4

RESOURCE-CONSERVING TECHNOLOGIES AND PROCESSES

> *'And the soil said to man: take good care of me or else, when I get hold of you, I will never let your soul go.'*
>
> Kipsigis proverb, as told by Mr arap Keoch, Chemorir,
> Kenya, 1990

ADOPTING RESOURCE-CONSERVING TECHNOLOGIES

The Multifunctionality of Technologies

Sustainable agriculture involves the integrated use of a variety of pest, nutrient, soil and water management technologies and practices. These are usually combined on farms to give practices finely tuned to the local biophysical and socioeconomic conditions of individual farmers. Most represent low-external input options. Most such farms are diverse rather than specialized enterprises. Natural processes are favoured over external inputs and by-products or wastes from one component of the farm become inputs to another. In this way, farms remain productive as well as reducing the impact on the environment.

This chapter gives details of both proven and promising resource-conserving technologies. These draw on a range of experiences from both farms and research stations, where the impacts of pests, diseases and weeds have been reduced; the viability of natural predators enhanced; the efficiency of pesticide and fertilizer use improved; and nutrients, water and soil conserved. Many of these are examples of farmers already taking steps to reduce costs and the adverse environmental effects of their operations. Some have done so by improving conventional practices; others by adopting alternatives. Most have tried to take greater advantage of natural processes and beneficial on-farm interactions, so reducing off-farm input use and improving the efficiency of their operations.

These technologies basically do two important things. They conserve existing on-farm resources, such as nutrients, predators, water or soil. Or they introduce new elements into the farming system that add more of these resources, such as nitrogen-fixing crops, water harvesting structures or new predators, and so substitute for some or all external resources.

Many of the individual technologies are multi-functional. This mostly implies that their adoption will mean favourable changes in several components of the farming system at the same time. For example, hedgerows encourage predators and act as windbreaks, so reducing soil erosion. Legumes introduced into rotations fix nitrogen, and also act as a break crop to prevent carry-over of pests and diseases. Grass contour strips slow surface runoff of water, encourage percolation to groundwater and are a source of fodder for livestock. Catch crops prevent soil erosion and leaching during critical periods, and can also be ploughed in as a green manure. The incorporation of green manures not only provides a readily available source of nutrients for the growing crop, but also increases soil organic matter and hence water retentive capacity, further reducing susceptibility to erosion.

The principles of integrated farming, a key element of sustainable agriculture, focus on increasing the number of technologies and practices, and the positive, reinforcing linkages between them. But this multi-functionality also makes classification of the technologies problematic. In this chapter, technologies and practices are presented in sections for pest and predator management, integrated plant nutrition, soil conservation, and water management systems. Some of this has to be arbitrary. A green manure can, for example, act as a break crop so preventing pest carry-over; add nitrogen and organic matter to the soil; and prevent soil and water loss by providing ground cover.

The best evidence for the effectiveness of resource-conserving technologies must come from farms and communities themselves. If a technology, such as a nitrogen-fixing legume is taken by farmers and adapted to fit their own cropping systems, and this leads to substantial increases in crop yields, then this is the strongest evidence of success. Wherever possible, the evidence for this chapter is drawn from the field. Some of these are 'traditional' practices that have been in existence for generations. Others are of recently introduced technologies, transferred from other farmers and communities or from research efforts.

As indicated in Chapter 2, it is possible to develop any number of productive and sustainable systems on research stations. The ultimate test for these, though, is whether different types of farmers find them useful and whether they can adapt them to their own conditions. A sign of sustainability, therefore, is the degree to which the skills and knowledge of farmers are enhanced, and whether they become involved in their own experimentation with technologies (see Chapter 6).

Transition Costs for Farmers

Although many resource-conserving technologies and practices are currently being used, the total number of farmers using them is still small. This is because their adoption is not a costless process for farmers. They cannot simply cut their existing use of fertilizer or pesticides and hope to maintain outputs, so making their operations more profitable. They will need to substitute something in return. They cannot simply introduce a new productive element into their farming systems and hope it succeeds. They will need to invest labour, management skills and knowledge. But these costs do not necessarily go on for ever.

These transition costs arise for several reasons. Farmers must first invest in learning. As recent and current policies have tended to promote specialized, non-adaptive systems with a lower innovation capacity, so farmers will have to spend time learning about a greater diversity of practices and measures. Lack of information and management skills is, therefore, a major barrier to the adoption of sustainable agriculture. During the transition period, farmers must experiment more and so incur the costs of making mistakes, as well as of acquiring new knowledge and information.

Another problem is that we know much less about the resource-conserving technologies than we do about the use of external inputs in modernized systems. As external resources and practices have substituted for internal and traditional ones, knowledge about the latter has been lost. Much less research on resource-conserving technologies is conducted by conventional research institutions. In India, for example, postgraduate research on modernized farming greatly exceeds that on sustainable or low input systems (see Table 8.4).

The on-farm biological processes that make sustainable agriculture productive also take time to become established. These include the rebuilding of depleted natural buffers of predator stocks and wild host plants; increasing the levels of nutrients; developing and exploiting micro-environments and positive interactions between them; and the establishment and growth of trees. These higher variable and capital investment costs must be incurred before returns increase. Examples include for labour in construction of soil and water conservation measures; for planting of trees and hedgerows; for pest and predator monitoring and management; for fencing of paddocks; for the establishment of zero-grazing units; and for purchase of new technologies, such as manure storage equipment or global positioning systems for tractors.

For these reasons, it is not uncommon for resource-conserving returns to be lower than conventional options for the first few years. One remarkable set of data from 44 farms in Baden Würtemburg, Germany, has shown that wheat, oats and rye yields steadily increased over a 17-year period following transition to a strictly organic regime (Dabbert, 1990).

It has been argued that farmers adopting a more integrated and sustainable system of farming are internalizing many of the agricultural externalities associated with intensive farming, and so could be compensated for effectively providing environmental goods and services. Providing such compensation or incentives would be likely to increase the adoption of resource-conserving technologies. None the less, these periods of lower yields seem to be more apparent in conversions of industrialized agriculture. Current evidence appears to suggest that most low input and Green Revolution farming systems can make rapid transitions to both sustainable and productive farming (see Chapter 7).

THE MANAGEMENT AND CONTROL OF PESTS AND DISEASES

Why Pesticides are Not Ideal

Although agricultural pests, weeds and pathogens are thought to destroy some 10–40 per cent of the world's gross agricultural production, pesticides are not the perfect answer to controlling pests and pathogens (Conway and Pretty, 1991). Here the term pesticide is used to refer to products that control insects, mites, snails, nematodes and rodents (insecticides, acaricides, molluscicides, nematicides and rodenticides), diseases (fungicides and bactericides) and weeds (herbicides). Throughout this book, the term pest is also used to refer to all these harmful organisms. Pesticides can be dangerous to human health and damage natural resources but, more importantly to the farmer, pesticides are often inefficient at controlling pests. They can cause pest resurgences by killing off the natural enemies of the target pests. They can produce new pests, by killing off the natural enemies of species which hitherto were not pests. Pests and weeds can also become resistant to pesticides, so encouraging further applications. And, lastly, pesticides provide no lasting control and so, at best, have to be repeatedly applied.

Ideally, pesticides should not lead to pollution, interfere with natural enemy control, or result in pests evolving resistance. Needless to say, this is unlikely. Many of the newer pesticide compounds are more selective, less damaging to natural enemies and less persistent in the environment. One consequence of greater regulation is the development of a number of chemicals that are highly targeted in their effect. But one problem is that many of these are more expensive to farmers than broad spectrum products. What farmers need is a wide range of possible technologies that can make use of the agroecological processes of predation, competition and parasitism to control pests more effectively than pesticides alone.

Most pest species are naturally regulated by a variety of ecological processes, such as by competition for food or by predation and parasitism by natural enemies. Their numbers are more or less stable and the damage caused is relatively insignificant in most cases. High input farms, though, are very different from natural ecosystems. Fields are planted with monocultures of uniform varieties, are well watered and provided with nutrients. Not surprisingly, these are ideal conditions for pest attacks, and frequently the scale and speed of attack means that farmers can only resort to pesticides.

Integrated pest management (IPM) is the integrated use of a range of pest (insect, weed or disease) control strategies in a way that not only reduces pest populations to satisfactory levels but is sustainable and non-polluting. IPM as an external intervention was first applied in 1954 for the control of alfalfa pests in California by making use of alternative strip cropping and selective pesticide use (Conway, 1971). Also in the 1950s, cooperative cotton growers in the Canete Valley of Peru developed IPM in the face of massive breakdown of control due to excessive use of pesticides (Smith and van den Bosch, 1967).

Inevitably IPM is a more complex process than, say, relying on regular calendar spraying of pesticides. It requires a level of analytical skill and certain basic training in crop monitoring and ecological principles. Where farmers have been trained as experts, such as in Honduras (Bentley et al, 1993) and in the rice-IPM programmes of South-East Asia (Kenmore, 1991), then there are substantial impacts. But where extension continues to use the conventional top-down approach of preformed packages, then few farmers adopt the practices, let alone learn the principles. As Patricia Matteson (1992) put it: *'few IPM programmes have made a lasting impact on farmer knowledge, attitudes or practice'*. The large-scale IPM for rice programmes are demonstrating that ordinary farmers are capable of rapidly acquiring and applying the principles and approaches (see Case 11, Chapter 7). These programmes are not necessarily teaching farmers new technologies and knowledge as this can become outdated very rapidly; rather they are concerned with developing farmers' own capacity to think for themselves and develop their own solutions. These are producing substantial reductions in insecticide use, while maintaining yields and increasing profits (Table 4.1).

Table 4.1 Impact of IPM programmes on pesticide use, crop yields and annual savings

Country and crop	*Average changes in pesticide use (as % of conventional treatments)*	*Changes in yields (as % conventional treatments)*	*Annual savings of programme (US $)*
Togo, cotton[1]	50%	90–108%	11–13,000
Burkina Faso, rice[1]	50%	103%	nd
Thailand, rice[2]	50%	nd	5–10 million
Philippines, rice[2]	62%	110%	5–10 million
Indonesia, rice[2]	34–42%	105%	50–100 million
Nicaragua, maize[3]	25%	93%*	nd
USA, nine commodities[4]	no. of applications up, volume applied down	110–130%	578 million
Bangladesh, rice[5]	0–25%	113–124%	nd
India, groundnuts[6]	0%	100%	34,000
China, rice[2]	46–80%	110%	400,000
Vietnam, rice[2]	57%	107%	54,000
India,rice[2]	33%	108%	790,000
Sri Lanka, rice[2]	26%	135%	1 million

* even though yields are lower, net returns are much higher
nd = no data
Sources: 1 Kiss and Meerman, 1991; 2 Kenmore, 1991; Winarto, 1993; van der Fliert, 1993; Matteson et al, 1992; FAO, 1994; 3 Hruska, 1993; 4 NRC, 1989; 5 Kamp et al, 1993; Kenmore, 1991; 6 ICRISAT, 1993

Cutting pesticide use by at least half produces substantial savings for governments. In Togo and Burkina Faso, farmer monitoring of pests in cotton and rice cultivation has also led to large cuts in pesticide use with no loss to farmers (Kiss and Meerman, 1991). In Madagascar, an IPM programme in the Aloatra basin is showing that the aerial pesticide applications on 60,000 ha of rice during the 1980s to control African stem borer were completely unnecessary (von Hildebrand, 1993). Pests here are well controlled by natural enemies and never actually cause economic losses. Integrated measures in Madagascar focus on cultural control, plant resistance, moderate herbicide use and a surveillance system. Substantial savings in foreign currency have also been made. Similar savings are being made in Nicaragua, where CARE is training farmers to use pesticides on maize more appropriately. Not only are net returns better, but farmers who received IPM training did not suffer decreased levels of the blood enzyme, cholinesterase. By contrast, farmers receiving no training had a 17 per cent reduction, indicating chronic exposure to organophosphate pesticides (Hruska, 1993).

