagreement in the directions, extents and spatial patterns of changes in precipitation. The fundamental reasons for this are that most GCMs used so far do not couple land use and land surface interactions that dominate weather at regional and local scales – topography, physiography, elevation and land cover (IPCC 2007; Allison *et al.*, 2009). GCM models predict intensification of the hydrologic cycle, with more extreme behaviour around the mean (more intense storms and longer dry periods in between) for both net reductions and increases in annual rainfall. Any meaningful assessment of the agricultural impacts of changed precipitation regimes requires more precise temporal and spatial prediction, which should be made with a higher level of certainty than is the norm at present.
3. Direct competition for land and water resources for the production of biofuels, in part related to GHG mitigation strategies (de Fraiture, 2008; FAO, 2008b; USDA, 2008).

Climate change **impacts on water resources** will reflect changes in water balance brought about by increased evaporation rates and changes in precipitation.

1. Where rainfalls decline there will be much larger corresponding reductions in surface runoff (CSIRO 2007; Milly *et al.*, 2005). In all cases where rainfall, runoff and groundwater recharge decline, current tensions between agricultural and environmental allocation of water will be magnified. It is becoming clear that allocation policy in the future will face considerably tougher dilemmas in balancing environmental flow allocations with those in agriculture (DSE, 2007). In general, it is likely that other high-value demands can be satisfied relatively easily, as the quantities demanded are small in relation to those for agriculture and natural ecosystems. The very definition of a natural eco-system under climate change will provoke much thought and discussion. Where surface runoff declines, groundwater recharge is also <u>likely</u> to decline.
2. Where rivers depend on glacier melt, shorter-term increases in runoff because of warming, and retreat of glaciers will be replaced by long-term declines in yield (Barnett *et al.*, 2005, Kulkarni *et al.,* 2007). Quantification of such changes is as yet poor, resulting from the variable contribution of snowmelt to total annual flow. It is likely that low flows (in summer) will fall, and the timing of seasonal flows will move from spring to winter flows. There is also an improving understanding of the complexity of mountain hydrology and the spatial extents of different runoff processes within large mountain areas (Fowler and Archer, 2005).
3. As rainfall regimes are expected to become more extreme, with more intense rainfalls and more frequent high-intensity rainfall, offset by longer periods of drought between rains, the following can be anticipated: reduction in base flows; increased frequency and severity of flooding, although where groundwater recharge is determined mostly by flood plain flows, then groundwater recharge may be stabilized or enhanced; increased frequency and severity of within-season, seasonal and annual droughts – and needs to adapt agricultural water management to those different time scales. Where rainfall increases, the frequency of flooding and high flow events is expected to increase.
4. The main implications for water resources for agriculture are:
   - Risks of within and across season water stress increase. This is particularly true for rainfed agriculture in low rainfall zones.

- Risks of flooding and erosion also increase.
- Water supplies for irrigation will become less reliable.
- Enhanced water storage will be required to enable supplies to meet deficits reliably within season, between seasons and across years. Overall, water supply security for agriculture will fall in all areas of declining rainfall, and may also do so in some cases with increasing rainfall.

Downscaling techniques (empirical, statistical and model based, using Regional Climate Models) offer considerable improvement in the prediction of likely impacts on agricultural production systems, and for irrigation in particular (USDA, 2008; Kumar *et al.*, 2006; Naylor *et al.*, 2007). However, they are still governed by potential errors and inconsistencies in the GCM output that drives them. This can be addressed through:

- Ensemble GCM modelling to develop probabilistic predictions.
- Improvement of GCM structure and processes to included land-surface interactions.
- Possible use of GCMs with higher spatial resolution.
- Ensemble modelling of RCM simulation to refine probabilistic outcomes at local and regional scales.

