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.

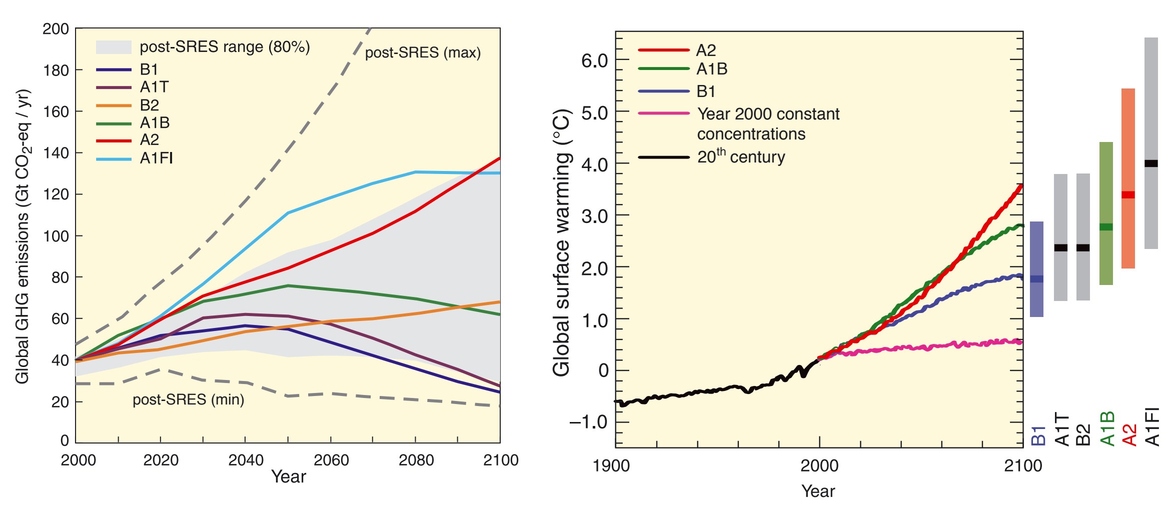
AR4 reports on modelling of four main 'storylines' (A1, A2, B1 and B2) with around ten variants of each one (Box 2.1). The models are calibrated against historical climate and the replication of observed trends, and have steadily improved in performance over the last ten years with the incorporation 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

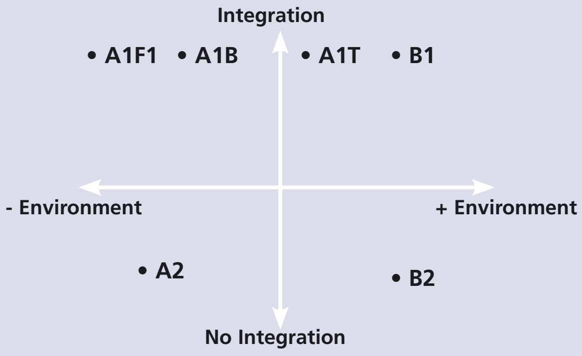
SRES (Special Report on Emissions Scenarios) storylines

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.



