Chapter 6

The resources outlook: by how much do land, water and crop yields need to increase by 2050?

Jelle Bruinsma[1]

The recent food crisis was characterized by sharp food price surges and caused, in part, by new demands on agriculture, such as demand for biomass as feedstock in biofuel production (Alexandratos, 2008). It made fears that the world is running out of natural resources (foremost among them land and freshwater resources) come back with a vengeance (e.g., Brown, 2009). Concerns are voiced that agriculture might, in the not too distant future, no longer be able to produce the food needed to feed a still growing world population at levels sufficient to lead a healthy and active life.

Such fears are by no means new and continually keep coming back, prompting a series of studies and statements concerning how many people the earth can support. The continuing decline of arable land per person (Figure 6.1) is often cited as an indicator of impending problems.[2] The underlying cause for such problems is perceived to be an ever-increasing demand for agricultural products facing finite natural resources such as land, water and genetic potential. Scarcity of these resources would be compounded by competing demand for them, originating in urbanization, industrial uses and use in biofuel production, and by forces that change their availability, such as climate change and the need to preserve resources for future generations (environmentally responsible and sustainable use).

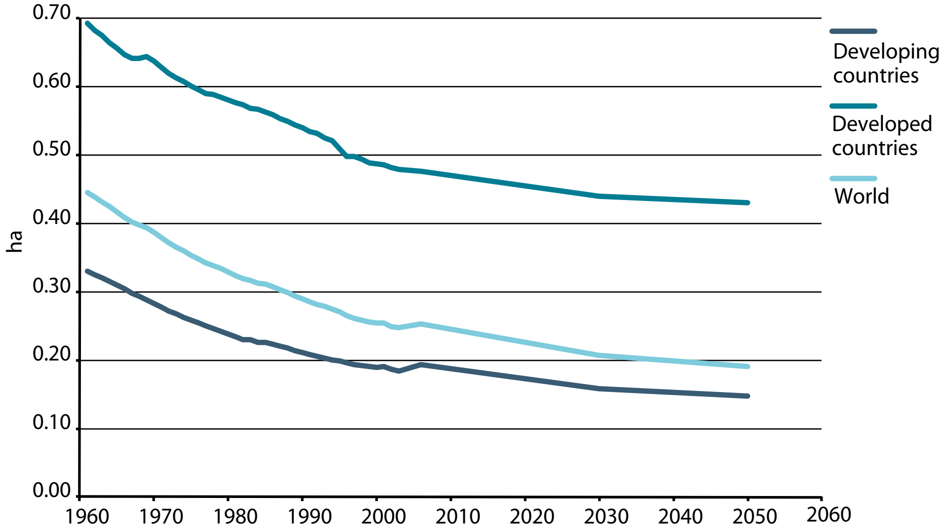
This chapter addresses some of these issues by unfolding the resource use implications of the crop production projections underlying the latest FAO

1. The author gratefully acknowledges substantial contributions by Gerold Boedeker, Jean-Marc Faures, Karen Frenken and Jippe Hoogeveen, as well as comments by FAO staff on an earlier draft.

2. Of course, declining land per person, combined with increasing average food consumption could also be interpreted as a sign of ever-increasing agricultural productivity.

perspective study (FAO, 2006b).[3] These projection results are also presented in Chapter 1. They can be considered as representing a baseline scenario, but do not take into account additional demand for agricultural products and for land needed by biofuel production, nor do they explicitly account for land-use changes due to climate change. This is not to say that such demands on agriculture would be additive to demand on agriculture and natural resources for food and feed purposes. There will be competition for resources and substitution among the final uses of agricultural products. These issues are discussed by Fischer, in Chapter 3 of this volume.

Figure 6.1
Arable land per capita



Sources: FAOSTAT and author.

In discussing the natural resource implications, this chapter focuses on the physical dimensions of natural resource use in agriculture. While acknowledging the validity and importance of environmental and sustainability concerns such as deforestation, land degradation and water pollution, the chapter does not explicitly deal with then, owing to space and time constraints.

The FAO (2006b) study has as base year the three-year average 1999/2001 based on FAOSTAT data as known in 2002 to 2004. At present, FAOSTAT offers

3. Unlike the preceding study (Bruinsma, 2003), for various reasons, the 2006 interim study did not deal with resource use issues, such as land and yield expansion, and water use in irrigation.

published data up to 2003 for supply utilization accounts, and up to 2007 for land use and production by crop; although time constraints and the non-availability of published food balance sheet data after 2003 meant that no new base year and projections could be derived, production and land-use data for the latest three-year average (2005/2007) are taken into account in the work underlying this chapter.

Another limitation is that while this chapter was being prepared, the results of the 2009 Global Agro-Ecological Zone (GAEZ) study were not yet available, so the results of the 2002 GAEZ study (reported in Fischer *et al.*, 2002) had to be used instead.

The chapter is based on analytical work for 146 countries: 93 developing, and 53 developed,[4] with 42 of the latter grouped into four country groups (Annex 6.1). At present, these countries account for almost 98 percent of the world's population and 100 percent of its arable land.

How much more needs to be produced?

FAO's (2006b) baseline projections show that by 2050 the world's average daily calorie availability could rise to 3 130 kcal per person, an 11 percent increase over the 2003 level. This would still leave 4 percent of developing countries' populations chronically undernourished in 2050.[5]

For these projections to materialize, annual world agricultural production would need to increase by 70 percent over the period from 2005/2007 to 2050 (Table 6.1). World population is projected to rise by about 40 percent over this period, meaning that per capita production would rise by some 22 percent. The reason this would translate into an increase of only 11 percent in per capita calorie availability is mainly[6] because of expected changes in diet, with a shift to higher-value foods of often lower calorie content (e.g., vegetables and fruits) and to livestock products, implying an inefficient conversion of calories from the crops used in livestock feeds. For example, per capita meat consumption would rise from 37 kg per year in 1999/2001 to 52 kg in 2050 (from 27 to 44 kg in developing countries), implying that much of the additional crop (cereal) production will be used as feed for livestock production.

