CHAPTER 11

Selected issues in agricultural technology

This chapter discusses selected issues in agricultural technology. First, it continues the evaluation started in Chapter 4 (Section 4.5.2) of the room for further yield improvements. It then discusses some technologies that could contribute to making agriculture more sustainable, such as integrated pest and nutrient management, conservation agriculture and organic agriculture. It continues with an assessment of prospects for agricultural biotechnology and concludes with some observations on the future agenda for agricultural research.

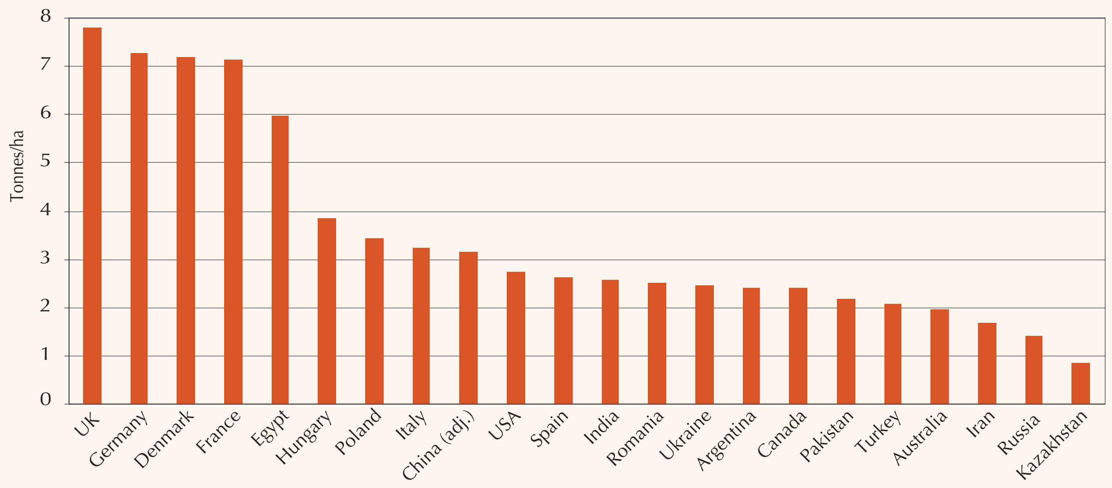
11.1 The scope for yield increases

As discussed in Chapter 4, world agriculture has derived more of its growth from an increased intensive use of land already under crops than from expansion of agricultural areas, even though area expansion has been and still is the main force in a number of countries, mainly in sub-Saharan Africa. Improved farming practices, irrigation, improved varieties, modern inputs, etc. all contributed to the growth of yields that underpinned many of the increases in agricultural production. This trend is expected to continue.

How far can this process go? Intensification and yield growth are subject to limits for reasons of plant physiology (see, for example, Sinclair, 1998) and because of environmental stresses associated with intensification (see Murgai, Ali and Byerlee, 2001 and Chapter 12). Moreover, in many circumstances it is simply uneconomical to attempt to raise yields above a certain percentage of the maximum attainable. In considering the prospects and potentials for further growth in world agriculture, we address below the question: what are the gaps between the actual yields of any given crop in the different countries and those that are agronomically attainable given the countries' specific agro-ecological endowments for that crop? Naturally, what is agronomically attainable changes over time as agricultural research produces higher-yielding varieties and farming practices improve.

As discussed in Chapter 4, intercountry differences in average yields can be very large, but they do not always denote potential for growth in countries with low yields. As an example, Figure 11.1 shows the wheat yields (five-year averages 1996/2000) in the major wheat producers of the world. Yields vary from a high range of 6.0-7.8 tonnes/ha in four EU producers (the United Kingdom, Denmark, Germany and France) plus Egypt; through an upper-middle range of 3.0 to 4.0 tonnes/ha (China, Hungary, Poland and Italy) and a lower-middle range of 2.4-2.7 tonnes/ha of the United States, Spain, India, Romania, Ukraine,

Figure 11.1 Wheat yields (average 1996/2000)



Note: Twenty-two countries with a production of over 4 million tonnes in 1996/2000 accounting for about 90 percent of world wheat output in 1996/2000

Argentina and Canada; down to the low-yield range of 1.0-2.2 tonnes/ha of Pakistan, Turkey, Australia, the Islamic Republic of Iran, Russia and Kazakhstan. Analogous wide yield differentials exist for all crops: those for maize in the major producers are shown in Figure 11.2.

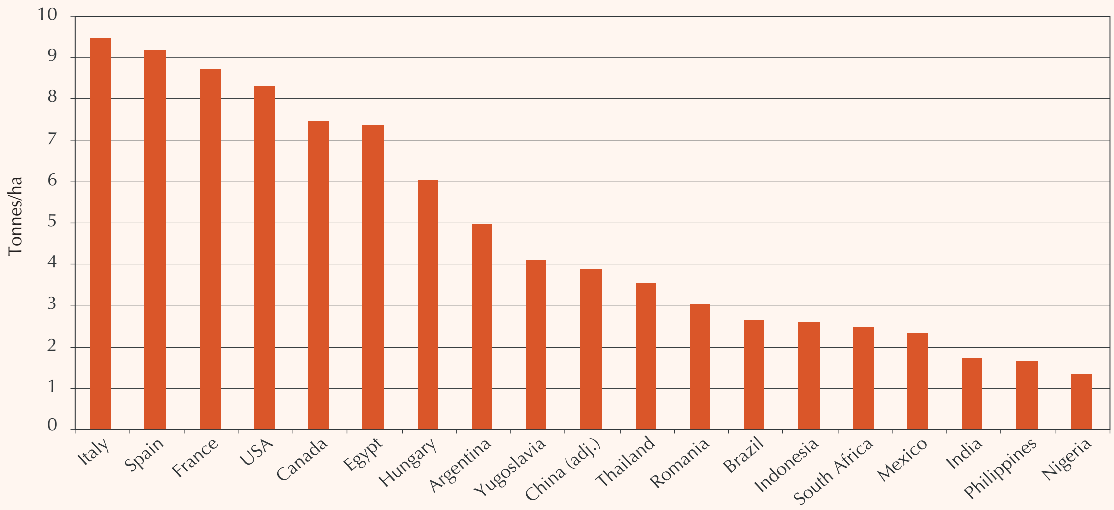
The reasons why country average yields differ from one another are many. Some are agro-ecological, others socio-economic. Irrigation is important in the achievement of high yields in several countries, e.g. Egypt. In addition, agro-ecological and demand factors influence the mix of varieties of the same crop grown in each country, for example, low-yielding durum wheat versus common or soft wheat with higher yields. Given that we are interested in the physical/agronomic potential for yield growth, we need to separate out the part of these inter-country yield gaps that is caused by agro-ecological diversity from the part caused by other factors.

The results of the global agro-ecological zones (GAEZ) analysis (see Chapter 4) provide a way of controlling agro-ecological diversity in such inter-country comparisons. In a nutshell, GAEZ describe at a fairly detailed geographic grid the agro-ecological conditions prevailing in each country. GAEZ also have models defining the agro-ecological requirements for the growth of each crop. Based on this, GAEZ derive estimates for attainable yields for each crop and in each grid cell in the different countries under three technology (input use and management) variants. A summary description of the procedure is given in Box 4.1. More detailed explanations are to be found in Fischer, van Velthuizen and Nachtergaele (2000).

The agro-ecologically attainable yields can be used to draw inferences about the scope for raising yields in countries where actual yields are "low" in relation to what is attainable for their agro-ecologies. Actual yield data in the agricultural statistics are normally available only as country national averages, not by agro-ecological environments. Therefore, for comparison purposes, the estimates of the agro-ecologically attainable yields for any given crop must also be cast in terms of national averages specific to each country's agro-ecological endowments in relation to that crop. Also, since we compare agro-ecologically attainable yields under rainfed conditions, the remainder of this section will focus on countries with predominantly rainfed agriculture to minimize the distortion caused by the unknown contribution of the normally higher irrigated yields.

For each crop, averaging out over the whole country, the yields for each grid cell give an estimate of "attainable" national average yield for that crop. These yields can be compared with actual national average yields to form an idea of the physical/agronomic scope for yield growth compatible with the country's agro-ecological endowments. In principle, countries with similar attainable averages

Figure 11.2 Maize yields (average 1996/2000)



Note: Nineteen countries with a production of over 4 million tonnes in 1996/2000 accounting for about 90 percent of world maize output in 1996/2000

for any given crop and technology level may be considered to be agro-ecologically similar for that crop. Naturally, any two countries can have similar attainable yields but for very different reasons, e.g. in some countries the limiting factors may be temperature and radiation, in others soil and terrain characteristics or moisture availability. Nevertheless, the GAEZ average attainable yields for any crop can be taken as a rough index of agro-ecological similarity of countries for producing that crop under specified conditions.

For example, France and Finland have actual wheat yields of 7.1 tonnes/ha and 3.2 tonnes/ha, respectively (averages 1996/2000). This gap does not indicate that Finland has considerable scope for raising yields towards those achieved in France, because Finland's agro-ecology is much less suitable for growing wheat than France's. The GAEZ evaluation suggests that the agro-ecologically attainable yields in the two countries (i.e. controlling for agro-ecological differences) are 6.6 tonnes/ha and 3.7 tonnes/ha, respectively (rainfed wheat yields under high inputs). By contrast, France and Hungary are very similar as to their agro-ecological environments for wheat growing since both have agro-ecologically attainable yields of around 6.5 tonnes/ha. However, Hungary's actual yield is only 3.9 tonnes/ha, compared with France's 7.1 tonnes/ha. The gap indicates that there is considerable agronomic potential for yield growth in Hungary if a host of other conditions (economic, marketing, etc.) were to become closer to those of France. However, this does not mean that it would be economically efficient for Hungary to emulate France's overall economic and policy environments in relation to wheat, e.g. the high support and protection afforded by the Common Agricultural Policy (CAP).

Table 11.1 shows the agro-ecologically attainable national average wheat yields for more countries and compares them with actual prevailing yields. These countries span a wide range of agro-ecological endowments for wheat production, with some countries having a high proportion of their "wheat land" in the very suitable category (Uruguay) and others having high proportions in the suitable and moderately suitable categories, e.g. Brazil, Paraguay and Sweden. Attainable average yields in these countries range from 7-7.5 tonnes/ha in Germany and Poland, through 5.0-5.8 tonnes/ha in the United States, Uruguay and Sweden and 4.0-4.8 tonnes/ha in Turkey, Russia, Canada, Australia, Argentina and Ethiopia, to 3.0-3.4 tonnes/ha in Paraguay, Brazil and the United Republic of Tanzania.

The divergence between economically efficient and agro-ecologically attainable yields can be very wide. For example, Uruguay and Sweden have nearly equal agro-ecologically attainable yields (5.0-5.3 tonnes/ha, although Uruguay has more land suitable for wheat growing than Sweden) but

Table 11.1 Agro-ecological similarity for rainfed wheat production, selected countries

	Area suitable for rainfed wheat				Yields attainable				Actual	
	Total	% of area by suitability class			Tonnes/ha				Average 1996/2000	
	mln ha	VS	S	M	VS	S	M	Average all classes	Area (mln ha)	Yield (tonnes/ha)
Germany	16.9	42.5	39.2	18.3	9.0	7.1	5.2	7.6	2.7	7.3
Poland	17.6	26.6	51.0	22.5	8.7	7.2	5.1	7.1	2.5	3.4
Japan	6.4	31.0	39.7	29.3	8.9	7.0	5.1	7.1	0.2	3.4
Lithuania	5.5	1.3	72.1	26.7	8.2	7.3	5.3	6.8	0.3	2.8
Belarus	16.5	1.2	64.8	34.0	8.2	7.4	5.4	6.7	0.3	2.5
United Kingdom	11.9	4.0	70.6	25.4	8.4	7.2	4.8	6.7	2.0	7.8
France	24.6	26.0	45.6	28.4	8.4	6.7	4.7	6.6	5.2	7.1
Italy	7.6	31.0	46.9	22.2	8.6	6.2	4.0	6.5	2.4	3.2
Hungary	6.1	11.6	51.5	36.9	8.5	6.8	5.2	6.4	1.1	3.9
Romania	8.4	14.6	50.8	34.5	9.1	6.8	4.5	6.3	2.0	2.5
Latvia	5.4	5.8	64.1	30.1	6.6	6.8	4.9	6.2	0.2	2.5
Ukraine	30.8	15.3	40.5	44.2	8.9	6.9	4.6	6.2	5.9	2.5
United States	230.4	18.8	54.1	27.1	6.5	6.1	4.6	5.8	23.7	2.7
Uruguay	13.8	66.7	28.8	4.5	5.8	4.5	3.2	5.3	0.2	2.3
Sweden	4.3	0.0	54.8	45.2	0.0	5.7	4.2	5.0	0.4	6.0
Turkey	7.6	8.2	31.3	60.4	5.7	5.9	4.0	4.8	9.1	2.1
Russia	167.4	7.5	36.5	56.0	6.2	5.5	3.5	4.4	24.8	1.4
Canada	42.2	10.7	35.0	54.3	6.3	5.6	3.1	4.3	10.9	2.4
Australia	24.3	17.5	38.0	44.5	6.2	4.5	3.2	4.2	11.1	2.0
Argentina	61.1	22.7	45.5	31.8	5.3	4.3	3.1	4.2	6.0	2.4
Ethiopia	10.5	26.3	43.0	30.7	5.1	4.1	3.0	4.0	0.9	1.2
Paraguay	6.9	0.0	39.8	60.3	0.0	4.2	2.9	3.4	0.2	1.4
Brazil	24.4	8.8	32.6	58.6	4.5	3.7	2.9	3.3	1.4	1.8
Tanzania, United Rep.	5.5	24.4	41.2	34.4	4.0	3.1	2.1	3.0	0.1	1.5
Myanmar	5.4	2.6	38.8	58.5	3.2	2.8	2.3	2.5	0.1	0.9

Note: Countries with predominantly rainfed wheat with over 5 million ha of land in the wheat suitability classes VS (very suitable), S (suitable) and MS (moderately suitable) under high input. See Box 4.1 for an explanation of classes. All data on potentials exclude marginally suitable land which in the GAEZ analysis is not considered appropriate for high-input farming.

actual yields are 6 tonnes/ha in Sweden (in practice exceeding what the GAEZ evaluation suggests as attainable on the average) and 2.3 tonnes/ha in Uruguay. In spite of Uruguay's yields being a fraction of those that are agro-ecologically attainable and of those prevailing in Sweden, it is not necessarily a less efficient wheat producer than Sweden in terms of production costs. Other examples of economically efficient wheat producers with low yields in relation to their agronomic potential include Australia (2.0 tonnes/ha actual versus 4.2 tonnes/ha agro-ecologically attainable) and the United States (2.7 tonnes/ha versus 5.8 tonnes/ha).