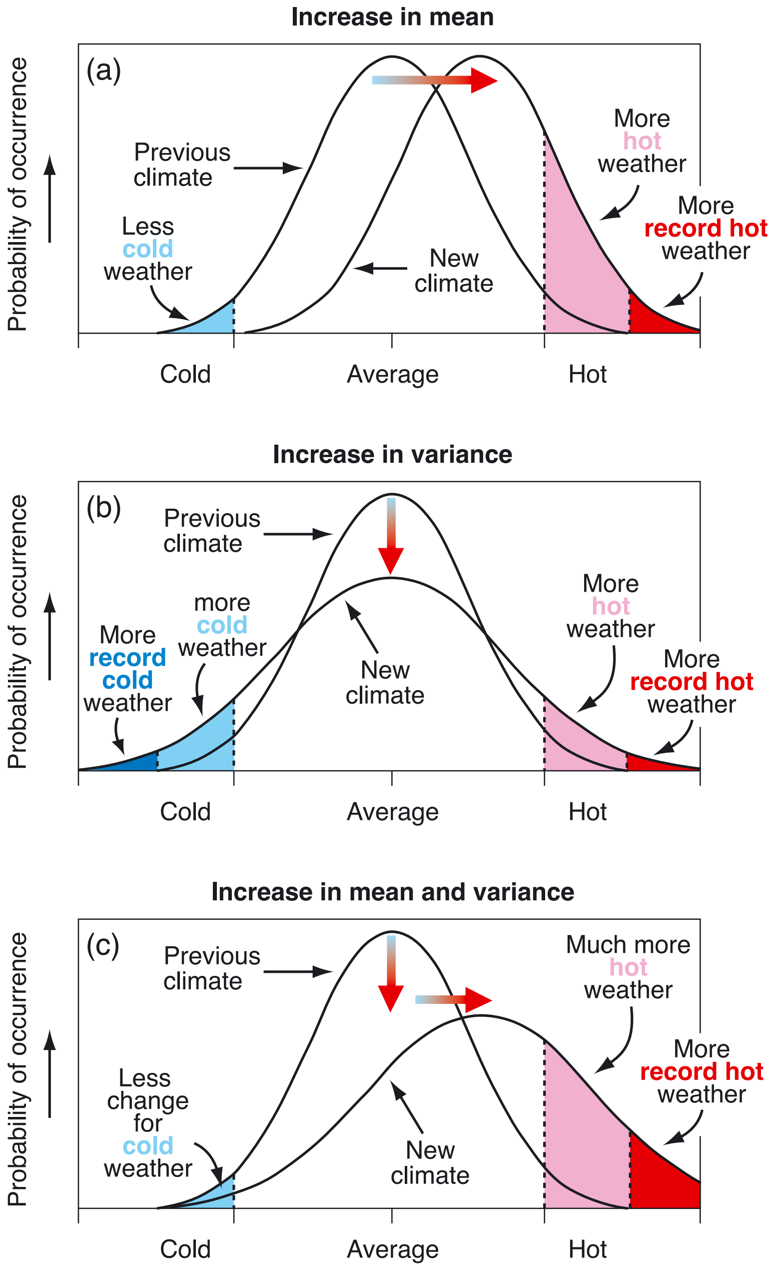
Scenario characteristics	SRES Scenario examples, 2100				
	1990	A1	A2	B1	B2
World Population (billion)	5.25	7.1	15.1	7.2	10.4
CO_2 concentration (ppm)	354	680	834	547	601
Mean global temp increase (C)	-	2.52	3.09	2.04	2.16
Range of temp rise (C)	-	1.7–3.66	2.12–4.41	1.37–2.99	1.45–3.14
Global mean sea-level 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.