Although climate change will reduce and limit potential land and water productivities, current levels of productivity are, in many instances, considerably below their potential[2], limited by water, nutrients and management techniques. Selection of agricultural development and adaptation options will depend to a considerable extent on their potential to realize higher real-world yields and water productivities within the limits imposed by future climate. Clearly, where cropping systems can be 'transferred' from existing AEZs/conditions to other locations that experience similar conditions in the future, then adaptation may be relatively straightforward.

Achieving higher real world yields and water productivity requires better provision for and management of limiting factor inputs. At the margins, notably in the semi-arid and arid mid-latitudes, the challenges of moving to yet hotter and drier conditions are daunting. There is uncertain potential to breed crops that have drought resistance, improved yield potential (temperature tolerance) and even increased water use efficiency (Huntingford *et al.*, 2005; Porter and Semenov, 2005; and Rebetzke *et al.*, 2008). There is considerable interest and activity in conventional and enhanced crop breeding, as well as in transgenic manipulation (GM crops). Achieving these goals is highly desirable, but positive outcomes are not a foregone conclusion and the time frames could be lengthy (Padgham, 2009). A sober reading of recent crop physiology literature suggests that it would be unwise to expect a silver bullet in terms of a second green revolution.

2 This is broadly true in the semi-arid, arid and humid tropics and sub-tropics. In northern America and Europe, agricultural productivity is much closer to its full potential.

Annex 2
Evaluating and selecting options for climate sensitive development

Better analysis of climate change impacts on food production systems needs to be focused on precise regions and localities, where it is possible to predict with some certainty the combined effects of increased temperature, changed precipitation and water resources availability, and the nature and frequency of extreme events (droughts and floods).

The typology (Table 4.2) developed to this point, defines specific contexts where irrigation (and other forms of agricultural water management) are 1) important; 2) have a specific form (with likely limitations on adaptation options); and 3) are vulnerable to specific combinations of climate threats (sea-level rise, reduced runoff, loss of water resources, heat waves and droughts, cyclone activity). Most of the examples in the typology do not yet include detailed and specific local analysis that would be required – for example the contrasting conditions and solutions for the Red River and Mekong Deltas (Delta category) in Vietnam.

1. The existing level of water development is an important second level of the typology that has not thus far been explicitly stated. The literature on adaptation contains many references to the benefits of increasing irrigation efficiency (usually not defined) as a means of saving water, with no reference to basin level water use and the possibility of making real net water savings at basin level.
2. A third level of the typology could (in nearly all categories) be extended to groundwater resource characteristics and use. Groundwater becomes an increasingly attractive mode of storage under climate change scenarios – to minimize infrastructure costs, maximize flexibility, and manage both short- and long-term variability in surface water supplies.

A decision tree can be mapped to help define the climate change impacts on crop production; this will be based on better elaboration of specific changes in temperature, rainfall, water resources availability, to arrive at solutions that are properly tailored to context and risk. This sits across and within the typology presented in Table 4.2.

The decision tree considers additional contextual (current development) information that is summarized in Figure 4.5 and links it more specifically to crop focused impacts outlined in Figure 4.1.

It attempts to provide a guideline framework to elaborate the generalized approach outlined in Figure 7.1. It addresses a specific national or regional context, or category within the typology. There are strategic (policy, programme, institutional development and public goods research) elements to an effective adaptation strategy. There are also likely to be a wealth of local (farmer, agro-industry) innovations in response to climate change. It will be important for planners and programme managers to be aware of such innovation and initiative and to take positive steps to reinforce all promising options.

