Chapter 5

Water management

Sustainable intensification requires smarter, precision technologies for irrigation, and farming practices that use ecosystem approaches to conserve water

Crops are grown under a range of water management regimes, from simple soil tillage aimed at increasing the infiltration of rainfall, to sophisticated irrigation technologies and management. Of the estimated 1.4 billion ha of crop land worldwide, around 80 percent is rainfed and accounts for about 60 percent of global agricultural output[1]. Under rainfed conditions, water management attempts to control the amount of water available to a crop through the opportunistic deviation of the rainwater pathway towards enhanced moisture storage in the root zone. However, the timing of the water application is still dictated by rainfall patterns, not by the farmer.

Some 20 percent of the world's cropped area is irrigated, and produces around 40 percent of total agricultural output[1]. Higher cropping intensities and higher average yields account for this level of productivity. By controlling both the amount and timing of water applied to crops, irrigation facilitates the concentration of inputs to boost land productivity. Farmers apply water to crops to stabilize and raise yields and to increase the number of crops grown per year. Globally, irrigated yields are two to three times greater than rainfed yields. Thus, a reliable and flexible supply of water is vital for high value, high-input cropping systems. However, the economic risk is also much greater than under lower input rainfed cropping. Irrigation can also produce negative consequences for the environment, including soil salinization and nitrate contamination of aquifers.

Growing pressure from competing demands for water, along with environmental imperatives, mean that agriculture must obtain "more crops from fewer drops" and with less environmental impact. That is a significant challenge, and implies that water management for sustainable crop production intensification will need to anticipate smarter, precision agriculture. It will also require water management in agriculture to become much more adept at accounting for its water use in economic, social and environmental terms.

Prospects for sustainable intensification vary considerably across different production systems, with different external drivers of demand. In general, however, the sustainability of intensified crop production, whether rainfed or irrigated, will depend on the adoption of ecosystem approaches such as conservation agriculture, along with other key practices, including use of high-yielding varieties and good quality seeds, and integrated pest management.

Rainfed cropping systems

Many crop varieties grown in rainfed systems are adapted to exploit moisture stored in the root zone. Rainfed systems can be further improved by, for example, using deep-rooting crops in rotation, adapting crops to develop a deeper rooting habit, increasing soil water storage capacity, improving water infiltration and minimizing evaporation through organic mulching. Capture of runoff from adjacent lands can also lengthen the duration of soil moisture availability. Improving the productivity of rainfed agriculture depends largely on improving husbandry across all aspects of crop management. Factors such as pests and limited availability of soil nutrients can limit yield more than water availability *per se*[2, 3]. The principles of reduced tillage, organic mulching and use of natural and managed biodiversity (described in Chapter 2, *Farming systems*) are fundamental to improved husbandry.

The scope for implementing SCPI under rainfed conditions will depend, therefore, on the use of ecosystem-based approaches that maximize moisture storage in the root zone. While these approaches can facilitate intensification, the system is still subject to the vagaries of rainfall. Climate change will increase the risks to crop production. Nowhere is the challenge of developing effective strategies for climate change adaptation more pressing than in rainfed agriculture[4].

Other measures are needed, therefore, to allay farmers' risk aversion. They include better seasonal and annual forecasting of rainfall and water availability and flood management, both to mitigate climate change and to improve the resilience of production systems. More elaborate water management interventions are possible to reduce the production risk, but not necessarily to further intensify rainfed production. For instance, there is scope to transition some rainfed cropping systems to low-input supplementary irrigation systems, in order to bridge short dry spells during critical growth stages[5], but these are still reliant upon the timing and intensity of rainfall.

On-farm runoff management, including the use of water retaining bunds in cultivated areas, has been applied successfully in transitional climates, including the Mediterranean and parts of the Sahel, to extend soil moisture availability after each rain event. Off-farm runoff management, including the concentration of overland flow into shallow groundwater or farmer-managed storage, can allow for limited supplementary irrigation. However, when expanded over large areas, these interventions impact downstream users and overall river basin water budgets.

Extending the positive environmental and soil moisture conservation benefits of ecosystem approaches will often depend upon the level of farm mechanization, which is needed to take advantage of rainfall events. Simpler technologies, including opportunistic runoff farming, will remain inherently risky, particularly under more erratic rainfall regimes. They will also remain labour intensive.

Policymakers will need to assess accurately the relative contributions of rainfed and irrigated production at national level. If rainfed production can be stabilized by enhanced soil moisture storage, the physical and socio-economic circumstances under which this can occur need to be well identified and defined. The respective merits of low-intensity investments in SCPI across extensive rainfed systems and high intensity localized investments in full irrigation need careful socio-economic appraisal against development objectives.

With regard to institutions, there is a need for re-organization and reinforcement of advisory services to farmers dependent on rainfed agriculture, and renewed efforts to promote crop insurance for small-scale producers. A sharper analysis of rainfall patterns and soil moisture deficits will be needed to stabilize production from existing rainfed systems under climate change impacts.

Irrigated cropping systems

The total area equipped for irrigation worldwide is now in excess of 300 million ha[6], and the actual area harvested is estimated to be larger due to double and triple cropping. Most irrigation development has taken place in Asia, where rice production is practised on about 80 million ha, with yields averaging 5 tonnes per ha (compared to 2.3 tonnes per ha from the 54 million ha of rainfed lowland rice). In contrast, irrigated agriculture in Africa is practised on just 4 percent of cropped land, owing mainly to the lack of financial investment.

Irrigation is a commonly used platform for intensification because it offers a point at which to concentrate inputs. Making this *sustainable* intensification, however, depends on the location of water withdrawal and the adoption of ecosystem based approaches – such as soil conservation, use of improved varieties and integrated pest management – that are the basis of SCPI. The uniformity of distribution and the application efficiency of irrigation vary with the technology used to deliver water, the soil type and slope (most importantly its infiltration characteristic), and the quality of management.

Surface irrigation by border strip, basin or furrow is often less efficient and less uniform than overhead irrigation (e.g. sprinkler, drip, drip tape). *Micro irrigation* has been seen as a technological fix for the poor performance of field irrigation, and as a means of saving water. It is being adopted increasingly by commercial horticulturalists in both developed and developing countries, despite high capital costs.

Deficit irrigation and variants such as *regulated deficit irrigation* (RDI) are gaining hold in the commercial production of fruit trees and some field crops that respond positively to controlled water stress at critical growth stages. RDI is often practised in conjunction with micro-irrigation and "fertigation", in which fertilizers are applied directly to the region where most of the plant's roots develop. The practice has been adapted to simpler furrow irrigation in China. The benefits, in terms of reduced water inputs, are apparent but they will only be realized if the supply of water is highly reliable.

Knowledge-based precision irrigation that offers farmers reliable and flexible water application will be a major platform for SCPI. Automated systems have been tested using both solid set sprinklers and micro-irrigation, which involve using soil moisture sensing and crop canopy temperature to define the irrigation depths to be applied in different parts of the field. Precision irrigation and precision fertilizer application through irrigation water are both future possibilities for field crops and horticulture, but there are potential pitfalls. Recent computer simulations indicate that, in horticulture, salt management is a critical factor in sustainability.

The economics of irrigated agriculture are significant. The use of sprinkler and micro-irrigation technologies, as well as the automation of surface irrigation layouts, involve long term capital expenditure and operational budgets. Rain guns provide one of the cheapest capital options for large area overhead irrigation coverage, but tend to incur high operating costs. Other overhead irrigation systems have high capital costs and, without the support of production subsidies, are unsuited to smallholder cropping systems.

The service delivery of many public irrigation systems is less than optimal, owing to deficiencies in design, maintenance and management. There is considerable scope for modernizing systems and their management, through both institutional reform and the separation of irrigation service provision from broader oversight and the regulation of water resources.

Drainage is an essential, but often overlooked, complement to irrigation, especially where water tables are high and soil salinity is a constraint. Investment will be required in drainage to enhance the productivity and sustainability of irrigation systems and to ensure good management of farm inputs. However, enhanced drainage increases the risks of pollutants being exported, causing degradation in waterways and connected aquatic ecosystems.

Protected cropping, mostly in shade houses, is enjoying increasing popularity in many countries, including China and India, mainly for fruit, vegetable and flower production. In the long term, highly intensive closed cycle production systems, using conventional irrigation or hydroponic and aeroponic cultures, will become progressively more common, especially in peri-urban areas with strong markets and increasing water scarcity.