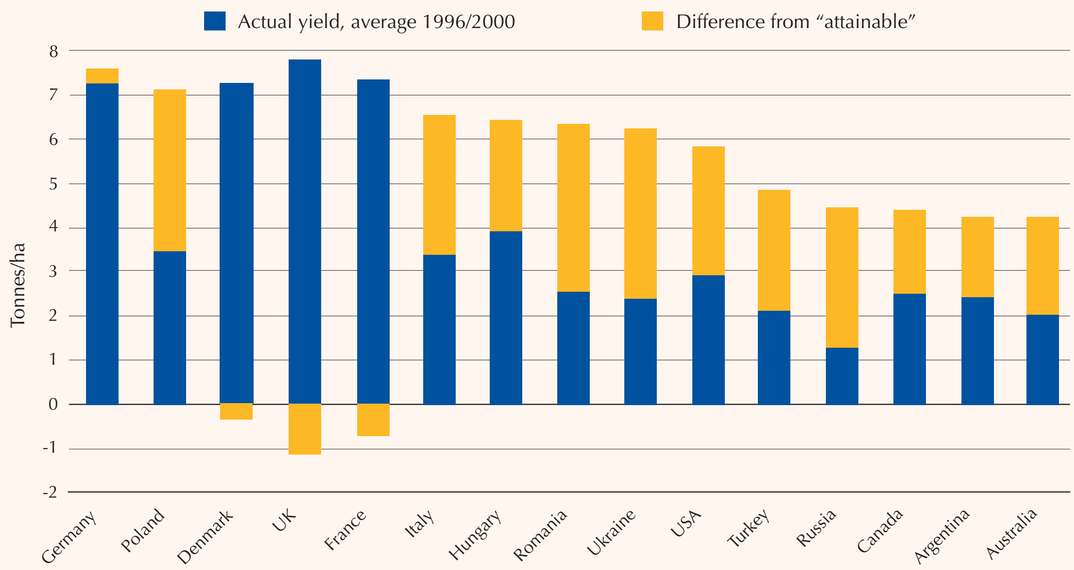
The yield gap in relation to agronomic potential is an important element when discussing agronomic potentials for yield growth. For the countries in which we find large differences between actual and attainable, it seems probable that factors other than agro-ecology are responsible. Yields in these countries could grow some way towards bridging the gap between actual and attainable if some of these factors could be changed, e.g. if prices rose. We could then take the countries with a sizeable "bridgeable" gap and see their aggregate weight in world production of a particular crop. If the weight is significant, then the world almost certainly has significant potential for increasing production through yield growth, even on the basis of existing knowledge and technology (varieties, farming practices, etc.).

Among the major wheat producers, only the EU countries (the United Kingdom, Denmark, France and Germany) have actual yields close to, or even higher than, those attainable for their agro-ecological endowments under rainfed high-input farming. In all other major producers with predominantly rainfed wheat production (11 countries) the gaps between actual and attainable yields are significant. This is shown in Figure 11.3. These 11 countries account for 37 percent of world wheat production. If we assumed that half of their yield gap (attainable minus actual) were "bridgeable", their collective production could increase by some 60 percent without any increase in their area under wheat – an increment equal to 23 percent of current world output. Yield growth would also occur in the other countries accounting for the rest of world production, including the major producers with irrigated wheat not included in those shown in Figure 11.3, such as China, India, Pakistan and Egypt. All this is without counting the potential yield gains that could come from further improvement in varieties, since the agro-ecologically attainable yields of the GAEZ reflect the yield potential of existing varieties.

Some states in India, such as the Punjab, are often quoted as examples of areas where wheat and rice yields have been slowing down or are even reaching a plateau. Fortunately, India is one of the few countries for which data at subnational level and distinguished by rainfed and irrigated area are available. Table 11.2 compares wheat and rice yields by major growing state with the agro-ecologically attainable yields, taking into account irrigation. It shows that, although yield growth has indeed been slowing down, in most cases actual yields are still far from agro-ecologically attainable yields (with a few exceptions such as wheat in Haryana). This suggests that there are still considerable bridgeable yield gaps in India.

The discussion above gives an idea of the scope for wheat production increases through the adoption of improved technologies and practices to bridge some of the gap that separates actual yields from obtainable yields. The broad lesson of experience seems to be that if scarcities develop and prices rise, farmers quickly respond by adopting such technologies and increasing production, at

Figure 11.3 Wheat: actual and agro-ecologically attainable yields (rainfed, high input)



Note: Fifteen countries with a predominantly rainfed wheat production of over 4 million tonnes in 1996/2000.

Table 11.2 Wheat and rice yields in India, by state[1]

	Yield					Area	Land under irrigation	Prod.	Actual yield	Maximum attainable yield (AEZ)		
Wheat	1972 /74	1984 /86	1993 /95	1972 -85	1986 -95	1997 /98	1995	1997 /98	1997 /98	Rainfed	Irrigated	Weighted
	kg/ha			% p.a.		mln ha	%	mln tonnes	kg/ha			
India total	1 260	1 947	2 477	3.9	2.9	27.1	86	68.6	2 534	1 786	4 352	3 998
All states below						25.8	85	66.4	2 571			
Uttar Pradesh	1 123	1 933	2 423	4.8	2.6	9.4	93	23.0	2 503	2 932	5 143	4 990
Punjab	2 280	3 263	3 993	3.4	2.5	3.3	97	13.6	4 093	1 994	5 661	5 544
Haryana	1 683	2 840	3 663	4.3	3.1	2.1	49	8.1	3 788	2 634	5 481	4 020
Madhya Pradesh	773	1 147	1 660	3.6	3.9	4.6	71	7.8	1 684	1 008	3 824	2 996
Rajasthan	1 200	1 900	2 213	4.0	2.1	2.7	96	6.8	2 494	1 940	4 279	4 192
Bihar	875	1 593	2 060	6.6	3.5	2.1	88	4.5	2 165	1 401	4 113	3 798
Gujarat	1 673	2 000	2 280	2.2	1.9	0.7	81	1.7	2 400	877	3 173	2 737
Maharashtra	580	777	1 377	3.2	6.1	0.9	65	1.0	1 094	1 356	3 144	2 520

Rice (paddy)	1973 /75	1984 /86	1994 /96	1973 -85	1986 -96	1998 /99	1997	1998 /99	1998 /99	Rainfed	Irrigated	Weighted
	kg/ha			% p.a.		mln ha	%	mln tonnes	kg/ha			
India total	1 630	2 215	2 830	2.2	2.6	44.0	51	126.4	2 871	2 516	8 161	5 395
All states below						40.5	50	116.1	2 867			
West Bengal	1 725	2 305	3 090	1.5	3.0	5.9	26	19.9	3 374	4 105	8 051	5 147
Uttar Pradesh	1 195	2 030	2 815	3.7	3.2	5.8	64	17.8	3 080	2 133	8 322	6 088
Andra Pradesh	2 350	3 150	3 875	3.2	2.1	3.8	96	15.0	3 909	1 638	8 182	7 894
Tamil Nadu	2 810	3 205	4 855	0.6	2.7	2.3	93	11.3	4 870	2 066	8 188	7 741
Punjab	3 185	4 655	5 011	3.4	0.6	2.4	99	11.9	4 963	1 463	8 914	8 847
Bihar	1 310	1 590	1 980	0.1	1.4	5.1	41	10.3	2 022	3 611	8 214	5 489
Orissa	1 265	1 670	2 125	1.2	3.0	4.5	37	8.7	1 944	2 180	7 457	4 132
Madhya Pradesh	1 000	1 405	1 725	1.2	2.5	5.4	24	7.4	1 385	1 450	7 905	2 973
Karnataka	2 635	2 850	3 570	1.2	3.2	1.4	68	5.1	3 678	1 916	8 131	6 136
Assam	1 500	1 650	2 015	0.7	2.5	2.5	21	5.0	2 028	6 426	7 733	6 700
Maharashtra	1 415	2 155	2 425	4.0	2.3	1.5	28	3.6	2 464	1 330	8 150	3 246

Note: [1] States in descending order of latest year production. Agro-ecological zone (AEZ) yields: rainfed under mixed inputs and irrigated under high inputs. The weighted AEZ yield (last column) was derived by applying the percentage of land under irrigation as a weighting factor.
Source for data: India Department of Agriculture Cooperation: Statistics at a glance, March 2001.

least those living in an environment of not too difficult access to improved technology, transport infrastructure and supportive policies. However, in countries with land expansion possibilities, the quickest response comes from increasing land under cultivation, including shifting land among crops towards the most profitable ones. Argentina's example is instructive: mostly from land expansion, it increased wheat production by 68 percent in 1996 and maize production by 48 percent in 1997 and another 25 percent in 1998, following price rises in the immediately preceding years.

Countries use only part of the land that is suitable for any given crop. This does not mean that land lies bare or fallow waiting to be used for increasing production of that particular crop. In most cases the land is also suitable for other crops and in practice is used for other crops (see Box 4.2). The point made here is that the gap existing between yields actually achieved and those obtainable under high-input technology packages affords significant scope for production increases through yield growth, given conducive socio-economic conditions, incentives and policies. The point is not that production increases can be obtained by expanding cultivation into land suitable for a particular crop, because such land may not be available if it is used for other crops.

Moreover, even if there probably is sufficient slack in world agriculture to support further increases in global production, this is small consolation to food-insecure people who depend for their nutrition on what they themselves produce. Such people often live in semi-arid agricultural environments where the slack for increasing production can be very limited or non-existent. The fact that the world as a whole may have ample potential to produce more food is of little help to them.

The preceding discussion may create the impression that all is well from the standpoint of potential for further production growth based on the use of existing varieties and technologies to increase yields. Nothing is further from the truth, for two main reasons:

- Exploitation of the yield gaps as defined in the preceding discussion means further spread of the conventional high external input technologies, which is precisely what we should be trying to mitigate if we are to avoid aggravation of the related environmental problems.
- Perhaps more important from the standpoint of meeting future demand, ready potential for yield growth does not necessarily exist in the countries where the additional demand will be, e.g. in the mature green revolution areas of India and other developing countries. When potential demand is in countries with limited import capacity, as is the case in many developing countries, such potential can be expressed as effective demand only if it can be predominantly matched by local production. As noted in Chapters 2 and 8, increases in local production in these countries, in addition to adding to food supplies, stimulate the demand for food because they create employment and incomes and stimulate the wider rural economy. In such circumstances, the existence of large exploitable yield gaps elsewhere (e.g. in Argentina or Ukraine) is less important than it appears for the evaluation of potential contributions of yield growth to meeting future demand.

It follows that continued and intensified efforts are needed on the part of the agricultural research community to raise yields (including through maintenance and adaptive research) in the often unfavourable agro-ecological and socio-economic environments of the countries where the additional demand will be. It is thought (see below) that biotechnology will play an important role here, as it has the potential to be a more efficient instrument than conventional plant breeding for overcoming constraints inherent in such environments (semi-aridity, susceptibility to pest infestations, etc.; see Lipton, 1999).

11.2 Technologies in support of sustainable agriculture

Various approaches have been developed in the past few decades to minimize the environmentally detrimental effects of agricultural production. Among the foremost of these are integrated pest management (IPM), Integrated Plant Nutrient Systems (IPNS) and no-till/conservation agriculture (NT/CA). Rather than as isolated technologies they should be seen as complementary elements of sustainable agriculture.

The conventional model of agricultural development stresses increased production and intensification through progressively specialized operations. By contrast, the approaches discussed in this section seek to meet the dual goals of increased productivity and reduced environmental impact. They do this through diversification and selection of inputs and management practices that foster positive ecological relationships and biological processes within the entire agro-ecosystem. With the help of participatory research and extension approaches, the principles of these technologies can be developed further into location-specific sustainable resource management systems. Even though each of these three approaches has some distinct features, many of the specific technologies used are, to various degrees, found in all of the approaches discussed in this section.

Sustainable agriculture is not a concretely defined set of technologies, nor is it a simple model or package that can be widely applied or is fixed over time. The lack of information on agro-ecology and the high demand for management skills are major barriers to the adoption of sustainable agriculture. For example, much less is known about these organic and resource-conserving technologies than about the use of external inputs in modernized systems.

11.2.1 Integrated pest management

Crop, forestry and livestock production systems throughout the world suffer losses caused by diseases, weeds, insects, mites, nematodes and other pests. The intensification of farming, forestry and livestock production favours pest buildup, and the high-yielding varieties and breeds utilized are often more susceptible to pests than traditional ones. The impact of many of these problems can be reduced with the help of pesticides but at a cost, including negative health and environmental effects. Because most chemical pesticides are hazardous to human health and toxic to many non-target organisms, there are potential hazards associated with their manufacture, distribution and application, particularly if pesticides are misused (GTZ, 1993). These hazards include exposure during handling or application, pesticide residues in or on foodstuffs, pollution of the environment (soil, groundwater, surface waters and air) and killing of non-target organisms. Because of the disruption of natural enemies, there has been a resurgence of existing pests and an outbreak of new ones. Almost all economically significant pests are already resistant to at least one chemical pesticide.

The goal of IPM is to avoid or reduce yield losses by pests while minimizing the negative impacts of pest control. The term IPM was originally used to describe an approach to pest control with the primary aim of reducing the excessive use of pesticides while achieving zero pest incidence. The concept has broadened over time. Today IPM can best be described as a decision-making and action-oriented process that applies the most appropriate pest control methods and strategy to each situation. To ensure the success of this process, the presence and density of pests and their predators and the degree of pest damage are systematically monitored. No action is taken as long as the level of the pest population is expected to remain within specified limits.

IPM promotes primarily biological, cultural and physical pest management techniques, and uses chemical ones only when essential. Naturally occurring biological control is encouraged, for example through the use of alternate plant species or varieties that resist pests, as is the adoption of land management, fertilization and irrigation practices that reduce pest problems. If pesticides are to be used, those with the lowest toxicity to humans and non-target organisms should be the primary option. Precise timing and application of pesticides are essential. Broad spectrum pesticides are used only as a last resort when careful monitoring indicates they are needed according to pre-established guidelines. This broader focus, in which judicious fertilizer use is also receiving attention (see the next section), is also referred to as integrated production and pest management (IPPM).

The Centre for Research and Information on Low External Input for Sustainable Agriculture distinguishes three stages in the development of IPM (IPMEurope Web site, 2002). In the first stage, the concept of pest population thresholds and targeted pests was introduced. Later, diseases and weeds were added to address more comprehensively the many crop protection problems that farmers face. In the second stage, crop protection was integrated with farm and natural resource management. Indigenous knowledge and traditional cropping practices were studied and adapted, while proper natural resource management became important because of the role of biodiversity in biological control. A whole-farm approach was thus adopted and integrated crop management practised to solve the conflicting needs of agricultural production and the environment.