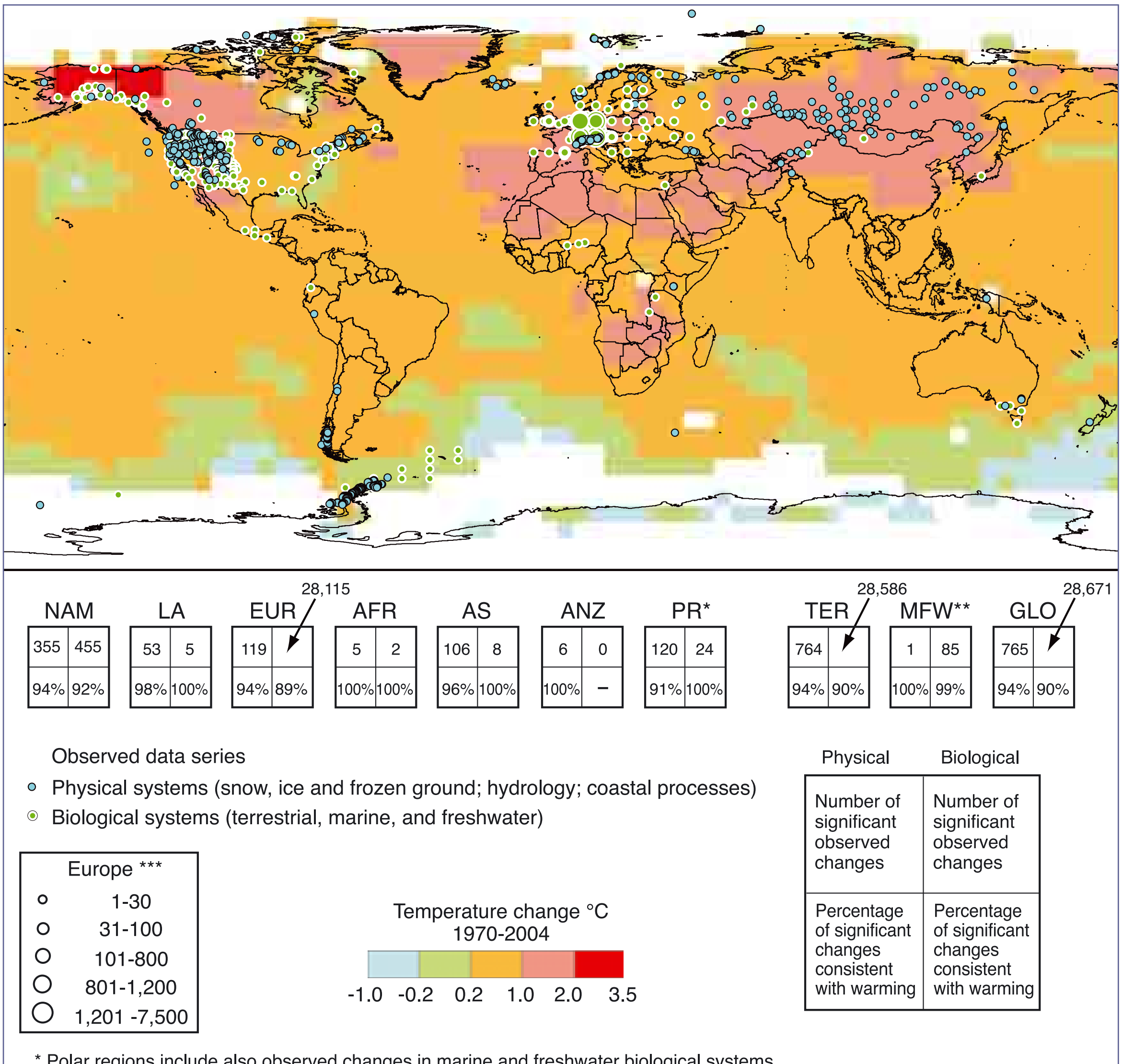
The balance of impacts from increasing temperature on aquatic ecosystems (rivers and lakes) is not clear. This is because of competing effects between reduced oxygen concentration in water at higher temperatures and higher aquatic productivity, with a likely net increase in oxygenation (there is more 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)



* Polar regions include also observed changes in marine and freshwater biological systems.

** Marine and freshwater includes observed changes at sites and large areas in oceans, small islands and continents. Locations of large-area marine changes are not shown on the map.