In recent years IPM has become widely adopted in the USA, focusing mainly on better scouting for pests, rotations and other cultural practices. On many crops IPM is employed on more than 15 per cent of total acreage; for some, such as apple, citrus and tomato, it is now the preferred approach. A wide range of studies have shown that farmers can maintain or improve yields following adoption of IPM, as well as maintain or increase profits (Allen et al, 1987; NRC, 1989). In general, more farmers have increased the number of pesticide applications as a result, though the volume of pesticides has declined because of precise timing and the use of more specific products.

Using Resistant Varieties and Breeds

A major line of defence is to have crops and animals that are resistant to the likely pests and diseases. During selection and breeding to produce high yielding crop varieties and livestock breeds, many natural defence mechanisms are lost. This may be deliberate since bitter compounds reduce the palatability of plants to humans as well as wild animals. But often the loss is inadvertent. The breeders' primary aim is increased yield and, by focusing selection on the genes that govern yield characteristics, the genes that confer protection may not be retained. High yielding, modern varieties of rice in the Philippines, for example, suffer proportionately higher yield losses, on average 20 per cent of yield, compared to 13 per cent for traditional varieties, although of course the yields of the former are in absolute terms larger (Litsinger et al, 1987).

Modern livestock breeds are also less resistant to diseases. One of the most economically important of these is trypanosomiasis,which is transmitted by tsetse fly and affects some 10 million ha of Africa. Annual losses of meat production alone are estimated to be some $5 billion (FAO, 1993). But some African cattle are trypanotolerant, having developed resistance to the parasite over thousands of years. One such breed is the N'Dama, which have long been kept by West African farmers in marginal areas. They are less productive than modern cattle, though thrive on low-quality forage, and have better survival and longevity. Embryo transfer techniques have been used to enhance these N'Dama cattle, and they have also been crossed with the Red Poll, a rare British breed, to produce the Senepol breed. This has been introduced into the Caribbean and southern USA (FAO, 1993).

Much of the success of modern agriculture has centred upon breeding varieties resistant to known pests and diseases. During the 1940s, wheat in Mexico suffered several destructive epidemics of wheat rust and the first task of the improvement programme was to breed varieties with stem rust resistance (see Chapter 2). By 1949 four pioneer hybrids with high levels of resistance were available to farmers and, by 1956, national average yields had risen from 650 to 1100 kg/ha. Rice, too, has benefited from the incorporation of resistant genes drawn from a variety of Asian sources. The first modern varieties had narrow genetic resistance as breeders had selected for a limited number of desired characteristics, including short straw, high tillering ratio, insensitivity to photoperiod and early maturity. Subsequently, however, protection has been built in, year by year, so that modern rice varieties are resistant to a much wider range of pests and pathogens (Khush, 1990).

Evolution, though, also works to counter the breeders' selections. New species of pests, weeds and pathogens appear, and, more important, new strains of existing pests and pathogens that overcome the hard-won resistance may develop. One example is the brown planthopper, a serious pest of rice, of which at least three strains have appeared in recent years. Each new strain results in a major outbreak and the hurried distribution of new resistant rice varieties. Another is the sorghum greenbug in the USA. In 1968, the greenbug caused US$100 million loss to the sorghum crop and farmers spent some $50 million in the following year to control the pest. By 1976, however, resistance to the greenbug was found and the new hybrids were being grown on 1.5 million hectares. A new biotype of greenbug capable of attacking this hybrid then emerged in 1980, but again researchers were successful in developing another resistant variety (NRC, 1989).

For low external input farmers, resistant crops and livestock represent an important alternative to pesticides in controlling pests and pathogens. The 'treadmill' nature of breeding for resistance does, however, mean that farmers must rely on regular supplies of new seed. Most of these treadmill problems occur because modern varieties are not planted in mixtures and, if palatable, present pest and diseases with unchecked opportunities for population growth. However, planting a diversity of varieties or genotypes in a field can help to harness the inherent variability in pest and pathogen resistance. One option is to create multilines by mixing seeds from similar lines of a crop variety. The lines are very similar in most of their characteristics, but have different genes for resistance. In theory, when new strains of a disease appear only one or two of the lines will prove susceptible. Build up of the disease is slow, an epidemic is prevented and most of the crop escapes damage.

Alternative 'Natural' Pesticides

Many farmers know which locally available plants have insecticidal or disease-controlling properties, and there is a wide range of locally available compounds to repel, deter or poison pests of their crops and animals (Table 4.2). Many of these are both selective in their action, killing pests and not predators, and degrade rapidly so do not contaminate the environment. Of those that are repellents, the effectiveness is short lived and usually considerably reduced by rain. Increasingly, scientists are identifying the mechanisms behind these 'traditional' approaches to control. Some, though, are toxic to people and broad spectrum in their action, and thus are not so different to many synthetic products (Conway and Pretty, 1991). Non-plant products are also widely used, such as solutions of cattle manure and animal urine to repel insects and animals; soil added to leaves to abrade the cuticle of insect pests; and sand or ash added to stored grain to stop the movement of weevils.

The most widely used natural plant compounds are the antifeedants that render plants unattractive and unpalatable to pests. The most common is neem (*Azardirachta indica*), which occurs over wide areas of Asia and Africa. Almost every part of the tree is bitter, although the seed kernel possesses the maximum deterrent value. The derivatives are known to control more than 200 species of insects, mites and nematodes (Saxena, 1987; FAO, 1993). Yet neem does not harm birds, mammals (including people) and beneficial insects such as bees. The seed is most commonly formulated in an oil or cake: in parts of India neem cake has been applied to rice for centuries. In the USA, neem extract controls Colorado potato beetle sufficiently well to give 27–47 per cent better yields than unsprayed potatoes (Zehnder and Warthen, 1988). Neem is also less toxic to beneficial predators.

But there is a disadvantage, since neem degrades fairly rapidly in sunlight and as a consequence the most successful applications have been in the control of stored grain, rather than field pests. However, a multinational corporation from the USA has recently synthesized a product which stabilizes azardirachtin, the active ingredient of neem. Although this is potentially good news for farmers worldwide, it has instead become a threat to the traditional technology. The company has now been granted a sole patent on both the stabilizer and azardirachtin. This means that it can, in theory, charge farmers for using their own traditional technology or prevent them from using it. In practice, this will of course be difficult. What is more likely to happen is that local supplies of neem will be bought up, formulated with the stabilizer, and then sold back to farmers. In 1993, the world's first commercial-scale facility, capable of processing 20 tonnes of neem seed each day, was opened (FAO, 1993).

Farmers also rely on many local plants for the control of livestock diseases. In industrialized countries, much traditional veterinary knowledge has died out with the decline of horses and the mechanization of farming since the 1950s. For centuries, British horsemen made use of many hundreds of herbs and wild plants, including agrimony to control fever, burdock for conditioning, feverfew for curing colds, horehound for keeping

Table 4.2 Selection of locally available compounds used for pest control in a range of countries

Plant	*Country*
Chili pepper (*Capsicum frutescens*)	*Kenya:* ground, stirred in water, left to stand and sprayed against aphids or fed to chickens to treat diarrhoea *Papua New Guinea:* ground, stirred in water with soap, sprayed to repel aphids *Benin:* milled with earth and mixed with beans during storage *Philippines:* pulverized and burnt monthly beneath food stores *Honduras:* mixed with garlic in water, left to stand, diluted and applied next day to repel insects
Custard apple, sweetsop (*Annona* spp)	*China and Philippines:* pulverized seeds used against human lice *West Africa:* water suspension of seeds controls insect pests
Turmeric (*Curcuma domestica*)	*Sri Lanka:* root shredded and added to cow urine, sprayed against insect pests; threads dipped in grated turmeric and stretched across fields to repel insects *Various locations:* dried, pulverized root added to stored produce to repel weevils and borers
Neem (*Azardirachta indica*)	Neem effective as aqueous solution, oil, kernel powder and press cake for insect pests and fungal control *India:* used on vegetables, citrus, cereal and bean crops *Ghana:* leaves burned, ashes mixed with water and spread on crops
Muna (*Minthustachys* spp)	*Peru:* muna twigs used to line inside of potato stores and pits
Croton oil tree (*Croton tiglium*)	*Thailand:* water extract made from pulverized seeds and used against aphids
Mexican marigold	*Kenya:* cut and laid around livestock bomas to repel safari ants
Simson weed (*Datura stranonium*)	*Cameroon:* leaves, stems, flowers and seeds shredded and soaked in water, soap and kerosene solution, and sprayed against leaf-eating caterpillars and aphids
Gliricidia spp	*Sri Lanka:* fresh leaves applied as a mulch to control transmitter of mosaic virus
Castor oil (*Ricinus communis*)	*Cameroon:* seeds mashed and heated in water, soap and kerosene solution, mixture sifted, diluted and sprayed immediately *Ecuador:* leaves placed in maize fields to attract beetles, which are paralyzed by the castor *India:* castor widely grown as intercrop with cereals and cotton to repel insects
Ryania (*Ryania speciosa*)	*South America:* powder or spray used against maize and fruit pests
Daluk (*Euphorbia antiquorum*)	*Sri Lanka:* chips of Euphorbia placed in water at point of impounding of irrigation water to control thrips

Sources: Stoll, 1987; Matthias-Mundy, 1989; Schrimpf and Dziekan, 1989; Pretty, 1990a; Upaswansa, 1989; Fre, 1993; Catrin Meir, personal communication

horses on their food and celandine for clearing worms (Evans, 1960). In Peru, shepherds use wild tobacco to control skin parasites of sheep and feed cattle with artichoke to prevent liver flukes (Matthias-Mundy, 1989). Pastoralists in Africa have been widely recorded as using many herbs for pest and disease control, as well as for setting broken bones and treating wounds (Schwabe and Kuojok, 1981; McCorkle, 1989; Fre, 1993).

Bacterial and Viral Pesticides

Pesticides based on bacteria and viruses are also promising in terms of selectivity and reduced potential for pollution. The greatest successes so far have been preparations of *Bacillus thuringiensis* (*Bt*). The bacillus produces a crystalline compound, which dissolves when ingested by insects producing toxic proteins that paralyse the gut and mouthparts. Strains of *Bt* have been used against moth pests for some 25 years, though new strains have been shown to be active against a range of other pests including nematodes, mites and beetles.

The crystal toxins of *Bt* are produced by a single gene, which has now been cloned and inserted into non-pathogenic bacteria that colonize plant roots, and also directly into crop plants such as tobacco and tomato. The potential for engineering plants to contain their own defensive compounds in this way is considerable. According to the OECD, field releases with transgenic tobacco, cotton, maize and tomato have taken place in the USA, Israel and Spain. As yet restrictions on genetically engineered micro-organisms have not permitted extensive field trials. Sales of *Bt* are now worth US$100 million per year. However, resistance to *Bt* has been reported in Australia, the USA, Japan, Philippines, Thailand and Taiwan, particularly where *Bt* products have been repeatedly applied as a spray or incorporated into crops (PT, 1993).

Some strains of bacteria are also effective at controlling crop diseases, such as *Agrobacterium*, which produces an antibiotic that controls crown gall tumours of orchard trees and ornamental plants (NRC, 1989). Antibiotic substances produced by the bacterium *Streptomyces* have been formulated into a biofungicide, which inhibits growth of *Rhizoctonia* in oil seed rape, *Fusarium* on cereals, *Pythium* on sugar beet and *Alternaria* on cauliflowers. Other new biopesticides include products based on fungi and toadstools. Although the demand for these 'biopesticides' is growing rapidly, the market share still remains small in relation to the remaining pesticide market.

