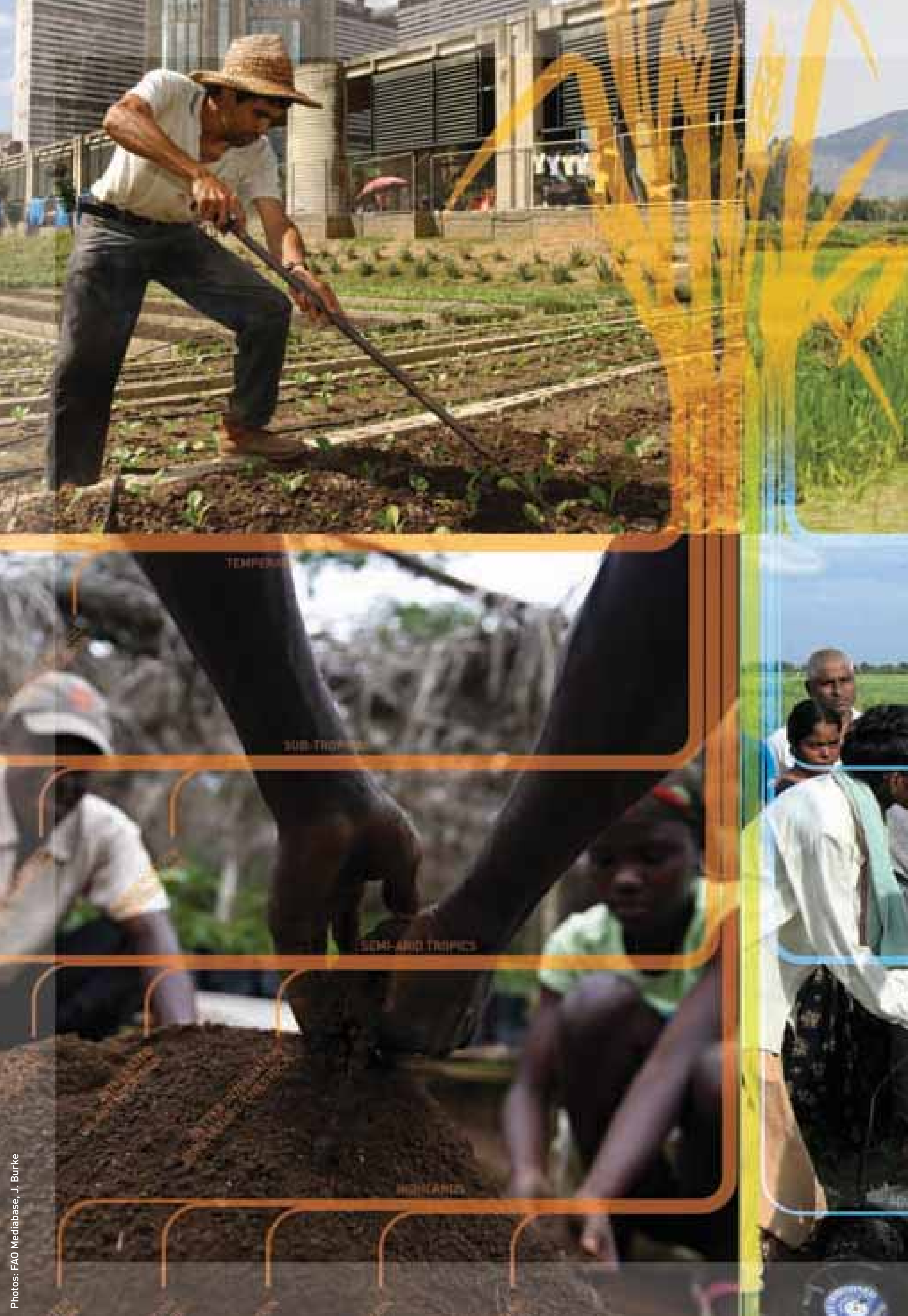
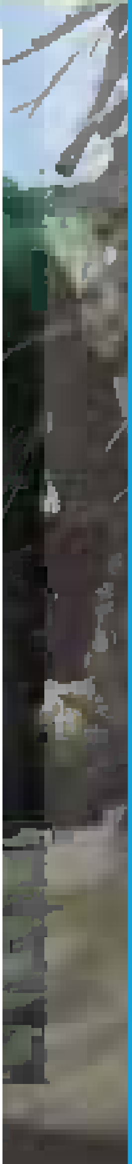


Photos: FAO Mediabase, J. Burke



# Chapter 4

# TECHNICAL OPTIONS FOR SUSTAINABLE LAND AND WATER MANAGEMENT

As discussed in Chapter 1, it is expected that more than four-fifths of the increased production to 2050 will come from existing land areas through increased productivity. Many systems are, however, already constrained either because of existing high productivity levels, or because there are technical, socio-economic or institutional constraints. In addition, as the intensity of farming increases, the risks and related trade-offs discussed in the previous chapter become more pressing. This chapter reviews technical options for moving towards 'sustainable land and water management' – that is, more intensive integrated management of soil, water, nutrients and other inputs to produce increased crop value while maintaining or enhancing environmental quality and conserving natural resources, both on-site and off-site.

Even though the growth in the area of rainfed agriculture has remained static, rainfed agriculture is still projected to produce one-third or more of the increase in global food output in the coming decades. Rainfed systems in temperate zones are already high-yielding, but face problems of nutrient and pesticide pollution. Smallholder rainfed systems in developing countries face far more problems of poor soil quality, soil moisture deficits and high levels of agro-climatic risk, exacerbated by climate change. They are also hindered by the absence of profitable market outlets and the resources to invest in improving productivity.

# Improving rainfed productivity

Yield increases play a significant role in poverty reduction. It has been estimated that every 1 percent increase in agricultural yields translates into a 0.6–1.2 percent decrease in the numbers of absolute poor is households that cannot afford basic needs for survival (Thirtle *et al.*, 2001). However, the data also underline the risk that, if the enabling environment does not encourage change to farming systems in developing countries, cereals yields under traditional management could stagnate at less than 2t / ha. Several African countries, for example, have yields that are at around 20 percent of potential. Others, by contrast, realized gains of several percentage points in recent years (for example in Southern Africa). Trends over the five year period 2000–5 confirm that these potential productivity gains can be realized, with both more-developed countries (four percent increase) and less-developed countries (three percent increase) reducing the yield gap). The gap between actual and potential is largest in parts of sub-Saharan Africa, which even under low-input farming have the potential to almost double cereals yields. There is thus considerable scope to close the yield gap for some of the poorest parts of the world, with potential for developing countries to double average cereals yields from 2.9 t / ha to 5.7 t / ha (Fischer *et al.*, 2010).

Rapid increases in rainfed yields in some areas in recent years show that improvements are realizable if favourable conditions are in place (Molden, 2007). These conditions include institutional reform to deliver research and advisory services, efficient markets for inputs and outputs, road infrastructure, mechanization, improved use of fertilizer and high-yielding varieties, and better soil moisture management. These are the conditions that have allowed the rapid growth of productivity in rainfed systems across Asia and in the developed world. However, although all of these conditions are well known and have shown their value, rainfed yields in many smallholder production systems in the developing world have stagnated, particularly in sub-Saharan Africa, despite efforts that have been made for many years to improve performance. Rainfed yields in Eastern Africa have stagnated at 16 percent of potential for years.

One major challenge in rainfed farming is how to introduce accessible technical solutions to improve management without increasing risks. Rainfed systems in developing countries are often characterized by low productivity, caused by low and variable water availability, and by environmental and soil problems of salinity, temperature and lack of nutrients. The technological solutions available are characteristically low-yielding: the innovations of the green revolution depended largely on water availability. In addition, productivity-boosting improvements for rainfed systems typically heighten levels of risk. The insecurity of rainfed production is intensified by the risks associated with climate variability.

In some areas, these constraints have been overcome. In China, combined soil and water management investments have delivered good returns with manageable levels of risk. The Loess Plateau watershed rehabilitation project demonstrated on an area of 1.5 Mha that soil and water management improvements could be profitable (Box 2.7). Elsewhere in the world (Argentina, Australia, Canada, Kazakhstan and sub-Saharan Africa) a range of rainwater management technologies and conservation farming techniques have been introduced with some success, and there is increasing evidence that farmers are taking these up (Pretty *et al.*, 2011). One of the greatest problems is that some innovations take time to pay back investments.

## Managing soil health and fertility

The challenges of low and depleting nutrients in soils and of poor soil structure are prevalent on rainfed croplands. The lowest average productivity of rainfed agriculture is found in sub-Saharan Africa, especially in small-scale systems, because of low inherent soil fertility of the land, compounded by severe nutrient depletion: cereal crop yields are often below 1 t/ha. Solutions that depend on large applications of fertilizers are often unaffordable and too risky within many low-potential rainfed cropping systems. In these cases, sustainable land and water management techniques, including conservation agriculture, may help to restore and improve soil fertility through integrated soil fertility management (Pretty *et al.*, 2011).

### Benefits of keeping soils healthy

The direct and indirect benefits of improving soil management in agricultural systems can be assessed in economic, environmental and food security terms:

- Economic benefits: improved soil management reduces input costs by enhancing resource-use efficiency (especially decomposition and nutrient cycling, nitrogen fixation, and water storage and movement). Less fertilizer may be needed if nutrient cycling becomes more efficient and fewer nutrients are leached from the rooting zone. Fewer pesticides are needed where a diverse set of pest-control organisms is active. As soil structure improves, the availability of water and nutrients to plants also improves. It is estimated that nutrient cycling provides the largest contribution (51 percent) of the total value (US$33 trillion) of all 'ecosystem services' (including cultural, services waste treatment, disturbance regulation, water supply, food production, gas regulation and water regulation) provided each year (Costanza *et al.*, 1997).

- Environmental protection: soil organisms filter and detoxify chemicals and absorb the excess nutrients that would otherwise become pollutants when they reach groundwater or surface water. The management of soil biota helps to prevent pollution and land degradation, especially through minimizing the use of agrochemicals and maintaining or enhancing soil structure and cation exchange capacity (CEC). Excessive reduction in soil biodiversity, especially the loss of keystone species or species with unique functions (for example, as a result of excess chemicals, compaction or disturbance) may have catastrophic ecological effects leading to loss of agricultural productive capacity. The mix of soil organisms also partially determines soil resilience.