4. Developed countries include the industrialized countries and countries in transition.

5. A partial update of the projections presented by Alexandratos in Chapter 1 of this volume shows a lower average calorie availability for 2050, of 3 050 kcal per person per day, and a slightly higher share of the developing countries' population chronically undernourished, at 5 percent.

6. Because total agricultural production is measured by weighing individual products with average international prices, the price-based index of the volume of production grows faster than the aggregates expressed in physical units or using a calorie-based index as diets change away from staples to higher-value commodities (FAO, 2006b; Box 3.1).

Table 6.1
Increases in agricultural production

Region	1961/1963	2005/2007	2050	1961/1963–2005/2007	2005/2007–2050
World (146 countries)					
Population[a] *(million people)*	3 133	6 372	8 796	103	38
Total production *(value)*				148	70
Crop production *(value)*				157	66
Cereals[b] *(million tonnes)*	843	2 012	3 009	139	49
Livestock production *(value)*				136	76
Meat production *(million tonnes)*	94	249	461	165	85
Developing (93 countries)					
Population[a] *(million people)*	2 139	5 037	7433	135	48
Total production *(value)*				255	97
Crop production *(value)*				242	82
Cereals[b] *(million tonnes)*	353	1 113	1 797	215	61
Livestock production *(value)*				284	117
Meat production *(million tonnes)*	42	141	328	236	132
Developed (53 countries)					
Population[a] *(million people)*	994	1 335	1 362	34	2
Total production *(value)*				63	23
Crop production *(value)*				64	30
Cereals[b] *(million tonnes)*	490	900	1 212	84	35
Livestock production *(value)*				62	17
Meat production *(million tonnes)*	52	108	133	108	23

[a] Population figures for 2005/2007 are population in 2005; for 2050 from the United Nations 2002 assessment; the 2050 projection from the United Nations 2008 assessment amounts to 9 056 million for the 146 countries covered.
[b] Including rice in milled form. The latest country balance sheet (CBS) cereal data data show a world cereal production of 2 138 million tonnes for 2006/2008, implying an increment to 2050 of less than 900 million tonnes if measured from the 2006/2008 average.
Source: Author.

Table 6.1 shows the increments in production for the past and future 44-year periods. It brings out the drastic slowdown in expected production growth, compared with the past, for the country and commodity groups shown. This mirrors the projected deceleration in demand for agricultural products, which in turn reflects the decelerating growth of population and the ever-increasing share of population gradually attaining medium to high levels of food consumption (FAO, 2006b).

This slowdown is particularly pronounced for the group of developed countries, but the group of better-off developing countries (defined as having a daily calorie supply of more than 3 000 kcal per person in 2005) is expected to follow a similar pattern.

Although the annual growth of world agricultural production is projected to fall from 2.2 percent over the last decade to 1.5 percent by 2030 and to 0.9 percent from 2030 to 2050 (Table 6.2), the incremental quantities involved are still very considerable: an additional billion tonnes of cereals and 200 million tonnes of meat would need to be produced annually by 2050. The additional meat production would require ample increases in the production of concentrate feeds. For example, 80 percent of the additional 480 million tonnes of maize produced annually by 2050 would be for animal feeds, and soybean production would need to increase by a hefty 140 percent, to reach 515 million tonnes by 2050. As mentioned, these increments do not include the additional production needed as feedstock for biofuel production.

Table 6.2
Annual crop production growth (percentage per annum)

Region	1961–2007	1987–2007	1997–2007	2005/2007–2030	2030–2050	2005/2007–2050
Developing countries	3.0	3.0	2.9	1.5	0.9	1.2
excluding China and India	2.7	2.8	3.1	1.8	1.3	1.6
Sub-Saharan Africa	2.5	3.2	2.9	2.5	1.7	2.1
Near East and North Africa	2.6	2.3	2.1	1.7	1.0	1.4
Latin America and Caribbean	2.6	2.9	3.6	2.1	1.3	1.8
South Asia	2.6	2.2	2.0	1.6	0.9	1.3
East Asia	3.5	3.4	3.3	1.0	0.5	0.8
Developed countries	0.9	0.2	0.7	0.9	0.4	0.7
World	2.2	2.1	2.2	1.3	0.8	1.1
14 developing countries with > 3 000 kcal/person/day in 2005[a]	3.3	3.3	3.2	1.3	0.7	1.0

[a] These account for 40 percent of the population in developing countries.
Source: Author.

Regarding natural resource use in agricultural production, it should be borne in mind that the bulk of the foods consumed are produced locally. At present, an average of only 16 percent of world production[7] (15 percent for cereals and 12 percent for meat) enters international trade, with wide variations among individual countries and commodities.

7. Measured as ((gross imports + gross exports)/2)/production.

What are the sources of growth in crop production?

Growth in crop production comes through growth in crop yields and/or expansion in the physical area (arable land) allocated to crops, which – together with increases in cropping intensities, such as increased multiple cropping and/or shortening of fallow periods – leads to an expansion in the area harvested.

For this chapter, a detailed investigation was made of present and future land/yield combinations for 34 crops under rainfed and irrigated cultivation conditions, in 108 countries and country groups. The informal method applied took into account whatever information was available, but the investigation is based mainly on expert judgement (see Box 6.1 for a brief description of the approach followed).