A successful example of the use of viruses has been the release of live coconut rhinoceros beetles infected with a baculovirus in islands of the South Pacific. The virus spread at 3 km/month and within 18 months of release beetle populations had declined at some locations by 60–80 per cent (Bedford, 1980; Young, 1974). Some naturally occurring viruses can also give good control. In Brazil, a major pest of cassava, the cassava hornworm, is being controlled by spraying with extracts of hornworm infected with a virus, *Baculovirus erinnyis* (CIAT, 1987). Mixtures made from recently infected larvae result in 90–100 per cent mortality within seven days of application, though virus from four-year-old frozen larvae still kill some 70 per cent of hornworms. Frozen virus is now available on a semi-commercial basis in Brazil, and farmers have been shown how to collect, prepare, store and apply infected larvae in newspaper, radio and TV campaigns. Farmers in the USA have also successfully made their own preparations (Box 4.1)

Box 4.1 Farmer's own technology for pest management, Florida

Eugene Alford and his neighbours use a naturally occurring fungal disease as part of their IPM programme to control velvet bean caterpillars on their soybeans. He collects dead dried caterpillars infected with the mould *Nomurea rileyi* and grinds them into a powder which he freezes for application the following summer. He applies this powder, which contains fungal spores, to parts of his fields most affected by caterpillars a few weeks before spraying time and monitors its effects. When conditions are optimum the disease will wipe out all caterpillars within 4–5 days. Alford estimates annual pesticide savings of up to US$10,000 on his 200 ha farm.

Source: International Ag-Sieve, 1988

Cutting Input Use in Industrialized Systems

The alternative to seeking safer compounds is to rely on more efficient and careful application of existing pesticides. Most damage arises today, not so much because of the intrinsic characteristics of the pesticide compounds but because of the way they are used. There is increasing evidence that farmers can reduce their pesticide applications through the precise targeting of pests and weeds in crops without suffering any reduction in profitability (Pretty and Howes, 1993).

In Britain, evidence is emerging to show that if farmers get the timing of applications of fungicide on cereals right, they can cut rates by 50–75 per cent and still maintain yields (see Table 7.2). Farmers regularly have to examine crops and then apply a quarter-rate mix when 75 per cent of plants are showing at least one active mildew spot (Wale, 1993). Careful monitoring and sequential sampling for pests on brassicas has reduced the need for pesticides by 85 per cent, while maintaining yields. In the fruit sector, many farmers have been able to cut their use of fungicides to 12–25 per cent of former levels following the adoption of a range of IPM technologies (Doubleday, 1992). But these low dose approaches do place extra management demands on farmers. As Stuart Wale put it: *'the use of low dose mixtures is not appropriate for all growers. It is primarily intended for those who can inspect crops regularly and make a timely application of [pesticide]'* (FW, 1993a).

An important new approach is patch spraying. This needs a combination of modern technology, regular field monitoring and modified spray systems that allow application exactly where there are known problems. A field map showing the location of weeds or pests is first constructed by using a combination of aerial photography, image analysis of maps and field walking. This information is then stored in a tractor-mounted computer which also controls the sprayer. In the field the operator enters the location of the tractor and a distance/speed monitor tracks its position as it moves. The position is compared with the pest or weed maps and herbicides or pesticides dispensed only when they are needed. The impact on cost reduction can be considerable, with some farmers cutting herbicide bills substantially with no impact on cereal yields. John Morrison (FW, 1993b), who farms in Derbyshire, has cut herbicide bills by 95 per cent in some fields. In one field he saved £1700 by patch spraying: *'we'd have had to spray the whole lot if it hadn't been for the modified spray system'*. In effect, farmers are substituting labour and knowledge for the former dependence on external measures for pest control.

Patch spraying can be more efficient with the use of global positioning systems (GPS). A GPS utilizes signals from satellites to fix the precise position of a tractor or combine harvester within a field. The system can produce yield maps for fields by combining data from existing yield monitors on combines with the exact position in the field. Even in modern agriculture, yield variations within a single field can be up to 4 t/ha. Seed, pesticide, herbicide and nitrogen rates can be matched to the variations within a field. One farmer cut nitrogen rates by 30 per cent, which reduced the amount of nitrogen leaching out in the field drains by 60 per cent (FW, 1991b). As another farmer, John Fenton, put it: *'it must make sense to tailor input levels to as small an individual area as possible. Blanket rates over a large area are wasteful'* (FW, 1993c). And because many factors affect crop yield, the technology is best used in combination with soil analysis, regular field walks and monitoring.

Pheromones for Disrupting Pest Reproduction

Some pest populations can be controlled by disrupting their reproduction. Synthetic chemicals that mimic pheromones, which are hormones released by female insects to attract males, will greatly reduce the chances of mating by confusing male insects, while the release of larger numbers of pre-sterilized males will ensure that most matings are sterile. Both of these, though, are high-input options and require intervention at a very large scale, involving cooperation among large numbers of individual farmers. So far they have only been effective on large enterprises, or as part of government or co-operative run schemes.

Slow-release formulations of synthetic pheromones that confuse males are very effective in disrupting mating in a variety of pests if applied on a large scale. Control of the pink bollworm (*Pectinophora gossypiella*) on cotton has been successful in Egypt, Pakistan and the USA, and of grape oriental fruit moth on peaches, tomato pinkworm and some pests of stored products (Campion et al, 1987; NRC, 1989). In Egypt pheromone formulations are sold at the same price as conventional insecticides and two to three applications are as effective as four to five sprays of conventional pesticide. Predators are more numerous in pheromone-treated than in insecticide-treated fields, and also more bees survive, leading to bumper crops of honey (Campion and Hosny, 1987). In Pakistan, only 7 per cent of cotton bolls are infested by pink bollworm in pheromone-treated fields, while 25 per cent are infested in conventionally treated fields (NRI, 1994). In the USA, the pink bollworm disruptant is applied on some 40,000 ha annually, holding infestations down to 1 per cent or less with a single application, so permitting a reduction of insecticide applications have by nearly 90 per cent (NRC, 1989). In the UK, the use of pheromone traps to monitor codling and tortrix moths has become standard practice in apple orchards (Doubleday and Wise, 1993).

Another approach, the release of sterile males, requires an even larger scale of operation. Massive rearing facilities are needed to raise large numbers of pests that are then sterilized by irradiation and released in a sufficient quantity to swamp the natural population. The first pest eradicated by this technique was the screwworm, *Cochliomya hominivorae*, a serious pest of cattle in the south-western USA (Knipling, 1960; Conway, 1971). From early 1958, over 50 million sterile flies were released each week, eventually eradicating the pest over large areas within a year. Although there have been other successes, the technique is only likely to succeed where the pest populations are relatively small and isolated.

Similar to pheromones are juvenile hormones, which kill or prevent insects from reaching a mature stage for reproduction. As metamorphosis is prevented, the insects are biologically dead, and the population eventually ceases to exist. These compounds offer the possibility of being active only in certain insects, with no biological activity in other organisms. They have not yet been used in field crops.

MANAGING NATURAL ENEMIES

Releasing Predators and Parasites

The natural enemies of pests include a great variety of parasitic wasps and flies, predators such as ladybird beetles, spiders, hoverflies, wasps, ants and assassin bugs, and larger animals such as lizards, birds and fish. Pests are also attacked by a range of pathogenic bacteria, fungi, viruses and nematodes. In natural conditions many such natural enemies may be present, acting together to regulate pest numbers. One problem with pesticide use is that if all the pests are killed, the predators may have nothing to feed on and so also die. This may mean pest numbers increase (see Chapter 3). Ideally the pest population needs to be brought down to a desired level and maintained there, hopefully permanently. This implies that the pest population is not eradicated and, indeed, is tolerated to an extent.

The use of natural enemies is commonly referred to as biological control. The term sometimes implies any form of non-pesticidal control, but it is less confusing if restricted to the use of natural enemies. It is also important to distinguish between what is called *classical biological control* which involves the release of new or exotic natural enemies and *augmentation* which relies on improving the degree of existing control. There has been considerable effort over recent years to develop effective biological control programmes (Waage and Greathead, 1988; Jutsum, 1988).

Occasionally the results are spectacular. One such success was the control of the prickly pear, *Opuntia*, a cactus that was introduced into Australia as a garden plant from Mexico at the end of the last century. It soon spread to pasture land and by the 1920s some 25 million ha were infested. But eventually *Cactoblastis cactorum*, the larvae of which tunnel into and destroy the cactus, was discovered in Argentina and taken to Australia. The cactus now only occurs as individual plants or in small patches (Conway, 1971).

Equally successful is the use of *Trichogramma*, an egg parasitoid of moth pests, which is used on 15 million ha worldwide. To be effective, though, the releases usually have to be carefully managed. A single, carefully timed release of the egg parasitoid *Trichogramma* early in the growing season gives as good control of moth pests on maize and sugar cane in China as weekly mass releases later in the season (Waage and Greathead, 1988).

A recent success story has been the parasitic wasp, *Epidinocarsis lopezi*, introduced from South America to control the cassava mealybug (*Phenacoccus manihoti*) in Africa (Kiss and Meerman, 1991; Neuenschwander and Herren, 1988). The mealybug first appeared in Congo and Zaire in 1973, and is now found in a wide belt from Mozambique through Zaire and across to Senegal. Severe attacks can cause up to 80 per cent reductions in cassava yields. Widespread searches were conducted throughout South America, the original home of cassava, and the wasp discovered in Paraguay was released in Nigeria in 1981. It is now present in 25 African countries. After the release of *E. lopezi*, cassava mealybug populations decline by up to 50 per cent, often leading to yield gains of some 2.5 t/ha (Hammond et al, 1987; Neuenschwander et al, 1989).

Although there have been some attempts to calculate benefit:cost ratios, these have been controversial as data is poor and many generalizations have had to be made. Norgaard concluded returns of $2.25 billion for an investment of $14.8 million, a ratio of 149:1, and IITA researchers concluded returns of $3 billion for a ratio of 178:1 (Norgaard, 1988; IITA/ABCP, 1988). The most controversial aspect of the programme, however, has been that farmers have not had to be involved, unlike other similar programmes (see Box 2.3).

Some of the most successful biological control programmes have been against pests of glasshouse crops, such as tomatoes, cucumbers and ornamentals. Pests in glasshouses rapidly multiply in the controlled and favourable environment, often with devastating effects. However, the high degree of environmental control can also favour the planned release of natural enemies. There has been rapid growth in the use of natural enemies in recent years and some expect more growth in this market than for conventional pesticides. One private company that supplies biological control agents to farmers, recently indicated that in the future the *'conventional crop protection market is expected to stagnate, while the natural biological products sector expands by 10–15 per cent per year, accounting for 5–10 per cent of the total market within the decade'* (FW, 1993d).

None the less, there have been many more failures with biological control than successes (Jutsum, 1988). Spectacular failures include the introduction of cane toads to sugar cane crops in Australia, that not only failed to control cane beetles but also became pests themselves; and the attempts to control cedar scale in Bermuda involving the introduction of over 50 species of natural enemies between 1946 and 1951. The problem is that a great deal needs to be known about the detailed population dynamics of pests and their natural enemies and, in some cases, where growth rates of pest populations exceed natural mortality, then biological control is physically impossible.