Using water for irrigation reduces instream flows, alters their timing, and creates conditions for shocks, such as toxic algal blooms. Secondary impacts include salinization and nutrient and pesticide pollution of water courses and water bodies. There are other environmental trade-offs from irrigated systems; rice paddies sequester higher levels of organic matter than dry land soils, and contribute less nitrate runoff and generate lower emissions of nitrous oxide (N_2O). Offset against this are relatively large emissions of methane (from 3 to 10 percent of global emissions) and ammonia.

Crops normally use less than 50 percent of the irrigation water they receive, and irrigation systems that lie within a fully or over-allocated river basin have low efficiency. In accounting terms, it is necessary to distinguish how much water is depleted, both beneficially and unproductively. Beneficial depletion by crops – evapotranspiration – is the intent of irrigation: ideally, transpiration would account for all depletion, with zero evaporation from soil and water surfaces. There is some potential to improve water productivity by reducing non-productive evaporative losses.

Basin level improvements in water productivity focus on minimizing non-beneficial depletion[7]. However, the downstream impacts of increased water depletion for agriculture are not neutral: there is evidence of big reductions in annual runoff from "improved" upper catchments that have adopted extensive water harvesting in parts of peninsular India[8].

Water management is a key factor in minimizing nitrogen losses and export from farms. In freely drained soils, nitrification is partially interrupted, resulting in the emission of N_2O, whereas in saturated (anoxic) conditions, ammonium compounds and urea are partially converted to ammonia, typically in rice cultivation. Atmospheric losses from urea can occur, therefore, as both ammonia and N_2O are released during wetting and drying cycles in irrigation. N is required in nitrate form for uptake at the root, but can easily move elsewhere in solution. A number of protected and slow release fertilizer compounds are under development for different situations (see Chapter 3, *Soil health*).

The dynamics of phosphate mobilization and movement in drains and waterways are complex. Phosphate export from agriculture can occur in irrigated systems if erosive flow rates are used in furrow irrigation, or if sodic soils disperse. Phosphate, and to a lesser extent nitrate, can be trapped by buffer strips located at the ends of fields and along rivers, which prevents them from reaching waterways. Hence, a combination of good irrigation management, recycling of tailwater and the incorporation of phosphate in the soil can reduce phosphate export from irrigated lands to close to zero.

The sustainability of intensified irrigated agriculture depends on minimizing off-farm externalities, such as salinization and export of pollutants, and the maintenance of soil health and growing conditions. That should be the primary focus of farm level practice, technology and decision-making, and reinforces the need for depletion water accounting and wiser water allocation at basin and catchment scales, and a better understanding of the hydrological interactions between different production systems.

Technologies that save and grow

Rainwater harvesting in Africa's Sahel[9]

A wide variety of traditional and innovative rainwater harvesting systems is found in Africa's Sahel zone. In semi-arid areas of Niger, small-scale farmers use planting pits to harvest rainwater and rehabilitate degraded land for cultivation of millet and sorghum. The technology improves infiltration and increases nutrient availability on sandy and loamy soils, leading to significant increases in yields, improved soil cover and reduced downstream flooding. Planting pits are hand-dug holes 20-30 cm in diameter and 20-25 cm deep, spaced about 1 m apart. Excavated soil is shaped into a small ridge to maximize capture of rainfall and run-off. When available, manure is added to each pit every second year. Seeds are sown directly into the pits at the start of the rainy season, and silt and sand are removed annually. Normally, the highest crop production is during the second year after manure application.

pearl millet

In eastern Ethiopia, farmers capture floodwater and runoff from ephemeral rivers, roads and hillsides using temporary stone and earth embankments. Captured water is distributed through a system of hand-dug canals up to 2 000 m long to fields of high value vegetables and fruit crops. Benefits include a 400 percent increase in gross production value from the fourth year of operation, improved soil moisture and fertility, and reduced downstream flooding.

Deficit irrigation for high yield and maximum net profits[10]

The highest crop productivity is achieved using high-yielding varieties with optimal water supply, soil fertility and crop protection. However, crops can also produce well with limited water supply. In deficit irrigation, water supply is less than the crop's full requirements, and mild stress is allowed during growth stages that are less sensitive to moisture deficiency. The expectation is that any yield reduction will be limited, and additional benefits are gained by diverting the saved water to irrigate other crops. However, use of deficit irrigation requires a clear understanding of soil-water and salt budgeting, as well as an intimate knowledge of crop behaviour, since crop response to water stress varies considerably.

A six-year study of winter wheat production on the North China Plain showed water savings of 25 percent or more through application of deficit irrigation at various growth stages. In normal years, two irrigations (instead of the usual four) of 60 mm were enough to achieve acceptably high yields and maximize net profits. In Punjab, Pakistan, a study of the long-term impacts of


cotton

deficit irrigation on wheat and cotton reported yield reductions of up to 15 percent when irrigation was applied to satisfy only 60 percent of total crop evapotranspiration. The study highlighted the importance of maintaining leaching practices in order to avoid the long-term risk of soil salinization. In studies carried out in India on irrigated groundnuts, production and water productivity were increased by imposing transient soil moisture-deficit stress during the vegetative phase, 20 to 45 days after sowing. Water stress applied during the vegetative growth phase may have had a favourable effect on root growth, contributing to more effective water use from deeper soil horizons. Higher water savings are possible in fruit trees, compared to herbaceous crops. In Australia, regulated deficit irrigation of fruit trees increased water productivity by approximately 60 percent, with a gain in fruit quality and no loss in yield.

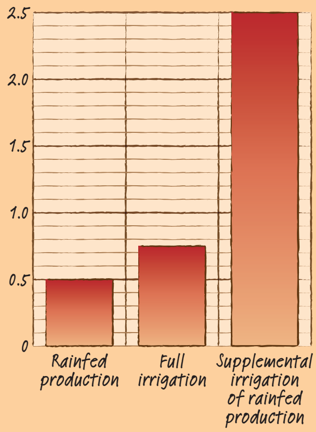
Supplemental irrigation on rainfed dryland[11, 12]

In dry areas, farmers dependent on rainfall for cereal production can increase yields using supplemental irrigation (SI), which entails harvesting rainwater run-off, storing it in ponds, tanks or small dams, and applying it during critical crop growth stages. One of the main benefits of SI is that it permits earlier planting – while the planting date in rainfed agriculture is determined by the onset of rains, supplemental irrigation allows the date to be chosen precisely, which can improve productivity significantly. For example, in Mediterranean countries, a wheat crop sown in November has consistently higher yield and shows better response to water and nitrogen fertilizer than a crop sown in January.

The average water productivity of rain in dry areas of North Africa and West Asia ranges from about 0.35 to 1 kg of wheat grain for every cubic metre of water. ICARDA has found that, applied as supplemental irrigation and along with good management practices, the same amount of water can produce 2.5 kg of grain. The improvement is mainly attributed to the effectiveness of a small amount of water in alleviating severe moisture stress.

In the Syrian Arab Republic, SI helped boost the average grain yield from 1.2 tonnes to 3 tonnes per hectare. In Morocco, applying 50 mm of supplemental irrigation increased average yields of early planted wheat

Productivity of water in wheat production (kg of grain/m³)



ICARDA. 2006. AARINENA water use efficiency network - Proceedings of the expert consultation meeting, 26-27 November 2006. *Aleppo, Syria.*

from 4.6 tonnes to 5.8 tonnes, with a 50 percent increase in water productivity. In Iran, a single SI application increased barley yields from 2.2 to 3.4 t/ha.

When integrated with improved varieties and good soil and nutrition management, supplemental irrigation can be optimized by deliberately allowing crops to sustain a degree of water deficit. In northern Syria, farmers applied half the amount of full SI water requirements to their wheat fields, which allowed them to double the cropped area, maximize productivity per unit of water and increase total production by one third.