In the third stage came the integration of the natural and social sciences. Most IPM projects now develop around a dynamic extension model, the farmer field school (FFS), which emphasizes farmers' ability to experiment and draw conclusions, and enhances their ability to make decisions. The knowledge base has been expanded for a wide range of crops both in terms of new technologies and ecological aspects. Much of this IPM knowledge has still not reached the farm level and lacks site-specific adaptation.

Experience shows that IPM has economic and other benefits for farmers and farm households. However, national policy frameworks in many developing countries have tended to strongly favour pesticide use through subsidies that distorted prices. Because of this, alternative pest control measures, even where successful technically, are often not financially competitive and farmers are reluctant to adopt them. In addition, generally weak extension services lack the capacity for the intensive educational programmes needed to familiarize and train farmers in the use of IPM practices.

In spite of these problems, IPM has been introduced successfully in many countries and for many different crops such as rice, cotton and vegetables. In Cuba, IPM has been integrated successfully into organic farming. Where farmers have had no previous access to chemical pesticides, the introduction of plant protection based on IPM is the preferred option to avoid financially and environmentally costly overdependence on pesticides.

IPM applied to rice has shown good to dramatic improvements in production, in some cases simultaneously reducing costs. Human capacities and networks developed for rice will continue to provide support for new initiatives. Combined with the proven successes, they will promote the introduction of IPM in other crops or cropping systems, particularly vegetables and cotton. Unfortunately, a quantitative evaluation of the uptake in terms of hectares covered and reduced pesticide use is only available for a few projects, making a global or regional estimate of its present and future use impossible.

11.2.2 Integrated Plant Nutrient Systems

Any agricultural crop production – extensive or intensive, conventional or organic – removes plant nutrients from the soil. Nutrient uptake varies according to soil types and the intensity of production. An increase in biomass production results in a higher plant nutrient uptake. Imbalance in the availability of nutrients can lead to mining of soil reserves of nutrients in short supply and to losses of plant nutrients supplied in excess. Insufficiency of one plant nutrient can limit the efficiency with which other plant nutrients are taken up, reducing crop yields. For a farming system to be sustainable, plant nutrients have to be replenished. The nutrient mining that is occurring in many developing countries is a major but often hidden form of land degradation, making agricultural production unsustainable.

IPNS aim to maximize plant nutrient use efficiency by recycling all plant nutrient sources within the farm and by using nitrogen fixation by legumes to the extent possible. This is complemented by the use of external plant nutrient sources, including manufactured fertilizers, to enhance soil productivity through a balanced use of local and external sources of plant nutrients in a way that maintains or improves soil fertility (FAO, 1998e). At the same time IPNS aim at minimizing plant nutrient losses to avoid pollution of soils and water and financial losses to the farmer.

At the plot level, IPNS are designed to optimize the uptake of plant nutrients by the crop and increase the productivity of that uptake. At the farm level, IPNS aim to optimize the productivity of the flows of nutrients passing through the farming system during a crop rotation. The decision to apply external plant nutrients is generally based on financial considerations but is also conditioned by availability and perceived production risks.

Advice on quantities of nutrients to be applied may be based on empirical results from experiments in farmers' fields, which provide information on the impact of combined nutrient applications, timing of nutrient supply and sources of nutrients on crop yields. In the absence of such detailed information, knowledge of the quantities of nutrients removed by crops at the desired yield level provides a starting-point for estimating nutrient requirements.

Improved plant nutrition management will be important for environmentally and economically sustainable crop production, be it conventional or organic. However, the rate of spread of IPNS and their implications for the use of mineral fertilizers in agricultural production cannot be predicted in isolation. Precise management of fertilizer use can raise efficiency by 10 to 30 percent and should therefore be included in all production systems aiming for sustainability, even if they do not emphasize IPNS.

11.2.3 No-till/conservation agriculture

By far the largest extent of agricultural land continues to be ploughed, harrowed or hoed before every crop. These conventional tillage practices aim to destroy weeds and loosen the topsoil to facilitate water infiltration and crop establishment. This recurring disturbance of the topsoil buries any soil cover and may destabilize the soil structure so that rainfall can cause soil dispersion, sealing and crusting of the surface. An additional problem of conventional tillage is that it often results in compacted soils, which negatively affect productivity.

This negative impact of soil tillage on farm productivity and sustainability, as well as on environmental processes, has been increasingly recognized. In response to the problem, no-till/conservation agriculture (NT/CA) has been developed. NT/CA maintains and improves crop yields and resilience against drought and other hazards, while at the same time protecting and stimulating the biological functioning of the soil. Various terms are used for variants of NT/CA in different countries, depending on the perceived importance of one or another aspect of the approach: zero tillage; minimum or low tillage; *plantio directo na palha* (direct planting in straw); *siembra directo permanente* (permanent direct seeding); and conservation tillage.

The essential features of NT/CA are: minimal soil disturbance restricted to planting and drilling; maintenance of a permanent cover of live or dead vegetal material on the soil surface; direct sowing; crop rotation combining different plant families (e.g. cereals and legumes); adequate biomass generation; and continuous cropland use. In some countries the above-mentioned systems might lack some essential features of NT/CA and will therefore not have the same beneficial effects.

Soil cover is needed to protect the soil from the impact of rainfall, which would destroy the porosity of the soil surface, leading to runoff and erosion. Crops are seeded or planted through this cover with special equipment or in narrow cleared strips. Direct planting or seeding is linked with NT/CA, since any more general tillage would bury most or all of the vegetal cover. Crop sequences are planned over several seasons to minimize the buildup of pests or diseases and to optimize plant nutrient use by synergy among different crop types and by alternating shallow-rooting crops with deep-rooting ones. When the same crop or cover crops are repeated on the same piece of land each year, NT/CA is an imperfect and incomplete system, because diseases, weeds and pests tend to increase and profits tend to decrease (Derpsch, 2000). The cropland is being used continuously and no burning of residues is allowed.

Besides protecting the soil against erosion and water loss by runoff or evaporation, the soil cover also inhibits the germination of many weed seeds, minimizing weed competition with the crop. After the first couple of years of NT/CA on a field, the stock of viable weed seeds near the soil surface usually declines, often to the point where weed incidence becomes minor, with remnant populations at scattered spots in the field. In the first few years, however, herbicides may still need to be applied. Systems without continuous soil cover or crop rotation may not even reduce the incidence of weed in the long term (e.g. wheat monoculture in the United States).

After a number of years, yields have often risen to some 20 to 50 percent higher than what they were before under conventional procedures. The yields also become less variable from year to year. Labour costs can be significantly lower, and labour demand is distributed much more evenly over the year. Input costs are lower as well, particularly for machinery once the initial investments have been made. In mechanized farming less fuel is needed and smaller tractors can be used or fewer draft animals are needed for a given area; in areas without these power sources, the heavy manual work preparatory to crop establishment is drastically reduced (see also Section 4.6.2).

There are several reasons, however, for the continued dominance of conventional tillage-based agriculture. There is a natural reluctance to change approaches that have been working in past years or for decades. Conventional wisdom on the benefits of ploughing and a lack of knowledge on the resulting damage to the soil system tend to maintain plough-based agriculture. Also, the transition to NT/CA is not free of cost, nor particularly simple. During the transition years, there are extra costs for tools and equipment. Higher weed incidence may increase herbicide costs initially and the yields and resilience against drought will improve only gradually.

A more important impediment to the successful introduction of NT/CA is probably the required

Box 11.1 No-till development support strategy: the Brazil experience

Large-scale expansion in Brazil to the current more than 10 million ha started in about 1980, after small and local initiatives during the 1960s. Large farmers used methods and equipment first from the United States and later from local manufacturers. Small farmers, with animal or small mechanical draught power, followed more than a decade later. During this period, small manufacturers together with innovative farmers designed smaller prototypes and started producing and marketing equipment adapted to small farms, including knife rollers to manage crop residues and combined direct seeders/fertilizer applicators.

The success of NT/CA in Brazil cannot be attributed to technical parameters alone. In conjunction with technical innovation, an effective participatory approach to adaptive research and technology transfer was adopted that tied farmers into a development strategy suited to their specific requirements. Institutional support was demand driven and concentrated on training and education that equipped participating farmers with the skills to adapt and refine NT/CA on their own farms. The cornerstones of the development support strategy were:

- *close collaboration between researchers, extensionists, the private sector and farmers* for the development, adoption and improvement of NT systems;
- *onfarm trials and participatory technology development;*
- *strengthening of farmers' organizations;* creation of local "Friends of the Land Clubs" where farmers exchange information and experiences and improve their access to extension and other advisory services as well as input and output marketing;
- *close cooperation with existing and new cooperatives* concentrating primarily on marketing and training for vertical diversification into livestock and processing;
- *aggressive dissemination strategy of technical, economic and environmental information* through the media, written documents, meetings and conferences – controlled and managed by producers' organizations (Friends of the Land Clubs) with emphasis on farmer-to-farmer exchange of experiences;
- *the national NT farmers' organization FEBRAPDP* played a significant role in advocating and supporting the promotion of NT/CA on large and small farms. As NT systems are complex to manage and require efficient farm management, training in record-keeping and a holistic understanding of farming systems' dynamics have been an integral aspect of support to small farmers;
- *private-public partnerships;* agro-input companies (Zeneca and Monsanto) supported demonstration projects in large and small farms through the provision of inputs and extension services;
- *targeted subsidies;* short-term subsidies played a significant part in supporting small farmer adoption of NT practices. In Paraná much of the hand-held or animal-drawn equipment was acquired with financial support from the state in the context of development programmes (mainly World Bank). Subsidized or free equipment is still made available to groups of farmers. Apart from economic constraints to adoption, the rationale for public subsidies has been the generation of offsite benefits from NT adoption. In some instances, private companies provided equipment for small farmers;
- *integration of crops and livestock;* special attention has been paid to the incorporation of crops and livestock (including poultry, hog and fish farming). A particular challenge is the development of rotational grazing patterns on cover crops, which do not jeopardize the sustainability of NT systems;
- *incorporation of environmental considerations;* correcting watershed degradation (e.g. soil erosion, pollution of streams and lakes and road damage) was a key reason for the adoption of NT farming practices. Environmental awareness raising among farmers also resulted in central facilities for the disposal of pesticide containers, household sanitation and recovery of gallery forests.

Source: Evers and Agostini (2001).

complex management skills. Any production system that includes crop rotation (see also Section 11.3 on organic agriculture) is more complex as it calls for coherent management over more than one or two crop seasons. Farmers will need to understand the new system and the reasons for the various procedures, and adapt them to their specific needs and conditions to balance crop rotation with market requirements. In mixed agriculture-livestock systems, practices such as stall-feeding or controlled grazing will need to replace free grazing on harvested fields.

NT/CA farmers appear to be keen to learn and embrace new developments (Derpsch, 2000). Being acquainted with more holistic management approaches to farming, many NT/CA farmers have introduced aspects of organic agriculture or converted entirely to organic agriculture where a market for organic products exists. On the other hand, some organic farmers have successfully adopted NT farming. Moreover, NT/CA farmers have also been faster adopters of IPM approaches than conventional ones (Pieri *et al.*, 2002).

The initial introduction of NT/CA in a new area, its adaptation to the environmental, social and economic conditions and its validation and demonstration in representative farms depend partly on the people involved. They require the determined and sustained efforts of competent, innovative governmental or non-governmental organizations and an active learning attitude of some of the most change-minded farmers and farmers' groups as well as the extension staff. Once NT/CA has been shown to work well on several farms in a given environment, the practices tend to spread spontaneously over large areas. Farmers need professional contacts with each other and local manufacturers need to be in a position to supply the necessary tools and equipment. During the initial phase many farmers will need some financial support in the form of loans or grants.

Some or all elements of NT/CA have been applied by farmers so far on between 50 and 60 million ha worldwide. Almost half of this is in the United States, where the area under zero tillage tripled over the last decade to about 23 million ha (USDA, 2001e), responding to government conservation requirements and to reduce fuel costs. But a considerable share of this is under monoculture and misses two essential features, namely full soil cover and adequate crop rotation, and cannot therefore be classified as NT/CA. In Paraguay about half of all the cropped land is under elements of NT/CA, mainly zero tillage. The area increased from about 20 000 to almost 800 000 ha between 1992 and 1999 because the government assisted by sharing part of the initial costs of conversion.

The spread of NT/CA approaches in the next three decades is expected to be considerable but, in addition to the constraints mentioned above, expansion will for several reasons vary widely across countries. Investment is needed to restore nutrient-depleted soils before crop residues can be produced in adequate amounts to satisfy the needs of livestock and maintain a soil cover. In arid areas without irrigation, the amounts of crop residues generally will not be sufficient for effective NT/CA systems. In some countries, established extension services or staff have been actively discouraging farmers from converting to NT/CA, while in others the scientific or extension institutes are not able to initiate the onfarm experiments needed to adapt and validate NT/CA systems locally. Even under favourable circumstances, it can take years before the new production system is widely known, understood and appreciated. A further ten years might be needed for its practical application over a large part of the country or a major farming system area (for example, the South Asian rice-wheat area, or the Brazilian *cerrados*).

11.3 Organic agriculture

Organic agriculture is a production management system that aims to promote and enhance ecosystem health, including biological cycles and soil biological activity (Box 11.2). It is based on minimizing the use of external inputs, and represents a deliberate attempt to make the best use of local natural resources. Methods are used to minimize pollution of air, soil and water (FAO/WHO, 1999), although they cannot ensure that products are completely free of residues, because of general environmental pollution. Organic agriculture comprises a range of land, crop and animal management procedures. Unlike food labelled as "environmentally friendly", "natural" or "free-range", organic agriculture is circumscribed by a set of rules and limits, usually enforced by inspection and certification mechanisms. Other terms used, depending on the language, are “biological” or “ecological”. “Biodynamic” refers to commodities that are produced according to organic and other additional requirements.

Synthetic pesticides, mineral fertilizers, synthetic preservatives, pharmaceuticals, GMOs, sewage sludge and irradiation are prohibited in all organic standards. Plant nutrient or pesticide inputs derived directly from natural sources are generally allowed, as is a minimum of pretreatment before use (water extraction, grinding, etc.). Industrially produced pesticides, for example, may not be applied in organic agriculture, but an extract of neem (*Azadirachta indica*) leaves, which have biocidal properties, is currently allowed.