Improving the Habitat for Natural Enemies

Natural enemy populations can also be encouraged by increasing the diversity of farms and their neighbouring environments. Many natural enemies need food sources in the form of pollen or nectar, which can often be provided by wild vegetation near or in the crops. There are usually more natural enemies in fields bordered by diverse hedgerows and in orchards adjacent to woodlands (Lewis, 1969; Altieri and Schmidt, 1986; Herzog and Funderbank, 1986; El Titi and Landes, 1990). These non-crop plants that harbour natural enemies of pests often give good control (Table 4.3). The predators, however, often need some encouragement to invade crops and fields. Perennial stinging nettle, for example, is a source of predators of aphids and psyllids, and, as predator numbers increase in the spring, so their dispersal to crop fields can be encouraged by cutting the nettles (Herzog and Funderbank, 1986).

One traditional technique in orchards has been to encourage populations of predatory ants. In China, bamboo bridges have for some 1700 years been placed between branches to encourage movement of citrus ants (*Oecophylla smaragdina*) from tree to tree (Huang and Pei Yang, 1987). These feed on various insects that attack orange, tangerine, lemon and pomelo trees. Whole orchards can be colonized by securing a nest on one tree and then connecting this to others with the bamboo strips.

The practice is also common in Indonesia. Raymon Wibisana (1987), a Javanese farmer, described his practice in this way: '*I have encouraged big red ants to breed in my orchard for they stop worms and mites from pestering the trees. The ants do not seem to harm the trees, and if their numbers become too great they can be used for chicken feed. The ants can also be used against the hopping insect. Two of my trees that were without red ants suffered, but a third, which was inhabited by the ants, grew well and bore fruit. So I ran a rope from the healthy tree to the other two so that the ants could move across. It took them two weeks to do so, but after that the ants ousted the pests and the trees had new leaves*'.

Birds and fish can also be important. Farmers in Sri Lanka encourage birds to come to their rice fields by putting food on unstable discs attached to stakes so that when birds attempt to perch, the food falls into the rice and in following it down they see the pests; and by inserting coconut fronds in the fields as owl perches to aid rat control. Farmers also preserve large trees and pockets of woodland close to the paddy to provide nesting and perching places for predatory birds (Upaswansa, 1989). A similar approach has been taken by groundnut farmers in Andhra Pradesh, India, who have stuck small tree branches into the soil (ICRISAT, 1993). These perches attract birds, which eat pod-borer caterpillars. Farmers on 400 ha of Guntar District stopped using pesticides, saving themselves some 1 million rupees (US$34,000). They also had higher yields than their neighbours still using pesticides, because natural enemies could survive in their fields.

Table 4.3 Selection of cropping systems from the USA and UK in which non-crop plants enhance the biological control of certain pests

Crop	*Non-crop plants*	*Pest regulated*	*Mechanism*
Apple	*Nasturtium*	Aphids	Enhancement of hoverfly populations
Brassicas	*Amaranthus and Chenopodium*	Green peach aphid	Increased abundance of predatory beetles
Cotton	Ragweed (*Senecio*)	Boll weevil	Alternative host for parasite *Eurytoma*
Peach	Ragweed	Oriental fruit moth	Alternative host for parasite *Macrocentrus*
Sugar cane	*Euphorbia*	Sugar cane weevil	Provision of nectar and pollen for *Lixophagus* parasite
Grape vines	Wild blackberry (*Rubus* spp)	Grape leafhopper	Alternative host for parasitic wasp, *Anagrus*
Wheat, barley, oats	Timothy grass (*Phleum pratense*) and Yorkshire fog (*Holcus lanatus*)	Cereal aphids	Grass beetle bank provides habitat for predatory ground beetles
Wheat, barley, oats	*Phacelia*	Cereal aphids	Flowering *Phaecelia* encourages hoverfly populations

Sources: Altieri and Liebman, 1986; Herzog and Funderbank, 1986; Pretty and Howes, 1993

Rice pests can also be controlled by cultivating fish in the paddy water. The fish move with the flood water in the rainy season from refuges, and help to keep down the incidence of insect pests and pathogens (see Table 4.6).

Beetle Banks and Flowering Strips in Industrialized Systems

A recent development in temperate agriculture to encourage predators while reducing pesticide applications has been to use beetle banks, flowering strips and conservation headlands. In Britain, several hundred potentially beneficial species of predators and parasites may live in or by cereal crops. Most of these are killed when the crops are sprayed to control pests. But if the field habitat is manipulated to increase plant diversity, then the need for spraying pesticides can be greatly reduced. When grass strips are constructed across large fields, then predatory beetles proliferate and can get to the field centres, the regions where aphid populations are greatest (Wratten, 1992; UoS/GC, 1992). The cost of establishing a 400 m bank in a 20 ha field is about £90, including cultivation, grass seed and loss of crop. In succeeding years the cost of land taken out of production is £30 for the same field. One aphid spray costs £300 across the same field, plus the cost of yield reduction due to aphid infestation. One farmer, Michael Malyon, recently created five beetle banks, indicating that *'we never get good yields in our large fields... The cost of putting in the banks in a field is negligible compared with the potential benefits'* (FW, 1993e).

Wild flowers also encourage predators. Hoverfly larvae are voracious predators of aphids, and because the adults need pollen and nectar to lay eggs, they thrive on farms rich in wild flowers. Headlands left unsprayed with herbicides support many more predators than those where flowering plants are removed; the weeds attract non-pest herbivorous insects, which encourage hoverflies and other predators of cereal aphids, such as the beetles *Agonum dorsale* and *Bembidion lampros*. The survival rate of partridge and pheasant chicks, which feed on the herbivorous insects, is also greater in these conservation headlands (Game Conservancy, 1993).

These practices are growing in popularity. Some 1800 km of conservation headlands were recorded in England and Wales in 1992. Recently, farmers have been experimenting with *Phacelia tanacetifolia*, a blue-flowering ornamental introduced from the USA. This has a long flowering period and again attracts hoverflies. Where it has been planted in strips, the number of eggs laid per aphid is twice as great as in fields with no flowering strips (Wratten, 1992). It is ironic, of course, that farmers who are putting in beetle banks and flowering strips may well have been encouraged to remove hedgerows in the recent past.

Rotations and Multiple Cropping

Crop rotations are a central component in the development of resource-conserving farming, with the maximum use made of crops that contribute to soil fertility and reduce pest damage. The approach is to rotate non-host crops with susceptible crops in sequence. While the non-host crop is present, the pest populations decline so that they are very low or even absent when the susceptible crop is grown again. The non-host crop provides a 'break', disrupting the relationship between a pest or pathogen and its host. It is a practice that rarely has ecological or economic drawbacks and many farmers regard rotation as an essential component of prudent management.

The retention of spatial and structural diversity through multiple cropping practices is as important as rotations. Many small farmers still rely on multiple cropping. In Latin America, some 60 per cent of maize is grown with beans (Francis, 1986; Altieri, 1990). Rice, cotton, beans and cassava are widely grown in mixtures. Generally the more diverse an agroecosystem, the less abundant are herbivore pests though, in some mixtures, herbivores do prevail (Conway and Pretty, 1991; Risch et al, 1983). Different crops can be grown row by row, or in alternate strips each consisting of several rows of the same crop, or they may be grown in a more complicated spatial pattern or, indeed, at random. Mixtures of spring barley varieties, for example, provide good control of powdery mildew: even though pure stands treated with fungicides yield slightly better than untreated mixtures, the untreated mixtures provided better economic returns (Wolfe, 1981; Wolfe and Barratt, 1986).

There are various factors in these crop mosaics that help constrain pest attack. A host plant may be protected from insect pests by the physical presence of other plants that may provide a camouflage or a physical barrier. Mixtures of cabbage and tomato reduce colonization by the diamond-back moth, while mixtures of maize, beans and squash have the same effect on chrysomelid beetles. The odours of some plants can also disrupt the searching behaviour of pests. Grass borders repel leafhoppers from beans and the chemical stimuli from onions prevents carrot fly from finding carrots.

Alternatively one crop in the mosaic may act as a trap or decoy – the 'fly-paper effect'. Strips of alfalfa interspersed in cotton fields in California attract and trap *Lygus* bugs. There is a loss of alfalfa yield but this represents less than the cost of alternative control methods for the cotton. Similarly crucifiers interplanted with beans, grass, clover or spinach are damaged less by cabbage maggot and cabbage aphid. There is less egg-laying on the crucifiers and the pests are subject to increased predation. Interplanting can also be combined with selective use of pesticides, applying them at the appropriate time solely to the trap crop.

INTEGRATED PLANT NUTRITION

Just as with integrated pest and predator management, there is a wide range of nutrient management measures that can both maintain soil fertility and sustain productivity. These are increasingly being known as integrated plant nutrition systems (FAO, 1991). These focus on improving the efficiency of inorganic fertilizers, introducing new crops into rotations that fix nitrogen or utilizing organic sources of nutrients.

Improving the Efficiency of Fertilizers

It is virtually impossible to maintain crop production without adding nutrients. When crops are harvested, nutrients are invariably removed and so have to be replaced. There are a variety of sources: the mobilization of existing nutrients in the soil and parent rocks; the fixing of nitrogen from the atmosphere; or the supply of organic or inorganic fertilizer. The application of fertilizer, ideally, should closely match the needs of plants but often farmers, for reasons of cost, will apply fertilizer in fewer and larger doses. Commonly, fertilizer is applied in excess of need, so some nutrients are lost from the farm as nitrates to surface or ground water, or as ammonia or nitrous oxide to the atmosphere. On average, some 30–60 per cent of applied nitrogen is lost in non-irrigated farming, rising to 60–70 per cent from paddy cultivation (Conway and Pretty, 1991). This represents a substantial loss to farmers.

Crops vary in the efficiency with which they take up nutrients and so breeding for efficiency of nitrogen use is a potentially productive approach. For instance, the widely cultivated rice variety IR36 was superseded by the more nitrogen-efficient IR42. The soil type and sources of nitrogen other than the inorganic fertilizers are also important factors. If reserves in the soil are known then it is possible to make fertilizer recommendations tailored for the specific requirements of each field and each crop.

Fairly precise recommendations are now available for farmers in Europe and North America, though not generally for farmers in the South (Conway and Pretty, 1991). In the UK, these are largely based on the previously grown crop (MAFF/ADAS, 1988). Cereals are assumed fully to deplete reserves, for instance, whereas pasture leaves high reserves for the next crop. The outcome is a set of recommendations for nitrogen fertilizer application rates dependent on both reserves and soil type. For instance, it is recommended that winter wheat likely to yield less than 7 t/ha when grown on sandy soil with low reserves should receive 175 kg N/ha. But if the reserves are high and the soil a clay, then no fertilizer needs to be applied.

Nutrient uptake and absorption can also be improved by using foliar sprays, slow-release products or by incorporating, with the fertilizer, certain compounds that inhibit the bacterial conversion of nitrogen compounds. Foliar fertilization is efficient because of rapid absorption and translocation into the plant (Alexander A, 1993). In some vegetable crops, it is possible to reduce fertilizer applications by 25 per cent by substituting foliar sprays.

Low input farmers are likely to be the greatest beneficiaries of deep placement fertilizers such as urea briquettes, urea marbles or urea supergranules (USG), as a small quantity of fertilizer is now capable of going further. In Taiwan, for example, USG increases rice yields by 20 per cent on farms in marginal areas, but has no impact in the already high yielding zone (De Datta, 1986). Nutrient uptake and absorption can also be improved by using slow-release products coated with sulphur. Sulphur-coated urea reduces the need for split applications and helps to fulfil sulphur requirements of the crop, with economic returns of the order of US$4–7 for every dollar spent (De Datta, 1986). Urea can also be combined with various aldehydes to make insoluble products, with methylene-urea the most common and also the best at preventing nitrate leaching. Polymer or resin-coated fertilizers can be tailored in such a way that the release period extends up to 12 months or more. Granules of fertilizer are coated with a diffusion barrier through which nutrients slowly pass (Alexander A, 1993).