The summary results shown in Table 6.3 should be taken as rough indications only. For example, yields here are weighted yields (international price weights) for 34 crops; historical data for arable land are unreliable for many countries; and data on cropping intensities for most countries are non-existent, and for this study were derived by comparing data on harvested land, aggregated over all crops, with data on arable land, and so on.

Table 6.3
Sources of growth in crop production (percentages)

	Arable land expansion		Increases in cropping intensity		Yield increases	
Region	1961–2005	2005/2007–2050	1961-2005	2005/2007–2050	1961–2005	2005/2007–2050
All developing countries	23	21	8	8	70	71
Sub-Saharan Africa	31	25	31	6	38	69
Near East and North Africa	17	-7	22	17	62	90
Latin America and Caribbean	40	30	7	18	53	52
South Asia	6	5	12	8	82	87
East Asia	28	2	-6	12	77	86
World	14	9	9	14	77	77
Developing countries with < 40 percent of potentially arable land in use in 2005[a]		30		15		55
Developing countries with > 80 percent of potentially arable land in use in 2005[b]		2		9		89

[a] 42 countries accounting for 15 percent of the total population in developing countries.
[b] 19 countries accounting for 35 percent of the total population in developing countries.
Source: Author.

Box 6.1 - Projecting land use and yield growth

This box gives a brief account of the approach followed in making projections for land use and future yield levels. (Bruinsma, 2003: Appendix summarizes the methodology applied.)

As a starting point, the projections took the crop production projections for 2030 and 2050 from the FAO (2006b) study. These are based on demand and trade projections (including for livestock and feed commodities), which together make consistent commodity balances and clear the world market. The baseline scenario presents a view of how key food and agricultural variables may evolve over time, not how they should evolve from the normative perspective of solving nutrition and poverty problems. To the maximum extent possible, use was made of the in-house knowledge available from various disciplines within FAO. The quantitative analysis and projections were therefore considerably detailed, to provide a basis for making statements about the future concerning individual commodities, groups of commodities and groups of countries, as well as about agriculture as a whole. The analysis was carried out for as many individual commodities and countries as practicable: 108 countries/country groups covering a total of 146 countries (Annex 6.1); 34 crops (Annex 6.2); and two land classes – rainfed and irrigated agriculture.

A major part of data preparation is the unfolding of production data – the FAOSTAT data for area harvested and average yield for each crop and country for the three-year average 2005/2007, converted into the crop classification used in this study – into its constituent components of area, yield and production for rainfed and irrigated land. Such detailed data are not generally available in standard databases, so it was necessary to piece them together from the fragmentary information in both published (e.g., EUROSTAT for the European Union [EU] countries) and unpublished documents (e.g., giving areas and yields by irrigated and rainfed land at the national level or by administrative district), supplemented by a good deal of estimation. For a number of countries, such as the United States of America, China, the EU15 countries, India and Indonesia, data for irrigated agriculture are assembled at the subnational level.

No data exist on total harvested land, but a proxy can be obtained by summing the harvested areas reported for different crops. Data are available for total arable land in agricultural use (physical area, called in FAOSTAT "arable land and land under permanent crops"). It is not known whether these two sets of data are compatible with each other, but this can be evaluated indirectly by computing the cropping intensity, i.e., the ratio of harvested area to arable land. This is an important parameter that can signal defects in the land-use data. For several countries, particularly in sub-Saharan Africa, the implicit values of the cropping intensities do not seem to be realistic. In such cases, the harvested area data resulting from crop statistics were accepted as being the more robust (or the less questionable), and those for arable area were adjusted (see FAO, 1995 for discussion of these problems).

Data reported in FAOSTAT on arable irrigated land refer to "area equipped for irrigation". However, it is the "irrigated land actually in use" that is needed, and this is often between 80 and 90 percent of the area equipped. Data for the area in use were taken from FAO's AQUASTAT database.

The bulk of the projection work concerned unfolding the projected crop production for 2030 and 2050 into (harvested) area and yield combinations for rainfed and irrigated land, and making projections for total arable land and arable irrigated area in use.

Initial mechanically derived projections for rainfed and irrigated harvested areas and yield by crop (constrained to arrive at exactly the projected production) were evaluated against such information as recent growth in area and yield (total by crop) and the attainable yield levels for most crops, obtained from the GAEZ study (Fischer *et al.*, 2002) and adjusted where needed. Similar projections were made for total arable rainfed and irrigated areas, which were then evaluated against estimates for the (maximum) potential areas for rainfed (from GAEZ) and irrigated agriculture (from AQUASTAT) and adjusted where needed. In addition, irrigated area projections were checked against cropping patterns and made to obey certain cropping calendars (i.e., not all crops can be grown in all months of the year). A final step was to derive the implicit cropping intensities for rainfed and irrigated agriculture, by comparing harvested land for all crops with the arable area, and to adjust areas and yields where needed. Normally this required several iterations before an acceptable picture of the future was arrived at.

As the whole exercise depends on expert judgement and requires evaluation of each and every number, it is time-consuming. The projections presented in this chapter are not trend extrapolations, as they take into account all the knowledge currently available regarding expected developments that might make evolutions in major variables deviate from their trend paths.

About 80 percent of the projected growth in crop production in developing countries would come from intensification in the form of yield increases (71 percent) and higher cropping intensities (8 percent, Table 6.3). Intensification's share goes up to 95 percent in the land-scarce region of South Asia, and to more than 100 percent in the Near East and North Africa, where increases in yield would also have to compensate for the foreseen decline in arable land area. Arable land expansion will remain an important factor in crop production growth in many countries of sub-Saharan Africa and Latin America, although less so than in the past.