Most industrial countries, but few developing countries, have national organic standards, regulations and inspection and certification systems that govern the production and sale of foods labelled as “organic”. At the international level, the general principles and requirements applying to organic agriculture are defined in the Codex guidelines (FAO/WHO, 1999) adopted in 1999. The growing interest in organic crop, livestock and fish products is mainly driven by health and food quality concerns. However, organic agriculture is not a product claim that organic food is healthier or safer, but rather a process claim intending to make food production and processing methods respectful of the environment.

Organic agriculture, broadly defined, is not limited to certified organic farms and products only. It also includes non-certified ones, as long as they fully meet the requirements of organic agriculture. This is the case for many non-certified organic agricultural systems in both developing and industrial countries where produce is consumed locally or sold directly on the farm or without labels. The extent of these systems is difficult to estimate since they operate outside the certification and market systems (El-Hage Scialabba and Hattam, 2002).

Organic practices that encourage soil biological activity and nutrient cycling include: manipulation of crop rotations and strip cropping; green manuring and organic fertilization (animal manure, compost, crop residues); minimum tillage or zero tillage; and avoidance of pesticide and herbicide use. Research indicates that organic agriculture significantly increases the density of beneficial invertebrates, earthworms, root symbionts and other micro-organisms (fungi, bacteria) (FiBL, 2000). Properly managed organic agriculture reduces or eliminates water pollution and helps conserve water and soil on the farm. Some countries (e.g. France and Germany) compel or subsidize farmers to use organic techniques as a solution to nitrate contamination in groundwater.

Box 11.2 What is an organic production system designed to do?

- Enhance biological diversity within the whole system.
- Increase soil biological activity.
- Maintain long-term soil fertility.
- Recycle wastes of plant and animal origin in order to return nutrients to the land, thus minimizing the use of non-renewable resources.
- Rely on renewable resources in locally organized agricultural systems.
- Promote the healthy use of soil, water and air as well as minimize all forms of pollution that may result from agricultural practices.
- Handle agricultural products with emphasis on careful processing methods in order to maintain the organic integrity and vital qualities of the product at all stages.
- Become established on any existing farm through a period of conversion, the appropriate length of which is determined by site-specific factors such as the history of the land and the type of crops and livestock to be produced.

Source: FAO/WHO (1999).

11.3.1 Land under organic management

Growth rates of land under organic management are impressive in western Europe, Latin America and the United States. Between 1995 and 2000, the total area of organic land tripled in western Europe and the United States. In the United States, land under certified organic agriculture has been growing by 20 percent p.a. since 1989, while in western Europe average annual growth rates have been around 26 percent since 1985 (with greatest increases since 1993). In 1999 alone, the United Kingdom experienced a 125 percent growth of its organic land area. However, these dramatic increases must be viewed against the small starting base levels. In some cases they may reflect a reclassification of land rather than an actual switch in farming systems.

Policy measures were instrumental in persuading small farmers to convert to organic farming by providing financial compensation for any losses incurred during conversion. The guidelines established by the organic agriculture community in the 1970s were formalized by national and supranational legislation and control systems (e.g. first in Denmark in 1987, followed in 1992 by Australia and the EU: Reg. no. 2092/91). The role of organic agriculture in reaching environmental policy objectives, including sustainable use of land set-aside (Lampkin and Padel, 1994), led to the adoption of agri-environmental measures that encourage organic agriculture (e.g. the 1992 reform of the Common Agricultural Policy and accompanying EU Reg. no. 2078/92).

The estimates given below are derived from a compilation of available information by the Foundation Ecology and Agriculture (SÖL) in Germany. In the absence of a statistical database on organic agriculture in FAO, this is the most comprehensive source available (Willer and Yussefi, 2002). SÖL reports a global area of land under certified organic agriculture of 15.8 million ha of which 48.5 percent are located in Oceania (Australia 7.7 million ha); 23.5 percent in Europe (with Italy having the highest area, nearly 1 million ha); 20 percent in Latin America (with Argentina having 3 million ha); 7.4 percent in North America (United States nearly 1 million ha); 0.3 percent in Asia; and 0.1 percent in Africa.

With 3 million ha, Argentina accounts for more than 90 percent of the certified organic land in Latin American countries and has the second largest area of organically managed land in the world after Australia. In both countries, however, most of this is grassland. Because of the large size of organic ranches in the pampas, the average size of organic farms is 3000 ha in Argentina. Some 85 percent of Argentina's organic production is exported.

In 2000, agricultural land under certified organic management averaged 2.4 percent of total agricultural land in western Europe, 1.7 percent in Australia, 0.25 percent in Canada and 0.22 percent in the United States. In most developing countries, agricultural land reported under certified organic production is minimal (less than 0.5 percent of agricultural lands). However, some traditional farms in developing countries have adopted modern organic management to improve their productivity, especially in areas where pesticides and fertilizers are inaccessible. The extent of such non-market organic agriculture is difficult to quantify but some attempts have been made. The Ghanaian Organic Agriculture Network, for example, estimates that there are around 250 000 families in South and East Africa farming around 60 million ha on an organic basis. Anobah (2000) estimates that over one-third of West African agricultural produce is produced organically.

A number of industrial countries have action plans for the development of organic agriculture. Targets are set for the sector's growth and resources are allocated to compensate farmers during, and sometimes after, the conversion period, and to support research and extension in organic agriculture. For example, the United Kingdom increased the budget of the Organic Farming Scheme to support conversion to organic agriculture by 50 percent for 2001-02 (£20 million per year) and allocations in the United States for the organic sector include US$5 million for research in 2001. India and Thailand have established their own organic standards to facilitate exports and to satisfy domestic demand. China, Malaysia and the Philippines are at present working towards establishing national standards.

11.3.2 Yields and profitability

Typically, farmers experience some loss in yields after discarding synthetic inputs and converting their operations from conventional, intensive systems to organic production. Before restoration of full biological activity (e.g. growth of soil biota, improved nitrogen fixation and establishment of natural pest predators), pest suppression and fertility problems are common. The degree of yield loss varies and depends on inherent biological attributes of the farm, farmer expertise, the extent to which synthetic inputs were used under previous management and the state of natural resources (FAO, 1999h). It may take years to restore the ecosystem to the point where organic production is economically viable.

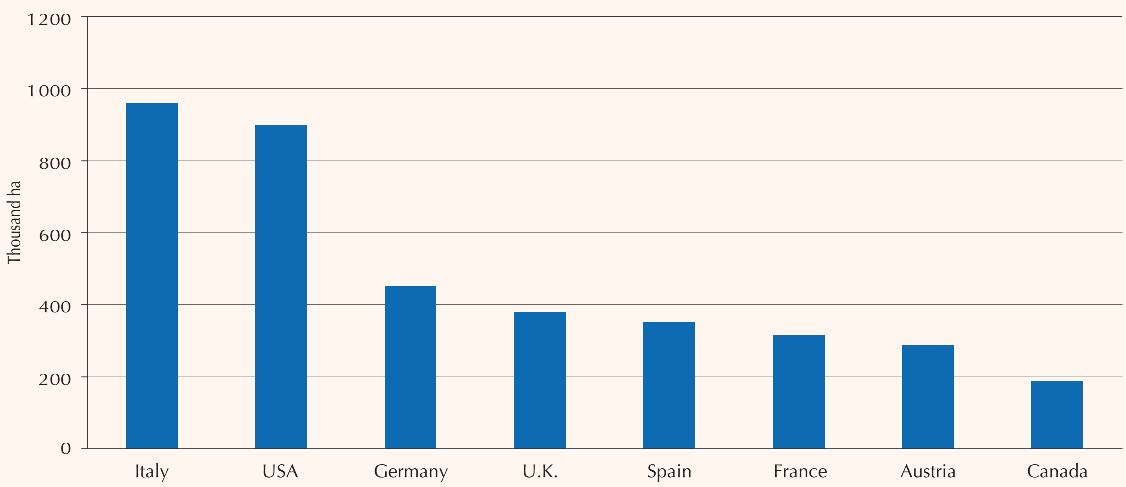
Transition to organic management is difficult for farmers to survive without financial compensation, especially in high intensive input agriculture and in degraded environments. After the conversion period, organic agriculture achieves lower yields than high external input systems. Depending on the previous management level of specialization, yields can be 10 to 30 percent lower in organic systems, with a few exceptions where yields are comparable in both systems. In the medium term, and depending on new knowledge, yields improve and the systems' stability increases. In the longer term, performance of organic agriculture increases in parallel with improvements in ecosystem functions and management skills.

Yields do not usually fall, however, when conversion to organic agriculture starts from low-input systems (often traditional) that do not apply soil-building practices. A study from Kenya indicates that, contrary to general belief, organic agriculture in the tropics is not constrained by insufficient organic material (to compensate for the non-use or reduced use of external inputs), but instead shows a good performance (ETC/KIOF, 1998).

As discussed in Chapter 4, average fertilizer consumption will rise in developing countries. The average figure masks, however, that for many (especially small) farmers the purchase of manufactured fertilizers and pesticides is and will continue to be constrained by their high costs relative to output prices or simply by unavailability. Organic agriculture emphasizes understanding and management of naturally occurring production inputs (such as farmyard manure, indirect plant protection and own seed production) as an alternative to enhance yields. It will not be possible for organic agriculture to attain the high yields achieved with the use of synthetic inputs in high-potential areas. But organic management offers good prospects for raising yields and the sustainability of farming in resource-poor and marginal areas, and can raise the productivity of traditional systems while relying on local resources (Pretty and Hine, 2000).

For example, India is collecting nationwide information regarding the experiments being carried out in organic agriculture, with a view to reintroducing it as part of its traditional "*rishi*

Figure 11.4 Farm area under certified organic management



Source: Willer and Yussefi (2002).
Note: Australia (7.7 million ha) and Argentina (3 million ha) are not included in this graph because most of the organic land is extensive grassland

agriculture". In Latin America, hundreds of thousands of indigenous farmers along the Andes have turned to the organic movement to reinstate sophisticated agricultural practices developed by the Incas. Individual small family vegetable plots and groups/associations managing organic produce for domestic urban markets and small informal fairs are widespread. Cuba adopted organic agriculture as part of its official agricultural policy, with investments in research and extension, to compensate for shortages in external inputs. In 1999 (non-certified) organic urban agriculture (in self-provision gardens, raised container beds and intensive gardens) produced 65 percent of the country's rice, 46 percent of fresh vegetables, 38 percent of non-citrus fruit, 13 percent of roots, tubers and plantains and 6 percent of eggs (Murphy, 2000).

In organic systems, external inputs such as fertilizers, herbicides and machinery are replaced by labour, most often increasing women's work. Labour can either be a major constraint to organic conversion, or an employment provider to rural communities. Often the introduction of organic agriculture shifts gender distribution of labour as men prefer to be involved with mechanized agriculture. Women rarely own land and are dependent on access to common property. Since access to credit frequently requires land as collateral, women (and landless people) are largely excluded from the formal credit market. As a result, women seek methods that require little external inputs. Organic agriculture facilitates women's participation as it does not rely on financial inputs and access to credit.

The economic performance of organic agriculture in industrial countries (mainly in Europe) is determined by financial support from governments, premium prices for produce and high labour costs. An extensive analysis of European farm economics in terms of labour use, yields, prices, costs and support payments, concludes that profits on organic farms are, on average, comparable to those on conventional farms (Hohenheim, 2000). However, only a few studies have assessed the long-term profitability of organic agriculture. Profitability of organic systems relates to whole-farm production (total production of a variety of species and not single crop yields) over the entire rotation period. This includes both marketed products and non-food production (to feed animals and soils). Incomes achieved over a given season may appear high because of price premiums when excluding the low profits over rotational seasons. Supply constraints faced by organic farmers, which are expected to increase if the sector expands, include the provision of adequate organic inputs such as organic seeds (e.g. GMO-free), natural pest enemies and mineral rocks (e.g. rock phosphate).

An increased organic food supply above a certain level would lead to a decline in premium prices. A study for Denmark (SJFI, 1998) concludes that the primary agricultural sector income may not fall if fewer than 25 percent of Danish farmers were to adopt organic methods. Most countries are far below such a threshold.

11.3.3 Demand for organic products

On the demand side, promotion and marketing strategies of retailers and supermarkets, in particular of major food-retailing chains, have created new market opportunities for organic agriculture in industrial countries. Food-retailing chains, which also stock and promote organic foods as a tool to improve their public image, account for a major share of the retail markets for fresh as well as processed organic foods. Concerns about growth-stimulating substances, GM food, dioxin-contaminated food and livestock epidemics (such as bovine spongiform encephalopathy) have given further impetus to organic food demand as consumers increasingly question the safety of conventional foods. The most recent outbreak of foot-and-mouth disease has added to concerns over the soundness of industrial agriculture. Several governments have responded with declarations of targets for the expansion of organic production. Many consumers perceive organic products as safer and of higher quality than conventional ones. These perceptions, rather than "science", drive the market.

The market opportunities arising from these concerns have also opened possible niche markets for developing country exporters. Major industrial countries' markets offer good prospects for suppliers of organic products that are not produced domestically (e.g. coffee, tea, cocoa, spices, sugar cane and tropical fruit) as well as off-season products (such as fruit and vegetables) and processed foods. Liberalization and privatization policies in developing countries open the way for a greater role for organic entrepreneurs and producers' organizations. Markets for value-added products such as organic commodities can help counterbalance falling commodity prices and withdrawal of government support for agricultural inputs and other services. Price premiums range from 10 to 50 percent over prices for non-organic products. There is also government support for organic exports. Examples include the organic coffee programme of the Coffee Development Authority in Uganda; the promotion of organic exports by India's Ministry of Commerce; and support by the Argentinean government for the export of over 80 percent of the country's organic produce.

The size of domestic organic production is not necessarily related to the importance of organic markets. Australia, which has the world's largest area of organic land, most of which is grassland, has a market of US$170 million of organic food retails. Japan, on the other hand, which has only 5 000 ha of organic lands, is the second largest world organic market (US$2.5 billion of retail sales in 2000). The largest markets of organic foods are in western European countries (Germany being the most important market at present), Japan and the United States. The UNCTAD/WTO International Trade Centre (ITC, 1999) estimated retail sales of organic foods in the largest markets at US$20 billion in 2000, of which US$8 billion in Europe and the United States each, and US$2.5 billion in Japan.