Nitrification inhibitors, such as dicyandiamide, prevent the conversion of ammonium to the more mobile nitrate form. These products can

improve yields as well as cut losses to the environment. But they are 10–20 per cent more costly than conventional fertilizers and are only available to farmers in industrialized countries. Inhibitors that reduce gaseous ammonia losses from broadcast applications of nitrogen to rice paddies delay the build up of ammonia in the water, but it is not clear whether there is a positive impact on yields too.

Livestock Manures and Composts

Farmers who can neither afford nor rely on a regular supply of inorganic fertilizers must find alternative organic sources of nutrients. These sources are often cheaper, more efficient than inorganic compounds and focus on recycling of nutrients. Livestock are therefore a critical component of sustainable agricultural systems. The nutrient value of manures largely depends on how they are handled, stored and applied. Losses of nitrogen tend to be highest when liquid systems of storage are used and when the manure is broadcast without incorporation. Livestock manures from cattle, pigs and chickens are important, as they positively affect soil structure and water retention, and benefit soil organisms. Soils under integrated farms, for example, have more earthworms than those under conventional management (El Titi and Landes, 1990; Edwards and Lofty, 1977).

It is becoming more common for farming households with only small farms to keep their animals permanently penned in zero-grazing or stall-feeding units rather than permit them to graze freely. In Kenya, zero-grazing units are a central part of efforts to improve soil and water conservation. Fodder grown on the farm in the form of improved grasses, tree fodder and the residues of cultivated crops are cut and carried to the animals. Because of the proximity to the crops, manures can be returned directly to the land, so improving nutrient supply and soil structure. In dryland regions migrating pastoralists and their livestock are frequently welcomed by farmers during the dry season. The livestock are kept in pens overnight on the crop fields and in some areas farmers are even willing to pay herdsmen for this overnight kraaling (McCown et al, 1979; Scoones and Toulmin, 1993).

Where manures are in short supply, farmers are often willing to pay for them to be imported (Wilken, 1987). In Mexico, farmers are willing to pay US$8–12 for a truckload of chicken manure and vegetable growers in Quetzaltenango in Guatemala buy chicken wastes that are transported 100 km from Guatemala City. In Oaxaca, Mexico the highest value organic material for fertilizing crops is the nutrient-rich debris from the nests of ants. The material is collected in bags and carefully applied to individual plants of high value crops, such as tomatoes, chilis and onions. The decline in use of ant refuse in recent years is said to be a result of substitution by commercial fertilizers (Wilken, 1987).

Composting is a technique of long standing that combines the use of animal manures, green material and household wastes. The materials are heaped or placed in a pit in such a fashion that anaerobic decomposition occurs. Harmful substances and toxic products of metabolism are broken down, while pathogens, and the seeds and roots of weeds are destroyed by the heat generated within the compost heap.

Composting is particularly valuable in the tropics since organic matter stores nutrients and protects them against leaching. It also makes the soil more friable and easier to plough, improves moisture retention and aeration, and remedies the problems caused by inorganic fertilizers. Farmers in Tanzania make compost from stall litter which includes crop residues, leafy tree branches and old roofing grass; in Rwanda farmers mix household wastes, crop residues, weeds, dried leaves and twigs of trees; and in Nepal farmers use a combination of up to 25 wild plants mixed with animal manures (Kotschi et al, 1989; Tamang, 1993). Wood ash is also commonly used, being carried from burnt bushland to compost heaps. But composting is demanding of labour, both in the building of heaps and in spreading on the fields. Its use is thus likely to be limited to kitchen gardens, though whole farms can benefit (see Case 13, Chapter 7).

Legumes and Green Manures

The impact of legumes grown together with or before a cereal crop can reduce, and sometimes eliminate, the need for nitrogen fertilizers. Symbiotic bacteria present in specialized nodules that develop on the roots of legumes can fix nitrogen directly from the atmosphere. The cultivation of cereals and legumes crops together can improve both total yields and stability of production. Bushes and trees with nitrogen-fixing capacity also have beneficial effects on plants growing with or after them.

In the Americas, the interplanting of maize, beans and squash, often the seeds being placed in the same planting hole, is a practice of great antiquity, probably dating to soon after agriculture began in the valleys of Mexico (Gleissman, 1990). In such situations, with soils of low inherent fertility, the cultivation of cereals and legumes crops together can improve both total yields and stability of production. In maize and cowpea mixtures, some 30 per cent of the nitrogen taken up by the maize is obtained from the legume (Aggarwal and Garrity, 1987). Cowpea and lablab are particularly useful legumes for inter-cropping with cereals, the former because it is adapted to acid, infertile soils, and the latter because it is drought-tolerant, produces good fodder and can regrow well after clipping. Here, legumes contribute not only through nitrogen fixation, but also because the green matter can be used as a mulch or green manure.

Undersowing is a once-common practice used now by only a few farmers in industrialized countries. Cereals are sown with a legume and/or grass, and these are already established at harvest. This can help control pests and diseases, provide ground cover and supply nitrogen. Undersowing cereals and brassica with trefoil and clover increases the number of insect predators, reduces the numbers of pests and gives better crop yields than monocrops (Potts, 1977; Dempster and Coaker, 1974; El Titi and Landes, 1990).

Legumes have long been used in milk production systems. However, the advent of readily available and cheap inorganic fertilizers has led to a decline in the reliance on legumes to maintain soil fertility. Mixed grass-clover swards gave way to high nitrogen input grass pastures as producers attempted to maximize yields in response to modern price incentives. Adding nitrogen reduces the content and production of clover, leading to monocultures of grass. But with the 1984 introduction of milk quotas in Europe, there has been renewed interest in the use of legumes in dairy production as a means of reducing unit costs. Grass-clover swards with no application of inorganic nitrogen can successfully support long term-dairy cattle grazing and intensive silage making under commercial farm conditions. These clover-rich swards can fix 80–280 kg N/ha/yr. The financial returns from high nitrogen input systems are no greater, and are often substantially lower, than the grass-clover system (Bax and Fisher, 1993; MMB/SAC, 1992; Younie, 1992; Pretty and Howes, 1993) (see Table 7.3).

Nutrients are also supplied when vegetation is incorporated in the soil as a 'green manure'. Green manures increase nutrient levels as well as improve the physical properties of the soil. This has long been practised; the Romans grew lupins and ploughed them in before sowing cereals more than 2000 years ago. Quick-growing legumes are valuable green manures for many low input systems, and have the potential to meet much, if not all, of the nitrogen requirements of succeeding non-legume crops. The equivalent amount of nitrogen fertilizer required to match the green manures can be 80–200 kg/ha. Many green manures can also add large amounts of organic matter, up to 30 tonnes/ha (Flores, 1988).

One of the most remarkable is the velvetbean (*Mucuna pruriens*). This has been widely promoted as part of the work of World Neighbors in Central America, though its effectiveness is attested by its spontaneous spread from village to village without outside intervention. It grows rapidly, is palatable to animals and people, fixes large amounts of nitrogen and can produce as much as 60 t/ha of organic matter (CIDICCO, *passim*). It can grow on most soils and its spreading habit suppresses weed growth. This compares with an average for the country of just 0.6 t/ha. Incorporating such green manures into cropping systems can substantially increase yields (Table 4.4). Honduran farmers are able to harvest some 2.5–3.2 t/ha of maize when grown after velvetbean (see Case 4, Chapter 7).

Sesbania rostrata, though, is probably the fastest nitrogen-fixing plant, accumulating 110 kgN/ha in only 45 days (Lathwell, 1990). In Rwanda, the shrub *Tephrosia vogelii* grows to a height of 3 m in 10 months and produces 14 tonnes/ha of above-ground biomass which, when worked into the soil, can increase cereal yields by as much as four fold to some 2800 kg/ha, a response equivalent to 120 kg/ha of inorganic fertilizer (Kotschi et al, 1989). In Nepal, some green manures can produce rice yields that outperform those produced by as much as 100:30:30 kg of NPK/ha (Joshy, 1991). In dryland North-East Thailand, short duration legumes can be grown following the first rainfall peak, which is insufficient for rice transplanting. Cowpeas, grown for 45–60 days before the rice, have increased rice yields by 5–20 per cent for poor farmers compared with conventional fallowing (Craig, 1987). The benefits are such that inorganic fertilizers are no longer necessary.

In Bhutan, *Sesbania aculeata* substitutes for external inputs, but the best performance occurs when farmers have access to some inorganic nitrogen (Table 4.5). *Sesbania* with no fertilizers produces the same rice yields as 40:40:30 kg NPK/ha; but if fertilizers are added to rice after the *Sesbania* then yields increase to 5.4–5.5 t/ha, levels that can be achieved only if 120

Table 4.4 The impacts of green manuring of legumes on cereal yields

Country	*Green manure*	*Cereal*	*Impact on yields (as % of conventional)*	*New yields (kg/ha)*
Rwanda[1]	*Tephrosia vogelii*	Maize	400%	2800
NE Thailand[2]	*Vigna* spp (Cowpea)	Rice	105–120%	2875
Honduras[3]	*Mucuna pruriens* (velvetbean)	Maize	295%	2500
Brazil[4]	*Mucuna aterrima*	Maize	nd	6800
	Crotolaria striata	Maize		5800
	Zornia latifolis	Maize		
Bhutan[5]	*Lupine mutubilis*	Potato	133%	21500
	Sesbania aculeata	Rice	131%	4560
Vietnam[6]	*Tephrosia candida*	Rice	136%	2160
	Stylosanthes spp	Rice	145%	2000
	Vigna spp	Rice	145%	2100
Nepal (mid-hill region)[7]	*Sesbania cannabeana*	Rice	116%	5845
	S rostrata	Rice	118%	6030
	Vigna radiata	Rice	145%	6600
Nepal (terai region)[7]	*Sesbania cannabeana*	Rice	194%	3340
	S rostrata	Rice	218%	3690
	Vigna radiata	Rice	200%	3380
Brazil (Santa Catarina)[8]	*Mucuna pruriens* (velvetbean)	Maize	nd	3000–5000
	Canavalia ensiformis (jackbean)	Maize		3000–5000
	Dolichos lablab (lablab)	Maize		3000–5000
	Vigna spp	Maize		3000–5000
	Melilotus albus (sweet clover)	Maize		3000–5000

nd = no data

Sources: 1 Kotschi et al, 1989; 2 Craig and Pisone, 1988; 3 Bunch, 1990; Flores, 1991; 4 Lathwell, 1990; 5 Norbu, 1991; 6 Thai and Loan (1991); 7 Joshy, 1991; 8 Bunch, 1993

kg N/ha are added. Use of *Sesbania* as a green manure can save the use of between 40–120 kg N/ha (Norbu, 1991). The key lesson would appear to be that green manures increase crop yields significantly by providing nitrogen. But if farmers are able to get hold of small amounts of inorganic nitrogen, then they will benefit still further.

There are 19 million hectares of upland rice worldwide and average yields are only about 1 tonne/ha. Yet if cowpea or lablab are intercropped with rice, and then allowed to continue growing through the dry season, the biomass can be incorporated as a green manure before the next rice crop (Aggarwal and Garrity, 1987). Rice yields increase to 1.4–1.9 t/ha as a result and there is the added bonus of the legume grain yield of 0.5–1 t/ha.