*** Circles in Europe represent 1 to 7,500 data series.

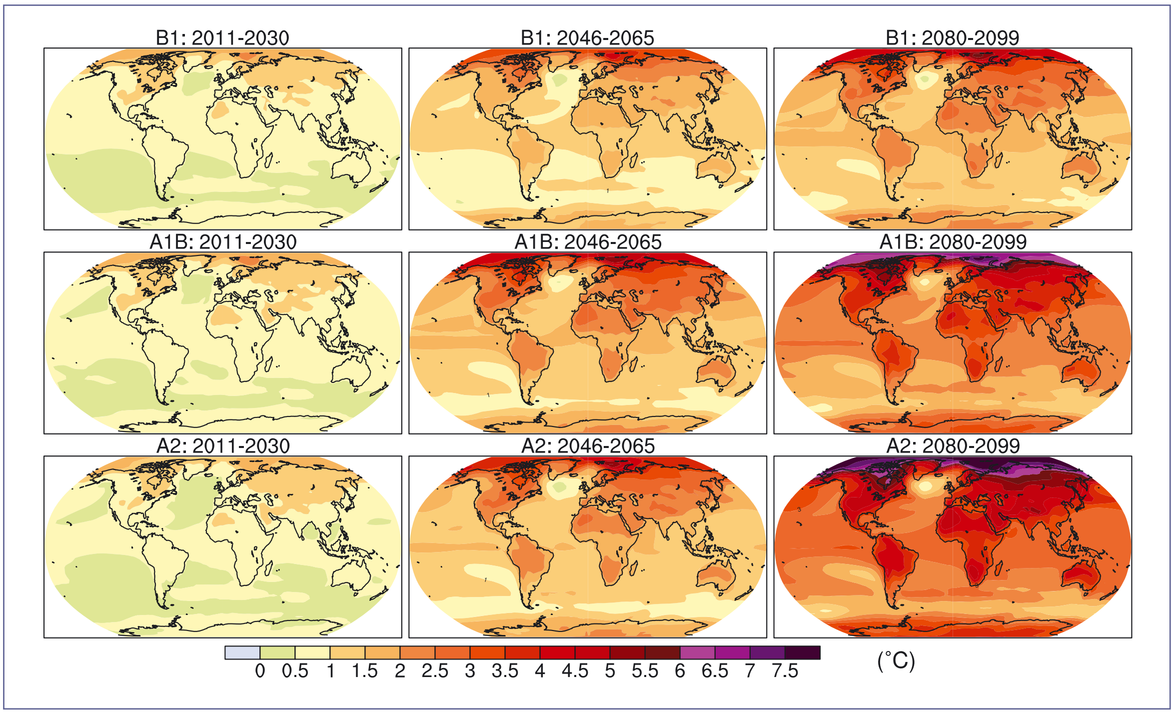
Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 1.2. IPCC, Geneva, Switzerland.

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.