In spite of dramatic growth rates, sales of organic agricultural products in industrial countries in 2000 represented less than 2 percent of total food sales at the retail level. However, in particular countries and for particular products, the market share of organic agricultural products can be appreciably larger. Organic food sales in Germany are 3 to 4 percent of total sales, while individual commodities such as organic milk products have over a 10 percent market share, with the figure for organic ingredients in baby foods in the range of 80 to 90 percent. Organic coffee, which accounts for 0.2 percent of world coffee consumption, accounts for 5 percent of the United States coffee market (Vieira, 2001). Some 100 developing countries produce organic commodities in commercial quantities, most of which are exported to industrial countries. Where they exist, developing countries' organic markets are still very limited and food is sold mainly in specialized stores in large cities. ITC (1999) estimates an annual sales growth of organic food between 10 and 40 percent over the medium term, depending on the market. Thus, organic food retail sales could grow from an average of 2 percent of total sales in 2000 to a share of 10 percent in major markets in a few years.

11.3.4 Long-term prospects for organic agriculture

The future growth of organic agriculture will depend more on supply constraints than on developments in demand, at least over the medium term. The tendency so far has been for the rate of demand growth to outstrip the rate of growth in available supplies. Developing countries are just starting to benefit from organic market opportunities but present conditions benefit primarily large producers and operators.

The supply and quality of organic raw material and rules governing organic production and processing might limit the extent to which developing countries could satisfy the demand for organic food in industrial countries. Organic food trade might be discouraged by difficulties in complying with foreign standards and costly control systems, especially if international equivalency is not established. Access to inspection and certification, as well as the need to develop new methods of processing organic food, are major challenges that are likely to be taken up by large and established food companies (Kristensen and Nielsen, 1997). Multinational food companies are expected to contract for and certify organic foods. In particular, the growth of processed organic foods will be facilitated by these companies' capacities to assemble ingredients from different parts of the world and to guide production to meet their specific needs. At the same time there are numerous opportunities for developing country producers and exporters to enter the markets for value-added organic products using simple technology.

Further long-term impetus towards adoption of environmentally friendly farming systems, including organic agriculture, will stem from moves towards decoupling agricultural support from purely production-oriented goals. There will be increasing emphasis on support to agriculture's role in providing public goods. Agricultural and environmental policies, including those responding to food safety concerns, will play a large role in facilitating or hindering the adoption of organic agriculture.

Besides financial support for conversion and regulations to protect the claim of organic producers, public investment in research and training is fundamental for such a knowledge- and management-intensive production system. It is still difficult for farmers and extension services to draw on a wide selection of well-researched methods and approaches. This often limits adoption to the most innovative farmers. Organic agricultural research receives only a fraction of the funds going to biotechnology research.

In developing countries, non-market organic agriculture and domestic certified organic agriculture are expected to increase in the long term. In particular, areas where economic growth is lagging (e.g. sub-Saharan Africa) and external inputs are unavailable or unaffordable, non-market organic agriculture could contribute to achieving local food security.

By about 2015, some organically produced tropical commodities (e.g. coffee, cocoa, cotton and tea) should have a moderate market share. The current tendency towards organic convenience food in industrial countries will increase, in particular for tropical beverages, baby food and frozen vegetables.

The oilcrops trade (especially soybeans and rape) is subject to major changes as oilcrops are the focus of biotechnology development. Future evidence on the safety of GM oilcrops might either increase their production or create new markets (and exports) for organic oilcrops. Cases are emerging where, because of the advent of GM crops, organic production will be constrained or no longer feasible; for example, organic farmers in Canada can no longer grow organic canola because of GM canola contamination in west Canada.

European governments' year 2010 targets for conversion of agricultural land to organic agriculture are ambitious: some countries (the Netherlands and Norway) aim to have 10 percent of agricultural land converted to organic agriculture. Germany has set a target of 20 percent. The United Kingdom Organic Food and Farming Targets Bill aims to increase total organic area to 30 percent (and domestic organic food retails to 20 percent). Denmark and Italy each aim at 10 percent and Sweden at 20 percent, as early as 2005. In view of the present levels and these targets, the EU, on average, might possibly have a quarter of its total agricultural land under organic management by 2030.

It is hard to make estimates on future expansion of area under organic management in developing countries. Expansion will depend on technological innovations and unforeseen factors that challenge agricultural development as a whole, similar to the development of organic agriculture in Europe. Here it took 30 years for organic agriculture to occupy 1 percent of agricultural land and food markets, but food safety concerns resulted in its recent spectacular and unforeseen increase.

11.4 Agricultural biotechnology

This section focuses on the potential, risks and likely benefits of agricultural biotechnology to 2030. The benefits of agricultural biotechnology arise from its potentially large contribution to productivity gains and quality improvements. Productivity gains encompass essentially all factors of agricultural production: higher returns on land and livestock, labour and capital or simply lower input requirements per unit of outputs. This may mean higher crop and livestock yields, lower pesticide and fertilizer applications, less demanding production techniques, higher product quality, better storage and easier processing, or enhanced methods to monitor the health of plants and animals. Ultimately, higher productivity will result in lower prices for food and fibre, a benefit for all consumers but particularly important for the poor who spend a relatively large share of their incomes on food and fibre.

Higher productivity also holds the key in the fight against rural poverty. The underlying mechanisms of the productivity-poverty nexus have been discussed in Chapter 8. Biotechnology holds the promise of boosting productivity and thus raising rural incomes, in much the same way as the green revolution did in large parts of Asia during the 1960s to 1980s. It could kick-start a new virtuous cycle of productivity growth, increased output and revenues.

But there are also numerous risks and uncertainties associated with these new technologies that have given rise to a host of concerns and questions.

The most important of these is whether and how developing countries can actually harness the potential of biotechnology to promote production and the productivity of the poor. This in turn raises other questions. Whether and to what extent are the needs of developing countries being taken into account in current research efforts? How fast and to what extent have GM crops been adopted by developing countries? Which crops took the lead? Are the products developed by and for developed countries suited to the economic and ecological environments of developing countries and to what extent will developing countries develop their own biotechnology applications? More specifically, will "orphan" crops such as millet or bananas, which often play a vital role in the livelihoods of the poor, receive sufficient attention by new research? Will farmers in developing countries be trained and equipped to reap the benefits of the new technologies? Will the proliferation of GM-based crops and livestock further weigh on biological diversity? How can consumer concerns about environmental safety and potential human health hazards be taken into account, at low costs and without unduly distorting international trade? The parameters that determine the answers to these questions are changing quickly and it is therefore impossible to provide definite answers, particularly in view of the long-term perspective of this study. Instead, the following section will discuss some of the factors that are likely to affect the development and adoption of these new technologies in the future.

11.4.1 What is agricultural biotechnology?

Many traditional forms of biotechnology continue to be used and adapted. Some biotechnologies, such as manipulating micro-organisms in fermentation to make bread, wine or fish paste, or applying rennin to make cheese, have been documented for millennia.

Modern biotechnology takes various forms. These include: (i) tissue culture, in which new plants are grown from individual cells or clusters of cells, often bypassing traditional cross-fertilization and seed production; (ii) marker-assisted selection (MAS), in which DNA segments are used to mark the presence of useful genes, which can then be transferred to future generations through traditional breeding using the markers to follow inheritance; (iii) genomics, which aims to describe and decipher the location and function of all genes of an organism; and (iv) genetic engineering, in which one or more genes are eliminated or transferred from one organism to another without sexual crossing. A GMO, also referred to as a living modified organism (LMO) or transgenic organism, means any living organism that possesses a novel combination of genetic material obtained through the use of modern biotechnology.[1]

Marker-assisted selection. Traditionally, plant breeders have selected plants based on their visible or measurable traits (phenotype). But this process was often difficult, slow and thus financially costly. MAS helps shorten this process by directly identifying DNA segments (genes) that influence the expression of a particular trait. The markers are a string or sequence of nucleic acid that makes up a segment of DNA.[2] As more and more markers become known on a chromosome, it is possible to create a detailed map of the markers and corresponding genes that codify certain traits. Using detailed genetic maps and better knowledge of the molecular structure of a plant, it is possible to analyse even small bits of tissue from a newly germinated seedling. Once the tissue is analysed, it is possible to check whether the new seedling contains the specific trait.

These new techniques are also important because they are not stigmatized by the negative attributes associated with GMOs, which have resulted in growing concerns about the safety of these new products for consumers and the environment (see below). They have revolutionized conventional breeding and help accomplish significant genetic improvements across almost all crops and livestock. And, should consumers' concerns *vis-à-vis* GMOs become more important, they could become the most crucial biotechnological application in the future.

1 This definition of LMO is taken from the Cartagena Protocol on Biosafety, Article 3(g). In Article 3(i), "modern biotechnology" is defined as "the application of: a. *In vitro* nucleic acid techniques, including recombinant deoxyribonucleic acid (DNA) and direct injection of nucleic acid into cells or organelles, or b. Fusion of cells beyond the taxonomic family, that overcome natural physiological reproductive or recombination barriers and that are not techniques used in traditional breeding and selection".

2 Of particular importance are the so-called quantitative trait loci that represent economically significant expressions of traits such as higher yields, improved quality or better resistance to diseases or various forms of abiotic stress.

Genomics. Genomics is the science of deciphering the sequence structure, the variation and the function of DNA in totality. More important than merely discovering and describing all genes of an organism is to describe the functions of the genes and the interactions between them. So-called functional genomics will help to discover the functionality of all genes, their functional diversity and the interactions between them. Functional genomics is expected to accelerate genetic improvement, the discovery of traits and to help solve intractable problems in crop production.

Recent progress in the mapping of the entire rice genome sequence, with the complete sequence expected to be delivered in 2004, represents a first important step towards understanding the overall architecture of the crop and provides valuable information for other techniques such as MAS or genetic transformation. But this would not yet include a full description of the biological functions of the various DNA sequences and their interactions, which would be a much more important step towards improved varieties. Many more years are likely to pass before all functions of all rice genes will be fully understood.

Genetically modified organisms. *Current trends and applications.* The first GMOs became commercially available in the mid-1990s. Since then, their importance has grown at an astounding pace. The number of GM varieties and species has increased rapidly and the area sown to GM crops has multiplied (some illustrative examples are given in Table 11.3). But the adoption across countries has been very uneven, with almost the entire expansion taking place in developed countries. Similarly, despite the rising variety of GM products available, commercial success has been concentrated on a few varieties or traits, notably herbicide-tolerant (Ht) maize and soybeans as well as *Bacillus thuringiensis* (Bt) cotton and maize. In 2001, Ht soybeans accounted for 63 percent of the area under transgenic crops, followed by Bt maize with a share of 19 percent (ISAAA, 2001).

Insect resistant traits. "Pest-protected" varieties were among the first GM crops to be developed, for the purpose of reducing production costs for farmers. Insect-resistant GMOs have been promoted both as a way of killing certain pests and of reducing the application of conventional synthetic insecticides. For more than 50 years, formulations of the toxin-producing bacteria *Bacillus thuringiensis* (Bt) have been applied by spraying, in the same way as conventional agricultural insecticides, to kill leaf-feeding insects. Studies on the safety of Bt for humans have not revealed any adverse effects on health.

In the late 1980s, scientists began to transfer the genes that produce the insect-killing toxins in bacteria *Bacillus thuringiensis* into crop plants. The intention was to ensure that all cells in these GMOs produced the toxin. Although no efforts were made to increase the growth rates or yield potential of the GM crops with these innovations, farmers have welcomed Bt crops because of the promise of better insect control and reduced costs. However, in the United States, the impact of Bt GMOs on crop yields and the number of conventional insecticide applications have varied widely by location and year. This is partly because of differences between the intended potential impact of the GM crops on target pests and their actual field performance. Some of these differences were a result of the uneven distribution of the toxin within the plants as they grew, some resulted from variations in target and non-target pest populations, and others were the result of toxins accumulating in plant-feeding insect pests, causing mortality of predators and parasites that ate those pests.

Herbicide-tolerant traits. The insertion of a herbicide-tolerant gene into a plant enables farmers to spray wide-spectrum herbicides on their fields killing all plants but GM ones. For that reason, the new GM seeds opened new markets for themselves and for herbicides. In fact, these crops contain a slightly modified growth-regulating enzyme that is immune to the effects of the active ingredient and allows it to be applied directly on the crops and kill all plants not possessing this gene.

Virus resistance. Virus-resistant genes have been introduced in tobacco, potatoes and tomatoes. The insertion of a resistance gene against potato leaf roll virus protects the potatoes from a virus usually transmitted through aphids. For that reason, it is expected that there will be a significant decrease in the amount of insecticide used. The introduction of a virus resistance gene in tobacco may offer similar benefits

Stacked traits. The so-called stacked traits embody a combination of properties introduced through

GM technologies. The most important applications at present are combinations of herbicide tolerance (Ht) and insect resistance (Bt). A number of other combinations have already become commercially available, such as herbicide-resistant maize varieties with higher oil contents. In the future, the addition of more traits with specific value will be added with combinations of stacked traits that provide insect tolerance, herbicide resistance and various quality improvements such as high lysine and/or low phytate content, possibly even in conjunction with higher oil content.

GM farm animals and fish. While there was considerable growth in the development and commercialization of GM crops, GM livestock have largely remained outside commercial food production systems. At the experimental level, more than 50 different genes have been inserted into farm animals, but these efforts still require substantial skill and are not as routine as those for plants. Early research in the development of transgenic farm animals has also been accompanied by manifestations of perturbed physiology, including impaired reproductive performance. These experiences raised ethical problems of animal welfare.

So far, the prospect of foods from transgenic farm animals has not been well received by consumers. Surveys consistently show that the public accepts transgenic plants more easily than transgenic animals. Experimenting with and altering animals are less acceptable prospects and have broader implications. Various cultures and religions restrict or prohibit the consumption of certain foods derived from animals. The use of certain pharmaceutical products from transgenic animals, however, seems more acceptable to the public.

Highly successful research has been carried out on GM fish, but no GM fish have entered the market as yet (see Chapter 7). Most GM fish are aquaculture species that have received genes controlling the production of growth hormones, which raises the growth rate and yield of farmed fish. Ethical questions on the welfare and environmental impact of these GM fish have been raised, but it is also argued that GM fish share many attributes of conventionally selected alien fish species and genotypes, both of which are proven and accepted means of increasing production from the aquatic environment (FAO, 2000f).

How important are GMOs for agriculture? *Current trends.* The importance of GM crops has risen dramatically following the first endeavours of larger-scale commercialization in the mid-1990s. The six-year period from 1996 to 2001 witnessed a 30-fold increase in the global area grown with GM crops. With more than 52 million ha in the year 2001 (Table 11.4), the area planted with GM crops has reached a level that is twice the surface of the United Kingdom. At the same time, the number of countries growing GM crops has more than doubled.