These summary results mask wide variation among countries. The actual combination of the factors used in crop production (e.g., land, labour and capital) in each country will be determined by their relative prices. Taking the physical availability of land as a proxy for its relative scarcity, and hence price, land would be expected to play a greater role in crop production the less scarce it is. For the 42 developing countries currently using less than 40 percent of their land estimated as having some rainfed crop production potential, arable land expansion is projected to account for almost one-third of crop production growth. At the other end of the spectrum, in the 19 land-scarce countries (with more than 80 percent of their suitable land already in use), the contribution of further land expansion to crop production growth is estimated to be almost nil, at 2 percent (Table 6.3).

In developed countries, the area of arable land in crop production peaked in the late 1960s, then remained stagnant for some time and has been declining since the mid-1980s. Growth in crop yields therefore accounted for all these countries' growth in crop production, and also compensated for declines in their arable land areas. This trend is foreseen to continue for the period to 2050. As a result, intensification (higher yields and more intensive use of land) is seen to contribute more than 90 percent of growth in crop production at the world level over the projection period.

It is interesting to see that growth in rice production in developing countries will increasingly have to come (at least on average) entirely from gains in yield (Table 6.4), which will also have to compensate for a slight decline in harvested land allocated to rice. This could be a sign that consumption of certain food commodities in some countries will reach saturation levels by 2050.

Table 6.4
Sources of growth in production of major cereals, developing countries (percentages)

		Annual growth			Contribution to growth	
Crop	*Period*	Production	Harvested land	Yield	Harvested land	Yield
Wheat	1961–2007	3.77	1.04	2.70	28	72
	2005/2007–2050	1.05	0.29	0.75	28	72
Rice, paddy	1961–2007	2.32	0.51	1.80	22	78
	2005/2007–2050	0.48	-0.11	0.59	-23	123
Maize	1961–2007	3.43	0.99	2.42	29	71
	2005/2007–2050	1.41	0.63	0.78	44	56

Source: Author.

In developing countries, the bulk of wheat and rice is produced in the land-scarce regions of Asia and the Near East and North Africa, while maize is the major cereal crop in sub-Saharan Africa and Latin America, regions where many countries still have room for area expansion. Expansion of harvested land will therefore continue to be a major contributor to the production growth of maize.

As discussed in FAO (2006b), an increasing share of the increment in cereal production, mainly coarse grains, will be used as livestock feed. As a result, maize production in developing countries is projected to grow at 1.4 percent per annum against 1.1 percent for wheat and only 0.5 percent for rice. Such contrasts are particularly marked in China, where wheat production is expected to grow only marginally and rice production to fall, while maize production grows by some 60 percent over the projection period. Hence there will be corresponding declines in the areas allocated to wheat and rice but a considerable increase in the maize area.

This study attempted to unfold crop production by rainfed and irrigated land, to analyse the contribution of irrigated to total crop production. In developing countries, irrigated agriculture is estimated to account for about a fifth of all arable land, 47 percent of all crop production and almost 60 percent of cereal production (Table 6.5). It should be emphasized that except for some major crops in some countries, there are only limited data on irrigated land and production by crop, and the results presented in Table 6.5 are in part based on expert judgement (Box 6.1). Nevertheless, they suggest a continuing importance of irrigated agriculture.

Table 6.5
Shares of irrigated land and production (percentages)

	All crops			Cereals	
Share	Arable land	Harvested land	Production	Harvested land	Production
World					
2005/2007	15	23	42	29	42
2050	16	24	43	30	43
Developing countries					
2005/2007	19	29	47	39	59
2050	20	30	47	41	60

Source: Author.

By how much does the arable land area need to increase?

At present, about 12 percent (more than 1.5 billion ha; Figure 6.2) of the globe's land surface (13.4 billion ha) is used for crop production (arable land and land under permanent crops). This area represents slightly more than a third (36 percent) of the land estimated to be to some degree suitable for crop production. The remaining 2.7 billion ha with crop production potential suggests that there is scope for further expansion of agricultural land. However, there is also a perception in some quarters that no more, or very little, additional land could be brought under cultivation. This section attempts to shed some light on these contrasting views, first by briefly discussing some estimates of land with crop production potential and some constraints to exploiting these suitable areas, and then by presenting the projected expansion of agricultural area over the period up to 2050.

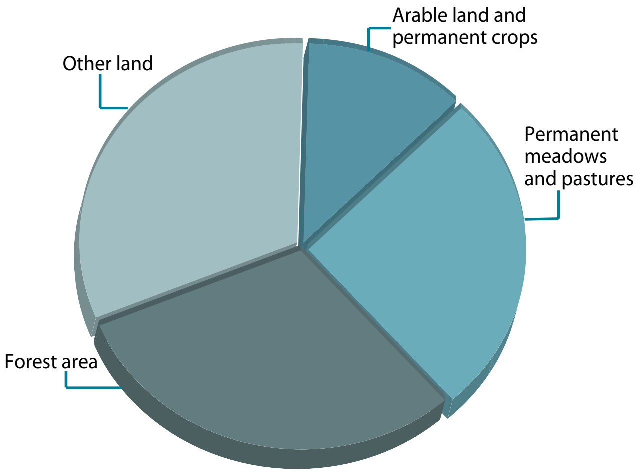
How much land is there with crop production potential?[8]

Notwithstanding the predominance of yield increases in the growth of agricultural production, land expansion will continue to be a significant factor in those

8. This section is an adaptation of a similar section in Bruinsma (2003). It is based on the GAEZ study published in 2002 (Fischer *et al.*, 2002). This study has recently been completely revised, but the results from the revision were not yet available when this chapter was being prepared.

developing countries and regions where the potential for expansion exists and the prevailing farming systems and more general demographic and socio-economic conditions are favourable. A frequently asked question in the debate on world food futures and sustainability is: How much land is there that could be used to produce food to meet the needs of the growing population?