Table 4.5 Impact of the green manure *Sesbania aculeata* on rice yields in Bhutan

Presence or absence of Sesbania green manure	*Presence or absence of NPK fertilizer (kg/ha)*	*Rice yields (t/ha)*
Zero	Zero	3.5
Green manure	Zero	4.6
Zero	40:40:30 of NPK	4.7
Green manure	40:40:30 of NPK	5.6
Zero	120:40:30 of NPK	5.4

Source: Norbu, 1991

Recent research in semi-arid India has shown that some legumes, such as chickpea and pigeonpea, have a unique mechanism that allows them to access phosphate in phosphate-poor soils (Johansen, 1993). They release acids from their roots, which react with calcium-bound and iron-bound phosphate to release phosphate for plant uptake. As their deep rooting also helps water infiltration, they have a positive residual affect on subsequent crops, as both phosphate and water availability are increased.

Azolla and *Anabaena*

Blue-green algae are another important source of nitrogen, the most widely exploited being the alga *Anabaena azollae*. This fixes atmospheric nitrogen while living in cavities in the leaves of a small fern, *Azolla*, that grows on the water of rice fields in both tropical and temperate regions. *Azolla* quickly covers the water surface in the ricefield, but does not interfere with the normal cultivation of the rice crop.

Very high nitrogen production is possible following *Azolla* inoculation in rice fields. In the Philippines, 57 tonnes of freshweight *Azolla* can be harvested after 100 days yielding more than 120 kg/ha of nitrogen (Watanabe et al, 1977; Kolhe and Mitra, 1987). Over the whole year, *Azolla* can fix more than 400 kg N/ha, a rate in excess of most tropical and subtropical legumes. This nitrogen is only available to the rice crop after *Azolla* has decomposed and so exploitation consists of incorporating the ferns into the soil while wet as a green manure or removing them for drying and then reapplying them to the ricefields.

The results of at least 1500 studies in China, Philippines, Vietnam, India, Thailand and USA have shown that when *Azolla* is grown in paddy fields, rice yields increase by on average 700 kg/ha, with a range of 400 to 1500 kg/ha (Liu and Weng, 1991; San Valentin, 1991; Kikuchi et al, 1984). In India, wheat crops following rice with *Azolla* have also been shown to produce improved yields (Kolhe and Mitra, 1987). Like most resource-conserving technologies, the incorporation of *Azolla* is labour and knowledge intensive. The timing of incorporation is also critical, since a sufficient period has to elapse for the green manure to decompose.

For most farmers, *Azolla* offers the opportunity of substituting for inorganic fertilizers. The incorporation of *Azolla* as a green manure in parts of Brazil has permitted for a 30–50 per cent reduction in the use of nitrogen fertilizers (Kopke, 1984). In the Philippines, recent studies have shown that incorporation of *Azolla* would allow nitrogen applications to be reduced by at least half (San Valentin, 1991). *Azolla* with 30:30:20 kg NPK fertilizer per hectare yields 34 per cent better than rice with the same NPK and no *Azolla*, producing yields of some 5.9 t/ha. This is 74 per cent better than rice with neither (3.4 t/ha). Some studies have, however, shown an important transitional period during which yields in the two years after *Azolla* drop from 4.95 to 3.6 and then to 3.8 t/ha (Castillo, 1992). The decreased variable costs did not offset this fall, but by the third year yields had recovered and net returns were higher.

Although the benefits of *Azolla* would appear obvious, many farmers are not using it. The National Azolla Action Programme was established in the Philippines to reduce the burden of high costs to farmers. A programme of working closely with farmers has established that *Azolla* combined with 30 kg/ha of nitrogen will sustain current yields, saving the country some US$23 million each year in foreign exchange (Box 4.2).

Box 4.2 The National Azolla Action Programme, Philippines

The National Azolla Action Programme was established in 1982 to reduce the burden of high costs to farmers in the Philippines. The objective was to replace half of the fertilizer nitrogen requirement for rice production with internal resources. The programme aims to cover 300,000 ha of irrigated lowland rice areas. The process has been as follows:

- establishment of a National Inoculum Center (NIC), with a network of regional sub-centres in agricultural universities and colleges, which screen and test local *Azolla* varieties;
- establishment of propagation centres to provide materials to municipalities and villages;
- preparation of information and materials on the culture and utilization of *Azolla* for extension workers and farmers;
- conduct of training, demonstrations and on-farm trials.

At the end of extensive on-farm trials, the results indicated that *Azolla* plus a small amount of nitrogen fertilizer (30 kg/ha) would give equivalent grain yields. The NAAP has estimated that if *Azolla* substitutes for half of the nitrogen requirement for rice in this way, this would generate annual savings of at least US$23 million.

Source: San Valentin, 1991

Agroforestry

There is a huge diversity of agroforestry systems throughout the world, in which the bushes and trees have many benefits. Those with nitrogen-fixing capacity have beneficial effects on plants growing with or after them. Some of this is a result of the fixed nitrogen, but significant quantities can also be supplied in the leaf litter or from deliberate pruning. Trees also improve the microclimate by acting as windbreaks, by improving the water-holding capacity of the soil and by acting as shade trees for livestock – so focusing the deposition of manure (Young, 1989). In the Majjia Valley, Niger, windbreaks of neem trees help to conserve moisture and soil, raising the yields of cereals grown between by some 20 per cent (Kerkhof, 1990).

On the southern coast of China, there are some 140,000 ha of coastal fields protected by windbreaks and shelter belts (Luo and Han, 1990; Zhaohua, 1988; Beckjord, 1991). The trees are species of mainly *Casuarina, Metasequoia, Leucaena, Acacia, Paulownia* and various bamboos. These protect crops from typhoon damage in the rainy season and cold spells in early spring and late autumn. As a result, wheat and rice yields can be 10–25 per cent higher than in unprotected zones. *Paulownia* is successfully intercropped with cotton, maize, beans, groundnut, sweet potato, rape, garlic, watermelon and vegetables. *Paulownia* is well suited to agroforestry systems, as its deep tap root does not compete with shallow rooted crops for nutrients and water. A tree can grow 2.5 m in one year, reaching 10–20 m after ten years, when it can supply 400 kg of young branches and 30 kg of leaves for fodder or soil amendment.

Woody shrubs and trees planted on the contour can protect the soil and provide fodder, fuelwood and timber. It has long been the practice in the countries of the Mediterranean to plant rows of trees such as olives between rows of cereals or vines. Most recently in tropical countries there has been a considerable research on alley cropping, in which trees of various kinds are planted in contour rows with, usually, subsistence crops in between. Often the trees are fast-growing legumes, which fix nitrogen into the soil. They also provide fodder for animals, green manures and fuelwood. However, much of this research has been conducted on research stations, where the constraints experienced by farmers are not replicated. As a result, very few alley cropping systems have been adopted as designed and many projects have failed because of the desire to stick to the rigid technical model (see Chapter 2).

The sloping agricultural and technology (SALT) model is one such alley cropping technology being promoted on Mindinao Island in the Philippines (Palmer, 1992; Tacio, 1991, 1992). Over the past 20 years, it has been developed on demonstration farms as a highly productive and potentially sustainable system. Contour hedgerows of *Leucaena* are mixed with maize, which yields three to four times as much as non-SALT farms and net returns are better. However, farmers have not as yet been willing to adopt the package and there is little evidence of widespread farmer interest (Garrity et al, 1993). Some farmers have, however, taken components and adapted them into their own systems (Palmer, 1992).

Many agroforestry systems also combine livestock, so increasing the number of internal linkages. Rubber monocrops can be transformed with the introduction of animals (Nair, 1989). Although intercrops are cultivated in immature rubber plantations, when the canopy closes only weeds survive. These are costly to control. In Malaysia, sheep rearing in rubber plantations can keep down weeds as well as give added returns from the sheep. Bees and chickens are other animals that will also survive in plantations.

SOIL CONSERVATION

Conservation Tillage

The way in which the soil is tilled can have a significant influence on how well soil, nutrients and water are retained. In conventional tillage, the topsoil is inverted and mixed by means of a mouldboard plough or disc, or a handtool such as a hoe. This incorporates most of the crop residues or stubble and the nutrients they contain. However, there is a lag period from the time the seed is sown to when there is sufficient vegetative cover to prevent soil erosion by wind or water. An alternative approach is to use conservation tillage in which the soil surface is disturbed as little as possible. Significant amounts of residue then remain on the soil surface, so helping to reduce runoff, sediment loss and loss of nutrients. The seed is directly drilled through the layer of residues. In no-till farming soil preparation and planting are done in one operation; in reduced-till farming there is limited preparation with disc or chisel plough.

These conservation tillage systems are widely promoted by the Soil Conservation Service in the USA. Between 1980 and 1993, the area devoted to conservation tillage grew from 16 to 40 million ha and so now covers some 35 per cent of all harvested land (AAN, 1993b). The main focus is on reduced tillage with chisel ploughing, using crop residues to provide a mulch cover. In practice this reduces soil erosion by up to 50 per cent. Other conservation tillage practices, such as no tillage, strip tillage and ridge tillage systems, reduce erosion by 75 per cent or more, but are less widely adopted. By 1992, no-till farming covered 11 million ha. The fastest growth was in Iowa, where some 1 million ha are under no-till systems. One problem with no-till, however, is that many farmers have to use more herbicides as weeds are no longer controlled by ploughing operations (NRC, 1989).

Contour Farming

Another approach for conserving soil nutrients is to resort to physical structures, such as terraces or bunds, of varying scale. These are common to many indigenous agricultural systems throughout the world (see Reij, 1991; Kerr and Sanghi, 1992; Kassogue et al, 1990). Most of these are designed to check the surface flow of water, and thus perform the dual role of water harvesting and retention. The simplest approach is to construct earth banks across the slope to act as a barrier to runoff. These are suitable on shallow slopes and are frequently used in conjunction with contour planting. Sometimes the earth bunds are reinforced with vegetation such as crop stalks, or planted with grass or trees, to create greater stability. As such vegetative bunds are partly permeable, crops planted in front of the bund also benefit from water runoff. These are not quickly damaged by runoff, and thus maintenance costs are low.

Simple walls may also be constructed along the bunds and these are quickly strengthened by natural processes. Elsewhere, rocks may be most appropriate substances for the construction of contour bunds or walls. After the first heavy rains, fine soil, branches and leaves begin to fill in the walls, making them more impermeable.

More costly to construct are various forms of terrace. Diversion and retention terraces are appropriate for shallow slopes and bench terraces are effective on steeper ones, but not on thin soils where the parent rock is close to the surface. All can raise crop yields by some 30–50 per cent over those on non-terraced slopes. But construction costs for bench terraces are usually very high. Many soil conservation projects have expended huge sums on food for work during the course of terracing (see Chapters 2 and 3).

Rather than construct physical structures that generally require a large labour input, a lower input alternative is to plant crops along contours. As water flows across the surface so it meets with rows of plants growing perpendicular to the flow, which slows it down and improves infiltration. In strip cropping the main row crop is grown along the contour in wide strips alternating with strips of protective crop, such as grass or a legume. If the protective strips are of grass they can be effective at filtering out particulate matter and nutrients from surface flow of water. Contour grass strips not only reduce loss of soil but help in the process of establishing terraces.

There is widespread evidence for improved crop yields and reduced erosion following terracing of fields in many countries (Pretty and Shah, 1994; Tato and Hurni, 1992; Reij, 1991). In Ethiopia, for example, one study of the impact of the *fanya juu* terrace (which involves throwing soil uphill to make a bund) found improved yields over non-terraced fields of some 30–40 per cent (Michael, 1992). The variability of yield on the terraced fields was also lower. In neighbouring Kenya, *fanya juu* terracing has improved yields of maize and beans by some 50–60 per cent (Pretty et al, 1994; SWCB, 1994; Tjernstrom, 1992; Figueiredo, 1986; Grönvall, 1987; Hunegnaw, 1987).