- Food security: improved soil management can improve crop yield and quality, especially through controlling pests and diseases, and enhancing plant growth. Soil biodiversity determines the resource-use efficiency, as well as the sustainability and resilience of agro-ecological systems.

### Techniques for managing soil fertility

Low-input agriculture depletes the soil, mining soil nutrients and leading to decline of agricultural production, and ultimately to non-sustainable farming systems. When correctly applied, the use of mineral fertilizer in combination with other techniques for improving soil health has proved effective in restoring and enhancing soil fertility and in generating increased yields. However, mineral fertilizer is not affordable to many farmers, and in any case can form only one component of the solution to the challenge of soil fertility.

Organic sources of plant nutrients enhance soil fertility and improve soil structure, water retention and biological activity. They can be derived from incorporation of crop residues, application of animal manure, composting of organic wastes or from biological fixation through leguminous crops, green manures or nitrogen-fixing trees. However, these sources are by themselves not sufficient to sustain soil fertility. Recycling of crop residues does reduce losses, but it does not compensate for the nutrients exported in harvests, nor does it add to the total amount of nutrients originally available. Organic fertilizers need to be used in conjunction with other sources of nutrients.

The use of locally available rock phosphate can be an important component in integrated plant nutrient systems, as an essential phosphorus supply or as a strategy of phosphorus recapitalization. The effects of rock phosphate are beneficial primarily on acid and phosphorus fixing soils found mainly in the humid tropics, which are forested or used for perennial crops such as oil palm, cocoa or coffee. In order to be effective it has to be accompanied by a balanced supply of the other major plant nutrients.

For strongly acid soils, the application of soil amendments of lime or dolomite remedies deficiencies in calcium and magnesium, and neutralizes aluminium toxicity, constraints that limit root penetration and hence reduce access to other nutrients and water in subsurface layers. Without amendment, the effectiveness of other soil fertility-enhancing measures is very limited. The application required depends on land use (some crops are acid-tolerant) and soil characteristics. Liming in excess can reduce the availability of essential trace elements.

Plant diversity in cropping systems reduces the negative impact of monocropping on soils, and can bring positive advantages to soil health, improving soil quality, improving nutrient cycling and sustaining biodiversity. Biodiversity within the farming system can be achieved through intercrops (growing two or more crop species simultaneously on the same land), crop rotations (growing different crops sequentially on the same land) and relay crops (growing different crops with partially overlapping growing seasons). There is also evidence that using a diversity of crops can improve the effectiveness of mycorrhizal (fungal root symbioses) associations in a cropping system, provided that soils are not mechanically disturbed (e.g. through tillage, which has negative impacts on fungal life, as well as meso- and macro-fauna).

The use of legumes enhances biological nitrogen fixation. However, while the amounts of nitrogen fixed by legumes under experimental conditions have been well investigated, there is less data on the gains obtained in cropping systems under farmer conditions. Inoculation is often required, and the infrastructure and extension for this is often lacking. Furthermore, the effectiveness of nitrogen fixation is constrained by phosphorus deficiency in soil. As farmers grow many legumes for food (e.g. phaseolus beans, cowpeas, pigeon peas, groundnuts), relay or mixed cropping may prove to offer an economic return.

Agro-forestry systems have contributed to soil fertility. The use of *Faidherbia albida (Acacia albida)* provides a good example. Yields of grain crops are substantially higher under the tree crown than in the open field (Box 4.1). The beneficial effect is attributed to a higher content of soil organic matter and to the fertilizing effect of dung of animals grazing in the shade of the tree. Maintaining protective soil cover is also important, such as through minimum or zero tillage, the use of crop residues and mulch to reduce evaporation from bare soils, and optimization of rainwater infiltration and groundwater recharge. These practices have a positive impact on soil fertility, and hence on crop yields and water use efficiency. They also mitigate drought risk.

## The need for improvement

Technical actions to enhance and restore soil fertility have to be selected and designed in accordance with the specific constraints and potentials of diverse environments. Advocating biological nitrogen fixation where legumes are not part of the

## BOX 4.1: FERTILIZER TREES – A SUCCESS

*Maize growing under* Faidherbia *trees in southern Tanzania*

The combination of trees in farming systems (agroforestry) with conservation farming is emerging as an affordable and accessible science-based solution to caring better for the land and increasing smallholder food production. Millions of farmers in Zambia, Malawi, Niger and Burkina Faso are restoring exhausted soils and increasing both crop yields and incomes with this approach. The most promising results are from the integration of fertilizer trees into cropping systems. These trees improve soil fertility by drawing nitrogen from the air and transferring it to the soil through their roots and leaf litter.

Scientists from the World Agroforestry Centre and national institutions have been evaluating various species of fertilizer trees for many years, including *Sesbania*, *Gliricidia* and *Tephrosia*. Currently, *Faidherbia albida* is showing promise. This indigenous African acacia is already a natural component of systems across much of the continent. Unlike most other trees, *Faidherbia* sheds its leaves during the early rainy season and remains dormant throughout the crop-growing period: the leaves grow again when the dry season begins. This reverse phenology makes it highly compatible with food crops, because it does not compete for light, nutrients or water during the crop-growing season.

In Zambia, 160 000 farmers now grow food crops within agroforests of *Faidherbia* over an area of 300 000 ha. Zambia's Conservation Farming Unit has observed that unfertilized maize yields in the vicinity of *Faidherbia* trees averaged 4.1 t/ha, compared with 1.3 t/ha nearby (but beyond the tree canopy). Similar promising results have emerged from Malawi, where maize yields increased up to 280 percent in the zone under the canopy of *Faidherbia* trees compared with the zone outside. In Niger, there are now more than 4.8 Mha of *Faidherbia*-dominated agroforests enhancing millet and sorghum production. Promising results have also been observed from research in India and Bangladesh.

*Source: Garrity et al. (2010) Photo: © World Agroforestry Centre* cropping pattern may face a low adoption rate. The use of rock-phosphate outside the acid soils of the humid and moist subhumid zones would have a limited impact. Liming may be effective in neutralizing aluminium toxicity in acid soils, but is superfluous on soils with fair calcium saturation. In order to be effective, applications of fertilizers in semi-arid areas need to be accompanied by water harvesting and water conservation, or by small-scale irrigation. Timing of fertilization needs to be designed for soils with low plant nutrient retention capacity. Relying on organic sources of plant nutrients in semi-arid areas, where biomass production is severely limited by water deficit, is unrealistic. The same applies to relying on animal manure in areas of severe tsetse infestation.

Cash inputs, in particular, are rarely adopted in subsistence systems. Despite significant growth in the use of fertilizers in a small number of countries in sub-Saharan Africa, the use of fertilizers has remained generally low as a result of unfavourable cost–benefit ratios, high risk and weak markets. However, in contrast with the past, staple food crops (e.g. maize, teff, barley, wheat) are now increasingly among the main crops that are fertilized (Morris *et al.*, 2007).

Packages also have to be designed for each local farming situation. Numerous attempts to improve soil fertility have failed because the proposed technology was not appropriate and because elementary information about the characteristics of the natural resource base was ignored. Recommendations that are formulated for entire countries or regions, without taking into account the great diversity that prevails at farmer level, are often counterproductive. Adapted packages are needed, with combinations of technical options tailored to meet site-specific ecological and socio-economic conditions.

There are many socio-economic constraints to adoption. Crop residues have alternative uses as fodder, fuel and building material, for which there are often no substitutes. Crop residues are also burnt in order to control weeds and pests. Applications of manure are effective in homestead gardens where farm animals are stabled, but elsewhere animals may be feeding on extensive rangeland from which manure cannot be collected. Composting is labour-intensive, and organic wastes on a small farm are limited. Grass and legume cover crops compete with food crops for land and for available water and nutrients. The same constraints apply to green manuring, which may require considerable labour for the incorporation of produced biomass. Major constraints to incorporating additional organic matter in the soil are the lack of draught power and the lack of short-term returns.

Packages thus need a ‘feasibility and risk’ assessment to build in incentives. Recent work in sub-Saharan Africa and Asia has developed packages that are designed to manage risk and provide incentives to farmers (Box 4.2). Some techniques, in fact,

BOX 4.2: INTEGRATED SOIL FERTILITY MANAGEMENT

*Farmyard manure, Nepal*

Integrated soil fertility management is a strategy to incorporate both organic and inorganic plant nutrients for higher crop productivity, prevention of soil degradation and reduction of nutrient loss. It relies on nutrient application through organic inputs such as compost, manure, inorganic fertilizer and/or the integration of nutrient-fixing crops. The integrated use of organic and mineral inputs in crop production has many positive interactions. However, for lasting positive effects on soil health, soil tillage should be avoided.

*Source: CDE (2010)  Photo: K. M. Sthapit*

seem to offer several incentives. Plant diversity has the benefit of offering other advantages to farmers that make adoption attractive, including spreading market risks, increasing income opportunities, improving dietary balance, spreading labour requirements more evenly throughout the year, and decreasing risk from pests and adverse environmental factors such as drought.

## Soil moisture management for rainfed areas

Improvement in rainfed agriculture is dependent on an adequate supply of water to plant roots. The first line of action in soil moisture conservation is to make the best use of the available rainfall. This involves minimizing unproductive water evaporation, increasing soil organic matter content and minimizing soil disturbances through appropriate techniques, including conservation agriculture.

Soil moisture management in high rainfall areas has traditionally been practised by a range of water-harvesting systems, including terracing and runoff diversion. There is considerable technical scope for improving agricultural water management in rainfed cultivation through more water harvesting and better soil moisture conservation techniques – but also many technical and socio-economic constraints to adoption.