Multiple uses of water systems[13]

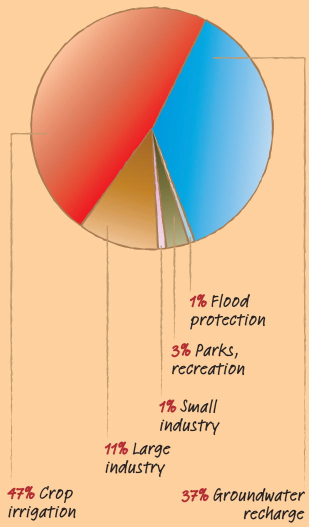
In addition to water for crop production, irrigation systems and infrastructure can provide multiple services, including supplying water for domestic use, animal production and electricity generation, and channels for transport. Analysis by FAO of 20 irrigation schemes revealed that non-crop water uses and multiple functions of irrigation schemes are more the norm than the exception.

For example, in the Fenhe irrigation district of Shaanxi Province, China, values derived from conventional irrigation were found to be lower than those from related services, such as aquaculture, timber plantations and flood protection. The district's infrastructure, which consists of two reservoirs, three diversion dams and five main canals, was built in 1950. In recent years, Shanxi province has suffered increasing drought, flooding and water pollution, and competition for water from industrial and domestic users is growing. Owing to water shortages,

surface irrigation is now limited essentially to winter wheat and maize crops. As a result, many farmers have diversified production away from staple crops toward intensive cash crop production using mainly groundwater, and the original command area of 86 000 ha has been reduced by about 50 percent.

Within this smaller area, many more functions are serviced by the district's water allocations from the Yellow River: productive services, such as crop irrigation, aquaculture, hydropower generation, timber plantations and industrial water supply, and amenities, including flood protection, groundwater recharge and forest parkland. In this way, intensification of water use has been accompanied by conservation of environmental services.

Use of irrigation water, Fenhe district, China (percent)



FAO. 2010. Mapping systems and service for multiple uses in Fenhe irrigation district, Shanxi Province, China. *Rome.*

The way forward

Sustainable agriculture on irrigated land – and also across the range of rainfed and improved rainfed production systems – involves trade-offs in land use, water sharing in the broadest sense, and the maintenance of supporting ecosystem services. These trade-offs are becoming more complex and have significant social, economic and political importance.

The overall governance of land and water allocations will strongly influence the scale of longer term investment in irrigated SCPI, particularly given the higher capital and input costs associated with irrigated production. Competing demands for water from other economic sectors and from environmental services and amenities will continue to grow. Water management in agriculture will need to cope with less water per hectare of land and will also have to internalize the cost of pollution from agricultural land.

With regard to policy, the nature of agriculture is changing in many countries, as the pace of rural outmigration and urbanization accelerates. Policy incentives that focus on the most pressing environmental externalities, while leveraging individual farmer's profit motives, have a greater chance of success.

For example, where agrochemical pollution of rivers and aquatic ecosystems has reached crisis point, a ban on dangerous chemicals could be accompanied by measures to raise fertilizer prices, provide farmers with objective advice on dosage rates, and remove perverse incentives to apply fertilizer excessively. Follow-up measures might promote management at "required or recommended" levels, and seek alternative approaches to higher productivity with more modest use of external inputs. In that case, more public investment would be needed to improve the monitoring of ecosystem conditions.

In the future, fertigation technology (including use of liquid fertilizers), deficit irrigation and wastewater-reuse will be better integrated within irrigation systems. While the introduction of a new technology into irrigated cropping systems has high entry costs and requires institutional arrangements for operation and maintenance, the use of precision irrigation is now global. Farmers in developing countries are already adopting low-head drip kits for niche markets, such as horticulture. In addition, the availability of cheap, plastic moulded products and plastic sheeting for plasticulture is likely to expand. However, the broad-scale adoption of alternatives, such as solar technologies, or the avoidance of polluting technologies, will need the support of regulatory measures and effective policing of compliance.

Shortcomings in governance of some irrigation investments have led to financial irregularities in capital funding, rent-seeking in management and operation, and poor co-ordination among agencies responsible for providing irrigation services to the farmer. Innovative approaches are required to create institutional frameworks that promote agricultural and water development, and at the same time safeguard the environment. There remains considerable potential to harness and learn from local initiatives in institutional development, to manage the externalities of intensification, and to reduce or avoid transaction costs. Solutions are more likely to be knowledge-rich than technology-intensive.

Chapter 6

Plant protection

Pesticides kill pests, but also pests' natural enemies, and their overuse can harm farmers, consumers and the environment. The first line of defence is a healthy agro-ecosystem

Plant pests are often regarded as an external, introduced factor in crop production. That is a misperception, as in most cases pest species occur naturally within the agro-ecosystem. Pests and accompanying species – such as predators, parasites, pollinators, competitors and decomposers – are components of crop-associated agro-biodiversity that perform a wide range of ecosystem functions. Pest upsurges or outbreaks usually occur following the breakdown of natural processes of pest regulation.

Because intensification of agricultural production will lead to an increase in the supply of food available to crop pests, pest management strategies must be an integral part of SCPI. However, they will also need to respond to concerns about the risks posed by pesticides to health and the environment. It is important, therefore, that potential pest problems associated with the implementation of SCPI are addressed through an ecosystem approach.

Although populations of potential pests are present in every crop field, every day, regular practices, such as crop monitoring and spot control measures, usually keep them in check. In fact, the total eradication of an insect pest would reduce the food supply of the pest's natural enemies, undermining a key element in system resilience. The aim, therefore, should be to manage insect pest populations to the point where natural predation operates in a balanced way and crop losses to pests are kept to an acceptable minimum.

When that approach does not seem sufficient, farmers often respond by seeking additional protection for their crops against perceived threats. The pest management decisions taken by each farmer are based on his or her individual objectives and experiences. While some may apply labour-intensive control measures, the majority turn to pesticides. In 2010, worldwide sales of pesticides were expected to exceed US$40 billion. Herbicides represent the largest market segment, while the share of insecticides has shrunk and that of fungicides has grown over the past ten years[1].

As a control tactic, over-reliance on pesticides impairs the natural crop ecosystem balance. It disrupts parasitoid and predator populations, thereby causing outbreaks of secondary pests. It also contributes to a vicious cycle of resistance in pests, which leads to further investment in pesticide development but little change in crop losses to pests, which are estimated today at 30 to 40 percent, similar to those of 50 years ago[2]. As a result, induced pest outbreaks, caused by inappropriate pesticide use, have increased[3].

Excessive use of pesticide also exposes farmers to serious health risks and has negative consequences for the environment, and sometimes for crop yields. Often less than one percent of pesticides applied actually reaches a target pest organism; the rest contaminates the air, soil and water[4].

Consumers have grown increasingly concerned about pesticide residues in food. Rapid urbanization has resulted in the expansion of urban and peri-urban horticulture, where pesticide use is more evident and its overuse even less acceptable to the public. The serious consequences of pesticide-related occupational exposure have been amply documented among farming communities, heightening social sensitivity towards agricultural workers' rights and welfare.

Public concerns are being translated into more rigorous standards both domestically and in international trade. Major retailers and supermarket chains have endorsed stricter worker welfare, food safety, traceability and environmental requirements. However, weak regulation and management of pesticides continue to undermine efforts to broaden and sustain ecologically-based pest management strategies. That is because pesticides are aggressively marketed and, therefore, often seen as the cheapest and quickest option for pest control.

Farmers would benefit from a better understanding of the functioning and dynamics of ecosystems, and the role of pests as an integral part of agro-biodiversity. Policymakers, who are often targets of complex information regarding crop pests, would also benefit from a better understanding of the real impact of pests and diseases in cropping ecosystems.

Integrated pest management

Over the past 50 years, integrated pest management (IPM) has become and remains the world's leading holistic strategy for plant protection. From its first appearance in the 1960s, IPM has been based on ecology, the concept of ecosystems and the goal of sustaining ecosystem functions[5-7].

IPM is founded on the idea that the first and most fundamental line of defence against pests and diseases in agriculture is a healthy agro-ecosystem, in which the biological processes that underpin production are protected, encouraged and enhanced. Enhancing those processes can increase yields and sustainability, while reducing input costs. In intensified systems, environmental factors of production affect the prospects for the effective management of pests:

- *Soil management* that applies an ecosystem approach, such as mulching, can provide refuges for natural enemies of pests. Building soil organic matter provides alternate food sources for generalist natural enemies and antagonists of plant disease and increases pest-regulating populations early in the cropping cycle. Addressing particular soil problems, such as salt water incursion, can render crops less susceptible to pests such as the rice stem borer.
- *Water stress* can increase the susceptibility of crops to disease. Some pests, notably weeds in rice, can be controlled by better management of water in the production system.
- *Crop varietal resistance* is essential for managing plant diseases and many insect pests. Vulnerability can arise if the genetic base of host plant resistance is too narrow.
- *Timing and spatial arrangement of crops* influence the dynamics of pest and natural enemy populations, as well as levels of pollination services for pollinator-dependent horticultural crops. As with other beneficial insects, reducing pesticide applications and increasing diversity within farms can increase the level of pollination service.