But much of this evidence is small scale and localized. As we discuss in Chapter 5, for the full benefits of conservation to accrue to farmers, it is necessary to consider the impacts at a wider, community scale. It is, however, increasingly being well established that whole communities are capable of adopting and adapting soil conservation practices and principles. A recent comprehensive study of Machakos District in Kenya has shown that even though there has been a three-fold increase in population since 1945, net imports of maize to the district have fallen from 17.4 to 7.6 kg per capita (Tiffen et al, 1993). More conservation has led to increases in agricultural yields and the diversity of crops grown. Land that was severely degraded in colonial times is now intensively and sustainably managed.

Other studies are illustrating that the Ministry of Agriculture's catchment approach to soil conservation in Kenya is leading to substantial local improvements (see Case 12, Chapter 7). Where there is mobilization of the community, support to local groups and committed local staff, there is also increased agricultural productivity, diversification into new enterprises, reduction in resource degradation and independent replication to neighbouring communities.

For further details of similar community-led soil conservation initiatives in Burkina Faso, India, Lesotho, Mali and the Philippines, see Chapter 7 (Cases 2, 3, 6–10, 14, 15 and 19).

Mulches and Cover Crops

Soil, water and nutrient conservation is also improved with the use of mulches or cover crops. Organic or inorganic material is spread on the soil surface to provide a protective physical cover, the mulch, for the topsoil. Mulches protect the soil from erosion, desiccation and excessive heating, thus promoting good conditions for the decomposition and mineralization of organic matter. Mulches can also help to reduce the spread of soil-borne diseases, as they reduce the splashing of lower leaves with soil during rainfall. The cheapest approach is to use plant residues from previous crops, from nearby perennials or from wild areas, such as reeds from swamps. But equally as useful as organic materials are non-degradable mulches like plastic film. Black plastic, for example, excludes light and thus prevents weed growth. Other types of non-crop mulches include newspaper, cardboard, sawdust, woodchips, leafmould and forest bark.

No-till and reduced tillage systems both result in good cover with residues, reinforcing the conservation value of an undisturbed soil. In Guesselbodi, Niger, mulching with twigs and branches permits cultivation on hitherto abandoned soils, producing some 450 kg cereals per hectare. In drought years, the yields on mulched soils are some five times better than on non-mulched (OTA, 1988; Heermans, 1988). In China, wheat or rice straw mulches can increase tea, fruit and legume yields by 6–16 per cent, as well as reduce splash erosion (Jin, 1991). And in the hot savannah region of northern Ghana, straw mulches minimize erosion as well as increase yields. Combined with livestock manures, these mulches produce double the maize and sorghum yields than the equivalent amount of nitrogen added as inorganic fertilizer (Bonsu, 1983). Many farming communities use or have used wild plants for mulches and green manuring, such as in Nepal (Tamang, 1993), India (Poffenberger, 1990), Britain (Pretty, 1990b), Canada (Omohundro, 1985) and Guatemala (Wilken, 1987). In Guatemala, farmers of Quetzaltenango collect from the mixed pine-oak forests up to 20–30 tonnes of leaf litter for each hectare of cropland. This is incorporated into the soil to improve moisture retention and soil tilth.

Cover crops consist of vegetation that is deliberately established after or intercropped with a main crop, not necessarily with a view to harvest but more to serve various regenerative and conserving functions. The best example of the effectiveness of cover crops comes from the work of EPAGRI in the State of Santa Catarina in Brazil (see Case 1, Chapter 7). EPAGRI are working intensively with some 60 species of cover crops, which are intercropped with subsistence crops or planted during fallow periods, mostly in the winter months. These plants act as both a green manure and mulch: some fix nitrogen, and all are cut and left on the soil surface. Several thousand farmers have now benefited from these green manure/mulch/cover crops. What they are showing is that providing ground cover is more important than constructing physical structures to prevent erosion.

Silt Traps and Gully Fields

Silt traps and gully fields are one particularly effective soil and water conservation measure used widely by farmers. Stones are placed across gullies or valleys, so as to capture nutrients, silt and moisture. Stones are often bedded into the upper surface of spillway aprons and walls to provide support for the next layer. The principle is to capture runoff from a broad catchment area and concentrate it in a reduced area, so transforming meagre rainfall into utilizable soil moisture. As water slows, any suspended debris is deposited, helping to form organic-rich soils. These gully or deposition fields have been recorded in India (Chambers, 1991; Shah et al, 1991); Pakistan (personal observation in Punjab and north-west frontier provinces); Ethiopia (ERCS/IIED, 1988); Mexico, known as *atajadizos, trincheras* and *trancas* (Johnson, 1979; Blackler, 1994); Nepal (Tamang, 1993); and Burkina Faso (Reij, 1988).

A well maintained silt trap creates a flat, fertile and moist field with a micro-environment quite unlike the surrounding area (UNEP, 1983; Chambers, 1991). Crops can thus be grown which may be of higher value than field crops on nearby drylands, such as rice in India, wheat and rapeseed in Pakistan, sorghum and rice in Burkina Faso, and chat and coffee in Ethiopia. Agriculture in these gully fields is often more productive and dependable. In Mexico, they permit earlier planting and in Gujarat they are the most stable component of a household's food supply (Griffin and Dennis, 1969; Shah et al, 1991). In Burkina Faso, sorghum yields can range between 970–2670 kg/ha, and in some fields rice can be grown (Reij, 1988). Farmers additionally benefit from these traps as groundwater levels are raised and damage to crops on the downstream side is reduced (Johnson, 1979; Reij et al, 1988).

In Gujarat, India, farmers have been plugging nullahs with earth embankments and stone pitching for at least 20 years. These are labour intensive for construction, but require relatively little maintenance. The yields of paddy in these fields are higher than in irrigated fields, and farmers are also able to take a residual crop after the rice and raise mango trees on the embankment. These structures are still not part of any official watershed management programme in the area (Shah et al, 1991).

Check dams are intrinsically incremental systems, in which farmers add to the height of their structures year by year. They do this to keep the wall above the level of the accumulating alluvium. Gene Wilken (1987) reports the narrative account of an Otomí farmer of Hidalgo, Mexico: '*An* *atajadizo isn't built all at once. Usually a farmer starts with a low wall across the path of an arroyo (gully). It takes a few years until the water has brought down enough debris and soil to level with the top of the wall. Then, the farmer will build up the wall a bit more, and so on, little by little until s(he) has built up a tall strong wall and a large level field. A well-made atajadizo is level so that the trapped water will cover all parts of the field evenly. It may be necessary to level the field by hand and, also, to tear down parts of the gully in order to enlarge the field. A well-made atajadizo always has a wall that is higher than the field behind it. This is necessary because water must be trapped so that it can soak into the field. But if the field is at the same level as the wall, the water will just flow over it and waste. There is no need to fertilize an atajadizo because every rainy season the water brings down new debris and soil'.*

It should not be surprising that these fields have been overlooked by professionals. Most soil conservation programmes focus on a restricted number of technologies, ignoring the diversity that already exists. In Niger, traditional stone lines in the Ader Doutchi Maggia can be observed by anyone driving on the main road from Konni to Tahoua (Reij, 1991). Despite the presence of conservation projects in the region since the early 1960s and visits by many soil conservation experts, no reports contain reference to these stone lines. In both Niger and Burkina Faso, farmers prefer stone lines and bunds, yet all major projects have constructed only earth bunds, which have of course not been maintained by local 'beneficiaries' (Reij, 1991). In India, John Kerr and N K Sanghi (1992) reflected on their own survey of soil conservation practices *'the fields which were neglected badly could be spotted easily from a distance (even while driving on the road). The indigenous technology (where soil and water conservation was successful) could not be appreciated until the specific fields were visited individually'.*

WATER MANAGEMENT SYSTEMS

Water Conservation and Harvesting

Where rainfall is unreliable and inadequate, water shortages often severely limit crop production. Water conservation and harvesting can carry crops over an otherwise disastrous dry period, can stabilize and increase production, and can even make agricultural production possible for the first time. Water harvesting systems commonly include a runoff-producing and a runoff-using area. Water harvesting systems can be found in many parts of the world, including the Middle East, south Asia, China, North America and sub-Saharan Africa (UNEP, 1983; Reij et al, 1988; Reij, 1991).

Water harvesting systems from short slopes are simple and cheap, and have a relatively high efficiency, because water is not transported over long distances. One very old system of micro-catchment use is *meskat* in Tunisia, where fruit trees, mainly olive, are fed by runoff from upper slopes in a 200–400 mm rainfall area. The *zai* system in Burkina Faso is another example. *Zai* involves the digging of small pits, local application of manure and the construction of stone bunds to catch runoff. The concentration of both water and nutrients have made *zai* a popular method to rehabilitate degraded land. Yields in the Yatenga region can be 1000 kg or more per ha, in areas where average yields are only 400–500 kg/ha (see Case 2, Chapter 7). In Kenya, semi-circular earth bunds with stone spillways collect water and increase sorghum yields from virtually nothing to some 2000 kg/ha (UoN/SIDA, 1989).

For water harvesting from long slopes, semi-permeable stone contour lines and bunds are necessary. Water runoff is slowed down, rather than concentrated and so has more time to infiltrate below the stones. Half-moon shaped bunds are used to concentrate water, almost always for forest or fodder trees. In the Tarija Basin of Bolivia, *media lunas* dug on the contours of very degraded hills are planted with trees for fodder and fuel, and legumes on the earth ridge (Bastian and Gräfe, 1989). The ground is rapidly colonized by wild grasses, and as a result soil erosion is halted, infiltration increased, and the vegetation period prolonged into the dry season.

Floodwater harvesting in the streambed, whether a valley bottom or floodplain, blocks the water which flows intermittently and often in flash floods. In North Africa and the Middle East, *wadi* floors are blocked, and fill with water from the adjacent slopes and the main water course. Many local variations of this basic principle have been documented, including from Mexico, India, Pakistan and Burkina Faso. In Burkina Faso on the Central Plateau, gully formation in the valley bottom results in concentration of runoff rather than the preferable even spread over the floodplain. Low semi-permeable dams of loose rock are constructed in the gullies to slow the water flow and push the water out of the gullies on to the floodplain. Soil is also conserved in the process, with rapid formation of terraces between the dams. Sorghum yields are 200–300 per cent higher on fields connected to the dams than unimproved fields (Scoones, 1991; Reij et al, 1988; Critchley, 1991).

Water harvesting systems do not only use water locally but can manipulate the direction of water flows to reach areas suitable for crop, tree or pasture production. By running into and around a series of obstacles water is forced to spread to parts that would otherwise not benefit from runoff. In China, such warping systems combine water manipulation with increased nutrient efficiency. Storm and floodwater is diverted at moments when nutrient and organic matter content of the water is high, so making use of water resources more efficiently and decreasing soil erosion. One warping area is the Zhaolao Gully, in Shanxi Province, over 2300 years old and feeding water to 2260 hectares. Soil moisture of warped farmland is 10 per cent higher compared to unwarped land, increasing to almost 80 per cent during dry periods. Both organic matter and nitrogen content of the soil increases, with obvious benefits for agricultural production. Warping increases the yields of maize, millet and wheat by some two to four fold over unwarped land (UNEP, 1983). Warping was also common in seventeenth- and eighteenth-century Britain, in some areas being the principal technology on which diversified and productive agriculture was based (Pretty, 1991).

Despite the apparent benefits of water harvesting systems, they are not widely used. One constraint may lie in labour requirements for both initial investment and maintenance. Where stones are transported over long distances or soil movement high on steep slopes, labour inputs rise greatly. Usually investments in water harvesting systems are high in the first year, after which labour inputs can drop by almost half. However, if there is no maintenance of structures as is likely to occur if farmers are forced to adopt the measures (see Chapters 2 and 3), the yields quickly fall. Many water harvesting systems require collective action on a large area for them to be effective. Financial costs of water harvesting can range between US$100/ha with simple, low-cost techniques and US$1000/ha with sophisticated systems.