Figure 6.2
World land area (million ha in 2005)



Source: FAOSTAT.

The GAEZ study published in 2002 (Fischer *et al.*, 2002), combining soil, terrain and climate characteristics with crop production requirements, estimates the suitability (in terms of land extents and attainable yield levels) for crop production of each land grid cell at the 5-arc-minute level, at three input levels – low, intermediate and high.

Summing over all the crops covered in GAEZ and the technology levels considered, an estimated 30 percent of the world's land surface, or 4.2 billion ha,[9] is to some extent suitable for rainfed agriculture (Table 6.6). Of this area, some 1.6 billion ha is already under cultivation (Table 6.7). Developing countries have 2.8 billion ha of land of varying qualities with potential for growing rainfed crops at yields above an acceptable minimum level, of which nearly 970 million ha is

9. Fischer *et al.* (2002: Table 5.15) report a lower 3.56 billion ha for the gross extent of land with rainfed crop production potential. This is based on a different version of the GAEZ 2002 from that used by Bruinsma (2003). OECD/FAO (2009), based on the GAEZ 2002, reports a total of 4.3 billion ha for the gross extent of land with rainfed crop production potential.

Table 6.6
Land with rainfed crop production potential

Region	Total land surface	Share of land suitable	Total land suitable	Very suitable[a]	Suitable[b]	Moderately suitable[c]	Marginally suitable[d]	Not suitable[e]
	(million ha)	(%)	(million ha)					
Developing countries	7 302	38	2 782	1 109	1 001	400	273	4 520
Sub-Saharan Africa	2 287	45	1 031	421	352	156	103	1 256
Near East and North Africa	1 158	9	99	4	22	41	32	1 059
Latin America	2 035	52	1 066	421	431	133	80	969
South Asia	421	52	220	116	77	17	10	202
East Asia	1 401	26	366	146	119	53	48	1 035
Industrial countries	3 248	27	874	155	313	232	174	2 374
Transition countries	2 305	22	497	67	182	159	88	1 808
World[f]	13 400	31	4 188	1348	1 509	794	537	9 211

Attainable yields: [a] 80 to 100 percent of the maximum constraint-free yield; [b] 60 to 80 percent; [c] 40 to 60 percent; [d] 20 to 40 percent; [e] < 20 percent.
[f] Including some countries not covered in this study.
Source: Author.

Table 6.7
Total arable land: data and projections

Region	Arable land in use: 1961/1963	1989/1991	2005	2005 adjusted	2030	2050	Annual growth: 1961-2005	1990-2005	2005-2050	Balance: 2005	2050
	(million ha)						%			(million ha)	
Sub-Saharan Africa	133	161	193	236	275	300	0.80	1.07	0.55	786	723
Latin America	105	150	164	203	234	255	1.01	0.64	0.52	861	809
Near East and North Africa	86	96	99	86	84	82	0.34	-0.02	-0.11	13	16
South Asia	191	204	205	206	211	212	0.15	0.07	0.07	14	7
East Asia	178	225	259	235	236	237	0.99	1.12	0.02	131	129
excluding China	73	94	102	105	109	112	0.85	0.71	0.15	78	75
Developing countries	693	837	920	966	1 040	1 086	0.67	0.65	0.27	1 805	1 684
excluding China and India	426	536	594	666	740	789	0.75	0.66	0.39	1 730	1 609
Industrial countries	388	401	388	388	375	364	-0.02	-0.21	-0.15	486	510
Transition countries	291	277	247	247	234	223	-0.32	-0.90	-0.23	250	274
World[a]	1 375	1 521	1 562	1 602	1 648	1 673	0.30	0.17	0.10	2 576	2 503

[a] Includes a few countries not included in the other country groups shown.
Source: Historical data from FAOSTAT, January 2009.

already under cultivation. The gross land balance of 2.6 billion ha (1.8 billion ha for developing countries) would therefore seem to provide significant scope for further expansion of agriculture. However, this favourable impression is qualified by a number of considerations and constraints.

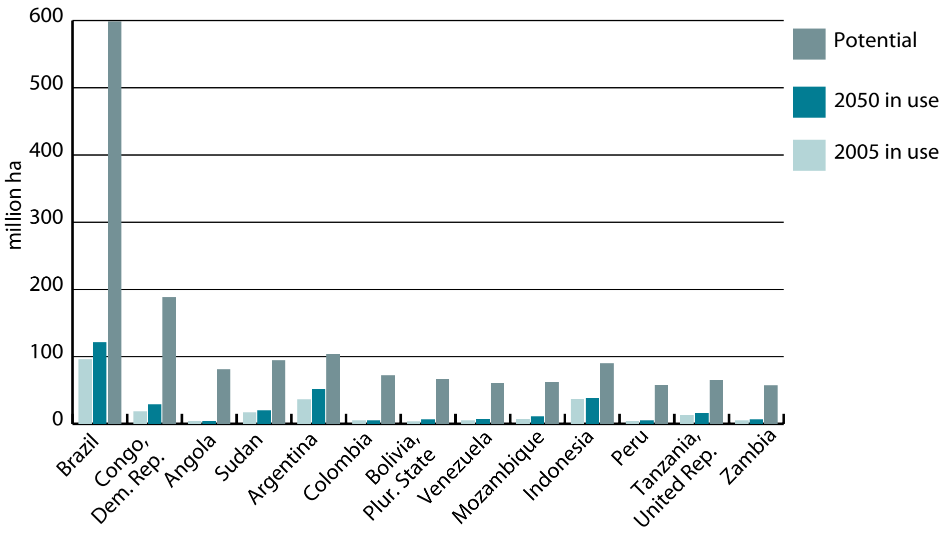
First, the calculation ignores land uses other than for growing crops, so forest cover, protected areas and land used for human settlements and economic infrastructure are not taken into account. Alexandratos (1995) estimated that forests cover at least 45 percent, protected areas some 12 percent and human settlements some 3 percent of the gross land balance, so the net land balance for developing countries would be only 40 percent of the gross balance. Naturally, there are wide regional differences. For example, in the land-scarce region of South Asia, some 45 percent of the land with crop production potential that is not yet in agricultural use is estimated to be occupied by human settlements. This leaves little doubt that population growth and further urbanization will be significant factors in reducing land availability for agricultural use in this region. A more recent estimate by Nachtergaele and George (2009) shows that at the world level, urban areas take up 60 million ha of the gross land balance, protected areas 200 million ha, and forests 800 million ha, so the net land balance would be 1.5 billion ha.