An associated set of steps are embedded in the decision tree, and could be listed as follows:

1. *Define climate change impacts on water resources availability.*
2. *Define (account for) current water resources use, and projected use for current development goals.*
3. *Determine climate change impacts on future water availability and implications for future allocations.*
4. *Define the production status and potential of current agricultural (cropping) systems under selected climate change scenarios.*
5. *Examine the water and land-use implications of alternative combinations of agricultural development activities, incorporating rainfed agriculture; irrigated agriculture; agroforestry; rangeland; and integrated mixed farming.*

a. *Match options to likely scale and nature of farming in the future in recognition of current and likely levels of urban migration and remaining rural population.*

b. *Evaluate mitigation options for synergy, practicality and cost effectiveness.*

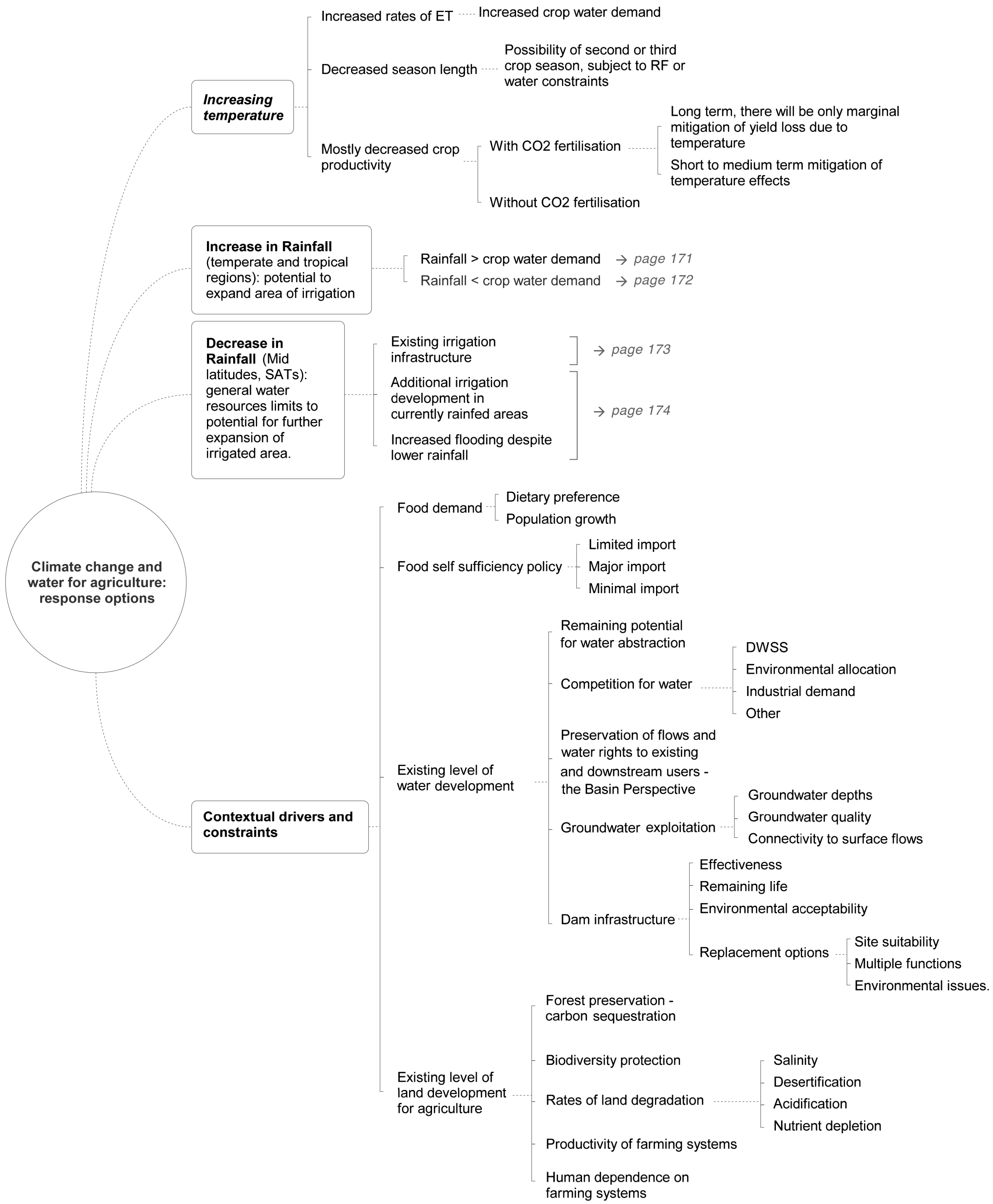
6. *Define resources and adaptations needed to maintain current levels of output and productivity.*
7. *Define resources and adaptations required to meet future demands.*
8. *Assess impacts on eco-systems and on the sustainability of the existing or proposed farming system.*
9. *Cost alternatives.*
10. *Prioritize options.*