The main question as to whether the investment in water harvesting systems will be worthwhile is determined by soil fertility. Where nutrient levels greatly limit agricultural production, an increase in water availability will have only temporary impact. Yield increases will be a passing phenomenon, and where water was once the main limiting factor, soil fertility takes over. The key lies in combining water harvesting with integrated nutrient management. By slowing water flows, water harvesting effectively controls soil erosion, and nutrients and water are harvested and conserved. In Burkina Faso, for example, the effect of *digue filtrantes* (permeable rock dams) on the quick decomposition of deposited organic matter has been signalled by farmers as of particular importance, reducing the need for manure application (Reij et al, 1988).

When the supply of water becomes more regular, then water harvesting becomes small-scale irrigation. Although this is not the place to discuss adequately the aspects of irrigation, it is none the less important to note the importance of irrigation relying on relatively local sources of water (Guijt and Thompson, 1994).

Land Drainage for Saline and Waterlogged Soils

Overuse of water in agriculture has led directly to the rapid increase in recent years of land lost to waterlogging and salinity. Although precise data are hard to come by, it is thought that something of the order of 1.5 million ha are lost annually (WCED,1987). Curing saline and waterlogged soils requires lowering the water table below the root zone of crops, followed by leaching to remove the excess salts. These salts then have to be removed from the soil by sub-surface drainage systems. The drainage technologies have been widely proven, but the implementation is far more difficult. Collective action is essential, as drainage technology is indivisble and cannot be implemented in parts (see Chapter 5).

In India, where the area of saline and waterlogged soils is 5–13 million ha, drainage technology costs some US$325–500 per ha. Returns, though, make this investment worthwhile, as immediate improvements occur in the form of increased cropping intensity, changed cropping patterns, higher yields and lower costs (Datta and Joshi, 1993; Datta and de Jong, 1991). But as Datta and Joshi make clear, technology alone is insufficient. Participation by local people is essential for long-term success: *'planning and executing the drainage systems to manage saline and waterlogged soils by government agencies may not yield the desired results unless there is a positive attitude and strong will of the beneficiaries to participate in the programme'* (Datta and Joshi, 1993).

The problem is that most state action has been to suppress this very action needed at local level. Just as in rehabilitation of irrigation systems, it is the attention to participation and local institutional strengthening or building that is critical (Uphoff, 1992a).

Raised Beds and Chinampas

Where there is too much water, raised beds are technologies that make effective use of available resources. The basic principle is that crops are cultivated on raised fields, which are surrounded by water channels. The channels are used for transport, provide additional food in the form of frogs, fish and ducks, and are a source of aquatic plants for composts and green manures. Nutrients are cycled between the two systems. Such raised beds are traditional in China, known as high-bed, low-ditch systems; in Mexico, known as chinampas; in Kashmir, known as 'floating gardens'; and in the high Andes of Peru, known as *waru-waru*.

In Mexico, chinampas have been under continuous cultivation for at least two and perhaps three thousand years (Gómez-Pompa and Jimenez-Orsonio, 1989; Gleissman, 1990; Wilken, 1987; Gómez-Pompa et al, 1982). A wide variety of crops are grown, the most common being maize, beans, chili, amaranth and squash. Willow and alder trees grow on the margins of the fields to provide shade, windbreaks and organic matter. They also are a good habitat for birds, as well as helping to protect crops from heavy frosts and rains. The canals acquire deposits of eroded soils, decomposed plants, and wastes from villages and farmhouses, and runoff from fields. Much of this is returned as farmers dredge the muck from the canals and replace it on the fields. Even though no external inputs are used, crop yields are high.

In the Lake Titicaca basin in Peru, *waru-waru* were used widely by the pre-hispanic farmers to cope with poor soils and frequent frosts, but had fallen into disuse. Efforts have been made in recent years to redevelop this ancient technology, leading to improved agricultural production in as many as 30 altoplano communities (see Case 17, Chapter 7)

In the Pearl River delta of China, much of the land is close to or below sea level. Farmers raise soil from ditches to form beds of width 1–10 m depending on the type of crops. Narrow beds are used for sugar cane and vegetables, while systems for longer duration crops, such as banana, citrus and lychees have wider beds and ditches. In the ditches rice, fish and edible snails are cultivated, and mud is excavated to put on the beds. These high-bed low-ditch systems have helped to lower water tables, reduce soil erosion and nutrient loss, preserve organic matter in ditches and increase the internal cycling of nutrients (Luo and Lin, 1991; Zhu and Luo, 1992).

Fish Production in Irrigation Water

One of the best examples of integrated farming is when fish production is combined with rice cultivation. For at least 2000 years, farmers of South and South-East Asia have combined rice–fish culture. With the advent of the Green Revolution technologies, however, many systems have been abandoned because of the toxicity to fish of the pesticides used.

The basic principle is that fish live in the water of the paddy fields, retreating to specially constructed refuges or ponds during the dry season. The fish are beneficial because they eat weeds, algae and insect pests, and help to keep disease carriers in check. Their manures help to fertilize the rice crops. When *Azolla* is present, they eat *Azolla*, converting it into forms of nitrogen readily available to the rice. Not only are the fish a source of protein for farming families, but rice yields are usually improved too. In recent years, there have been coordinated efforts to increase rice–fish culture in the Philippines (Bimbao et al, 1992; de la Cruz et al, 1992); in Thailand (Jonjuabsong and Hawi-Khen, 1991; Boonkerd et al, 1991); Bangladesh (Kamp et al, 1993); Indonesia (Fagi, 1993); and Taiwan (Chen and Yenpin, 1986).

Although rice–fish culture in Thailand was first important in the central region, this fell away with the advent of the Green Revolution technologies. Recent spread has been in the rainfed regions of the north-east, where a wide range of government agencies and NGOs are working with farmers to improve fish yields. Fish farming can be technically difficult to get right. Bunds must be raised around fields to keep the fish in and predators out. A nursery pond has to be constructed to hold the fry until they reach fingerling size and a refuge has to be dug for the dry season. There then needs to be careful choice of fish, and control of stocking rates and supplementary feeding. In addition, farmers themselves have to reduce or eliminate pesticide use, and ensure they are not affected by neighbours.

In Bangladesh, a recent programme coordinated by CARE combines rice–integrated pest management with fish culture (Kamp et al, 1993). It is demonstrating that farmers can eliminate pesticides entirely, improve rice yields and get a harvest of carp (Table 4.6). Farmers in the programme monitor their insect populations on a regular basis and they soon see that their fields are not more infested with pests than their neighbours who have sprayed with pesticides. Reduced pesticide use could have further beneficial impacts, on human health and on duck and wild fish populations.

In the Philippines, the government rice–fish culture programme was launched in 1979, but was hampered by the modern varieties' need for heavy use of fertilizers and pesticides (Bimbao et al, 1992; de la Cruz et al, 1992). Since then, the area of rice–fish has slowly increased, as the shift from rice monoculture to rice–fish culture increases net returns by up to 40 per cent. Rice production also improves, by some 4 per cent, and farmers also benefit from vegetables grown on the banks of the raised bunds. Some 200–300 kg fish per ha are also harvested. However, there are technological constraints, such as pesticide applications, and availability of fingerlings and water that are holding back spread. In addition, most farmers are now accustomed to rice monoculture, and a shift to rice–fish means at first more work and higher costs.

Sometimes these rice–fish systems are developed into more complex polyculture farms. In Taiwan, pigs and ducks are also common elements of farms, with tilapia the most common fish (Chen and Yenpin, 1986; Lightfoot and Noble, 1992).

Table 4.6 The impact of combinations of IPM training and fish culture on rice farming in Bangladesh

Farmer trained in:	*Change in pesticide use (as % of normal practice)*	*Rice yields (as % of normal practice)*	*Food and income from fish*
Normal practice	100%	100%	No
IPM only	24%	110%	No
Rice–fish	0%	117%	Yes
IPM and rice–fish	0%	124%	Yes

Source: Kamp et al, 1993

SUMMARY

There are many proven and promising resource-conserving technologies that can be integrated to produce a more sustainable agriculture. These technologies do two important things: they conserve existing on-farm resources, such as nutrients, predators, water or soil; and/or they introduce new elements into the farming system that add more of these resources, such as nitrogen-fixing crops, water harvesting structures or new predators, and so substitute for some or all external resources.

Many of the individual technologies are also multifunctional, implying that their adoption will mean favourable changes in several components of farming systems at the same time. But their adoption by farmers is not a costless process. Farmers cannot simply cut their existing use of external inputs and hope to maintain or even improve outputs. They need to substitute labour, management skills and knowledge in return. Farmers must, therefore, invest in learning. As recent and current policies have tended to promote specialized systems, so farmers will have to spend time learning about a greater diversity of practices and technological options. Lack of information and management skills is a major barrier to the adoption of resource-conserving agriculture.

IPM is the combined use of a range of pest control strategies in a way that not only reduces pest populations to satisfactory levels but is sustainable and non-polluting. It is a more complex process than relying on spraying of pesticides, and makes use of resistant varieties and breeds, alternative 'natural' pesticides, bacterial and viral products, and pheromones for reducing the impact of pests. Predators and parasites are encouraged by direct releases, improving their physical habitat, increasing farm diversity, and adopting rotations and multiple cropping.

Integrated plant nutrition involves a combination of a more efficient use of fertilizers with the adoption of alternative sources of nutrients, such as livestock manures, composts, legumes, green manures, *Azolla* and agroforestry. Soil conservation can be enhanced through the use of conservation tillage, contour farming and physical structures, mulches and cover crops, and silt traps and gully fields. Many of these technologies, in one form or another, have been in existence in traditional agricultural systems for centuries. There are a range of water management systems that ensure the efficient use of available water. Water conservation and harvesting can improve agricultural yields in dry areas. Where too much water has been used, leading to waterlogging and salinization, then land drainage technologies making use of collective action can be used. Where environments are very wet, then thoroughly integrated systems making use of aquaculture, livestock, trees and crop production, can be remarkably efficient and productive.

For these resource-conserving technologies to be fully effective, however, they need to be adopted by whole groups or communities of farmers or land managers.

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LOCAL GROUPS AND INSTITUTIONS FOR SUSTAINABLE AGRICULTURE

> *'One resurrected rural community would be more convincing and more encouraging than all the government and university programmes of the past 50 years. Renewal of our farm communities could be the beginning of the renewal of our country and ultimately the renewal or urban communities. But to be authentic, a true encouragement and a true beginning, this would have to be a resurrection accomplished mainly by the community itself.'*
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> Wendell Berry, in Enshayan, 1991

COLLECTIVE ACTION AT LOCAL LEVEL

Individual Actions Only Provide Partial Protection

The widespread and growing evidence for the economic and environmental viability of resource-conserving technologies (see Chapter 4) appears to suggest that a more sustainable agriculture is a likely outcome. Once farmers get to hear of the potential benefits, of increased yields or reduced costs, then they will adopt widely and the transition will be under way.

But without attention to local institutions, this is far from likely. Sustainable agriculture cannot succeed without the full participation and collective action of rural people and land managers. This is for two reasons. First, the external costs of resource degradation are often transferred from one farmer to another, and second, the attempts of one farmer alone to conserve scarce resources may be threatened if they are situated in a landscape of resource-degrading farms.

This need for coordinated resource management applies to most aspects of resource conservation, including pest and predator management; nutrient management; controlling the contamination of aquifers and surface water courses; maintaining landscape value; and conserving soil and water resources. There are many examples of individual initiatives