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

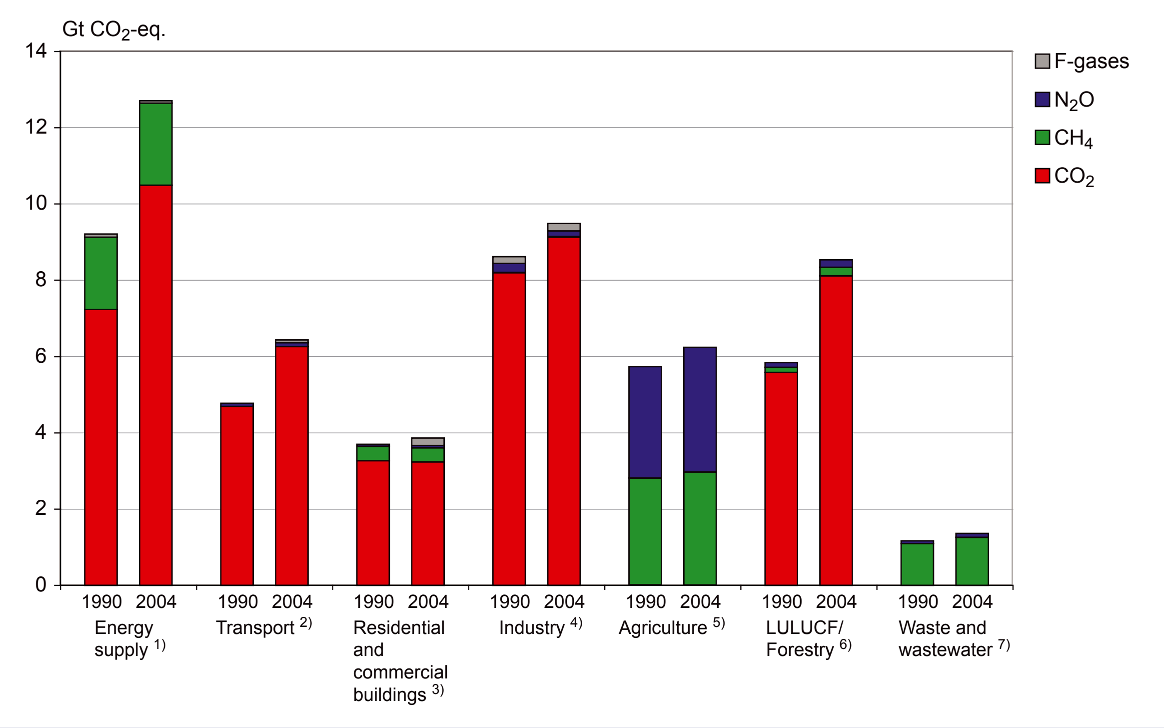
Prospects for mitigation

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).

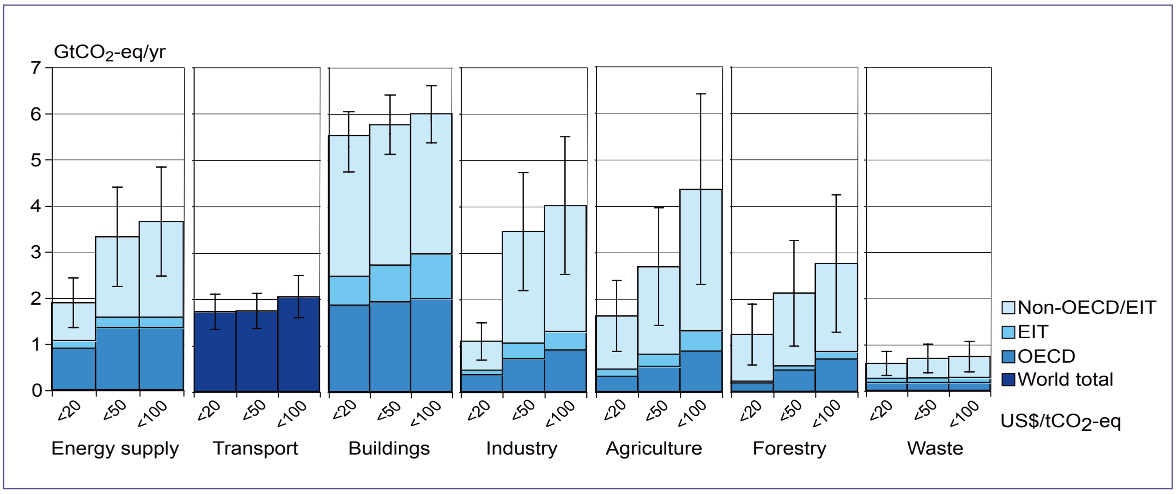
Fossil energy use in US maize production as far back as 1994 was reported to equate to 400 gallons of oil equivalent per capita per year (McLaughlin *et al.*, 2000) with a percentage breakdown as follows:

- 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.