This impressive growth notwithstanding, the annual increments in GM crop area have been levelling off both in absolute terms and in terms of percentage growth. This reflects to a large degree a saturation effect, as certain GM traits (soybeans) account already for a considerable share of the overall area. In addition, there was an actual decline

Table 11.3 A selection of commercially available and important GMOs

GMO	Genetic modification	Source of gene	Purpose of genetic modification	Primary beneficiaries
Maize	Insect resistance	*Bacillus thuringiensis*	Reduced insect damage	Farmers
Soybean	Herbicide tolerance	*Streptomyces spp.*	Greater weed control	Farmers
Cotton	Insect resistance	*Bacillus thuringiensis*	Reduced insect damage	Farmers
Escherichia coli K 12	Production of chymosin or rennin	Cows	Use in cheese-making	Processors and consumers
Carnations	Alteration of colour	Freesia	Produce different varieties of flowers	Retailers and consumers

Source: FAO (2000f).

Table 11.4 Area under GM crops, globally, from 1996 to 2001

	Number of countries	Million ha	Change in area over previous year %	Million ha
1996	6	1.7		
1997		11.0	550	9.3
1998	9	27.8	153	16.8
1999	12	39.9	44	12.1
2000	13	44.2	11	4.3
2001	13	52.6	19	8.4

Source: ISAAA (2001).

in the area planted to GM canola, which is attributed to lower canola prices and the introduction of non-GM herbicide-tolerant varieties in Canada. But this slowdown also coincided with growing consumer concerns in developed countries that the new crops could jeopardize biosafety and pose a serious risk to human health. These fears have led to a growing pressure for legislation to label GM food, to increase the stringency of requirements for their approval and release or even to outright active resistance (Graff, Zilberman and Yarkin, 2000). These concerns were particularly forcefully voiced by consumers in developed countries. As a result, nearly all the additional area grown with GM crops came from developing countries, while area used for GM crops virtually stagnated in developed countries (Table 11.5). Canada's GM area even declined, leaving the United States and Argentina as the principal growers of GM crops with an overall share of 91 percent.

Which GM crops are important? Soybeans, maize, canola and cotton represent almost 100 percent of area grown with GM crops globally in 2001 (Figure 11.5). Ht soybeans alone account for 58 percent of all GM crops. Ht soybeans are not only the most important transgenic crop but, after Bt cotton, also the most rapidly growing one. The rapid market penetration of these first GM crops is impressive, particularly when compared with the introduction of similar technologies, such as hybridized varieties of maize and sorghum. In 2001, GM soybeans accounted for 63 percent of all area under GM crops. GM varieties of maize, cotton and canola accounted for 19, 13 and 5 percent, respectively.

What is in the pipeline? *Input-oriented technologies*. The next important improvement is likely to result from a further market penetration of so-called stacked traits, combining the benefits from two or more genetic modifications. The first stacked traits of cotton and maize (Bt/Ht cotton and maize) have already been released, offering both herbicide tolerance and insect resistance. In parallel, herbicide tolerance and insect resistance are planned to be extended to other varieties, notably sugar beet, rice, potatoes and wheat, while new releases of virus-resistant varieties are expected for fruit, vegetables and wheat. Fungus-resistant crops are in the pipeline for fruit, vegetables, potatoes and wheat. In addition, efforts are being made to create new traits with greater tolerance to drought, moisture, soil acidity or extreme temperatures. Chinese researchers claim to have developed salt-tolerant varieties of rice, which could help mitigate water scarcity and allow land lost to salinization problems to be recovered. The potential to cultivate marginal land appears to be particularly interesting for poorer farmers who are often more dependent on these environments. However, the ability of poor farmers to pay for these new technologies may be much more limited. This suggests that both speed of research and speed of introduction in the field are likely to be less impressive than for the first generation of GM crops.

Output-oriented technologies. A shift in focus is expected with the transition from the first to the second generation of GM crops. The new generation of GM crops is expected to offer higher output and better quality of the produce. Many of these new traits have already been developed but have not yet been released on the market. They include a great variety of different crops, notably soybeans with

Table 11.5 Area under GM crops by country, 1999 and 2001

	1999		2001		1999-2001	
	Area	Share in global area	Area	Share in global area	Change in area	
	Million ha	Percentage	Million ha	Percentage	Million ha	Percentage
Developed countries	32.8	82	39.1	75	6.3	19.2
United States	28.7	72	35.7	68	7	24.4
Canada	4	10	3.2	7	-0.8	-20.0
Australia	0.1	<1	0.2	<1	0.1	100.0
Others	<0.1	<1	<0.1	<1	n.a.	n.a.
Developing countries	7.1	18	13.5	24	3.6	90.1
Argentina	6.7	17	11.8	23	3.3	76.1
China	0.3	1	1.5	1	0.2	400.0
South Africa	0.1	<1	0.2	<1	0.1	100.0
Others	<0.1	<1	<0.1	<1	n.a.	n.a.
Total	39.9	100	52.6	100	12.7	31.8

Source: ISAAA (2001) and own calculations.

higher and better protein content or crops with modified oils, fats and starches to improve processing and digestibility, such as high-stearate canola, low phytate or low phytic acid maize. Another promising application is cotton with built-in colours that would spare the need for chemical dyes.

First efforts have been made to develop crops that produce nutraceuticals or "functional foods": medicines or food supplements directly within the plants. As these applications can provide immunity to disease or improve the health characteristics of traditional foods, they could become of critical importance for improving the nutritional status of the poor.

In the pipeline are also a number of non-food applications of GM technology. These include speciality oils (e.g. jet engine lubricants), biodegradable thermoplastics, hormones, "plantibodies" (e.g. human antibodies for treatment of infectious and auto-immune disease), vaccines or pharmaceuticals (e.g. anticancer drugs such as taxol) (Thomashow, 1999). Non-food applications that have already reached practical importance include a transgenic variety of *Cynara cardunculus* thistle, which is grown in Spain for electricity generation and GM poplars grown in France for paper production which demand less energy and produce less waste during processing.

The success of the second generation of GM crops will ultimately depend on their profitability at the farm level and their acceptance by consumers. Unlike the first-generation products, quality-focused products such as functional foods provide a higher perceived benefit for the consumer. This may increase the risk that consumers are willing to assume, suggesting a high market potential for the second generation of GM crops.

Specific products in the pipeline

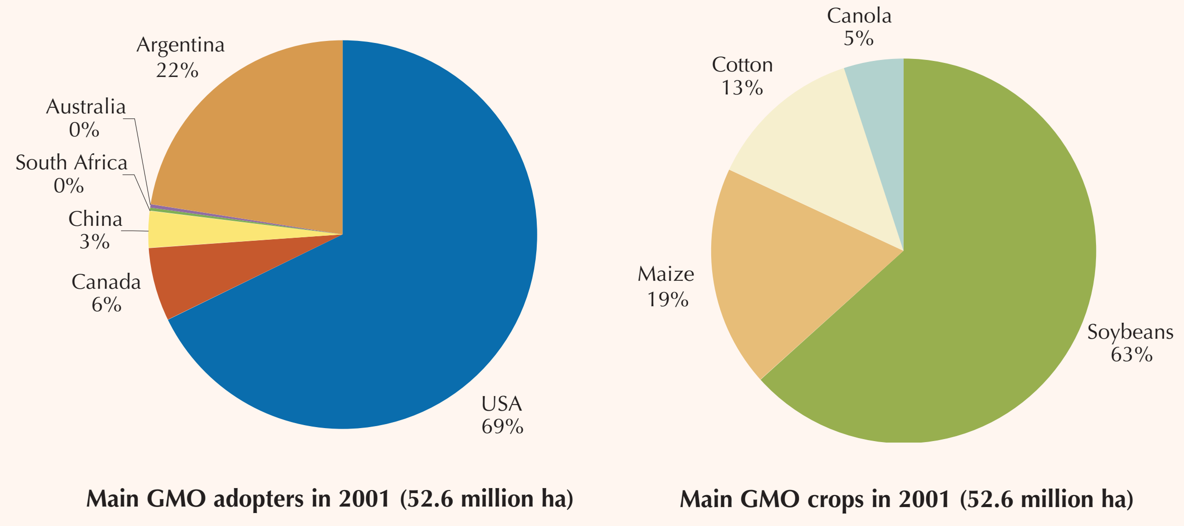
Soybeans

- High oleic soybeans contain less saturated fat than that in conventional soybean oil. The oil produced is more stable and requires no hydrogenation for use in frying or spraying. For that reason, this variety has a "health" image.
- Soybeans with improved nutritional traits for animal feeding contain higher levels of two amino-acids (lysine and methionine) which will reduce the need for higher-cost protein meals in the preparation of feed mixes.
- High-sucrose soybeans have better taste and greater digestibility.

Rapeseed and canola

- High-lauric variety produces an oil containing 40 percent of lauric acid for chemical and cosmetic purposes.

Figure 11.5 GMO crops by country and crop



Source: ISAAA (2001).

- High-stearate variety produces oil high in stearic acid, solid at room temperature without hydrogenation. This oil could be used for baking, margarine and confectionery foods that cannot use liquid oils.

Maize

- Several researches, both conventional and biotechnological, aim to produce value-enhanced maize that will offer improved nutritional traits for livestock. Since grain is fed primarily as a source of energy, many of the new value-enhanced varieties aim to increase the content or availability of energy. But some new varieties will also include more protein and better amino-acid balances, which would reduce the need to buy supplemental feed ingredients.

Cotton

- Coloured cotton is already available on a niche market basis. This trait would reduce the need for chemical dyes. Fibre quality improvement, such as polyester-type traits, would make sturdier fabrics.
- Chinese researchers are breeding a new strain of cotton that includes rabbit keratin. Fibres of this cotton are longer and more resilient and they have an increased ability to maintain warmth. Research is also being carried out to develop wrinkle-resistant cotton and even fire-retardant qualities.

Prospects for the nearer term. Given the enormous speed of progress in generating and adopting new biotechnology applications, any longer-term outlook is necessarily speculative. Somewhat greater confidence, however, can be attached to forecasts of possible developments over the nearer term. The following short-term developments are discernible.

First, adoption rates for GM crops are likely to increase in developing countries. With the rapid adoption of Bt cotton in China, GM crops have made an important inroad into a potentially important market. China's GM potential rests not only on the sheer size of its agriculture but also on the particular importance for China of soybeans, maize, and tobacco – crops in which GM traits have been introduced successfully elsewhere. Moreover, an approval of the respective GM traits in China may have important knock-on effects in other developing countries. The significant catch-up potential in some developing countries, however, masks limiting factors and constraints that prevail elsewhere. To the extent that the new GM products favour capital-intensive and labour-extensive environments, the incentives to adopt these technologies are limited in other developing countries.

Second, growth of the area under traditional GM crops such as Ht soybeans and Bt maize is likely to slow down. This is in part a reflection of the impressive growth in the past, which limits the remaining potential. GM soybeans, for instance, already account for two-thirds of soybean area worldwide and for an even larger share of developed countries' soybean area. An expansion of GM soybeans must therefore come from an overall growth in soybean area rather than from a shift out of non-GM soybean production. Growth may also be curbed because of food safety and environmental concerns that have received particular attention in Europe.

Third, there is a considerable growth potential for new GM applications in developed countries. Examples include GM fish varieties or GM crops for renewable energy. Other possibilities are GM-based nutraceuticals or GM applications for health and cosmetic applications. As these new applications are likely to produce much wider benefits than just cheaper food and feedstuffs, consumers in developed countries are also more likely to accept greater risks and thus to adopt these non-traditional applications at faster rates.

Prospects for the medium and longer term. Substantial progress has been made over the last five years, both in terms of theoretical advances and practical importance of biotechnology. These advances over such a short timespan make it impossible to identify specific products that are likely to dominate developments in biotechnology over the next 30 years. It is, however, easier to identify the overall parameters that are likely to affect future trends.

The overall direction of research and development is likely to be determined by economic incentives. Developments in prices of production factors and products are critical in the context of a 30-year outlook. These, in turn, will be crucially affected by future changes in the relative abundance/scarcity of production factors, notably land, capital and labour. In developed countries, costs of labour may increase relative to land, which would favour the further development of labour-saving technologies. In developing countries, by contrast, factor proportions may change in the opposite direction with increasingly abundant labour and increasingly scarce land. This would favour labour-intensive and land-saving technologies. The critical question in this regard is whether and to what extent the private sector will cater for diverging needs and to what extent investments from the public sector are needed to reconcile these needs.

Many of the currently available technologies have catered for land-intensive and labour-extensive environments. This is particularly noticeable

Box 11.3 Golden rice: a polarized debate

There is still considerable uncertainty as to how much of the potential of GM crops can be harnessed for the benefit of the poor. The most prominent example in this context is the so-called "golden rice", a betacarotene-enriched variety that was developed with the help of free-of-charge licences from a number of life science companies. The proponents of the technology claim that "golden rice" provides a low-cost means to alleviate one of the gravest health problems of the developing world. The main goal of this development was the creation of a tool to help combat vitamin A deficiency (VAD), a public health problem that affects 118 countries and more than 400 million people worldwide, especially in Africa and Southeast Asia, and that most affects young children and pregnant women. As betacarotene is provided through rice which is the main staple food in many developing countries, the distribution is largely self-targeting.

Opponents, however, underline that these new varieties include too little betacarotene and that it would be impossible to cover needs through golden rice alone. They claim that the returns on the investment of US$300 million are relatively small and that the same effects could be achieved by a combination of existing tools. Critics also argue that VAD is not best characterized as a problem, but rather as a symptom of broader dietary inadequacies associated with both poverty and agricultural transition from diverse cropping systems to rice monoculture. It would therefore be more important to have a more varied diet rather than relying too heavily on "a magic-bullet solution" while leaving poverty, poor diets and extensive monoculture intact. Moreover, opponents suggest that golden rice could have counterproductive impacts on nutritional problems by curtailing the progress made in educating people to diversify their diet and increase the diversification of agriculture production. Finally, if only a limited number of varieties were genetically modified and widely cultivated, this would have a negative impact on crop biodiversity.

for GM crops, where productivity gains are based on savings in input needs (labour, capital) even when output (yields) is stagnant or declining. This was one of the main factors that contributed to the high adoption rates for GM crops in developed countries. If today's relative factor proportions are a guide to the future, the incentives to adopt these new technologies in developing countries are likely to be subdued. Moreover, private investors have little incentive to provide proprietary technologies where the chances of recouping investments in research and development are small. This suggests that the public sector will have to play a significant role in providing the technologies to cater for the specific needs of developing countries.

11.4.2 Why agricultural biotechnology matters to developing countries

The principal benefits. *Productivity gains.* Biotechnology has the potential to increase crop and livestock yields. The first generation of GM crops was largely input-oriented and provided the same or only marginally increased yield potential. The fact that some GM crops rendered higher yields in practice largely resulted from the effect that "built-in" inputs such as pesticides have reduced output losses that are typically caused by inappropriate or inadequate input applications. Moreover, the fact that GM technology embodies this expertise directly into the seeds is particularly important for environments where sophisticated production techniques are difficult to implement or where farmers do not command the management skills to apply inputs at the right time, sequence and amount. This suggests a much larger potential for GM crops (stacked traits of Bt/Ht cotton or Bt/Ht maize) in developing countries even for the first generation. The second generation of GM crops is expected to raise both the volume of output and the quality of the produce. These technologies are currently being tested but only a few traits are available in practice.