As an ecosystem-based strategy, IPM has achieved some notable successes in world agriculture. Today, large-scale government IPM programmes are operational in more than 60 countries, including Brazil, China, India and most developed countries. There is general scientific consensus – underscored by the recent International Assessment of Agricultural Science and Technology for Development[8] – that IPM works and provides the basis for protecting SCPI. The following are general principles for using integrated pest management in the design of programmes for sustainable intensification.

- *Use an ecosystem approach* to anticipate potential pest problems associated with intensified crop production. The production system should use, for example, a diverse range of pest-resistant crop varieties, crop rotations, intercropping, optimized planting time and weed management. To reduce losses, control strategies should take advantage of beneficial species of pest predators, parasites and competitors, along with biopesticides and selective, low risk synthetic pesticides. Investment will be needed in strengthening farmers' knowledge and skills.

- *Undertake contingency planning* for when credible evidence of a significant pest threat emerges. That will require investment in seed systems to support deployment of resistant varieties, and crop-free periods to prevent the carryover of pest populations to the following season. Selective pesticides with adequate regulatory supervision will need to be identified, and specific communication campaigns prepared.
- *Analyse the nature of the cause of pest outbreaks* when problems occur, and develop strategies accordingly. Problems may be caused by a combination of factors. Where the origin lies in intensification practices – for example, inappropriate plant density or ploughing that disperses weed seeds – the practices will need to be modified. In the case of invasions by pests such as locusts, methods of biological control or disease suppression used in the place of origin can be useful.
- *Determine how much production is at risk*, in order to establish the appropriate scale of pest control campaigns or activities. Infestation (not loss) of more than 10 percent of a crop area is an outbreak that demands a rapid policy response. However, risks from pests are often over-estimated, and crops can to some extent compensate physiologically for pest damage. The response should not be disproportionate.
- *Undertake surveillance to track pest patterns* in real time, and adjust response. Georeferenced systems for plant pest surveillance use data from fixed plots, along with roving survey data and mapping and analysis tools.

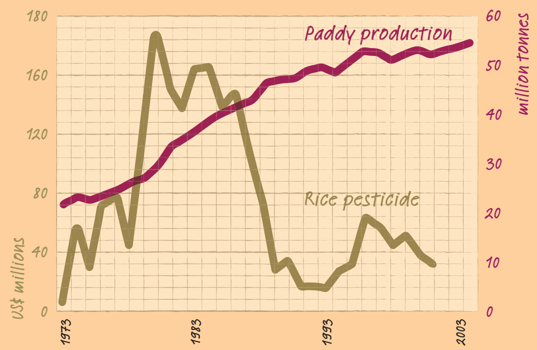
Approaches that save and grow

Ecosystem approaches have contributed to the success of many large-scale pest management strategies in a variety of cropping systems. For example:

Reduced insecticide use in rice

Most tropical rice crops require no insecticide use under intensification[9]. Yields have increased from 3 tonnes per ha to 6 tonnes through the use of improved varieties, fertilizer and irrigation. Indonesia drastically reduced spending on pesticide in rice production between 1988 and 2005[10]. However, in the past five years, the availability of low-cost pesticides, and shrinking support for farmers' education and field-based ecological research, have led to renewed high levels of use of pesticides and large-scale pest outbreaks, particularly in Southeast Asia[11].

Changes in rice production and spending on pesticides in Indonesia



Gallagher, K.D., Kenmore, P.E. & Sogawa, K. 1994. Judicial use of insecticides deter planthopper outbreaks and extend the life of resistant varieties in Southeast Asian rice. In *R.F. Denno & T.J. Perfect, eds.* Planthoppers: Their ecology and management, *pp. 599-614.*

Oudejans, J.H.M. 1999. Studies on IPM policy in SE Asia: Two centuries of plant protection in Indonesia, Malaysia, and Thailand. *Wageningen Agricultural University Papers 99.1. Wageningen, the Netherlands.*

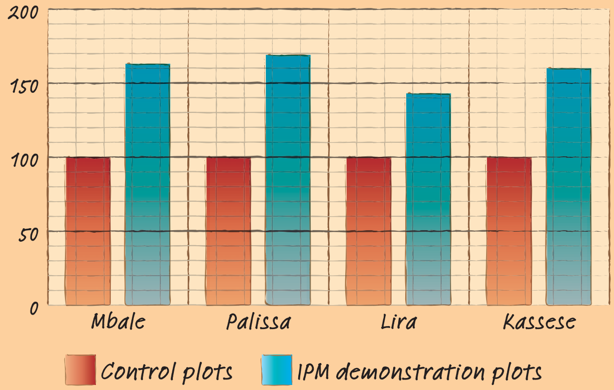
Watkins, S. 2003. The world market for crop protection products in rice. *Agrow Report. London, PJB Publications.*

Biocontrol of cassava pests

In Latin America, the centre of origin of the cassava, pest insects are normally kept under good natural population regulation. However, pests cause heavy damage when inappropriately treated with insecticides or when the crop and its pests are moved to another region, such as Africa or Asia, where effective natural enemies are absent. A biocontrol initiative led by IITA successfully brought under control the cassava green mite and the cassava mealybug throughout most of sub-Saharan Africa. This control was provided by natural enemies from Latin America, which were widely established in Africa in the 1980s and are now being introduced to Asia[12, 13].

cassava

Impact of IPM and improved agronomic practices on seed cotton production, in four districts of eastern Uganda (percent)



Hillocks, R., Orr, A., Riches, C. & Russell, D. 2006. Promotion of IPM for smallholder cotton in Uganda. *DFID Crop Protection Programme, Final Technical Report, Project R8403. Kent, UK, Natural Resources Institute, University of Greenwich.*

Natural enemies of cotton pests

Cotton systems have a diverse natural enemy fauna, consisting of general predators that keep sucking pests, such as white flies and leaf hoppers, under adequate natural control. Cotton's tolerance for these pests changes during the crop cycle and treatment thresholds vary according to crop stage and the extent of natural enemy presence. The mosaic of crops near cotton plays an important role in IPM systems, because neighbouring crops – such as melons, and tomatoes – can serve as sources of pests or, as in the case of fodder crops such as alfalfa, of natural enemies. In addition, effective host plant resistance conferred by transgenic Bt cotton has reduced insecticide use significantly[14].

Ecosystem approach to citrus diseases

Traditionally, growers in China and Viet Nam relied on manipulating ants to defend citrus trees from a wide range of insect pests. Recent pest outbreaks on citrus in Australia, Eritrea, Israel and the United States of America have followed excessive insecticide spraying, which disrupted naturally occurring biocontrol. While Huanglongbing disease (HLB) has not been resolved, several ecosystem approaches have slowed the impact of infection. They include certification programmes for mother trees and geographical isolation of nursery production, which is conducted in secure insect proof screen houses. In commercial plantations, insect vectors are controlled using chemical insecticides and, where applicable, biocontrol or intercropping with repellent plants such as guava. Infected trees are removed to reduce HLB inoculum sources[15, 16].

oranges

Control of viral diseases in tomatoes

tomatoes

Over the past 10 to 15 years, epidemics of viral diseases associated with high populations of whiteflies have plagued tomato production in West Africa, severely reducing yields. In some cases, tomato growing is no longer economically viable. A multipartner international public-private research collaboration helped establish in Mali an IPM programme which included an area-wide campaign to eliminate infected host plants, followed by planting of high-yielding early maturing varieties and extensive sanitation efforts that removed and destroyed tomato and pepper plants after harvest. The programme screened and evaluated new, early maturing disease-tolerant varieties, and used monthly monitoring of whitefly populations and virus incidence to assess the impact of control practices. As a result, recent tomato production was the highest in 15 years[17].