The continuing development of packages of adaptation options including adapted crops (breeding); soil water conservation techniques; nutrient management; improved irrigation modes (full, deficit, supplemental) and technology (water storage; agroforestry) can be based on:

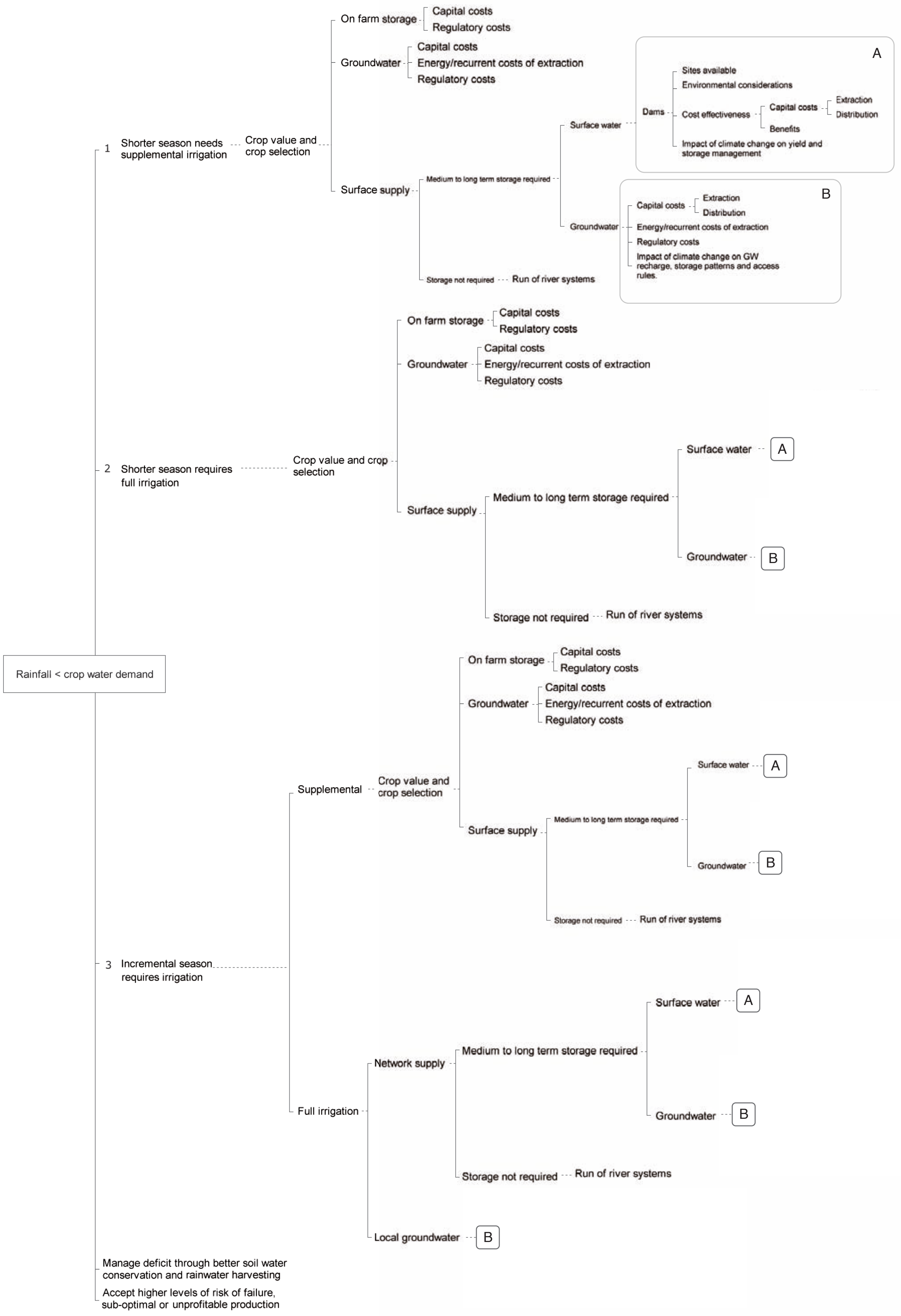
- Observation, assessment and promotion of appropriate and effective innovations developed by farmers at field level.
- Well-targeted research that addresses the specific climate change and socio-economic context (as defined through this process).
- Experience and knowledge transferred from similar contexts.