More, cheaper and better food. A second factor arises from the prospects for lower prices for better food. Higher productivity lowers production costs and will ultimately result in lower food prices. While this is not in itself a guarantor of improved food security or reduced poverty, more and better food at lower prices is particularly important for poor consumers. They would particularly benefit where GM products offer less expensive and nutrient-enriched food staples, which account for a large share of their food expenditure.

A higher capacity to feed a more populous world. The capacity that GM crops offer to produce more and better food is even more important when the future food needs of growing populations are considered. Much of the incremental food production in the future has to come from higher yields, yet the potential to raise actual yields through more traditional agronomic improvements such as earlier ploughing, scotch carts, higher fertilizer and pesticide applications is declining. A slowdown in yield growth has already been observed in some high-intensity systems in Asia, where the gap between yields attained by farmers and the economic maximum yield has narrowed noticeably.

The potential to save and improve resources or recoup marginalized land. A fourth factor is the potential to save resources or recoup marginalized land. Empirical studies suggest that the poor are cultivating the most marginal agronomic environments, and that they are more often dependent on these marginal growing environments than other groups.[3] These marginal production environments are often characterized by drought or moisture stress, extreme temperatures, soil salinity or acidity. The potential to grow food in such environments is therefore doubly important in the fight against hunger and poverty: the potential to produce food where food is needed most helps ease the food problems of the poor directly. Moreover, to recoup land that was lost through environmental stress (e.g. soil salinity or acidity) could help contain further encroachments on areas with high environmental value or high sensitivity.

More and better non-food products. GM crops could also offer a more attractive way to produce non-food products. Plants with higher energy conversion and storage capacities could be bred and make a more meaningful contribution to alternative energy use in the future. If successfully implemented on a large scale, this could boost agriculture's role as a carbon sink. Transgenic plants and animals could significantly extend the possibilities of various areas of technology and overcome some

3 In fact, these environments are available to the poor because only the poor are willing to accept the low factor returns (wages) for the inputs they can provide (low-skill labour).

Box 11.4 GURTs: technical aspects and possible impacts

What are GURTS?

The acronym GURTs stands for genetic use restriction technologies and refers to biotechnology-based switch mechanisms to restrict the unauthorized use of genetic material. Two types of GURTs can be distinguished: variety use restriction (V-GURTs), rendering the subsequent generation sterile (the so-called "terminator" technologies), and use restriction of a specific trait (T-GURTs), requiring the external application of inducers to activate the trait's expression.

… and what are their principal impacts?

Agricultural biodiversity. Impacts on agricultural biodiversity will vary across different farming systems. In low- and medium-intensity farming systems a change from local to GURT varieties may imply a loss of agricultural biodiversity while in high-intensity farming systems the impact may be minor.

The environment. While the environmental containment aspect of GURTs may reduce potential risk associated with eventual outcrossing, there remains a possibility of pollination of neighbours with GURTs pollen, leading to yield drops in cultivated areas, as well as to alteration of wild ecosystems.

Research and development. By stimulating further investment, GURTS may increase agricultural productivity in certain farming systems. However, restricted introgression of genes from GURTs into local gene pools may reduce incentives for farm-level breeding, if desirable traits in introduced GURTs varieties cannot be accessed, widening the technological and income gap between resource-poor and better-off farmers.

Market structure. While strengthened control over the use of GURTs products may likely increase investment in further breeding, GURTs may well reinforce the concentration and integration trends in the breeding sector in such a way as to lead to possibilities for misuse of monopoly power, rendering farmers fully dependent on formal seed supply systems.

Food security. GURTs could also increase the seed insecurity of resource-poor farmers who cannot afford to purchase seed and who depend on the local grain market for their seed needs. This may generate a low level of acceptance by low-income farmers in developing countries.

Source: FAO (2001k)

of the traditional constraints that medical research and applications face today.

The principal concerns. Notwithstanding the potentially large benefits of GM technology for developing countries, there are growing concerns that these new technologies are associated with significant costs, risks and problems.

Market concentration in the seed industry. Some concerns have arisen out of the significant market concentration in the seed industry. In 1998, 60 percent of the world market for seeds was controlled by just 35 companies. One company alone controlled over 80 percent of the market for GM cotton, 33 percent of the market for GM soybeans and 15 percent of the GM maize market (Then, 2000). This growing horizontal concentration is accompanied by an increasing vertical concentration between seed producers and agrochemical companies whereby larger agrochemical companies have been absorbing the few large seed companies that resulted from the horizontal consolidation process within the seed industry. The trend towards larger and more integrated operations (the so-called life science companies) was largely driven by the chemical industry. Chemical firms were looking for partners in the seed industry to protect the value of their intellectual property rights (IPR) in patented herbicides (Just and Hueth, 1999). The consolidation process between the agrochemical and the seed industry is currently being extended to a third stage, as the life science companies broaden their reach through strategic alliances with major trading companies such as Cargill or ADM. While this concentration process has offered new possibilities to reap scale effects and to overcome barriers in creating and commercializing GM products, it has also given rise to concerns that these non-competitive market structures may impose significant social and private costs (Phillips and Stovin, 2000). These are only now being considered.

Intellectual Property Rights (IPR). The impact of the application of IPR, the mechanisms for their enforcement and the excludability that is associated with them is another source of concern. In general, the excludability is of critical importance in encouraging private research in all sectors. Without it, innovators would not be able to recoup their investments, private research would languish, productivity gains would slow down and social welfare would suffer. Recognition of the importance of IPR has brought about a strengthening of legal protection for biotechnology processes and products and spurred on significant private investment in biotechnology. But the strengthening of IPR has also given rise to concern. First, the scope of intellectual property protection may be too wide, thereby choking off spillovers, follow-on innovations and diffusion. Second, IPR afford private companies the possibility of protecting the alteration of a single gene derived from freely accessible germplasm that has been generated by farmers and public research efforts over centuries. Developing countries in particular believe that they should be compensated for their contributions to existing genetic resources. The International Treaty on Plant Genetic Resources for Food and Agriculture (PGRFA), adopted in November 2001, addresses these concerns (Box 11.5). It could assume a pivotal role in facilitating access to plant genetic resources in the future and in safeguarding traditional indigenous contributions to the breeding process (farmers' rights).

Biosecurity. A third area of public concern revolves around the risk that biotechnology applications in food and agriculture pose to human health and the environment. Consumers in all countries would like assurances that GM products reaching the market have been adequately tested, and that these products are being monitored to ensure safety and to identify problems as soon as they emerge. Because of the complexity of food products, research on the safety of GM foods is thought to be more difficult than carrying out studies on components such as pesticides, pharmaceuticals, industrial chemicals and food additives. Through the Codex Alimentarius Commission and other fora, countries discuss standards for GMOs and ways to ensure their safety. One approach, which is being used in assessing the risks of GMOs, derives from the concept of substantial equivalence.[4] If the GMO-derived food is judged to be substantially equivalent to its traditional counterpart, then it is considered as safe as its conventional counterpart. If it is not, further tests are conducted.

Critics claim that only 1 percent of public research funds has been allocated to assess the risks associated with the introduction of GM technologies. It is suggested that the experience with traditional counterparts cannot be applied to products based on GM technology, as the substantial equivalence approach implies, and that the new technologies require a new risk assessment approach. Underestimating or ignoring the risks means that external costs associated with the technology are not fully accounted for and that the welfare gains of the new technology may be overstated. The recent accidental use for human food consumption of GM maize that contains a potentially allergen protein has reinforced such concerns.

Genes can end up in unexpected places. The artificially inserted genes might be passed on to other members of the same species, and perhaps to other species. Antibiotic-resistance genes are often inserted into GMOs as markers so that researchers can tell whether gene transfer has succeeded or not. These genes may be transferred to bacteria within the human body with yet unclear impacts. While this technique is now being replaced, other problems may remain. There is even a possibility that the gene for herbicide resistance may transfer to weeds, with potentially disastrous impacts for agriculture and food security.

Genes can mutate. It is still unclear what impact the artificially inserted gene has on the stability of the genome. There are claims that it may cause more unexpected mutations. While mutations could be neither new nor necessarily bad, GMOs may cause unexpected and undesirable instability.

"Sleeper" genes could accidentally be switched on. Organisms can contain genes that are not activated except under certain conditions, for example under the influence of pathogens or as a result of certain

[4] Substantial equivalence acknowledges that the goal of the assessment is not to establish absolute safety but to consider whether the GM food is as safe as its traditional counterpart, where such a counterpart exists. It is generally agreed that such an assessment requires an integrated and stepwise, case-by-case approach. Factors taken into account when comparing a GM food with its conventional counterpart include: (i) identity, source and composition; (ii) effects of processing and cooking; (iii) the transformation process, the DNA itself and protein expression products of the introduced DNA, and effects on function; and (iv) potential toxicity, potential allergenicity and possible secondary effects; potential intake and dietary impact of the introduction of the GM food.

Box 11.5 The International Treaty on Plant Genetic Resources for Food and Agriculture

A new International Treaty on Plant Genetic Resources for Food and Agriculture (PGRFA) was adopted by the FAO Conference in November 2001. The main areas covered by the treaty include: (i) a multilateral system of access and benefit sharing of plant genetic resources for major food crops; (ii) an agreement on access to *ex situ* genetic resources not covered by the Convention on Biological Diversity (CBD); and (iii) a recognition of the contributions of local and indigenous communities and farmers to PGRFA (farmers' rights). The PGRFA covered by the treaty include most major food crops (cereals such as rice, wheat, maize, sorghum and millet; grain legumes such as beans, peas, lentils, chickpeas and cowpeas; roots and tubers such as potatoes, sweet potatoes, cassava and yams), plus a list of forages (32 genera). The treaty will enter into force once it has been ratified by 40 or more countries. This is expected to be in 2003 or 2004.

Provision of access and benefit sharing. The treaty provides for facilitated access to material in the multilateral system for the purposes of food and agriculture research, breeding and training in this area. It obliges signatories to provide access to PGRFA listed in the multilateral system for the purposes listed above. The treaty also provides that benefits arising from the use, including commercial use, of PGRFA under the multilateral system shall be shared fairly and equitably through exchange of information, access to and transfer of technology, capacity building and the sharing of the benefits arising from commercialization. It includes special provisions for monetary benefit sharing in the case of commercialization of products that are PGRFA and that incorporate material accessed from the multilateral system.

Conservation of PGRFA. The treaty also calls for an integrated approach to the exploration, conservation and sustainable use of PGRFA and includes specific provisions on surveying, inventorying and collecting PGRFA, as well as on *in situ* and *ex situ* conservation. Explicit reference is given to "onfarm" conservation by farmers, as distinct from in situ conservation of wild PGRFA. It requires parties to develop and maintain appropriate policy and legal measures that promote the sustainable use of PGRFA.

Farmers' rights. The treaty also addresses the need to "recognize the enormous contribution that the local and indigenous communities and farmers of all regions of the world, particularly those in the centres of origin and crop diversity, have made and will continue to make for the conservation and development of plant genetic resources which constitute the basis of food and agriculture production throughout the world". Three substantive elements of farmers' rights are included: (i) protection of traditional knowledge relevant to PGRFA; (ii) the right to participate equitably in sharing benefits arising from the utilization of PGRFA; and (iii) the right to participate in making decisions, at the national level, on matters related to the conservation and sustainable use of PGRFA.

Source: Cooper and Anishetty (2002)

weather conditions. The "promoter" gene that is used to insert the new gene could activate "sleeper" genes, potentially in inappropriate circumstances.

Allergens can be transferred. Genes that cause allergies could be transferred into another species. The problem is twofold: it extends the range of potentially allergen products and creates uncertainty as to what products are potentially allergens. For example, an allergenic Brazil-nut gene was transferred into a transgenic soybean variety. It was found in testing, and the soybean was not released.

Sterility could be transferred. There is the theoretical risk that a dominant gene from a GURT plant could be passed on through cross-pollination to non-GURT plants, thereby reducing their fertility rate. However, this risk would be relatively small and, even if it were to happen, the inherited dominant non-germination gene would anyway be self-eliminating.

Controls over GM releases are inadequate. In 2000, a maize variety intended only for animal feed was accidentally used in products for human consumption. There is no evidence that this variety was dangerous to humans, but it could have been.

Animal welfare is at risk. There is evidence of abnormal physiology in some transgenic animals. Some effects on animals are unpredictable and could range from benign to distressful to dangerous.

Unintended effects on the resource base. Unusual traits in a plant could have unintended effects on the farming system. For example, a wheat variety capable of extracting more nutrients from the soil may exhaust the soil. Plants bred for land that has been made saline by unsuitable irrigation may enable a farmer to use even more brackish water, destroying the land completely.

Loss of biodiversity. GM plants could compete with traditional farmers' varieties, causing loss of crops that have been bred for millennia to cope with local stresses. For example, the existence of traditional potato varieties in Latin America permitted a recovery from the catastrophic potato blight in Ireland in the 1840s. Today, traits from farmers' varieties and wild relatives are often used to improve climate tolerance and disease resistance. GM crop varieties might also cross, and thus compete, with wild relatives of crops such as wheat and barley. This is especially risky in the developing world, where wild relatives may be found growing close to farmed crops.

11.4.3 Who benefits and who bears risks and costs?

The principal problem: disjoint risks and benefits. As with any new technology, there are winners and losers associated with the use of GMOs and biotechnology. At country level, the costs and benefits accrue to different stakeholders and cause concerns about, or even the outright rejection of, the new technology. Addressing and reconciling these problems are part of the policy response of the respective country. A second, less common source of concern emerges when risks and benefits accrue to stakeholders in different countries. This either requires international policy coordination or leaves externalities unaddressed. The introduction of GM technology is associated with both dimensions of the problem, i.e. there are disjoint risk and benefits within and across countries. An analysis of these disjoint costs and benefits may help identify appropriate policies. It may also provide insights as to what directions the new technologies will take.

Rich versus poor countries. The risks and benefits associated with an innovation are the principal determinants for the degree of adoption by a country. The willingness to assume risks may therefore be disconnected from the extent and possibility of capturing the benefits of GM technologies. The disconnection of risks and benefits affects numerous stakeholders: consumers versus producers, developed versus developing countries and private companies versus public research institutions. For example, the benefits of GM maize – and thus the willingness of rich societies to assume the associated risks – may be too small to pursue the technology. The benefits of the same technology for poor societies may be large, but their ability to pay for it is too small to develop it. If left unaddressed, such disjoint interests can result in a situation that neglects the interests of the poor. Bridging these gaps calls for appropriate policy action and for international policy coordination.