The examples above suggest various tactics that can be employed to counter or avoid plant pests in intensified production systems:

- ***Insect pests.*** It is important to conserve predators, parasitoids and beneficial pathogens to avoid secondary pest release, manage crop nutrient levels to reduce insect reproduction, deploy resistant varieties and make selective use of insecticides.
- ***Plant diseases.*** Organize seed systems that can deliver clean planting material, and deploy varieties with durable pest resistance. Use of clean irrigation water will help ensure that pathogens are not spread, while crop rotations will help suppress pathogens and support soil and root health. Farmers need to manage antagonists of plant pests to enhance biological control.
- ***Weeds.*** Management of weeds requires selective and timely manual weed control, crop rotation, cover crops, minimum tillage, intercropping and fertility management, including organic amendments. Herbicides should be used for targeted, selective control and managed so as to avoid the evolution of herbicide resistance.

The way forward

The "business as usual" approach to pest management, still followed in many countries and by many farmers, limits their potential for implementing sustainable crop production intensification. Improvements in agro-ecosystem management can help avoid indigenous pest outbreaks, respond better to pest invasions and reduce risks from pesticides to both human health and the environment. Entry points for improved ecosystem-based pest control include:

- a major pest or disease outbreak that threatens food security;
- food safety concerns arising from high levels of pesticide residues in farm produce;
- incidences of environmental pollution or human poisoning;
- striking losses of beneficial species, such as pollinators or birds;
- pesticide mismanagement, such as the proliferation of obsolete pesticide stockpiles.

In each of these cases, there is need for a pest control strategy that can be sustained and does not produce adverse side effects. After a nationally or regionally recognized pest problem has been brought under control with IPM, policymakers and technical staff are usually much more receptive to the approach, and also more willing to make the necessary policy and institutional changes to support it in the long term. The changes may include removal of pesticide subsidies, tighter enforcement of pesticide regulations, and incentives for local production of IPM inputs, such as insectaries for natural predators.

Countries should give preference to less hazardous pesticides in registration processes. They should also ensure that they apply ecologically informed decision-making to determine which pesticides may be sold and used, by whom and in what situations. Eventually, pesticide-use fees or pesticide taxes, which were pioneered in India in 1994, may be used to finance the development of alternative pest management practices and subsidize their adoption.

Policymakers can support SCPI through IPM programmes at a local, regional or national scale. They should be aware, however, that the success of effective pest management using IPM techniques depends ultimately on farmers. It is they who make key management decisions on the control of pests and diseases. Policy instruments include:

Changing perceptions of emergencies that involve pest or disease outbreaks

Perceptions	"Business as usual"	Ecosystems approach
Emergency	Sudden and severe pest outbreaks	Loss of agro-ecosystem functions resulting in severe pest outbreaks
Indicators	High presence of pests Visual crop damage Yield losses and reduced farmer incomes	Changes in pest population age structure Emergence of pesticide resistance and abnormal outbreaks of secondary pests Upward spiralling of pesticide use Yield losses and diminished farmer incomes
Causes	Pesticide resistance Appearance of new pests Insufficient availability of pesticides Weather conditions	Pesticide overuse Poor crop management Weather conditions Emergence of new pests
Response	Supply more or different pesticides	Analysis of causes of pest problem and development of strategy for recovery of agro-ecosystem functions and rehabilitation of institutional capacity to guide recovery Avoid solutions that perpetuate the problem Strengthen IPM capacity through investment in human capital

- *Technical assistance and extension support* to farmers in applying ecologically based management practices and developing and adapting technologies, taking into account their local knowledge, social learning networks and conditions.
- *Targeted research* in areas such as host plant resistance to pests and diseases, practical monitoring and surveillance methods, innovative approaches to field pest management, the use of selective pesticides (including biopesticides) and biocontrol.
- *Private sector regulation*, including effective systems of governance for the registration and distribution of pesticides (specifically cov-

ered by the International Code of Conduct on the Distribution and Use of Pesticides).

- *Removal of perverse incentives* such as pesticide price or transport subsidies, the unnecessary maintenance of pesticide stocks, which encourages their use, and preferential tariffs for pesticides.

Large-scale adoption of ecosystem approaches would provide opportunities for small local industries. The scaling up of ecological pest management practices can be expected to increase demand for commercial monitoring tools, biocontrol agents such as predators, parasitoids or sterile organisms, pollination services, micro-organisms and biopesticides. Today, private companies produce more than 1000 bio-products, worth some US$590 million in 2003, based on bacteria, viruses, fungi, protozoa and nematodes[18]. This local industry would expand significantly with a shift to a more ecosystem-centric approach.

From the perspective of the food processing industry, more stable and sustainable agro-ecosystems will result in a more consistent and reliable supply of agricultural produce free of pesticide residues. Additionally, labelling food products with an IPM or similar label can help ensure access to new markets for producers.

Sustaining IPM strategies requires effective advisory services, links to research that respond to farmers' needs, support to the provision of IPM inputs, and effective regulatory control of chemical pesticide distribution and sale. One of the most effective means of promoting IPM at local level is the farmer field school, an approach that supports local learning and encourages farmers to adapt IPM technologies by drawing upon indigenous knowledge. Farmers need ready access to information on appropriate IPM inputs. The adoption of IPM can be accelerated by using, for example, cellular phones to supplement traditional methods of outreach, such as extension, media campaigns and local inputs dealers.

Chapter 7

Policies and institutions

To encourage smallholders to adopt sustainable crop production intensification, fundamental changes are needed in agricultural development policies and institutions

Unprecedented challenges to agriculture – including population growth, climate change, energy scarcity, natural resources degradation and market globalization – underscore the need to rethink policies and institutions for crop production intensification. Models used for intensification in the past have often led to costly environmental damage, and need to be revised in order to achieve greater sustainability. While "business as usual" is clearly not an option, what alternatives are available?

The focus here is on defining the conditions, policies and institutions that will enable smallholder farmers – in low-income developing economies in particular – to adopt sustainable crop production intensification. It also considers overarching issues that affect not only SCPI, but are important for the development of an agricultural sector in which SCPI is facilitated and supported. It recognizes that programmes to promote SCPI may need to go beyond "agricultural" institutions and involve other centres of policymaking.

Past experience, future scenarios

The Green Revolution was supported largely by public sector investment, with almost all of the research and development (R&D) on modern varieties being carried out in international and national research centres. Seed and agrochemicals were disseminated through government-sponsored programmes at subsidized prices.

Since the mid-1980s, the locus of agricultural research and development has shifted dramatically from the public to the private multinational sector[1]. Greater protection of intellectual property in plant innovations, rapid progress in molecular biology and the global integration of agricultural input and output markets have generated strong incentives for the private sector to invest in agricultural research and development[2]. So far, investments have targeted agriculture mainly in developed countries. Meanwhile, overall growth in public sector investment in agricultural research and development in developing countries has declined significantly. In sub-Saharan Africa, investment actually decreased during the 1990s[3].

Throughout the 1980s and until the mid-1990s, many developing countries implemented structural adjustment programmes aimed at eliminating inefficient public sector activities and allowing a dynamic private sector to reinvigorate agriculture. The results have been mixed: in many cases a dynamic private sector failed to materialize, or developed only in high potential and commercialized production, while access to agricultural services and inputs declined in more marginal areas[4]. More recently, there has been a shift towards redefining the role of the public sector to support the development of the private sector, and to provide the public goods required for development[5].

Growth in organized and globalized food value chains is another major transformation with important implications for SCPI. These chains create new income opportunities for smallholders but also generate barriers to market access. There are concerns that the concentration of market power at specific points in the chain reduces the incomes of other actors in the chain, particularly small farmers[6, 7].

Considerable potential exists for improving the economic returns to farming systems while also reducing environmental and social impacts. However, that will require alternative models of agricultural technology and marketing development. Although productivity increases may be achieved faster in high-input, large-scale, specialized farming systems, the greatest scope for improving livelihood and equity exists in small-scale, diversified production systems[8].