Second, and probably more important than allowing for non-agricultural uses of land with crop production potential, is the method used to derive the estimates: it is enough for a piece of land to support a single crop at a minimum yield level for it to be classified as suitable land. For example, large tracts of land in North Africa that permit the cultivation of only olive trees (and a few other minor crops) are counted as suitable, even though there may be little use for them in practice. The notion of overall land suitability is therefore of limited meaning, and it is more realistic to discuss suitability for individual crops.

A third consideration is that the land balance (land with crop production potential not in agricultural use) is very unevenly distributed among regions and countries. Some 90 percent of the remaining 1.8 billion ha in developing countries is in Latin America and sub-Saharan Africa, and half is concentrated in just seven countries: Brazil, the Democratic Republic of the Congo, Angola, the Sudan, Argentina, Colombia and the Plurinational State of Bolivia (Figure 6.3). At the other extreme, there is virtually no spare land available for agricultural expansion in South Asia and the Near East and North Africa. In fact, a few countries in these two regions have negative land balances, with land classified as not suitable made productive through human intervention – such as terracing of sloping land and irrigation of arid and hyper-arid land – and put into agricultural use. Even within the relatively land-abundant regions there is great diversity of land availability, in terms of both quantity and quality, among countries and subregions.

Fourth, much of the remaining land suffers from constraints such as ecological fragility, low fertility, toxicity, high incidence of disease or lack of infrastructure. These reduce its productivity, and require high input use and management skills to permit its sustainable use, or prohibitively high investments to make it accessible or disease-free. Fischer *et al.* (2002) show that more than 70 percent of the land with rainfed crop production potential in sub-Saharan Africa and Latin America suffers from one or more soil and terrain constraints. Natural causes and human intervention can also lead to deterioration of the land's productive potential, for example through soil erosion or salinization of irrigated areas. Hence the evaluation of suitability may contain elements of overestimation (see also FAO, 2000), and much of the land balance cannot be considered as a resource that is readily usable for food production on demand.

Figure 6.3
Developing countries with the highest (gross) land balance



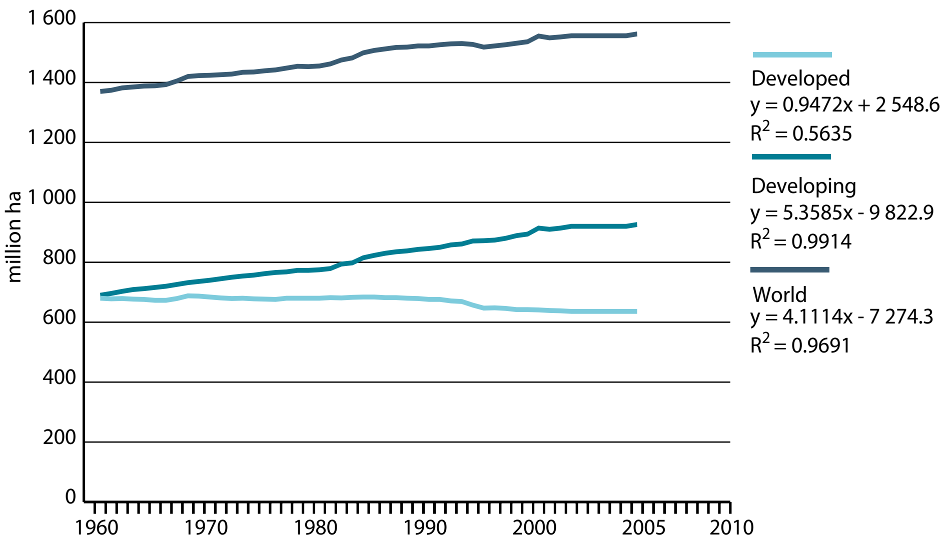
In 2005, these 13 countries with gross land balance of more than 50 million ha accounted for two-thirds of the total gross land balance in developing countries.
Source: Author.

These considerations underline the need to interpret estimates of land balances with caution when assessing land availability for agricultural use. Cohen (1995) summarizes and evaluates all the estimates of available cultivable land, together with their underlying methods, and shows their extremely wide range. Young (1999) offers a critique of the estimates of available cultivable land, including those given in Alexandratos (1995), stating that they often represent gross overestimates.

Expansion of land in crop production

The perception that there is no more or very little new land to bring under cultivation might be grounded in the specific situations of land-scarce countries and regions such as South Asia and the Near East and North Africa, but may not apply, or may apply with much less force, to other parts of the world. As discussed, there are large tracts of land with varying degrees of agricultural potential in several countries, most of them in sub-Saharan Africa and Latin America, with some in East Asia. However, this land may lack infrastructure, or be partly under forest cover or in wetlands that should be protected for environmental reasons, or the people who would exploit it for agriculture lack access to appropriate technological packages or the economic incentives to adopt them.