Rainwater harvesting aims to improve water control and ensure adequate soil moisture for crop roots during the growing season (Box 4.3). Such harvesting captures runoff from a managed catchment area and reserves it either in a storage area or in the soil profile. Technologies include simple on-farm structures diverting water to a planting pit, structures in the catchment that divert runoff to storage or run-on fields, permanent terraces and dams (CDE, 2010). Effective rainwater harvest-

### BOX 4.3: RAINWATER HARVESTING

*Furrow-enhanced rainwater (runoff) harvesting, Syria*

Rainwater harvesting uses a range of technologies that gather runoff to make it available for agricultural production or domestic purposes. Rainwater harvesting aims to minimize variations in water availability and enhance the reliability of agricultural production. The basic components of a rainwater harvesting system are (1) a catchment area, (2) a concentration / storage area and (3) a cultivated area. When runoff is stored in the soil profile, (1) and (3) are synonymous. Rainwater harvesting covers a broad spectrum of different technologies, from simple measures such as V-shaped structures with a planting pit to more complex and large structures such as dams. The investment costs vary considerably.

*Source: CDE (2010) Photo: F. Turkelboom* ing can boost yields by two to three times over conventional rainfed agriculture, especially when combined with improved varieties and minimum-tillage methods that conserve water. Several of the Consultative Group on International Agricultural Research (CGIAR) centres are researching issues of rainwater harvesting, and related issues of drought-tolerant and water-efficient germplasm and agronomic management for dryland conditions (World Bank, 2006: 170).

Farming on slopes comes with problems of rapid loss of moisture from the soil profile and erosion by runoff. Many vegetative and structural techniques for soil and water conservation on slopes are available, including vegetative strips on contours to retain moisture and prevent erosion (Box 4.4), and terraces and bunds that act as structural barriers (Box 4.5). Vegetative measures usually require lower investment and are more easily established, and farmers tend to give them priority over more demanding structural measures. Structural measures should be promoted where

## BOX 4.4: VEGETATIVE STRIPS

*Natural vegetative strip, Philippines*

Vegetative strips may be composed of grass, shrubs and trees. These are often used along contours, helping to hold back excessive runoff, but may also be set perpendicular to the wind, to control wind erosion. Vegetative strips along the contour often lead to the formation of bunds and terraces due to 'tillage erosion' via the downslope movement of soil during cultivation. Compared with terraces and bunds they are thus much easier and cheaper to establish. Vegetative strips can also be utilized on flat land as shelterbelts, windbreaks or as barriers surrounding fields.

*Source: CDE (2010) Photo: A. Mercado, jr*

### BOX 4.5: STRUCTURAL BARRIERS

*Establishment of small bench terraces, Thailand*

Structural barriers are measures on sloping lands in the form of earth/soil bunds and stone lines for reducing runoff velocity and soil erosion. This is achieved by reducing the steepness and/or length of slope. Structural barriers are well known and are commonly prominent as traditional soil and water conservation measures. Structural barriers are often combined with soil fertility improvement (e.g. soil cover, manure or fertilizer application).

*Source: CDE (2010) Photo: S. Sombatpanit*

vegetative measures are not sufficient on their own, such as on very steep and erodible slopes. Ideally, structural measures are combined with vegetative or agronomic measures for protection, and to improve soil fertility and water management.

These techniques have traditionally relied on high levels of cheap or subsidized labour and animal draught. On marginal lands in low rainfall areas, the limited opportunities for on-farm control and related soil conservation still remain risky. Recent experience with introduced techniques in many countries is that they are often not profitable for farmers and can increase risk. They are thus rarely replicated in the absence of project support.

The best options are adaptable management practices that increase vegetative cover, and enhance retention of organic matter and soil moisture, along with adoption of adapted crop varieties. Strategies to provide yield stability in the face of climatic variability and to increase yields through improved soil, water and biological resource management will go hand in hand. Investment in improving agricultural water management needs to form part of a package that integrates soil, water and agronomy with a broader rural development and livelihoods approach, particularly to open access to input and output markets.

## Integrated approaches to improving productivity in rainfed systems

Several integrated production approaches have developed that combine best practices in sustainable land and water management, adapted to both the local ecosystem and social circumstances as well as to a viable market demand (Neely and Fynn, 2010; CDE, 2010). They incorporate improved soil and water management techniques in a way that intensifies production through integrated soil fertility management, improved water-use efficiency and crop diversity. These approaches offer opportunities for farmers, particularly smallholder rainfed farmers, to improve productivity sustainably. Some of these approaches are also applicable in larger-scale farming.

### Agro-ecological approaches

Agro-ecological approaches combine ecological knowledge and agriculture to promote a whole-systems approach to agriculture and food systems, using a range of traditional and modern approaches. Agro-ecological approaches use combined methods sourced from traditional knowledge, alternative agriculture, advanced science and technologies, and local food systems. Typically, the approaches employ minimum- and low-till methods, rotational grazing, intercropping, crop rotation, crop–livestock integration, intraspecies variety and seed saving, habitat management, and pest management rather than ‘control’. Agro-ecological approaches also encourage beneficial predatory and parasitic insects, and the enhancement of beneficial biota including mycorrhizae and nitrogen-fixers, as well as conserving resources, including energy, water (through dry farming and efficient irrigation), stocks of soil nutrients and organic matter (Neely and Fynn, 2010; Pretty *et al.*, 2011).

### Conservation agriculture

Conservation agriculture approaches seek to conserve natural resources while increasing yields and resilience. Conservation agriculture systems are grouped around three core technologies that, applied simultaneously, provide a basis for sustainable improvements in productivity through synergetic effects: minimal soil disturbance, permanent soil cover and crop diversity.

Conservation agriculture provides (1) improved rainwater infiltration (with reduced runoff, evaporation and erosion) (2) increased biodiversity and soil organic matter, and (3) improved soil structure. Labour requirements are reduced, and the use of synthetic fertilizer, pesticide and fossil fuels is minimized. Each of the technologies can serve as an entry point. However, only the simultaneous application of all three results in full benefits. Conservation agriculture is suited to both small- and large-scale farming. Its adoption is particularly attractive for situations facing acute labour shortages. Because of its proven track record, conservation agriculture is now being promoted by FAO globally, and there are currently around 117 Mha under conservation agriculture worldwide.

## Organic agriculture

Organic agriculture avoids the use of synthetic input, conserves soil and water, and optimizes productivity by organic means. It is a holistic management system that minimizes or eliminates synthetic fertilizer, pesticides and genetically modified organisms, conserves soil and water, and aims to optimize the health and productivity of interdependent communities of plants, animals and people.

Organic agriculture includes a series of measures: crop rotations and enhanced crop diversity; different combinations of livestock and plants; symbiotic nitrogen fixation with legumes; application of organic manure; and biological pest control, such as ‘push–pull’. All these strategies seek to make the best use of local resources. However, medium- and large-scale organic production often requires imports of organic material (in the form of compost, mulch, etc.) in order to maintain soil productivity. Medium- and large-scale organic production also often includes mechanical tillage.

Organic agriculture is a sustainable system that minimizes conflict with other ecosystem services, and has an enhanced economic value due to growing consumer preference for organic products. Over 32 Mha worldwide are now farmed organically by 1.2 million farmers, with organic wild products harvested on around 30 Mha (CDE, 2010; Neely and Fynn, 2010).

## Agroforestry

Agroforestry is a land-use system in which woody perennials are integrated with agricultural crops and livestock in order to access beneficial interactions, and to balance ecological needs with the sustainable harvesting of tree and forest resources. Agroforestry provides many benefits and services – more productive and sustainable use of soil and water resources, multiple fuel, fodder and food products, and provision of a habitat for associated species. There are usually both ecological and economic interactions between the components of the system.

There are five main forms of agroforestry: alley cropping, forest farming, silvopastoralism (Box 4.6), riparian forest buffers and windbreaks. Agroforestry may

### BOX 4.6: SILVOPASTORALISM, SHINYANGA, TANZANIA

Silvopastoralism systems include the introduction of trees into grazing areas, providing shade and shelter, increased resilience, and in some cases improved forage quality. Silvopastoralism can bring dramatic results: 20 years ago in the Shinyanga region of Tanzania soil erosion was such that dust storms were common; today the activity of the Shinyanga Land Rehabilitation Programme (HASHI) means that woodlots yield firewood and building timber, while fruit orchards provide food and fodder trees supply protein-rich feed for livestock.

*Source: Neely and Fynn (2010)*

integrate a wide range of technologies: contour farming, multistorey cropping, (relay) intercropping, multiple cropping, bush and tree fallows, parkland, or home gardens. Many of the approaches form part of traditional land-use systems, which can be upgraded with the introduction of new or improved technologies.

## Integrated crop–livestock systems

Mixed and integrated systems optimize the use of the biomass and nutrient cycles within a crop and livestock production system. Integrated crop and livestock systems can positively affect biodiversity, soil health, ecosystem services and forest preservation. Due to the integration of components, they are able to compete economically with intensive large-scale specialized operations. Variants include systems with or without trees or aquaculture, and agropastoral systems with or without trees.

The aim is for components to interact synergistically. For example, waste products such as manure from livestock are used to improve soil fertility for crop production, while crop residues provide supplementary feed for animals. Mixed systems diversify production, making resource use more efficient, and improve resilience to risks of climate change, market variability or production failure.

## Traditional agriculture systems

Traditional agricultural systems comprise indigenous forms of ecological agriculture resulting from the coevolution of social and environmental systems. These systems are usually characterized by a high degree of complexity and plant biodiversity. Much can be learned from the very specific use of environmental knowledge and natural resources in these systems, because of their highly evolved synthesis between productive and natural systems. Some have now achieved the status of Globally Important Agricultural Heritage Sites (GIAHS). Careful introduction of management improvements to these systems, based on sustainable land and water management technologies, can result in higher yields, particularly from agroforestry and integrated crop and livestock practices. However, some forms of traditional agriculture are encountering pressures that may make them less sustainable, and changes may be needed (CDE, 2010; Neely and Fynn, 2010).

### Sustainable agropastoral and pastoral practices

Healthy and productive grasslands are obtained in drylands by bunching the stock into large herds and moving them frequently. Controlled grazing allows for more even distribution of dung and urine that can enhance soil organic matter and nutrients for plant productivity. In fact, overgrazing is often more a function of time than of the absolute numbers of animals – it happens when livestock have access to plants before the above-ground parts and rooting systems have had time to recover. The holistic planned grazing method (Savory and Butterfield, 1999) should improve soil cover, plant diversity and biomass, increase water infiltration, and increase animal density to better distribute dung and urine, while limiting grazing time. It results in improved biomass production, as well as improved livestock quality and productivity.