Given the uncertainty of future demand and supply conditions, a range of scenarios for sustainable intensification in developing countries is possible. Important factors that could constitute major deviations from the baseline growth path are:

- *Climate change.* The impact of climate change on global agriculture is potentially enormous. Assessments are complex, involving projections of potential changes in climate and their impacts on production, interacting with demographic growth and dietary patterns, and market, trade and price developments[9]. A recent IFPRI analysis[10] of climate change impacts on agriculture up to 2050 indicated dramatic negative effects on productivity, with reduced food availability and human well-being in all developing regions. Together with increased demand owing to income and population growth, this was likely to contribute to a more or less significant increase in real agricultural prices between 2010 and 2050, depending on the scenario. The report estimates that public funding of at least US$7 billion annually is needed on three categories of productivity-enhancing investments – biological research, expansion of rural roads, and irrigation expansion and efficiency improvements – to compensate for the productivity losses associated with climate change by 2050. Other studies show less dramatic outcomes, with the overall impact of climate change on global food prices ranging between 7 percent and 20 percent in 2050[11]. Since agriculture is also a major source of greenhouse gas emissions, financial support and incentives to promote the adoption of low emission agricultural growth paths will become increasingly important. Reducing emissions per unit of production will be a key aspect of SCPI[12, 13].

- *Natural resources degradation.* The quality of land and water resources available for crop intensification has major implications for the design of SCPI in many areas. In the past, favourable production areas were given priority for crop intensification[14]. Increasingly, intensification will be required in more marginal areas with more variable production conditions, including soil and water quality, access to water, topography and climate. In this context, an important issue is ecosystem degradation, which reduces the availability and productivity of natural resources for SCPI. Restoration of degraded ecosystems can involve considerable expense and time, and will need long-term financing.
- *Reduction of food losses and changes in food consumption patterns.* FAO has reported post-harvest food losses of as high as 50 percent. Because action to prevent those losses would reduce the need for productivity increases, reduce costs throughout the supply chain and improve product quality, it should be part of SCPI policies and strategies. An alternative scenario, which favours environmental sustainability as well as human health, is a slowdown in growth in demand for animal products, which would reduce demand growth for feed and forage.
- *Market integration.* To be attractive to farmers, SCPI must lead to remunerative market prices. A rising trend in agricultural prices, stimulated in part by the resource constraints that are driving the move to SCPI, will enhance the profitability of investments in intensification. On the other hand, rapid productivity growth at local levels and under conditions of closed markets could generate market surpluses, driving down local prices. Price effects will also be mediated by the state of the value chain. The development of agricultural value chains must aim at enhancing smallholders' capacity for SCPI adoption and provide incentives.

Policies that save and grow

A successful strategy for sustainable intensification of crop production requires a fundamental change in the management of traditional and modern knowledge, institutions, rural investment and capacity development. Policies in all of those domains will need to provide incentives to various stakeholders and actors, especially the rural population, to participate in SCPI development.

Input and output pricing

To be profitable, SCPI requires a dynamic and efficient market for inputs and services as well as for the final produce. The prices farmers pay for inputs and are paid for agricultural outputs are perhaps the main determinant of the level, type and sustainability of crop intensification they adopt. Input prices are of particular importance for SCPI strategies, and creative policies will be needed to promote efficiency and influence technology choices. One example is the reintroduction of "market smart" subsidies, aimed at supporting the development of demand and participation in input markets using vouchers and grants. The approach seeks to avoid past problems with subsidies, such as inefficiency, negative effects on the environment, and the waste of financial resources that are needed for investments in other key public goods, such as research and rural infrastructure[5].

In contrast, environmentally harmful (or "perverse") subsidies, which encourage the use of natural resources in ways that destroy biodiversity[15], need to be carefully evaluated and, when appropriate, reformulated or removed. Perverse subsidies worldwide have been valued at from US$500 billion to US$1.5 trillion a year, and represent a powerful force for environmental damage and economic inefficiency[16].

Of course, most incentives are not designed to be "perverse" but rather to benefit a particular social or economic sector. When planning their removal, it is important, therefore, to consider the multiple objectives of incentives and to take into account the complexity of interactions among the different sectors affected positively and negatively by them[17]. Some countries have done so successfully: New Zealand abolished agricultural subsidies, starting in the 1980s[18]; Brazil has reduced livestock farming in the Amazon basin; and the Philippines has abolished fertilizer subsidies[17, 19].

Stabilization of agricultural output prices is an increasingly important condition for sustainable intensification of crop production, given the volatility experienced in commodity markets in the past few years. For farmers dependent on agricultural income, price volatility means large income fluctuations and greater risk. It reduces their capacity to invest in sustainable systems and increases the incentives to liquidate natural capital as a source of insurance.

Short-term, micro-level policies to address price volatility have frequently failed. Greater coherence at the macro policy level – for example, transparency over export availabilities and import demands – is likely to provide much more effective solutions. Reform of existing instruments, such as the Compensatory Financing Facility and the Exogenous Shock Facility of the International Monetary Fund is also needed. Through the provision of import financing or guarantees with limited conditionality, they could serve as global safety nets[18].

Seed sector regulation

Achievement of SCPI will also depend on the effective regulation of the seed sector in order to ensure farmers' access to quality seeds of varieties that meet their production, consumption and marketing conditions. Access implies affordability, availability of a range of appropriate varietal material, and having information about the adaptation of the variety[21].

Most small farmers in developing countries obtain seed from the informal seed sector, which provides traditional farmer-bred varieties and saved seeds of improved varieties. One of the main reasons farmers rely on the informal seed sector is the availability of germplasm adapted to their production conditions. Some local varieties may outperform improved varieties in marginal agricultural environments[22]. Supporting the informal sector is, therefore, one way of improving farmer access to planting material suitable for SCPI.

However, the informal seed sector lacks a viable means of informing farmers about the adaptation and production characteristics of the variety embodied in seeds, as well as their genetic purity and physical quality[23]. In some cases, the necessary information is supplied simply by observing the performance of crops in a neighbour's field. But that is not a viable option in exchanges involving strangers and non-local seed sources. Seed in formal systems is genetically uniform, is produced using scientific plant-breeding techniques, and must meet certification standards. Seed from this sector tends to be sold through specialized agro-dealers, agri-businesses or government outlets, which are subject to regulation. Any comprehensive strategy for improving farmers' access to new varieties and quality seed needs to support and expand the formal seed sector, and improve its links with the informal sector.

Payments for environmental services

The lack of market prices for ecosystem services and biodiversity means that the benefits derived from those goods are neglected or undervalued in decision-making[24]. In the agriculture sector, food prices do not incorporate all the associated costs to the environment of food production. No agencies exist to collect charges for reduced water quality or soil erosion. If farmgate prices reflected the full cost of production – with farmers effectively paying for any environmental damage they caused – food prices would probably rise. In addition to charging for agricultural disservices, policies could reward those farmers who farm sustainably through, for example, payments for environmental services (PES) schemes.

Support is growing for the use of payments for environmental services as part of the enabling policy environment for sustainable agricultural and rural development. The World Bank recommends that PES programmes be pursued by local and national governments as well as the international community[5]. PES are being integrated increasingly as a source of sustainable financing in wider rural development and conservation projects in Global Environment Facility and World Bank portfolios[25]. FAO says that demand for environmental services from agricultural landscapes will increase and PES could be an important means of stimulating their supply. However, effective deployment will depend on enabling policies and institutions at local and international levels which, in most cases, are not in place[26].

Currently, the role of PES programmes in support of sustainable agriculture is rather limited. PES initiatives have focused mainly on land diversion programmes, and there is relatively little experience with their application to agricultural production systems. To realize their benefits, PES programmes will need to cover large numbers of producers and areas, which would achieve economies of scale in transaction costs and risk management. Better integration of PES with agricultural development programmes is an important way of reducing transaction costs.

Given the limits on public finance, creative forms of alternative or additional funding from private sources will need to be developed, especially where private beneficiaries of PES can be identified. For example, a recent FAO feasibility assessment of PES in Bhutan found that the government's support for forest protection and reforestation amounted to about a third of the Ministry of Agriculture's budget[27]. Half of the funding for watershed management was assigned to plantations[28]. Were more of this investment responsibility shifted to the companies that benefit from forest protection, additional public funding could be released for under-funded activities – such as crop diversification, livestock improvement and sustainable land management – which would improve farm productivity and increase resilience to climate change[29, 30].

Agricultural investment

To engage in SCPI, the private sector – including farmers, processors and retailers – needs adequate public infrastructure and services. These are essential not only to ensure that local farming and marketing can compete with imports, but also to ensure that consumers have access to affordable, locally produced food. It is particularly important that governments ensure low transaction costs for input acquisition, produce marketing, and access to natural resources, information, training, education and social services. That will require adequate funding for both maintenance and net investment.