Figure 6.4
Arable land and land under permanent crops, past developments



Source: Author.

In reality, land in agricultural use continues to expand (Figure 6.4), mainly in countries where there are growing needs for food and employment but limited access to the technology packages that could increase intensification of cultivation on land already in agricultural use. The data show that expansion of arable land continues to be an important source of agricultural growth in sub-Saharan Africa, Latin America and East Asia (Table 6.7). This includes countries that have ample land resources with potential for crops and that face fast demand growth, particularly for exports and non-food uses, such as for soybeans in South America and oil-palm in Southeast Asia. Indeed, oil crops have been responsible for a good part of the increases in total cultivated land in developing countries and the world as a whole (FAO, 2006b), albeit often at the expense of deforestation.

The projected expansion of arable land in crop production shown in Tables 6.7, 6.8 and 6.9 has been derived for rainfed and irrigated land separately. As explained in Box 6.1, starting with the production projections for each crop, land and yield projections were derived from expert judgement and taking into account: i) base year (2005/2007) data on total harvested land and yield by crop; ii) data (or often estimates) for harvested land and yield by crop, for rainfed and irrigated land; iii) data on total arable rainfed and irrigated land, and their expected increases over time; iv) likely increases in yield, by crop and land class; v) plausible increases in cropping intensities; and vi) the land balances for rainfed and irrigated agriculture. As mentioned in Box 6.1, base year data for total arable land in several developing countries were adjusted (particularly for China)[10] partly to arrive at cropping intensities that seemed more meaningful. This is reflected in the column headed "2005 adjusted" in Table 6.7.

The overall result for developing countries is a projected net increase in the arable area of some 120 million ha (from 966 million ha in the base year to 1 086 million ha in 2050), or 12.4 percent (Table 6.7). Not surprisingly, the bulk of this projected expansion is expected to occur in sub-Saharan Africa (64 million ha) and Latin America (52 million ha), with almost no land expansion in East and South Asia, and even a small decline in the Near East and North Africa. The slowdown in expansion of arable land is mainly a consequence of the projected slowdown in the growth of crop production and is common to all regions.

The bulk of arable land in use is concentrated in a few developing countries (Figure 6.5). Towards the end of the projection period, a number of developing countries would witness a decline in arable land area (e.g., China, the Republic of Korea and others) and would embark on a pattern already seen in most developed countries, with production increasing only very slowly and increases in yield permitting a reduction in crop area.

Between 1961/1963 and 2005, the arable area in the world expanded by 187 million ha, as a result of two opposite trends: an increase of 227 million ha in developing countries, and a decline of 40 million ha in developed countries.

10. Data on arable land for China are unreliable. FAOSTAT data show an (unlikely) upwards trend from 1983 onwards, which distorts the historical growth rates in Table 6.7 for East Asia and for the total of developing countries.

The arable land area in the latter group peaked in the mid-1980s, at 684 million ha, and has declined ever since. This decline has been accelerating over time (Table 6.7). The longer-term forces determining such declines are sustained yield growth combined with a continuing slowdown in the growth of demand for the agricultural products grown in developed countries. The projections in this chapter foresee a further slow decline in developed countries' arable area, to 587 million ha in 2050 (although this may change under the impact of an eventual fast growth in biofuels). The net result for the world is an increase of 71 million ha in arable land area, consisting of an increase of 120 million ha in developing countries and a decline of 48 million ha in developed countries (Table 6.7 and Figure 6.6).

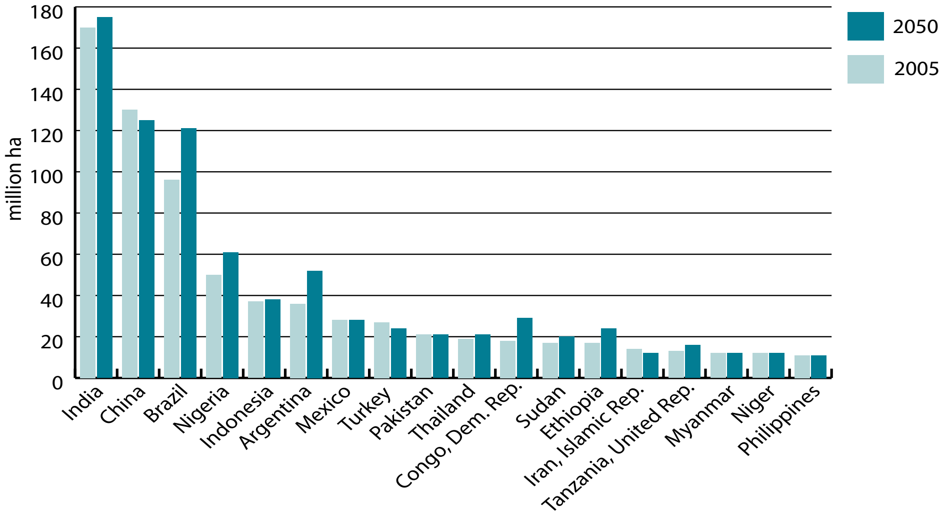
In the group of land-scarce countries,[11] arable land would practically remain constant (at 265 to 268 million ha), but irrigated land could expand by some 12 million ha, of which 9 million ha would be through conversion of rainfed land. Some of these countries are still highly dependent on agriculture and are experiencing above-average population growth. This, combined with their resource constraints, could make solving their food security problems extremely cumbersome, if not impossible, at least without external assistance and/or by finding non-agricultural development opportunities (Alexandratos, 2005).