Many researchers on pastoral systems have concluded that extensive livestock production on communal land is the most appropriate use of semi-arid lands in Africa (Scoones, 1995). Therefore, the conversion of de facto common property resources that are commonplace in rangelands into private user rights encourages short-term resource exploitation rather than the long-term conservation they require. Community managed conservancies in Kenya are utilizing holistic grazing of livestock to increase productivity of the livestock, as well as wildlife numbers (Box 4.7).

Key constraints stemming from lack of tenure, promotion of privatization, and minimal health and education services must be addressed to ensure that the synergistic relationship between livestock-based livelihoods and environmental health can be successful and sustainable (UNCCD, 2007). Improving pastoralists' capacities to move towards sustainable management of rangelands requires a combination of measures that include adaptive management approaches, social organization and tenurial arrangements that cover the common property resources upon which their livelihoods depend.

### Constraints and challenges

The approaches described are all context-specific, and should be adapted to the local agro-ecological and socio-economic context. Major challenges are knowledge, incentives and resources. All approaches require knowledge and knowledge transfer, and the institutional basis for this has to be available. All of the approaches have their own economic rationale, but often financial costs are higher than in traditional systems, and overall profitability may be uncertain. Part of the benefit of 'ecologically adapted' agriculture goes off-site, to downstream or global beneficiaries,

## BOX 4.7: REVERSING DESERTIFICATION IN BARINGO GRASSLANDS, KENYA

In the land around Lake Baringo in Kenya's central Rift Valley, a quiet natural revolution is taking place to reverse devastating land degradation and re-establish grassland resilience. The Rehabilitation of Arid Environments (RAE) Trust recognized that, in pastoral areas, grass is the most important commodity. With community members, they are transforming the Baringo basin. Some 2 200 ha have been successfully rehabilitated using trees and grass plantings, and improved livestock management. Bringing back the grass has now positively impacted some 15 000–30 000 people – including individual families, pastoralists managing communal fields and group ranches, as well as self-help and women's groups. Grass seed is being harvested and is now sold throughout Kenya.

Getting the perennial grasses back has not just refurbished the ecosystem processes (land, nutrients, water and biodiversity) but has resulted in the confidence and competence for the communities to be self-sustaining. A focus on the drylands and grazing lands of Africa is indispensible to efforts for reversing degradation and reducing poverty.

*Source: Elizabeth Myerhoff and Murray Roberts, RAE Trust. Photo: W. Lynam*

whereas the farmer bears all of the cost. Even if the profit incentive is present, the investment costs and lead time before these approaches 'pay back' is a constraint for farmers, particularly poor smallholders.

## Sourcing water for irrigated agriculture

### New diversions and multipurpose projects

Over the four decades to 2050, a net increase of water withdrawals for agriculture of about 150 km$^3$ is anticipated, with the largest gross increases in Southeast Asia, Southern America and sub-Saharan Africa. Most of this will have to come from surface water, as groundwater is already fully developed in most locations.

Opportunities for large storage dams are fewer than in the past, and low economic returns and environmental and safety considerations have reduced interest in the construction of large dams. High cost means that large dams can usually only be justified by hydropower benefits. However, projects are under way or under consideration in a number of countries, including China, Iran and several African countries. Some irrigation water may also be added by optimizing release rules on existing dams. Transboundary cooperation on water resources development and management could also increase water availability for irrigation. For example, hydropower dams on the Blue Nile in Ethiopia could provide extra irrigation water downstream.

But most new storage specifically for irrigation is likely to be at a small scale. In many countries there are options for such small structures. All such impoundments require social, economic and environmental assessment of the risks and trade-offs involved, and projects need to be studied within a basin-planning framework. At the policy level, diversion of extra water for agriculture would require decisions about locking in entitlements to agriculture over other, possibly higher value uses, and about downstream risks to the aquatic environment and wetlands. Where transboundary resources are concerned, governments would have to weigh the benefits of optimizing investment at the basin scale (which might, for example, suggest upstream investment in hydropower and downstream diversion for irrigation) against sovereignty and water security issues. A decision to invest in irrigation development rather than in rainfed agriculture or in other pro-poor assets and services would be conditioned by the impacts of possible investment alternatives.

### Groundwater

Despite the problems of depletion and pollution, groundwater will continue to offer a key buffer in maintaining optimal soil moisture for irrigated crops, and this role will grow with increasing climatic variability (FAO, 2011d). In many countries, though, there are few opportunities for new groundwater development, so better use of existing groundwater resources is a vital priority.

But groundwater depletion as a consequence of intensive agriculture is unrelenting (Siebert *et al.*, 2010). Although introduction of management approaches is unlikely to restore many aquifers to complete sustainability, aquifer life and productivity can be improved. Recent experience with community self-management of groundwater is encouraging, where recharge of shallow aquifers is active and user interests in maintaining dependable levels of agricultural production are high (World Bank, 2010a).

Salinization of aquifers arises from percolation of polluted or saline waters from irrigated agriculture, and also when aquifer stocks are depleted and concentrations of salts rise. In addition, depletion of coastal aquifers can result in saline intrusion. The key solution is active management of aquifers, to reduce extraction to the sustainable yield. Aquifer health may also be restored by artificial injection of freshwater to dilute saline water or to create salt water intrusion barriers, but this can be costly and requires a high degree of control (Mateo-Sagasta and Burke, 2010).

### Scope for investing in non-conventional sources of water

Globally, only about 60 percent of water withdrawn is actually consumed in direct evaporation – some 2 900 km$^3$ out of 5 200 km$^3$. The rest is returned to the hydrological system and is potentially recoverable for secondary uses, such as agriculture. If all this water were recovered, it would represent more than three-quarters of the present consumptive use in agriculture. Thus, particularly in water-short countries, investment in re-use of drainage water and municipal or industrial wastewater can offset scarcity.

Drainage water can be re-used either through loops in systems or by farmers pumping direct from drains. Use of these relatively saline waters poses agricultural and environmental risks due to soil salinization and water quality degradation downstream, and thus salinity risk assessment and monitoring are needed. Actions to prevent further salinization of land and water, or to remediate saline or sodic soils, also have to be implemented. Successes include in Egypt, which re-uses over 10 percent of its annual freshwater withdrawals without deterioration of the salt balance. Desalination of salty groundwater and brackish drainage water for agriculture is so far uneconomic due to high energy costs, with the exception of intensive horticulture for high-value cash crops, such as vegetables and flowers (mainly in greenhouses) grown in coastal areas, where safe disposal of the brine is easier than in inland areas (Mateo-Sagasta and Burke, 2010). However, desalinated water, including drainage water, is becoming a more competitive option, because costs are declining while those of surface water and groundwater are increasing.

As cities expand, more municipal and industrial wastewater will become available. Wastewater has the advantage of being rich in nutrients, and is available close to centres of population and markets, so is ideal for peri-urban market gardening and aquaculture. However, contaminants in wastewater pose risks for human health and the environment. To maximize benefits and minimize risks related to the use of wastewater, a robust policy and institutional framework has to be designed (WHO-FAO-UNEP, 2006). Decisions on *technical* aspects need to be taken up-front, because this will determine the treatment method for re-use of effluent. The *water resources allocation* aspects need to be planned: who will receive the water needs to be assessed and become subject to contractual arrangements. On the *environmental* side, rules and regulation are required to control contaminants at source, and to protect human health. Finally, on the *agricultural* side, restricted irrigation and cropping practices may need to be applied.

## Modernizing irrigation systems

### Improving water service in large irrigation schemes

The scope for efficiency gains and improved land and water productivity in irrigation is considerable. Efficiencies worldwide are well below technical maximums; pressurized systems and protected agriculture still occupy only a small area; low-value staples predominate in cropping patterns; and agricultural yields and farmer incomes are well short of potential (Molden *et al.*, 2010). Three elements can contribute to 'more value per drop': improving water service, improving on-farm water use efficiency (especially on-farm) and improving agronomic efficiency.

Pathways to improve productivity and bridge the yield gap in irrigation include increasing the flexibility, reliability and timing of water service through operation and maintenance of the diversion and canal system, or better distribution within the system (for example, by increasing supplies to tail-end areas). In principle, improved water service is feasible on almost all irrigation schemes.

An integrated approach is required to invest in the different inputs to the production system – soil, water, agronomy, along with economic and institutional improvements. The concept of large-scale irrigation scheme modernization embraces all the changes in the irrigation delivery system, in agronomic practices, and in the institutional and incentive structure needed to provide farmers with a sustainable, efficient and demand-responsive water delivery service that will underpin a high productivity and sustainable farming system (FAO, 2007e).

A second pathway is to improve water-use efficiency (consumptive use of water in irrigation as a proportion of water withdrawal for irrigation) so that a larger share of water diverted is used beneficially (for example, by reducing losses in the irrigation system, improving on-farm water management or recycling drainage water). The scope for increasing the beneficial use of water withdrawn for irrigation is demonstrated by the very low ratio in many areas between water required and water withdrawn, as up to three times as much water is withdrawn on irrigation schemes as is actually required for plant growth. However, the scope for saving water must be considered with caution, as a large part of unused water returns to rivers and aquifers through percolation and drainage.

Integrated modernization will require both 'hardware' and 'software' investments. Hardware investments will go beyond the simple rehabilitation of existing systems to include physical improvements to the system, such as the correct selection of gates and control structures, lining of canals with geosynthetics, construction of interceptor canals and reservoirs, and installation of modern information systems, as well as on-farm irrigation improvement technologies such as drip irrigation, and a drainage network that allows a non-polluting management of the salt balance. Modernization investments also include a range of 'software' improvements such as scheme management and institutional structures, on-farm water management practices, combined water and soil fertility management, drainage water management, and integrated approaches to combating drought, salinity and floods. Investment in irrigation modernization for sustainable, high-productivity agriculture requires an economic environment that provides undistorted incentives, manageable risk and market access.

### The scope for improving productivity in small-scale and informal irrigation

The scope for improvements in irrigation productivity is not confined to large formal schemes. Many smallholders in Asia, Africa and the Middle East make their livelihoods from agriculture practised in small-scale and traditional irrigation systems. Often, small-scale irrigation is based on community-constructed water diversion and conveyance systems operated by user-managed institutions. These include flood-based systems (such as spate diversion or flood recession), spring and shallow well systems, small-scale perimeters lifting water from rivers, run-off / run-on systems, water-harvesting systems, and local market-gardening systems using wells, local runoff or even tap water.