The agricultural sector in developing countries will need substantial and sustained investment in human, natural, financial and social capital in order to achieve SCPI. According to FAO estimates, total average annual gross investment of US$209 billion, at constant 2009 prices, is needed in primary agriculture (such as soil fertility, farm machinery and livestock) and in downstream sectors (storage, marketing and processing) in order to achieve the production increases needed by 2050. Public investment would also be needed in agricultural research and development, rural infrastructure and social safety nets[21].

Current investment in the agriculture of developing countries is clearly insufficient. Inadequate levels of domestic funding have been exacerbated by the reduction in Official Development Assistance to agriculture since the late 1980s. Together, these shortfalls have led over the last two decades to a drastic decline in capital for agricultural development. If SCPI is to succeed, agricultural investment must be significantly increased.

Funding for climate change adaptation and mitigation is highly relevant to SCPI. For example, one key means of adapting to climate change – increasing resilience in agricultural production systems through the use of new varieties generated by expanded plant breeding and seed systems – is an essential component of sustainable intensification. SCPI could thus benefit from funding allocated to climate change adaptation. Sustainable intensification could also play an important role in climate change mitigation, through increased carbon sequestration in sustainably managed soils and reduction of emissions owing to more efficient use of fertilizer and irrigation.

At present, there is no international agreement or framework for channelling mitigation funding on a significant scale to agriculture in developing countries. However, it is one area of discussion in the UNFCCC negotiations within the context of developing countries' Nationally Appropriate Mitigation Actions[12, 21].

Enabling institutions

A lack of institutional capacity and functioning is a common constraint on agriculture in developing countries, and limits the effectiveness of policies at local level. Institutions for SCPI will have two basic functions: to ensure the necessary quantity and quality of key resources – natural resources, inputs, knowledge and finance – and to ensure that small farmers have access to those resources. In the following, institutions are divided into two main categories: those related to key resources for SCPI, and those that influence the functioning of agricultural product markets, including value chains.

Access to key resources

Land. The shift to SCPI requires improvements in soil fertility, erosion control and water management. Farmers will undertake them only if they are entitled to benefit, for a sufficiently long period, from the increase in the value of natural capital. Often, however, their rights are poorly defined, overlapping or not formalized. Improving the land and water rights of farmers – especially those of women, who are increasingly the ones making production decisions – is a key incentive to adoption of sustainable intensification.

Land tenure programmes in many developing countries have focused on formalizing and privatizing rights to land, with little regard for customary and collective systems of tenure. Governments should give greater recognition to such systems, as growing evidence indicates that, where they provide a degree of security, they can also provide effective incentives for investments[31]. However, customary systems that are built on traditional social hierarchies may be inequitable and fail to provide the access needed for sustainable intensification. While there is no single "best practice" model for recognizing customary land tenure, recent research has outlined a typology for selecting alternative policy responses based on the capacity of the customary tenure system[32].

Plant genetic resources. Crop improvement is fundamental to SCPI. During the Green Revolution, the international system that generated new crop varieties was based on open access to plant genetic resources. Today, national and international policies increasingly support the privatization of PGR and plant breeding through the use of intellectual property rights (IPRs). The number of countries that provide legal protection to plant varieties has grown rapidly in response to the WTO Agreement on Trade Related Aspects of Intellectual Property Rights, which stipulates that members must offer protection through "patents or an effective *sui generis* system"[33].

Plant variety protection systems typically grant a temporary exclusive right to the breeders of a new variety to prevent others from reproducing and selling seed of that variety. They range from patent systems with rather restrictive rules to the more open system under the International Union for the Protection of New Varieties of Plants, which contains the so-called "breeders' exemption", whereby "acts done for the purpose of breeding other varieties are not subject to any restriction".

IPRs have stimulated rapid growth in private sector funding of agricultural research and development. Only 20 years ago, most R&D was carried out by universities and public laboratories in industrialized countries and generally available in the public domain. Investment is now concentrated in six major companies[34]. There is evidence of a growing divide between a small group of countries with high levels of R&D investments and a large number with very low levels[3, 35]. More importantly, technology spillovers from industrialized to developing countries are driven by research agendas that are oriented towards commercial prospects rather than maximum public good.

Increasing concentration in the private plant breeding and seed industry, and the high costs associated with developing and patenting biotechnology innovations, raise further concerns that the introduction of inappropriate IPRs will restrict access to the plant genetic resources needed for new plant breeding initiatives in the public sector[34, 36]. It has been argued that decentralized ownership of IPRs and high transactions costs can lead to an "anti-commons" phenomenon in which innovations with fragmented IPRs are underused, thus impeding the development of new varieties[37].

Mechanisms are needed, therefore, to safeguard access to plant genetic resources for SCPI, at both global and national levels. The emerging global system for the conservation and use of plant genetic resources will provide the necessary international framework (see Chapter 4, *Crops and varieties*). There are several kinds of national IPR regime, with varying degrees of obligations and access[38]. Countries should adopt IPR systems that ensure access of their national breeding programmes to the plant genetic resources needed for SCPI.

Research. Applied agricultural research must become much more effective in facilitating major transformations in land use and cropping systems for SCPI. Many agricultural research systems are not sufficiently development-oriented, and have often failed to integrate the needs and priorities of the poor in their work. Research systems are often under-resourced, and even some that are well-funded are not sufficiently connected with the broader processes of development[39]. The following are the most important steps needed for strengthening research for SCPI:

- *Increase funding.* The decline of public investment in agricultural R&D needs to be reversed. Funding for the CGIAR Centers and national research systems must be substantially enhanced, and linkages between public and private sector research strengthened.
- *Strengthen research systems, starting at local levels.* To generate solutions that are relevant, acceptable and attractive to local populations, research on SCPI practices must start at the local and national levels, with support from the global level. While important, the research efforts of the CGIAR "can neither substitute, nor replace the complex and routine strategizing, planning, implementing, problem-solving and learning needed on multiple fronts, which only national institutions and actors can and must do"[39]. There is a huge, underutilized potential to link farmers' traditional knowledge with science-based innovations, through favourable institutional arrangements. The same holds for the design, implementation and

monitoring of improved natural resource management that links community initiatives to external expertise.

- *Focus research on SCPI in both high and low potential areas.* High-potential areas will continue to be major providers of food in many countries. However, the productive capacity of land and water resources is reaching its limits in some areas, and will not be sufficient to guarantee food security. Therefore, much of future growth in food production will need to take place in so-called low potential or marginal areas, which are home to hundreds of millions of the poorest and most food insecure people. SCPI and related rural employment offer the most realistic prospects for improving those people's nutrition and livelihoods.
- *Give priority to research that benefits smallholders.* In low-income, food importing countries, small-scale producers, farm workers and consumers can benefit directly from SCPI research focused on staple food crops, which have a comparative advantage. Priority should also go to agricultural productivity growth and natural resources conservation in heavily populated marginal areas, diversification to higher value products in order to increase and stabilize farmers' incomes, and improved practices that increase returns to labour of landless and near-landless rural workers[40].
- *Learn from failures and successes.* A recent IFPRI study of proven successes in agricultural development[10] highlights the breeding of rust-resistant wheat and improved maize worldwide, improved cassava varieties in Africa, farmer-led "re-greening of the Sahel" in Burkina Faso (see Chapter 3, *Soil health*), and zero-tillage on the Indo-Gangetic Plain (see Chapter 2, *Farming systems*). Those successes were the result of a combination of factors, including sustained public investment, private incentives, experimentation, local evaluation, community involvement and dedicated leadership. In all cases, science and technology were a determinant.
- *Link research with extension.* Solutions to the problems of low productivity and degradation of natural resources are needed at large scale, but replication of SCPI practices is constrained by the vast range and diversity of site-specific conditions. Linking local, national and international research and site-specific extension services is, therefore, particularly important. To be relevant for the advancement of SCPI, research and extension systems must work together with farmers in addressing multiple challenges.