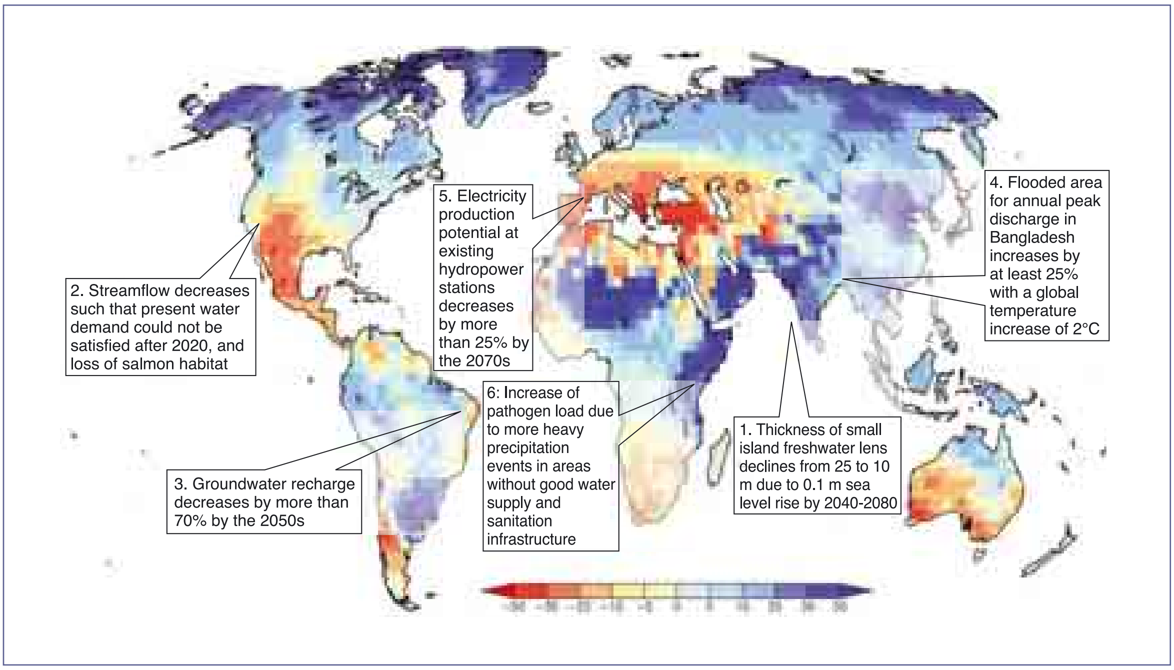
FIGURE 2.5

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.

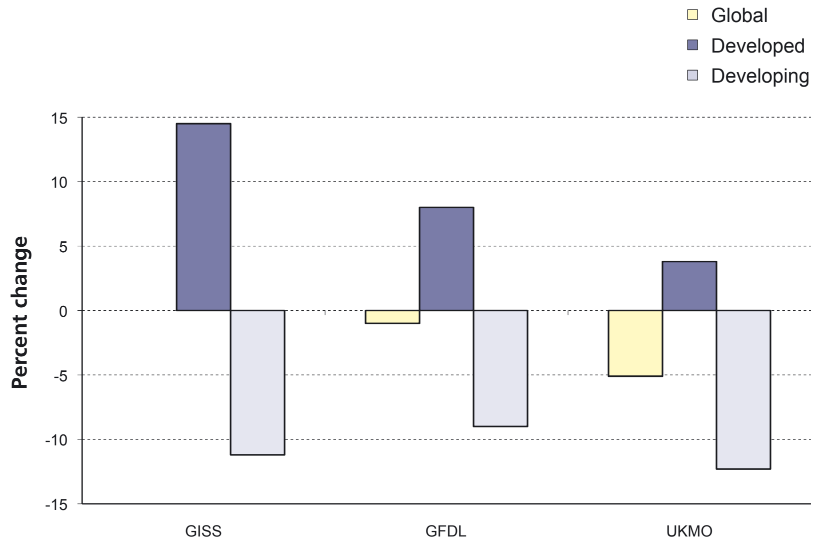
Rising temperature, rising potential evapotranspiration rates and declining rainfalls conspire to increase the severity, frequency and duration of droughts. Large-scale land-use change is expected on all continents. AR4 estimates that some 75 million ha of land that is currently suitable for rainfed 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)