Small-scale irrigation systems exist in almost all agro-ecological zones, and are important where water is a significant constraint on crop production and where water resources are limited or overused, particularly in semi-arid to subhumid zones. Often these schemes are partly (or even mainly) rainfed, using only supplementary irrigation. Typically, yields are well below those of larger formal schemes due to lack of economies of scale, lack of appropriate varieties and water control, and difficulties of accessing markets. Their strengths lie in well-developed traditional knowledge, sustainable management of land and water resources, and levels of local social capital.

The challenge is how to improve performance on these schemes without compromising their present sustainability. Some technologies are available – for example,

BOX 4.8: DRIP IRRIGATION TECHNOLOGY

*Drip irrigation system*

The aim to increase returns to water, ('more crop per drop'), can be achieved through many ways, including more efficient water collection, abstraction, storage, distribution and application in the field. Drip irrigation schemes are water-efficient systems that apply small volumes of water at frequent intervals close to the root-zone. In drip irrigation systems, water flows through a filter into special drip pipes and is discharged directly onto the soil near the plants. When this technology is properly managed, the advantages include better water control, improved plant nutrition and reduction in labour requirement. It is well suited for high-value crops, including vegetables and fruit trees.

*Source: CDE (2010) Photo: W. Critchley*

canal lining for spring-fed schemes, or treadle pumps for market gardening. What is needed are mechanisms to transmit knowledge, technology and investment support, ensuring that change is introduced within the framework of traditional sustainable land and water management practices (Box 4.8).

## Increasing on-farm water productivity

### Water-use efficiency

Improving on-farm water-use efficiency (beneficial consumptive use by evapotranspiration as a proportion of water delivered) depends on the on-farm water management skills of farmers. Measures to improve on-farm water-use efficiency combine increasing the skills of farmers to better manage the timing and quantity of irrigation for their crops with investment in on-farm irrigation technology that provides better control over water deliveries and reduces wastage. Better control can be provided by piped distribution systems, and by precision delivery to wet the plant roots, (e.g. by drip or bubbler irrigation). These technologies will also reduce non-beneficial water consumption by reducing transmission losses to percolation and non-beneficial evaporation. Efficiency can be increased further by controlling the micro-climate around the crop, such as in protected agriculture under greenhouses.

Agronomic efficiency depends on the skills of farmers, though some constraints, such as climatic and socio-economic factors, are outside their control. Agronomic efficiency can be improved by:

- Water control and soil moisture management to ensure adequate availability of moisture to plant roots for optimal growth. Conservation agriculture, in particular, reduces significantly unproductive water losses.

- Water, soil and nutrient management to ensure timely availability of nutrients in the root zone and efficient nutrient uptake by plants. In particular, water, soil and input management to raise nitrogen availability is critical for high yield per unit of evapotranspiration.

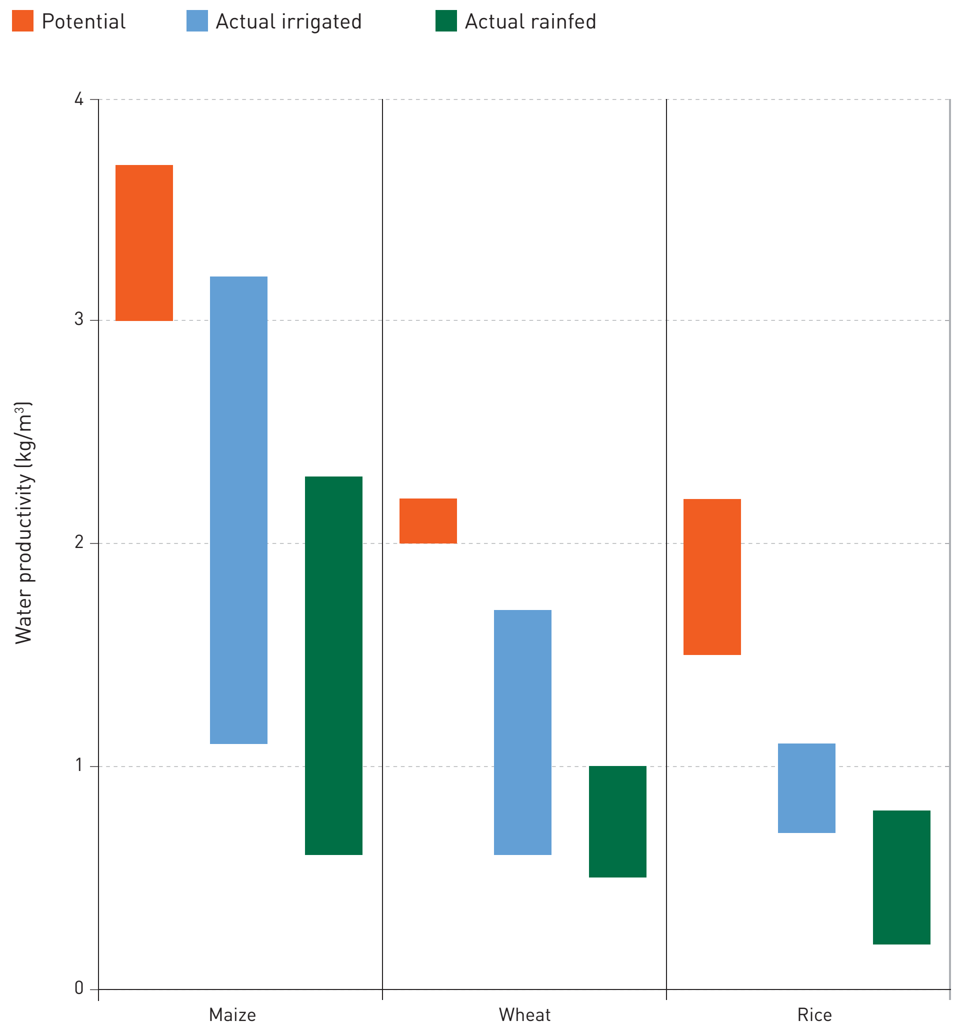
- Crop husbandry to select the optimal cropping pattern, choose the best-performing varieties, align the cropping calendar with moisture availability, sow at the right time, and manage weeds, arthropod pests and diseases.

### Water productivity

An additional route towards a more productive use of irrigation water is to increase agronomic or economic productivity so that more output is obtained per unit of water consumed. This can be obtained through better agricultural practices, leading to increased yields of irrigated crops (including by achieving a higher harvest index) and for which no additional irrigation water is needed, or through hanging cropping patterns and moving towards higher-value crops, bearing in mind the overall biophysical limits (Steduto et al., 2007).

Despite the considerable improvements in water productivity in recent years, a gap remains between the actual and attainable yield per unit of water consumed. Figure 4.1 shows actual recorded water productivity for both irrigated and rainfed crops, matched against the realizable potential water productivity. The data confirm that water productivity in irrigated agriculture is typically higher than in rainfed. For both irrigated and rainfed conditions, actual productivity falls well short of the potential. Wheat and rice show the largest gaps, indicating where water productivity can still improve substantially.

FIGURE 4.1: WATER PRODUCTIVITY FOR MAIZE, WHEAT AND RICE: POTENTIAL, IRRIGATED AND RAINFED



*Source: Sadras et al. (2010)*

It is generally observed that cropping patterns progressively change towards higher-value crops in water-constrained areas. In China, for example, there have been shifts, with a slight decrease in rice and wheat, and sharp increase in maize, vegetable and other high-value crops. The potential for closing the water productivity gap is considerable, but realizing higher levels of water productivity requires more intensive production techniques.

Many of the on-farm practices to increase crop water productivity are well known and could double water productivity. Situations vary widely across crops and production systems, and analysis and proposals for improvement need to be highly specific. Box 4.9 contains five case studies drawn from environmentally, technologically and culturally diverse regions, and covering farming systems ranging from subsistence to high-tech production systems. In most situations, adopting measures to improve soil moisture availability and raise the capacity of crops to capture water are the lowest-cost and quickest ways to raise water productivity. In addition, overall water productivity can be raised by improved methods to reduce harvest and post-harvest losses, which may add up to 30–40 percent of the yield originally produced at the farm (Lundqvist *et al.*, 2008).

### BOX 4.9: FIVE CASE STUDIES OF IMPROVING CROP WATER PRODUCTIVITY

Rainfed **wheat** in southeast Australia, Mediterranean Basin, China Loess Plateau and North American Great Plains: a considerable gap between actual and maximum potential yield per unit of water was found. The average gap was 68 percent for the southern Great Plains of North America, 63 percent for the Mediterranean Basin, and 56 percent for China Loess Plateau, Northern Great Plains and southeast Australia. The reasons for these gaps included nutrition, sowing time and soil constraints. Soil moisture management was a key problem. Among the solutions identified were rapid ground cover to reduce evaporation, minimum tillage approaches and stubble management.

A similar yield gap exists for commercial rainfed **sunflower** in the western Pampas of Argentina, with nutrient and water availability and interaction at sowing time the most important leverage point to increasing yield and water productivity.

For **rice** systems in the lower Mekong River Basin, the yield gap is large, with actual productivity per unit of water consuming only 15–30 percent of maximum possible. The main opportunities for improvement include using high-yielding varieties, increasing application of fertilizer, herbicides and pesticides, and supplementary irrigation. Changing cropping patterns to higher-value crops such as coffee, vegetables and peanuts (which outperform rice in economic returns per mm of water use) may also be an option.

The irrigated commercial **maize** systems in the western US corn belt were only 10–20 percent below maximum productivity. Nonetheless, better management of water could still improve productivity; for example, irrigation scheduling based on real-time crop requirements and some water monitoring.