Technologies and information. Successful adoption of SCPI will depend on the capacity of farmers to make wise technology choices, taking into account both short- and long-term implications. Farmers also need to have a good understanding of the role of agro-ecosystem functions. The wealth of traditional knowledge held by farmers and local communities all over the world has been widely documented, in particular by the report of the International Assessment of Agricultural Knowledge, Science and Technology for Development[8]. Institutions are needed to protect this knowledge and to facilitate its exchange and use in SCPI strategies.

Institutions must also ensure farmers' access to relevant external knowledge and help link it to traditional knowledge. Rural advisory and agricultural extension services were once the main channel for the flow of new knowledge to – and, in some cases, from – farmers. However, public extension systems in many developing countries have long been in decline, and the private sector has failed to meet the needs of low-income producers[12]. The standard, public sector and supply-driven model of agricultural extension, based on technology transfer and delivery, has all but disappeared in many countries, particularly in Latin America[41].

Extension has been privatized and decentralized, with activities now involving a wide array of actors, such as agribusiness companies, non-governmental organizations (NGOs), producer organizations and farmer-to-farmer exchanges, and new channels of communication, including mobile phones and the Internet[42]. One key lesson from this experience is that the high transactions costs of individual extension contacts are a major barrier to reaching small and low-income producers. Advisory services to support SCPI will need to build upon farmer organizations and networks, and public-private partnerships[12].

FAO promotes farmer field schools as a participatory approach to farmer education and empowerment. The aim of the FFS is to build farmers' capacity to analyse their production systems, identify problems, test possible solutions and adopt appropriate practices and technologies. Field schools have been very successful in Asia and sub-Saharan Africa, notably in Kenya and Sierra Leone, where they cover a broad range of farming activities, including marketing, and have proved to be sustainable even without donor funding.

To make wise decisions about what to plant and where and when to sell, farmers need access to reliable information about market prices, including medium-term trends. Government market information services suffer many of the same weaknesses as extension services[43]. There is now renewed donor and commercial interest in market information, taking advantage of SMS messaging and the Internet.

Financial resources for farmers. Credit will be essential for creating the technical and operational capacities needed for SCPI. In particular, longer term loans are needed for investment in natural capital, such as soil fertility, that will increase efficiency, promote good agricultural practices and boost production. Although many new types of institutions – such as credit unions, savings cooperatives and micro-finance institutions – have spread to the rural areas of developing countries in recent years, the majority of small farmers have limited or no access to them. The inability of local financial institutions to offer longer term loans, coupled with farmers' lack of collateral, hampers sustainable crop intensification.

Insurance would encourage farmers to adopt production systems that are potentially more productive and more profitable, but involve greater financial risk. In recent years, pilot crop insurance programmes have been introduced as a risk management tool in many rural communities in developing countries. Index insurance products – where indemnities are triggered by a measurable weather event, such as drought or excess rain, rather than by an assessment of losses in the field – have found enthusiastic support among donors and governments. Assessments by IFAD and the World Food Programme of 36 weather-based index insurance pilot programmes have demonstrated their potential as a risk-management tool[44].

Alternatives to insurance, especially the accumulation of savings and other saleable assets, are often overlooked. Also, preventive, on-farm measures and instruments to reduce exposure to risk should be seriously considered.

Productive social safety nets. Social safety net programmes include cash transfers and distribution of food, seeds and tools[45]. They ensure access to a minimum amount of food and other vital social services. Recent initiatives include Ethiopia's Productive Safety Net Programme and the Kenya Hunger Safety Net Programme. There is debate about whether such programmes risk creating dependency and weakening local markets. However, recent evidence indicates that trade-offs between protection and development are not pronounced[46]. Instead, safety net programmes can be a form of social investment in human capital (for example, nutrition and education) and productive capital, allowing households to adopt higher risk strategies aimed at achieving higher productivity[27].

Policymakers need to understand the determinants of vulnerability at the household level and to design productive safety nets that offset the downward spiral of external shocks and coping strategies. The latter include selling assets, reducing investments in natural resources and taking children out of school, all of which undermine sustainability. Safety nets are also increasingly being linked to rights-based approaches to food security[47].

Agricultural marketing institutions and value chains

Growth of the food marketing sector offers new opportunities for smallholder farmers by broadening their choice of input suppliers and of outlets for produce, as well as increasing their access to credit and training[48, 49]. However, access to both input and output markets has proved problematic for many smallholders, who remain at the margins of the new agricultural economy[50-53].

How smallholders fit into a specific agricultural value chain depends largely on the underlying cost structures of the chain and of their farm production processes[54]. The primary cost advantage of smallholders is their ability to supply low-cost labour for labour-intensive crops. When smallholders have no apparent comparative advantage, agribusinesses may seek alternative structures for organizing production, such as vertical integration or buying directly from large holders. In those cases, the challenge is to create comparative advantages for smallholders or to reduce the transaction costs associated with purchasing from large numbers of farmers producing small quantities. To forge links to high-value markets, small farmers need to be organized in institutions that reduce transaction costs, and given access to information on market requirements[48, 49, 54, 55].

Contract farming provides mechanisms of vertical coordination between farmers and buyers, which allows for an evident degree of assurance in some of the main negotiation parameters: price, quality, quantity and time of delivery[56]. While farmers have benefited from contractual agreements, substantial evidence suggests that the smallest farmers are often unable to enter formal arrangements[55]. Improving the legal and institutional framework of contracts would dramatically reduce transaction costs[55, 57]. However, farm consolidation, resulting from increased off-farm rural employment or migration to urban areas, appears inevitable.

Small farmer access to markets can also be improved through better organization and greater cooperation, which may involve not only farmers but also a larger number of stakeholders, including agricultural support service providers, NGOs, researchers, universities, local government and international donors. One example is the *Plataforma de concertación* in Ecuador, which has helped farmers to achieve higher yields and gross margins, while reducing the use of toxic pesticides. Nevertheless, its self-financing capability has still to be verified[54].

The way forward

From the outset, policymakers should take a long, hard look at past and current experiences in order to identify clear options and steps that need to be taken now to foster sustainable crop production intensification. There is no "one-size-fits-all" set of recommendations for choosing the most appropriate policies and institutions. However, it is possible to identify the key features of a supporting policy and institutional environment for SCPI:

- *Linking public and private sector support.* The private sector and civil society have an important role to play in increasing the availability of investment funds, promoting greater efficiency and accountability of institutions, and ensuring a participatory and transparent policy process. Resource mobilization should take into consideration the full range of services and products that SCPI can generate. Payments for environmental services generated by a sustainable production system may prove to be an important source of investment resources.

- *Incorporating the value of natural resources and ecosystem services into agricultural input and output price policies.* That can be achieved by establishing realistic environmental standards, eliminating perverse incentives, such as subsidies on fertilizer and pesticides, and by creating positive incentives, such as payments for environmental services, or environmental labelling in value chains.

- *Increasing coordination and reducing transaction costs.* Involving small farmers in SCPI development requires coordinated action to reduce the transaction costs of access to input and output markets, extension and payments for environmental services. Institutions and technologies that facilitate participation – including farmer groups, community organizations, customary forms of collective action, and modern communication technologies – are therefore a key requirement for SCPI.
- *Building regulatory, research and advisory systems for a very wide range of production and marketing conditions.* SCPI represents a shift from a highly standardized and homogeneous model of agricultural production to regulatory frameworks that allow for and encourage heterogeneity – for example, by including informal seed systems in seed regulatory policies and integrating traditional knowledge into research and extension.
- *Recognizing and incorporating customary access and management practices into SCPI initiatives.* Assessing and strengthening the current capacity of customary systems of access to the inputs needed for SCPI, and of indigenous systems of agricultural management, will both be important.

Policies and programmes for sustainable crop production intensification will cut across a number of sectors and involve a variety of stakeholders. Therefore, a strategy for achieving sustainable intensification needs to be a cross-cutting component of a national development strategy. An important step for policymakers in achieving SCPI adoption is to initiate a process of embedding or mainstreaming strategies for sustainable intensification in national development objectives. SCPI should be an integral part of country-owned development programmes, such as Poverty Reduction Strategy Processes and food security strategies and investments, including follow-ups to the commitments to support food security made at the Group of 8 summit in L'Aquila, Italy, in 2009.

The roll-out of SCPI agendas and plans in developing countries requires concerted action at international and national levels, with the participation of governments, the private sector and civil society. Multi-stakeholder processes are now considered the key to food security at all levels. At the global level, FAO and its development partners will play an important supporting role.