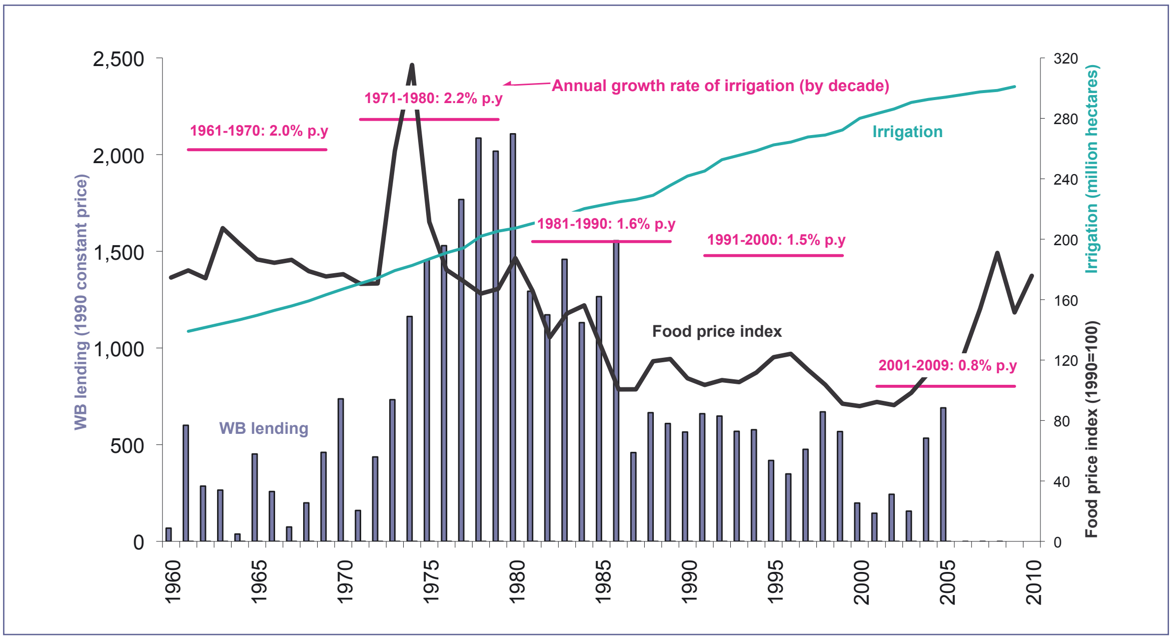
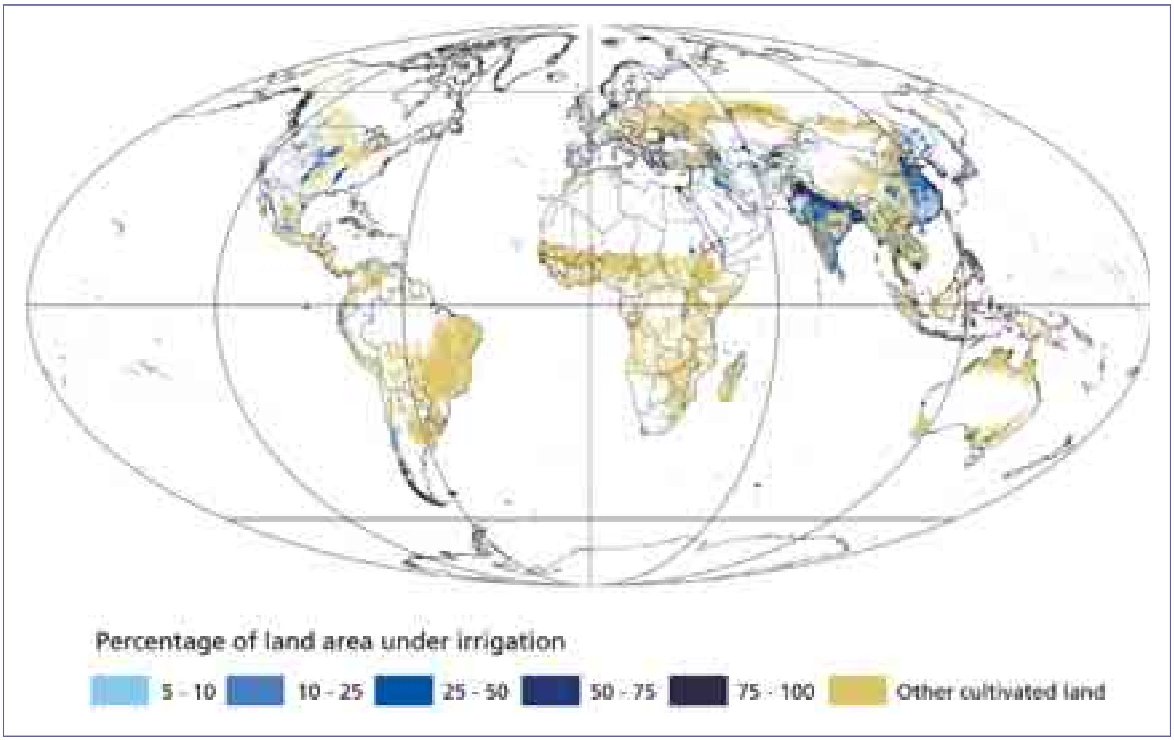


FIGURE 2.9
Distribution of area under irrigation in the world (FAO, 2010, Siebert *et al.*, 2007)



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.

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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.