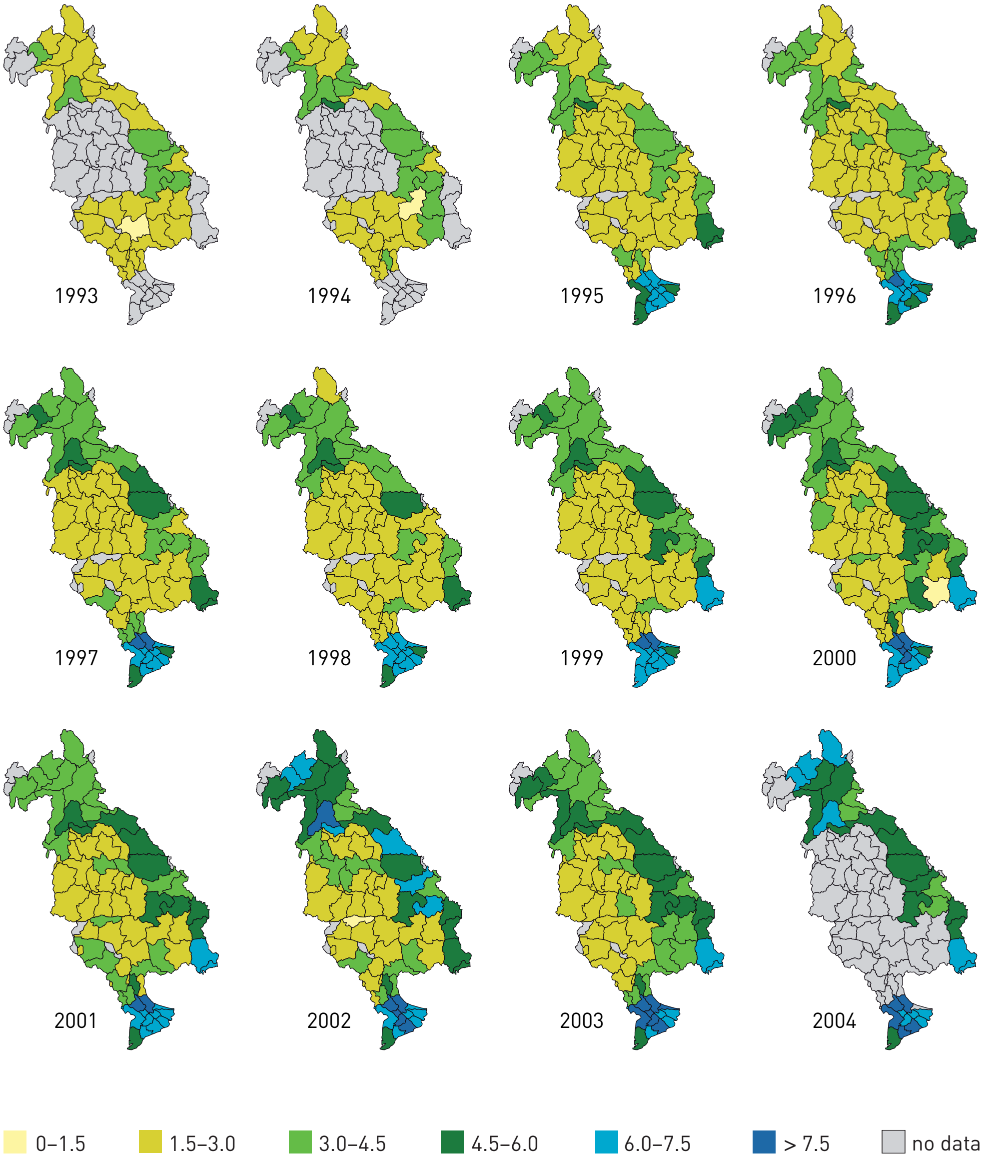
Environmental, management and plant-related factors contribute to very low water productivity of **millet** in the Sahel, averaging only 0.3 kg for each $m^3$ consumed. Improving water productivity of millet in dry, hot environments of Africa requires higher inputs, chiefly large fertilizer doses. However, the low harvest index of millet that contributes to its low water productivity needs to be considered in the context of a trade-off between grain production and valuable crop residues.

*Source: this study*

## Where will improving crop water productivity make a difference?

Water productivity can improve, even over a relatively short timeframe, as recent progress in some systems shows. For example, the water productivity of rice in the lower Mekong River Basin is low (14–35 percent of potential), but has been increasing rapidly in recent years (Figure 4.2). The improvements arise from adoption of high-yielding varieties, better application of fertilizer, herbicides and pesticides, and supplementary irrigation. There are some straightforward technical gains for crops such as chickpea and sunflower, where large improvements in yield per unit of water

**FIGURE 4.2: MEKONG RIVER BASIN YIELD PER UNIT EVAPOTRANSPIRATION OF RICE AT A REGIONAL SCALE (IN kg GRAIN/ha/mm)**



*Source: adapted from Mainuddin and Kirby (2009)*

**BOX 4.10: CHINA IS A WATER-SAVING SOCIETY**

China has made significant achievements in saving water used for agriculture, largely because of institutional and technological innovations. Between 1980 and 2004, while the total volume of water being used rose by 25 percent, the amount allocated to irrigation remained at 340–360 km$^3$. At the same time, the irrigated area increased by 5.4 Mha, food production capacity increased by 20 million tonnes and 200 million people gained food security. In the past decade, China's irrigation water use per hectare dropped from 7 935 to 6 450 m$^3$ nationwide.

*Source: Wang et al. (2007)*

consumed may result from simply shifting the growing season from spring–summer to autumn–winter, provided diseases and weeds are properly managed.

The technical scope for improving crop water productivity varies between crops, production systems and regions (Box 4.10). Among food grains, there is most potential for rice, but also considerable scope for improvement in wheat and some maize systems. Some parts of the world already exhibit high physical crop water productivity, with limited prospects for improvements with present technology. This is the case in many of the most productive regions, such as the Lower Yellow River Basin, and most of Europe, North America and Australia. The areas with the highest potential gains are sub-Saharan Africa, and parts of South, Southeast and Central Asia. In all these areas, increases in water productivity would increase land productivity and result in higher output from the existing cultivated area, with little change in overall water consumption. However, these productivity gains need to be considered in relation to overall river basin and aquifer balances. (Perry *et al.*, 2009).

## Managing environmental risks associated with intensification

The techniques associated with higher productivity have to be accompanied by adequate and balanced use of fertilizers, to boost yields and to compensate for the removal of soil nutrients in crop yields. Intensive production also often requires further treatment of weeds, diseases and insects. But the use of inputs brings the associated risks of pollution from fertilizers and pesticides. Where the technical and socio-economic conditions are not in place for sustainable land and water management, on-site risks arise, and there are also significant risks to downstream water bodies and to human health. Management of inputs is essential to avoid these negative impacts (FAO, 1996).

In irrigation there may also be another spin-off in terms of improved health: malaria and bilharzia often plague irrigation schemes. Improved water management can reduce risks of infection (e.g. by reducing pools of standing water). In addition, modernization combined with water savings gives opportunities to extend schemes to supply water to local communities (Molden, 2007).

### Fertilizer pollution and nutrient management

The largest quantities of fertilizer applied to crops are nitrogenous and phosphorous compounds. Nitrogen is required as nitrate for uptake by roots. The maximum achievable efficiency (uptake/application) is only around 50 percent, and in practice fertilizer efficiencies are rarely better than 20–30 percent. Because nitrogen fertilizers are highly water-soluble and are rapidly cycled in the soil, much of what is not taken up by the plant may be dissolved as nitrate in solution, finding its way into drainage systems, downstream watercourses and groundwater. Nitrogen is also released to the atmosphere as ammonia or nitrous oxide.

Managing nitrogen fertilizer loss can be achieved through a combination of (1) better application practices, (2) more efficient nitrogen take up by the plant and (3) better water management. Additionally, a healthy soil is needed to better hold nitrogen. Measures to improve the efficiency of application – and so reduce the release of nitrates – include such simple steps as:

- Split applications across the most responsive growth stages of a particular crop.

- ‘Little and often’ application in horticulture, using soluble fertilizers mixed into the irrigation water and applied with some precision. Farmers in Sunraysia (Australia), for example, have found that they achieve the highest fertilizer efficiency in fertigation by applying nitrogen at the end of an irrigation (in a 10–15 minute period, 25 minutes before the end of the watering).

- Placing the fertilizer in the root zone below and either side of the crop, at a shallow depth, where there is the highest concentration of roots.

- Deep placement of ammonia fertilizer as depot (CULTAN method). Nitrogen is partly taken up by the plants as ammonia, without passing through the state of nitrate, avoiding nitrate leaching.

Measures to promote higher uptake by plants include the use of protected and slow-release compounds, which release nitrogen progressively at a rate determined by soil moisture content, pH and soil temperature, thus creating a longer period of availability. These compounds have good commercial potential in high-value and shallow-rooted crops, and in areas where there is high potential for nitrate loss.

Biological additives may also be used to enhance nitrogen-use efficiency by encouraging stronger root growth and more active uptake, and by slowing the release of nitrogen as ammonia. Additives have resulted in 54 percent less ammonia volatilization in sugar cane and 79 percent less in wheat.

Soil management solutions include enabling the medium to hold nutrients and to convert them efficiently into plant nutrients. It is essential to pay more attention to soil health. This not only improves internal nutrient availability, and hence improves fertilizer efficiency; it also significantly reduces wastage of soil nutrients through erosion and leaching. It has been proven in several places (e.g. Brazil, Germany) that intake of nitrates and phosphates into water bodies is directly linked to soil tillage and that the reduction or avoidance of soil tillage could be crucial to significantly reduce the pollution to acceptable levels, without negatively impacting on production levels.

Although the fertilizer industry is innovating to improve fertilizer use efficiency and reduce environmental externalities, farmers may have neither the knowledge nor the incentives to reduce polluting behaviour. There are several policy options: (1) continue research, in partnership between the fertilizer industry, farmers and research bodies; (2) use selective regulation and incentives to encourage the use of slow release fertilizers wherever possible, and particularly in areas where risks of nitrogen being exported to water bodies are highest; and (3) farmer education (see Box 4.11).