Examples of the overall decision tree, and the expansion up to 12 levels are given on the following five pages. The first page covers the broad range of response options to different sets of agricultural impacts. The other pages investigate more in details the cases related to increase or decrease of rainfall and implications for various type of agricultural water management.

Example of decision tree

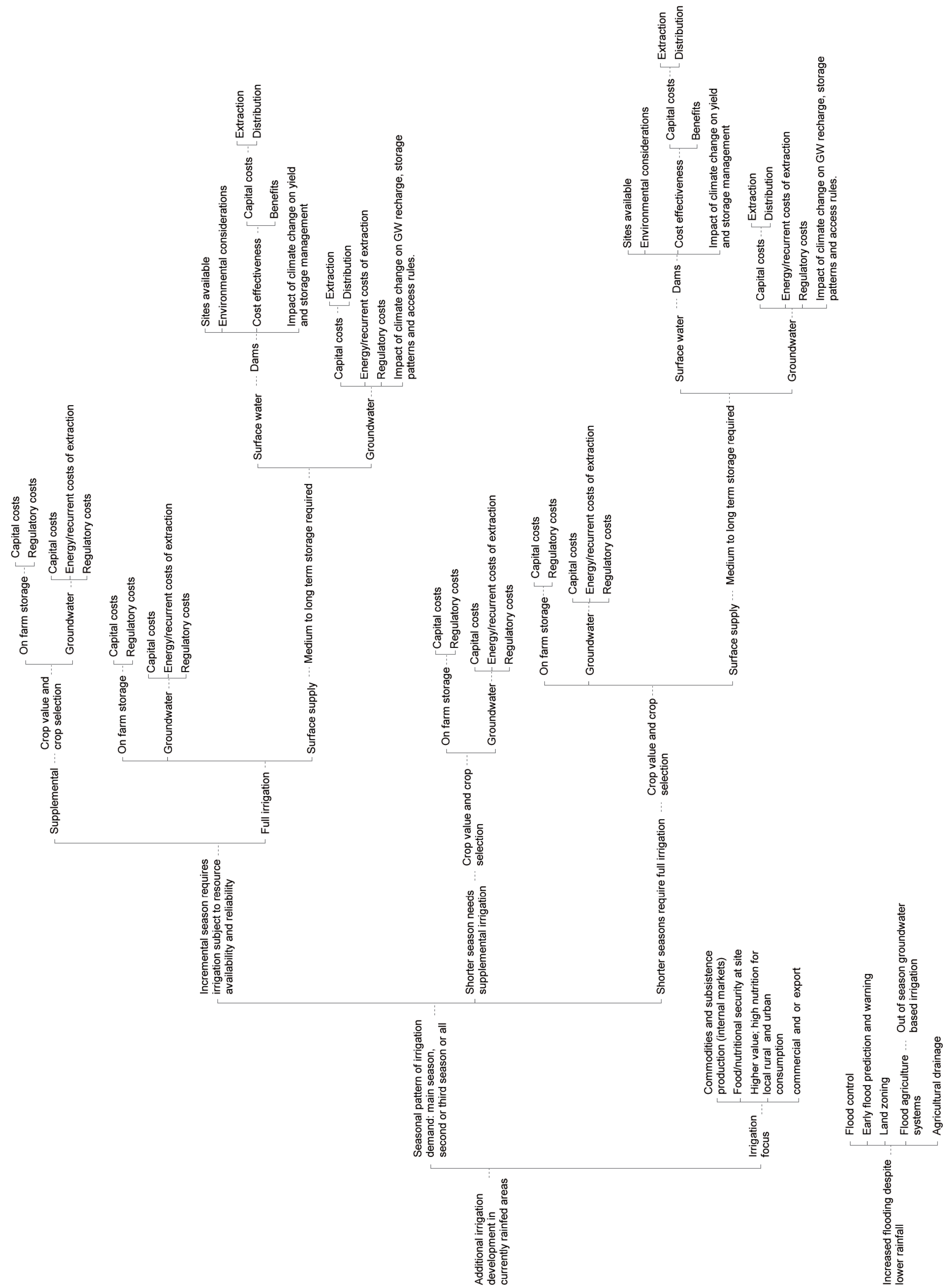


- Rainfall > crop water demand
  - 1 Continue with Rainfed Agriculture
    - Optimise whole system productivity
      - Breed for drought tolerance
      - Better soil water conservation and management
      - Improved yield in average to above average years
        - Greater and longer term crop storage
    - Expand area to substitute for lost productivity as well as meet increased demand.
  - Increased drought period frequency within season
    - Supplemental irrigation
      - On farm storage
      - Groundwater
      - Surface supply
    - Improved soil water conservation techniques
      - Zero tillage
      - Carbon sequestration
      - Root zone deepening
      - Other soil amendments - such as poly-electrolytes
    - Drought tolerant varieties
    - Accept sub-optimal production in some years - mitigate at regional or national level through enhanced crop storage
  - 2 Increased annual drought frequency
    - Irrigation as insurance
    - Forecasting systems based on ENSO, NAO, PDO etc
    - Crop insurance
    - Enhanced regional and national crop storage
  - 3 Increased flood frequency
    - Field drainage
    - Network drainage
    - Change land surface management - broad beds, etc
    - Flood adapted crops or varieties
    - Re-zone land appropriate to production risk and sensitivity



Rainfall < crop water demand
1 Shorter season needs supplemental irrigation
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
Groundwater
Storage not required
Run of river systems
A
Dams
Sites available
Environmental considerations
Cost effectiveness
Capital costs
Extraction
Distribution
Benefits
Impact of climate change on yield and storage management
B
Capital costs
Extraction
Distribution
Energy/recurrent costs of extraction
Regulatory costs
Impact of climate change on GW recharge, storage patterns and access rules.
2 Shorter season requires full irrigation
Crop value and crop selection
3 Incremental season requires irrigation
Supplemental
Full irrigation
Network supply
Medium to long term storage required
Local groundwater
Manage deficit through better soil water conservation and rainwater harvesting
Accept higher levels of risk of failure, sub-optimal or unprofitable production