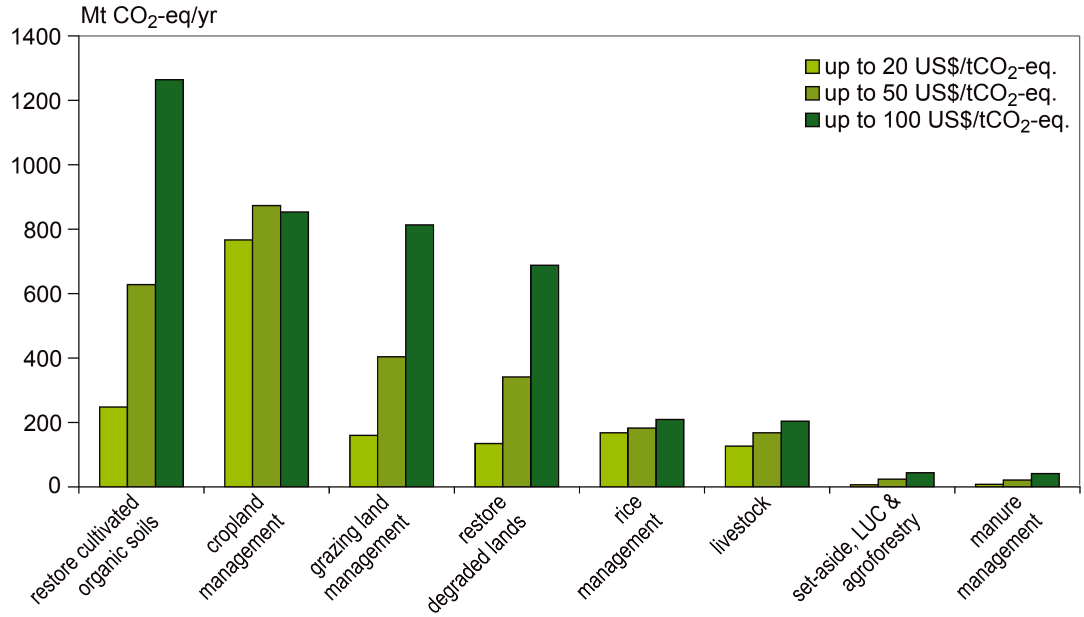
The options and their potential for mitigation within agriculture are based on three different prices for one tonne of carbon dioxide; these are summarized in Figure 6.3 (Smith, 2008). Cropland management has highest potential, whereas water management has rather low potential, as the costs per tonne 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 net 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.

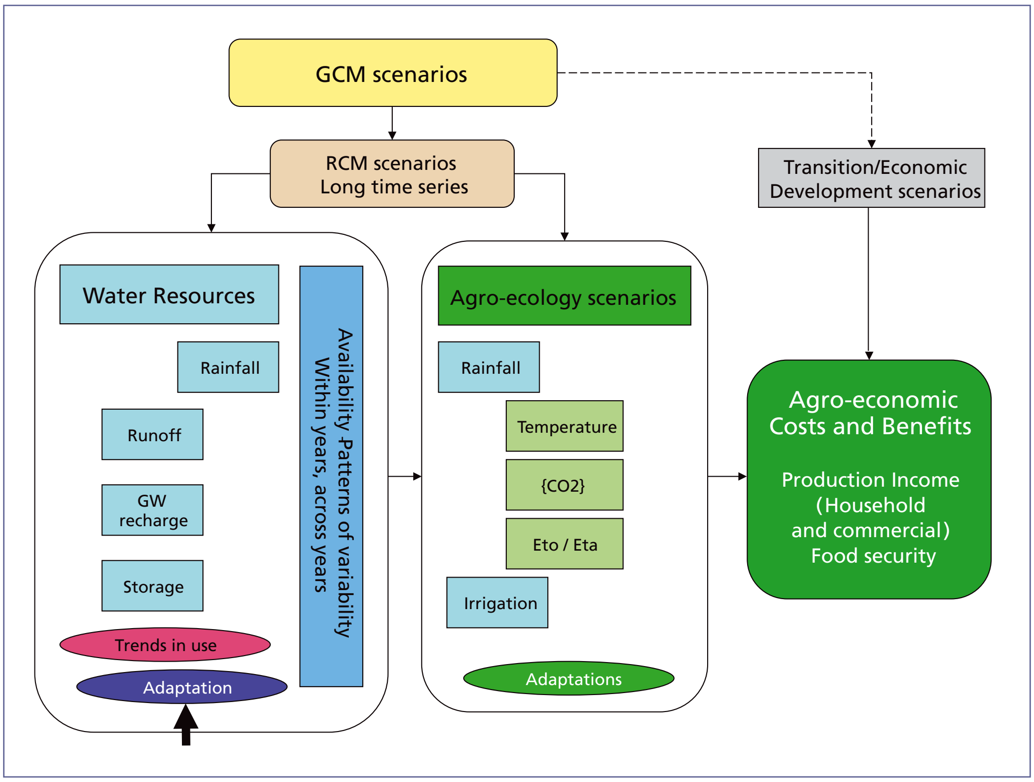
Insurance has been much touted as a response to climate change. It is worth remembering that insurance classically works to mitigate the impacts of rare events, with high risk. What are now rare events will (actuarially) fall outside of the category of rare or extreme events in the future. Therefore 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.