Unlike nitrogen, phosphate is generally bound to soil particles and is made slowly available to plants. It is thus less likely to find its way into the drainage system or groundwater. A combination of good water management and soil incorporation of phosphate can reduce phosphate export to close to zero. Overall, where policies and

### BOX 4.11: CHINA'S NITROGEN POLLUTION PROBLEM

The highest rates of nitrogen application in the world are now reported to be in China (around 550 to 600 kg N/ha/year in the east, southeast and North China Plain). Fertilizer use has increased rapidly between 1998 and the present, especially in the use of NPK fertilizers in horticulture and nitrogen fertilizers more generally. One consequence is that more than half of the nation's 131 large lakes are suffering from eutrophication. Surveys have revealed that most farmers are unaware of the efficiency of use and the environmental consequences of excessive fertilizer application. It has been suggested that price is too low and that this encourages overuse. But surveys reveal that farmers without access to irrigation water do not apply much nitrogen fertilizer, which indicates price sensitivity. Reducing nitrogen pollution thus depends on development and use of appropriate fertilizers, regulation and incentives, and farmer education.

*Sources: Turral and Burke (2010); Jua et al. (2009)*

programmes have been applied, there have been some successes in reducing pollution loads from agriculture, though most successes have been in reduction of urban loads.

### Pesticide pollution

A range of IPM methods have been developed to address problems of pesticide pollution of water and risk to human health. IPM encourages rational and minimal use of inputs by regular monitoring and identification of pest numbers, and seeks to preserve healthy populations of natural predators and supportive habitats. IPM also incorporates the breeding and planting of pest-resistant varieties (bred by conventional or gene modification methods), strategic mixtures of varieties with different resistance characteristics, as well as crop rotation and fallowing. It may also include the introduction of natural predators of pests.

IPM approaches have been widely adopted by commercial farmers in developed countries in order to improve effectiveness and efficiency and in response to increasing environmental awareness. Take-up in developing countries has been slower, though farmer field schools have been highly effective at increasing farmer knowledge and uptake of IPM (Settle and Garba, 2011). Legislation, product approval requirements, farmer education and product price also play a role in restraining the use of pesticides. The lag in regulatory activity between developed and developing countries is a cause for concern, especially when cheap generic pesticides are produced locally after being removed from the market in richer countries.

Wider adoption of conservation agriculture, in which mechanical disturbance of the soil and other physical impacts are minimized, also has the potential to reduce the contamination of waters with pesticides due to erosion.

Many pesticides are soluble and mobile, and water management techniques are required to minimize their export to water courses (Box 4.12). Strict on-site regulation of compounds is needed when the risk of downstream contamination is high.

### Minimizing risks from arsenic

Arsenic contamination of groundwater has been reported in more than 20 countries where contaminated shallow groundwater is used for both drinking and irrigation purposes. Additional industrial sources, such as from mineral extraction and processing wastes, poultry and swine feed additives, pesticides, and highly soluble arsenic trioxide stockpiles, have further contaminated soils and groundwater. Some 130 million people are at risk from arsenic toxicity (arsenosis), which causes skin lesions and various cancers. Arsenic accumulation in the food chain, such as arsenic transfer in rice in Asia, is a major concern (FAO, 2007d). Management options to prevent and mitigate arsenic contamination of food are being developed and tested. Strategies for management of arsenic that would enable rice production to continue in polluted

### BOX 4.12: RECOMMENDATIONS FOR PESTICIDE MANAGEMENT UNDER IRRIGATION

1. Do not apply pesticide immediately before irrigation or in the likelihood of heavy rain.
2. Irrigation scheduling should avoid high-risk periods (especially where furrow or overhead irrigation are used).
3. Apply pesticides with the appropriate droplet size and dose rate to avoid runoff of spray liquid from the target areas.
4. Reduce soil and sediment loss in surface runoff. Significant reduction in pesticide transport from runoff can result, particularly for compounds such as paraquat, trifluralin and chlorpyrifos, which have high adsorption to soil particles.
5. Risk of significant off-site movement from the farm can be reduced by not treating large areas at one time. This will reduce the potential source if irrigation is scheduled or heavy rain falls.
6. Some herbicides are highly mobile and can move quickly off-farm (either in runoff or by leaching), particularly if irrigation or rainfall occurs.
7. Newly applied pesticides are often more mobile than those that have had time to bind to soil or foliage.
8. Irrigation tail-water can contain high levels of pesticide residues; recycling and avoiding excessive irrigation after application can minimize off-site losses.
9. Additional precaution should be taken where storm or irrigation runoff discharges near streams or sensitive habitats. Good water management is strongly linked to effective pesticide management.
10. In highly porous soils or in areas with shallow water tables, less mobile alternatives should be considered to minimize potential contamination of groundwater or baseflows in streams.

*Source: Simpson and Ruddle (2002)*

areas include growing rice in an aerobic environment and switching to non-contaminated surface or deep groundwater to avoid further build-up of arsenic in the soil.

## Salinity and drainage

In irrigated areas, the on-site and off-site risks from salinization and waterlogging have become a serious problem in many parts of the world (Mateo-Sagasta and Burke, 2010). Leaching and drainage are required to maintain salt balance in the soil profile and to sustain crop yields in arid areas. However, removal of salts from the soil through leaching and drainage increases the salinity of drainage water, which then might be up to 50 times more concentrated than irrigation water. Its disposal can raise the salinity of receiving water bodies to levels that make them no longer usable.

Solutions start with more efficient water use to reduce excess application and maintain the correct salt balance through tactical leaching doses. Subsequent drainage options are: (1) drainage water management; (2) drainage water reuse; (3) drainage water disposal; and (4) drainage water treatment. Each of these has differing impacts on the hydrology and water quality, and complex interactions and trade-offs occur when more than one option is applied.

Drainage water management is the primary method of controlling soil salinity. A drainage system should permit a small amount of the irrigation water (about 10–20 percent of drainage or leaching fraction) to be drained and discharged out of the irrigation project. This can be achieved by open ditches, tile drains or pumping from boreholes. The choice depends on the permeability of the soil, subsoil and underlying aquifer material, on the funds available for the capital works, on the resources of local communities for operation and maintenance, and on the energy costs of pumping.

Saline drainage water can be re-used downstream if blended with freshwater. These approaches require planning at the watershed scale to adapt agricultural practices and crops to the higher salt content. Here crop selection is important, as crops vary considerably in their ability to tolerate saline conditions: durum wheat, triticale and barley tolerate higher salinity than rice or corn. Irrigation with saline water can even improve the quality of some vegetables, as the sugar content in tomatoes or melons can increase.

Disposal options include direct discharge into rivers, streams, lakes, deserts and oceans, and discharge into evaporation basins. But such discharge of salty water can bring environmental problems to downstream areas. The hazards must be considered very carefully and, if necessary, mitigating measures taken. If possible, the drainage should be limited to wet seasons only, when the salty effluent inflicts the least harm. Constructed wetlands are a relatively low-cost option for protecting aquatic ecosystems and fisheries, either downstream from irrigated areas or in closed basins.

## Land and water approaches in view of climate change

### Agriculture and climate change

The relationship between land and water management and climate change has been identified across some of the key agricultural systems (FAO, 2011d). Land and water management practices have a strong impact on climate change drivers, both negatively and positively. Many past and current agricultural practices are among the causes of climate change, with agriculture and associated deforestation activities responsible for up to a third of total anthropogenic greenhouse gas emissions. At the same time, climate change is expected to have a considerable impact on land and water use for agriculture (IPCC, 2007; Fisher *et al.*, 2007), and the funding of adaptation strategies for increasing resilience of agricultural systems in the face of increasing climate threats, especially in poorer countries already at the margins of food insecurity, is now a global priority.

Sustainable land and water management can not only increase resilience of farming in the face of climate change but also have a positive impact on the drivers of climate change, offering cost-effective mitigation options (Tubiello *et al.*, 2008). Many management techniques that strengthen production systems also tend to sequester carbon either above or below the ground, as well as reducing direct greenhouse gas emissions.

## Options for adaptation to climate change

Adaptation responses will require farmers and policy-makers to address key additional challenges: (1) from the farmer's side, the ability to implement new (or adapt previously known) technologies as the climate changes; and (2) from the policy-maker's side, the ability to develop the right incentives and deliver the necessary infrastructure in a planned and forward-looking fashion. *Autonomous adaptation* actions will be implemented by individual farmers on the basis of perceived climate change, and without intervention from above. *Maladaptation* (for example, pressure to cultivate marginal land, or to adopt unsustainable cultivation practices as yields drop) may increase land and water degradation, possibly jeopardizing future ability to respond to increasing climate risks. *Planned adaptation*, including changes in policies, institutions and dedicated infrastructure, will be needed to facilitate and maximize long-term benefits of adaptation responses.

From the technical perspective, adaptation options are largely similar to the existing activities that have been developed in the past in response to climate variability. Broadly speaking, adapting to changes will require farmers to (1) adapt management, (2) choose other more robust crop varieties, (3) select other crops and (4) modify water management practices. Such changes will come as a result of a combination of scientific knowledge and field experience. If widely adopted, these adaptations singly or in combination have the potential to offset negative climate change impacts and take advantage of positive ones. Adapting to increased frequency of extreme events, on the other hand, will be much harder, especially since such new regimes may not have historical analogues.

Options for cropping include: changes in crop varieties and species for increased resistance to heat shock and drought, flooding and salinization; adaptation of fertilizer rates; altering the timing or location of cropping activities; diversifying crop production; making wider use of integrated pest management; developing and using varieties and species that are resistant to pests and diseases; improving quarantine capabilities and monitoring programmes; and matching livestock stocking rates and grazing to pasture production. In particular, conservation agriculture, through simultaneous improvements in crop diversification, soil structure and organic matter content, can reduce the impacts of climate variability and represents a broad response to climate change adaptation.

Water management is a critical component of adaptation to climate pressures in coming decades. These pressures will be driven by changes in water availability (volumes and seasonal distribution), and in water demand for agriculture and other competing sectors. Practices that increase the productivity of irrigation water use may provide significant adaptation potential for all land production systems under future climate change. At the same time, improvements in irrigation performance and water management are critical to ensure the availability of water both for food production and for competing human and environmental needs (FAO, 2007e, 2011d). A number of farm-level, irrigation system-level and basin-level adaptation techniques and approaches are specific to water management for agriculture. They include: modification of irrigation amount, timing or technology; adoption of supplementary irrigation and improved soil moisture management techniques in rainfed cropping; adoption of more efficient water allocation rules; conjunctive use of surface water and groundwater; and adoption of structural and non-structural measures to cope with floods and droughts.