High-value versus low-value goods. The willingness of a society to bear the risks of a new technology is positively related to the benefits drawn and expected from it. The benefit from cheaper food staples such as rice, maize or soybeans is likely to be small for rich consumers in the north and high for poor consumers in the south. Rich consumers are therefore unlikely to assume the same risks as poor consumers and, if the benefits are sufficiently small, they are rational to reject the new technology altogether.

Consumers in the developed countries accept the higher risks for functional food, medical applications or cosmetics as the (perceived) benefits from these applications exceed the risks that they carry. But given the small benefits from less expensive food staples for the same consumers, staples such as rice, wheat or coarse grains are likely to be most affected by a decline in research expenditure. Even more so are tropical staples such as some roots and tubers. But such food staples are of critical importance for consumers in developing countries, particularly for the rural poor.

What does it mean for the direction of research? The different perception and importance of risks and benefits in developed and developing countries could reduce the speed of progress and change the direction of GM research and development. In the north, which has the funds to afford research, consumers perceive the risks associated with these technologies to be high and their benefits to be small. Yet the greatest need and the greatest benefits are in the south, where the ability to pay for the development of the technologies is small. The allocation of risks and benefits could mean that the north may reduce investments in these technologies, as the consumers in the north are unwilling to accept their products, while the consumers in the south, in need of the products, are unable to pay for the technology.

Where the south can afford to develop and import the technology, this may adversely affect trade in the final products. GM-based food and fibre may be faced with growing non-tariff barriers, which reflect the lower willingness to accept risks in the north or an added form of protecting domestic agriculture. A smaller market volume for GM crops in turn may adversely affect the profitability of developing the new technology. A lack of market access may render research and development non-viable for the south.

What policies could help to reconcile risks and benefits? Appropriate policy action could help reconcile some of the conflicting interests of the various stakeholders.

Addressing the concerns of consumers in developed countries: more transparency. Part of the risk that makes consumers in developed countries reluctant to accept GM products is not actual risk but perceived risk. In part, this risk perception reflects a lack of transparency and calls for measures that help to maximize transparency for the consumer. Appropriate labelling is an important step towards higher transparency and thus towards lower risk. It would also help facilitate trade since labels help products to comply with international standards. However, excessive labelling requirements may result in "regulatory capture", which in itself is detrimental to trade. Moreover, labelling of GM food requires segregation of GM from non-GM products and can generate substantial additional costs and incentives for fraud. The higher costs of segregation are a particular problem for poorer countries that often lack the necessary regulatory capacity.

The second part of the risk that consumers in developed countries face is real. It is a reflection of insufficient testing and premature releases of GM crops for field applications. This calls for better risk assessment procedures and commensurate rules and regulations to minimize the risks associated with applying GM technology.

Addressing the concerns of developing countries: lowering seed costs. A crucial factor that limits access to the new technologies in developing countries is the high cost of GM seeds. To the extent that high seed costs reflect the monopoly rents from a lack of competition in the life science industry, antitrust measures could provide a remedy. In addition, national and international research institutions themselves could charge royalties for the germplasm that has traditionally been provided free of charge to the private sector. These payments could then be used to promote targeted GM research for developing countries. This, of course, may reduce the overall incentive for the private sector to invest in crop research and could result in an overall loss in productivity.

Private-public partnerships in GM research. The public sector could explore a number of routes to collaborate with the private sector to target developing countries' specific needs, such as poverty reduction, public goods provision and the capture of spillover effects. National and international research institutions could define specific breeding tasks, or the development of field-proven varieties with certain characteristics and put them out for competitive tender. Companies could use their patented germplasm as an input into work under such tenders, but the final product would have to be made available free of IPR charges or genetic technical use restrictions (Lipton, 1999).

11.5 Directions for agricultural research

Agricultural research has been crucial in meeting the challenge of increasing food production faster than population growth over the past 50 years. A main characteristic of research efforts was the focus on increasing productivity through a set of technologies in what has come to be known as the green revolution. The impressive global achievements mask considerable regional differences. Asia received most attention while sub-Saharan Africa was largely bypassed, as were, within many countries, the remote and poorest communities that did not have the resources, physical and financial, to capitalize on the potential of the new high-input demanding technologies (Conway, 1997). Also, the impacts of the new technologies on the environment (see Chapter 12) were largely ignored in the early years of the green revolution.

What has emerged most strongly in various reviews of the green revolution is that development of technologies by themselves is not enough. Relevant and sustainable technology innovation must be planned, developed, tested and delivered within a broad-based agricultural and rural development framework. Nor can productivity be the sole criterion to guide technology development; the potential implications of technologies for agro-ecological stability and for sustainability and equitability must be fully addressed at the "drawing board" stage. This has fundamental implications for the planning of future agricultural research strategies.

To meet the food security needs of an expanding global population in the decades ahead and to reduce poverty, there is a need to maintain and increase significantly agricultural productivity on land at present available across the developing world and at the same time to conserve the natural resource base. This will require (i) increasing productivity of the most important food crops both on the more fertile soils and on marginal lands; (ii) exploring possibilities for limiting the use of chemical inputs and substituting these inputs with biologically based inputs; (iii) more precise use of soil, water and nutrients in optimized integrated management systems; and (iv) increasing production efficiency and disease tolerance in livestock.

These challenges call for a comprehensive and complex research agenda that must integrate current advances in the molecular sciences, biotechnology and plant and pest ecology with a more fundamental understanding of plant and animal production in the context of optimizing soil, water and nutrient-use efficiencies and synergies. Effective exploitation of advances in information and communication technology will be necessary not only to facilitate the necessary interactions across this broad spectrum of scientific disciplines but also to document and integrate traditional wisdom and knowledge in the planning of the research agenda and to disseminate the research results more widely. This agenda calls for a three-dimensional research paradigm that integrates scientific investigation across genetics and biotechnology, ecology and natural resources and not least socio-economics to keep in focus the development environment that characterizes the livelihoods and food security of the poor.

The first dimension (genetics and biotechnology) has been discussed in the preceding section. The following section will focus on the other two dimensions.

Ecology and natural resources management research. A comprehensive understanding of the ecology of all life forms within the farming system is a prerequisite to the development of sustainable agriculture in the context of sound knowledge-driven use and management of the natural resources with which the farming system interacts. Recent advances in ecology have been described alongside molecular genetics as the second great revolution in modern biology. The past decade or so has seen the use of mathematical modelling, the articulation of comprehensive hypotheses and advances in experimental design in support of more precise laboratory and field experiments. These trends have transformed the study of ecology into a rapidly developing science (Begon, Harper and Townsend, 1990), which should lead to a better understanding of the complex dynamics that are at work within agricultural systems. Increasingly, natural resource management calls for closer collaboration between ecologists and agricultural scientists whether they are addressing technical (biotic or abiotic), social or economic dimensions of agricultural development. By definition, agro-ecosystem research embraces the "ecological and socio-economic system, comprising domesticated plants and/or animals and the people who husband them, intended for the purpose of producing food, fibre or other agricultural products" (Conway, 1987).

Within the biophysical boundaries of the ecosystem, ecological research has much to contribute at three levels: (i) at the level of the plant, its pests and predators; (ii) at the level of the plant and its competition from weeds; and (iii) at the level of the plant rooting system and the roles of beneficial and competing micro-organisms in the capture and utilization of soil nutrients. Research at the plant-pest-predator level is opening up new insights in pest control, in one measure through the genetic development of pest-resistant plant varieties and, at the other end, in the refinement of IPM.

At the level of plant-weed competition, the geneticist's approach has been to develop herbicide-resistant crops, while the ecology-based approach has been to develop crop rotations and intercropping and high-density systems that minimize weed damage. Both approaches require still further research, particularly with greater focus on marginal lands and food crops that are mostly grown by the poor. More fundamentally, a better understanding of plant genetics and of plants' relation to other competing plants may offer new insights to stable cropping systems. This would provide a more informed basis on which to design cropping systems and rotations that can sustain higher and more stable yields.

At the plant rooting levels, there is a need for much more fundamental research at the physical, biochemical/physiological and genetic bases of plant-micro-organism interactions and symbiosis (Cocking, 2001). Nutrient utilization and biological nitrogen fixation lie at the heart of this research, which can have enormous benefits for low-input agriculture and the poor. The benefits to sustainable agriculture and the environment are obvious in the reduction of dependence on chemically produced nitrogenous fertilizer and associated greenhouse gas emissions. Future ecosystem research must also address soil nutrient availability and utilization more comprehensively within alternative cropping systems in the context of NT/CA, integrated cropping and crop-livestock systems.

At the community and watershed levels, agro-ecology, ecosystem and natural resources management research must address the biophysical and socio-economic dimensions of resources use and their potential enhancement and/or depletion. In this context, CGIAR has recently articulated a comprehensive agenda of integrated natural resources management research that embraces the more important topics that need to be addressed (CGIAR, 2000):

- *Water:* model system flows (river-basin level) allocated across multiple users, with particular attention to onsite and offsite effects, develop recharge balance models for aquifers at risk of excessive drawdown.
- *Forests:* characterize the complexity of forest systems and the range of stakeholders who interact with them, and develop strategies to influence the global policy agenda.
- *Fisheries:* identify the types of farming systems and agro-ecologies into which integrated aquaculture-agriculture can be sustainably incorporated.
- *Livestock:* develop databases, models and methods for analysing livestock-based systems to help identify priorities for research and development interventions.
- *Soils:* develop soil erosion models for various multifunctional land use systems, and nutrient balance and flow models.
- *Carbon stocks:* document and model alternatives for above and below ground carbon stocks and relate changes in those stocks to global climate change impact.
- *Pest and disease incidence:* describe, define and track key insect pests using GIS and develop models that relate incidence to agroclimatic conditions.
- *Biodiversity:* project alternative scenarios of functional biodiversity under different land management systems.

Research priorities for the poor. Defining research priorities (and the development of stakeholder-specific research agendas) is becoming a complex and increasingly sophisticated process. It demands the interactive interpretation of information flows between the scientist and the end-user of research outputs. The criteria for making strategic choices among alternative research programmes vary depending on the stakeholder. In private-sector-funded research, the ultimate criterion is profit in one form or another. In academic research the goal is often loosely defined around scientific advancement and knowledge. And in national and international research institutions the broad objective is primarily the production of information and products for the "public", usually termed "public goods".

Establishing research priorities that specifically address the needs of the poor or multidimensional goals such as food security, sustainability, conservation of biodiversity and natural resources, becomes increasingly difficult as the distance (socio-economic as well as spatial) between the research planners and the target beneficiaries widens. In essence, bridging this gap is the challenge of the new research agenda, not only at the research planning stage but also at the interpretation and field-testing stage of the technologies and other research outputs.

In determining research priorities, it is also vitally important to understand how new technologies may influence the lives and livelihoods of the poor. New technologies can lead to increased productivity on the family farm, resulting in increased food consumption and family incomes. Such technologies can result in lower food prices, benefiting a wide range of the urban and rural poor. Growth in agricultural output generally leads to increased employment opportunities for the landless and the poor in both the rural and urban non-farm economy. Perhaps not emphasized adequately in research programmes is that new technologies can lead to the production of food crops rich in specific micronutrients that are often deficient in the diets of the poor.

Research to underpin a new technology revolution with greater focus on the poor must put special emphasis on those crop varieties and livestock breeds that are specifically adapted to local ecosystems and that were largely ignored throughout the green revolution. These include crops such as cassava and the minor root crops, bananas, groundnuts, millet, some oilcrops, sorghum and sweet potatoes. Indigenous breeds of cattle, sheep, goats, pigs and poultry and locally adapted fish species must also receive much greater priority. A particular focus in the new research agenda should be on plant tolerance to drought, salinity and low soil fertility as nearly half of the world's poor live in dryland regions with fragile soils and irregular rainfall (Lipton, 1999).

Research modalities and dialogue. Research that addresses only one component in the development chain, for example crop yield potential, will not result in an equitable or sustainable increase in food production. New research efforts should address a minimum of four critical questions at key salient points along the research continuum, from the conception/planning stage to the stage of application of the outputs by the targeted beneficiary. The key questions are: (i) whether the technology will lead to higher productivity across all farms, soil types and regions; (ii) how the technology will affect the seasonal stability of production; (iii) how the technology will impinge on the sustainability of the targeted farming system; and (iv) what are the sectors that will benefit most (or lose out) as a result of the widespread adoption of the technology. It is comparatively easy to tailor these questions to specific research programmes depending on the nature of the research to be undertaken, but it is much more difficult to arrive at well-supported answers, in particular at the research planning stage. This research challenge needs scientists from a range of disciplines and from different agencies, both public and private, to engage in close collaboration, not only among themselves but also with the intended beneficiaries – the farmers – either directly or through the extension services.

Effective dialogue among all scientists and extension workers in this research development continuum also calls for a new information-sharing mechanism that embraces transparent interactive dialogue and easily accessible information. Modern information and communication technology can provide the vehicle for this information sharing and dialogue, opening up the possibility of a global knowledge system through which the sharing of global knowledge on all emerging technologies relating to food and agriculture can be effectively realized (Alberts, 1999). This in turn will lead to the strengthening of the research process at all stages.

National government and international donor support for research has declined significantly over the past decade, despite compelling evidence on very high rates of return to investment in agricultural research and in particular in genetic improvement programmes for crops and livestock. This is particularly worrying at a time when there is a widely shared consensus on the absolute need and importance of strengthening agricultural research. While more and more funds go into biotechnology research, the other areas mentioned above are trailing behind. This is especially true for research focusing on marginal areas and crops. The private sector can and must contribute more than just funding. As outlined above, its expertise, technologies and products are essential to the development and growth of tropical agriculture based on rapidly advancing biotechnologies and genetically engineered products. It is argued by some that incentives (e.g. in the form of tax concessions) should be offered to induce private sector participation. It is also argued that collaborative partnerships with private sector companies or foundations in well-articulated and mutually beneficial agreements can mobilize the required cooperation and make significant contributions to agricultural research in the developing countries.

To conclude, the scientific community bears a responsibility to address ethical concerns. On the one hand, it must ensure that the technologies and products of research do not adversely affect food safety or risk damage to the environment. In this context, timely and transparent communication of relevant research findings and their interpretation (risk analysis) to all pertinent audiences including the general public is required. On the other hand, scientists, together with public servants, politicians and private sector leaders, bear a more profound humanitarian responsibility to ensure that all people can realize their most fundamental right – the right to food.