- Existing irrigation infrastructure
  - Gravity/surface systems
    - Decreased runoff
      - 1 reduce service area
        - Maintain higher levels of unit area productivity (yield) at lower levels of water use efficiency
      - 2 ration water supplies across existing or reduced area
        - Accept lower yields, substituted by higher water use efficiency over a relatively larger area
        - Deficit irrigation
        - Crop insurance
      - 3 change demand pattern
        - improve or optimise use of rainfall
          - crop season dates
          - improved soil water management and conservation
        - change crop patterns to ones with lower demand
          - Crop choice
            - Policies and incentives
          - Crop breeding?
          - Deficit irrigation
        - Reduction of evaporative loading
          - Shade houses/protected agriculture
    - Changed pattern of runoff
      - 1 Snowmelt systems
        - reconfigure storage systems to match flow availability
          - groundwater
          - surface water
        - reconfigure and "control" abstraction patterns to match storage and flow availability
      - 2 Changed timing and duration of monsoons
        - adapt crop season timing and duration
          - seasonal forecasting
          - Annual forecasting, ENSO, NAO, etc
        - improved productive use of flood flows
          - local soil water conservation
          - groundwater recharge
          - surface water storage
      - 3 Increased proportion of storm/flood events
        - improved productive use of flood flows
          - local soil water conservation
          - groundwater recharge
          - surface water storage
        - adapt and zone farming system to maximise productivity and minimise risk in flood prone and flood managed areas.
  - Groundwater systems
    - Decreased recharge
      - reconfigure and "control" abstraction patterns to match storage and flow availability
      - enhance recharge (with reference to whole water balance and existing uses and users)
      - groundwater banking/preservation for drought periods
        - policy
          - Energy costs and technologies
        - monitoring
        - enforcement
    - Greater risk of over-pumping
      - policy
        - Energy costs and technologies
        - depth controls and preservation of high value urban, industrial supply
      - monitoring
      - enforcement
  - On-farm adaptation
    - On-farm storage
      - Hydrologic implications and limits
      - Capital costs
      - Regulatory costs
    - Improved soil water conservation
    - Crop selection and crop pattern
    - Change season dates for single and double cropping regimes
    - Improved husbandry
      - 'Precision Farming'
      - Better efficiency of use of factor inputs, such as fertiliser and pesticides: reduced use where possible
    - Organic farming (pros and cons)
    - Agroforestry systems
    - Integrated livestock and cropping systems
    - Managing and minimising salinity


Additional irrigation development in currently rainfed areas
Seasonal pattern of irrigation demand: main season, second or third season or all
Incremental season requires irrigation subject to resource availability and reliability
Supplemental
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Full irrigation
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
Dams
Sites available
Environmental considerations
Cost effectiveness
Capital costs
Extraction
Distribution
Benefits
Impact of climate change on yield and storage management
Groundwater
Capital costs
Extraction
Distribution
Energy/recurrent costs of extraction
Regulatory costs
Impact of climate change on GW recharge, storage patterns and access rules.
Shorter season needs supplemental irrigation
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Shorter seasons require full irrigation
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
Dams
Sites available
Environmental considerations
Cost effectiveness
Capital costs
Extraction
Distribution
Benefits
Impact of climate change on yield and storage management
Groundwater
Capital costs
Extraction
Distribution
Energy/recurrent costs of extraction
Regulatory costs
Impact of climate change on GW recharge, storage patterns and access rules.
Irrigation focus
Commodities and subsistence production (internal markets)
Food/nutritional security at site
Higher value; high nutrition for local rural and urban consumption
commercial and or export
Increased flooding despite lower rainfall
Flood control
Early flood prediction and warning
Land zoning
Flood agriculture systems
Out of season groundwater based irrigation
Agricultural drainage

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Climate change, water and food security

The impacts of climate change on the global hydrological cycle are expected to vary the patterns of demand and supply of water for agriculture – the dominant user of freshwater. The extent and productivity of both irrigated and rainfed agriculture can be expected to change. As a result, the livelihoods of rural communities and the food security of a predominantly urban population are 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. Adaptation measures that build upon improved land and water management practices will be fundamental in boosting overall resilience to climate change. And this is not just to maintain food security: the continued integrity of land and water systems is essential for all economic uses of water.

This report summarizes current knowledge of the anticipated impacts of climate change on water availability for agriculture and examines the implications for local and national food security. It analyses expected impact of climate change on a set of major agricultural systems at risk and makes the case for immediate implementation of 'no-regrets' strategies which have both positive development outcomes and make agricultural systems resilient. It is hoped that policy makers and planners can use this report to frame their adaptation responses when considering both the water variable in agriculture and the competing demands from other users.

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