Better data and more attention to monitoring would support better climate forecasting, particularly seasonal forecasting. Forecasting technologies, even to the optimization of rainfall use, already exist and are commercially available in some countries. Much still needs to be done to improve the quality of forecasting and its communication in a user-friendly way if they are to have a positive adaptive benefit.

Government-level solutions should focus on developing new infrastructure, policies and institutions, including addressing climate change in development programmes, increasing investment in water control and irrigation infrastructure and in precision water-use technologies, ensuring appropriate transport and storage infrastructure, adapting land tenure arrangements (including attention to well-defined property rights), and establishing accessible, efficiently functioning markets for products and inputs (including water pricing schemes) and for financial services (including insurance).

### Contribution to climate change mitigation

All action contributing to the protection of land and water resources, the efficient use of resources and inputs, reducing wastes and losses in agriculture, and making land- and water-use systems more resilient to the vagaries of weather and markets should all already facilitate mitigation and adaptation. The impact of more sustainable land and water management could be significant (Box 4.13). It is estimated that if

## BOX 4.13: DRYLAND PASTORAL SYSTEMS AND CLIMATE CHANGE

Pastoral systems hold great potential for synergies between climate change mitigation and adaptation. They occupy two-thirds of global dryland areas and their rural population is proportionally poorer than in other systems. They also have a higher rate of desertification than other land-use systems, which negatively affects the accumulation of carbon in the soils. Improved pasture and rangeland management in extensive dryland areas would contribute to substantial carbon accumulation and storage.

Improved grazing is a proven strategy for restoring soil and increasing land resilience while building the carbon pool. One of the most effective strategies for sequestering carbon is fostering deep-rooted perennial plant species on land used for agriculture, through rotations that include grass fallow or grass leys, and integrating fodder crops, trees or other perennial species into the cropping systems (i.e. maintaining mixed crop-livestock–tree systems).

Management practices that sequester carbon have the potential to generate economic benefits to households in degraded drylands, both through payments for carbon sequestration and, importantly, through co-benefits in terms of enhanced production, increases in ecosystem processes and sustainable resource use, thus enhancing climate change adaptation. While payments for carbon sequestration are currently limited to voluntary carbon markets, negotiations on future global climate change agreements as well as emerging domestic legislation in several developed countries may soon increase the demand for emission reductions from rangeland management activities in developing countries (Lipper *et al.*, 2010).

The economic feasibility of carbon sequestration in grasslands also depends on the price of carbon. IPCC (2007) note that, at US$20 per t$CO_2$eq, grazing land management and restoration of degraded lands have potential to sequester around 300 Mt $CO_2$eq up to 2030; at US$100 per t$CO_2$eq they have the potential to sequester around 1 400 Mt $CO_2$eq over the same period.

action is taken on improved crop and livestock management and agroforestry practices, reduced tillage and land restoration, production of bio-energy from biomass, and forestry sector mitigation strategies, total $CO_2$ reductions could be 4–18 billion tonnes, sufficient nearly to offset sector emissions (Table 4.1).

### Reducing methane and nitrogen emissions

Methane and nitrogen emitted by agricultural production have a high global warming potential. Mitigation of these non-$CO_2$ greenhouse gases is therefore very important. In addition to measures specific to livestock, which are outside the scope of this book, mitigation options for reducing methane from cultivation concern principally the development of more efficient rice cultivation systems, including lower require-

TABLE 4.1: MITIGATION POTENTIAL IN AGRICULTURE AND FORESTRY IN 2030

| | Billion $tCO_2eq$ |
|---|---|
| **Global mitigation potential** | **15–25** |
| **Agriculture mitigation potential** | **1.5–5.0** |
| Reduction of non $CO_2$ gases | (0.3–1.5) |
| Agroforestry | (0.5–2) |
| Enhanced soil carbon sequestration | (0.5–1.5) |
| **Forest mitigation potential** | **2.5–12** |
| REDD+ | (1–4) |
| Sustainable forest management | (1–5) |
| Forest restoration* | (0.5–3) |
| **Bio-energy mitigation potential** | 0.1–1.0 |
| **Total sector mitigation potential** | **4–18** |
| **Total sector emissions** | **13–15** |

* Including afforestation and reforestation.

*Sources: FAO (2008); Tubiello and van der Velde (2010)*

ments for water use (e.g. aerobic rice cultivation, in which flooding of cultivation fields is avoided), shifts from transplanted rice to direct-seeded rice systems and alternate wet–dry production system (FAO, 2006c).

In intensive agricultural systems with crops and livestock production, $N_2O$ emissions from fertilized fields and animal waste can contribute more than half of total greenhouse gas emissions from farms. As these nitrogen emissions are diffuse over space and time, they are hard to mitigate. Current techniques focus on reduction of absolute amounts of nitrogen fertilizer applied to fields while minimizing soil compaction (which causes anaerobic conditions and thus increases nitrous oxide emissions), as well as on changes in livestock feeding regimes.

An effective strategy for mitigating non-$CO_2$ gases in intensive mixed crop–livestock farming systems, such as those in place in both Europe and North America, could involve a change in human diet towards less meat consumption, reducing both direct methane and $N_2O$ emissions, and reducing the consumption of grain by livestock. However, patterns of development of cultures, tastes, lifestyles and demographic changes drive strongly in the opposite direction, towards major dietary changes – mainly in developing countries, where shares of meat, fat and sugar to total food intake continue to increase significantly (Tubiello and van der Velde, 2010).

## Sustainable agriculture and forestry

Many of the sustainable agricultural and agroforestry management practices that have long been recommended for broader ecological and economic reasons also have a climate change mitigation impact, largely through carbon sequestration. Trees integrated into farming systems, whether as shelterbelts, for slope protection, or for woody biomass or fruit and nut production, not only form part of sustainable land and water management approaches for improved soil water retention and reduced erosion, but also have a carbon-fixing impact (Box 4.14). In addition, micro-climate improvement brought about through trees and shrubs in agroforestry systems combines with better soil cover to help regulate the climate and reduce the impact of extreme events (for example, reduced impact of strong winds in humid and dry areas, and protection against high temperatures and radiation, and against moisture loss in dry and warm areas).

## Synergies between mitigation and adaptation

Many of the land and water management strategies discussed earlier link to both climate change mitigation and adaptation (Tubiello *et al.*, 2007). For example, reduced tillage, agroforestry and other ‘best practice’ soil and water management strategies not only improve productivity and sustainability by increasing the ability of soils to hold soil moisture and better withstand erosion, and by enriching ecosystem biodiversity through the establishment of more diversified cropping systems. They also enhance the long-term stability and resilience of cropping systems in the face of climate variability, helping cropping systems to better withstand climate-change-induced droughts and floods (adaptation). In addition, they contribute to soil carbon sequestration (mitigation). Box 4.15 illustrates how sustainable farming investments in vegetative sand barriers protect cropland against erosion (adaptation) and will also fix carbon (mitigation). Similarly, avoiding deforestation and improving techniques for forest conservation and management can not only lead to more resilient and healthy ecosystems, but also have important adaptation and mitigation effects.

### BOX 4.14: COMMUNITY REFORESTATION, BRAZIL: RESPONSE TO FLOODS AND LANDSLIDES

Many people from Brazil’s interior have moved to cities such as Rio de Janeiro, and now live in slums (*favelas*) with poorly constructed houses on steep hillsides. The rapid growth of the *favelas* has led to deforestation, soil erosion and landslides, which in turn have caused sedimentation, flooding and wet areas with mosquitoes. The city created the Community Reforestation Project in 1986, which aimed to control erosion and reduce the associated landslide and flood risks through the reforestation of erosion-prone areas of the city. The project employs residents and is reintroducing native tree species that are suited to erosion control.

*Source: CDE (2010)*

## BOX 4.15: VEGETATIVE SAND BARRIERS AGAINST WIND EROSION IN GANSU PROVINCE, CHINA

*Vegetative barriers*

Northern China is suffering from severe land desertification, which brings economic losses to dryland agriculture – and also damage to the railway line. The railway department raised funds to construct tall living barriers. These consist of bushes and trees of an appropriate height and penetrability, suitable for dry and sandy conditions. It helps to protect fields and infrastructure from drifting sand.

*Source: CDE (2010) Photo: Yang Zihui*

## Prospects for implementation

Increasing pressures on land and water resources will, in some regions, place severe constraints on efforts to appropriately intensify agricultural production in order to meet projected needs for food. The production systems 'at risk' where these conditions currently exist or are anticipated warrant appropriate remedial action. Remedial management actions should encompass not only the technical options to promote sustainable intensification and reduce risks as described in this chapter, but should also be accompanied by the enabling conditions required to eliminate institutional mechanisms that reinforce inefficiency, social inequity and the degradation of resources, as well as knowledge exchange and research, as addressed in other chapters of SOLAW (see also Box 4.16).

## BOX 4.16: THE SUCCESSFUL SPREAD OF INDIVIDUAL PRIVATE IRRIGATION IN NIGER

In Niger, traditional small-scale irrigation using simple water-lifting techniques (*shaduf*, bucket) were long employed, but the introduction of pumps has led to rapid expansion and intensification. By 2006, the area covered by small-scale private irrigation was 16 000 ha. Plots are typically less than 1 ha (usually 0.1–0.75 ha). Most production is of horticultural crops for market. Producers in some areas are specializing (onions, peppers, garlic, tomatoes). Demand is strong for produce, both domestically and for export.

In 1996, the government took the decision to support the growth of small-scale private irrigation, and encouraged the establishment of an apex association for the private irrigation profession. With project support, the association has helped farmers acquire new technology (typically treadle pumps) and has promoted changes in husbandry and cropping patterns. An artisanal industry has emerged, comprising drillers, well technicians, and pump makers and repairers. Accessible microfinance, private sector farming advisory services and farmer-run input supply have also been promoted. Farmers' net annual income has increased from US$159 to US$560 (in a country where median annual per capita income is US$60). The distribution of benefits is broad: over 26 000 poor families have benefited. The programme makes a good contribution to growth, exports, household income and poverty reduction.

*Source: World Bank (2008)*