The projected 2.75 million ha average annual increase in developing countries' arable area (120 million ha over 44 years) is a net increase. It is the total of gross land expansion minus land taken out of production for various reasons, such as owing to degradation, loss of economic viability or conversion to settlements. An unknown part of the new land to be brought into agriculture will come from land currently under forests. If all the additional land were to come from forested areas, it would imply an annual deforestation rate of 0.14 percent, compared with 0.42 percent (9.3 million ha per annum) for the 1990s, and 0.36 percent (7.5 million ha per annum) for the period 2000 to 2005 (FAO, 2006a). The latter estimates include deforestation from all causes, such as informal or unrecorded agriculture, grazing, logging and gathering of fuelwood.

What does the empirical evidence show concerning land expansion for agricultural use in developing countries? Micro-level analyses have generally established that under the socio-economic and institutional conditions prevailing in many developing countries, increases in output are – at least initially – obtained mainly through land expansion, where the physical potential for doing so exists. For example, in an analysis of Côte d'Ivoire, Lopez (1998) concludes that "the main response of annual crops to price incentives is to increase the area

11. These are the 19 countries with more than 80 percent of their land with rainfed and/or irrigation potential in use in 2005, of which six are in the Near East and North Africa, five in sub-Saharan Africa, and four in South Asia.

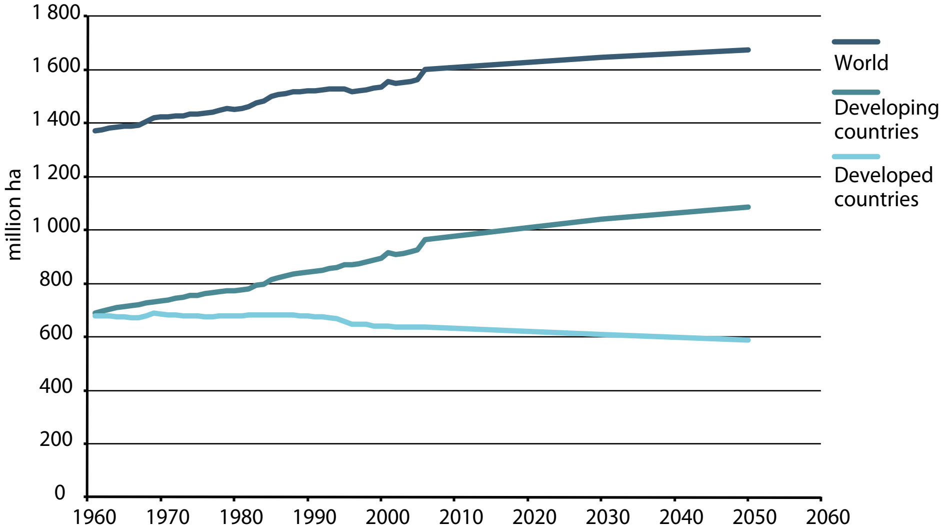
Figure 6.5
Developing countries with more than 10 million ha of arable land in use



In 2005, these 18 countries accounted for 75 percent of the total arable land in use in developing countries.

Source: Author.

Figure 6.6
Arable land and land under permanent crops, past and future



Source: Author.

cultivated". Similar findings, such as the rate of deforestation being positively related to the price of maize, are reported for Mexico by Deininger and Minten (1999). However, some land expansion takes place at the expense of longer rotation periods and shorter fallows, a practice still common in many sub-Saharan African countries, with the result that the soil's natural fertility is reduced. As fertilizer use is often uneconomic, the end-result is soil mining and stagnation or outright reduction of yields.

Although developing countries' arable area is projected to expand by 120 million ha over the projection period, the harvested area would increase by 160 million ha, or 17 percent, owing to increases in cropping intensities (Table 6.8). The overall cropping intensity for developing countries could rise by about 4 percentage points over the projection period (from 95 to 99 percent). Cropping intensities would continue to rise through shorter fallow periods and more multiple cropping. An increasing share of irrigated land in total agricultural land would also contribute to more multiple cropping. Almost one-third of the arable land in South and East Asia is irrigated, a share that is projected to rise to more than 36 percent in 2050. This high share of irrigated land is one of the reasons why average cropping intensities are considerably higher in these than in other regions. Average cropping intensities in developing countries – excluding China and India, which together account for well over half of the irrigated area in developing countries – are and will continue to be much lower.

Rising cropping intensities could be one of the factors responsible for increasing the risk of land degradation, and thus threatening sustainability, particularly when not accompanied by land conservation measures, including adequate and balanced use of fertilizers to compensate for the removal of soil nutrients by crops. This risk is expected to continue because, in many cases, socio-economic conditions do not favour implementation of the technological changes required to ensure the sustainable intensification of land use.

How much more water will be required in irrigation?

Expanding irrigated land

The area equipped for irrigation has been continuously expanding (mainly in developing countries, and only slowly in developed countries), although recently this expansion has slowed considerably (Figure 6.7). The projections of irrigation presented in this section are based on scattered information about existing irrigation expansion plans in different countries, potentials for expansion (including water availability) and the need to increase crop production. The projections include expansion in both formal and informal irrigation, the latter being particularly important in sub-Saharan Africa.

Table 6.8
Arable land in use, cropping intensities and harvested land

Region	Period	Total land in use			Rainfed use			Irrigated use[a]		
		Arable land *(million ha)*	Cropping intensity *(%)*	Harvested land *(million ha)*	Arable land *(million ha)*	Cropping intensity *(%)*	Harvested land *(million ha)*	Arable land *(million ha)*	Cropping intensity *(%)*	Harvested land *(million ha)*
Developing countries	2005/2007	966	95	919	777	83	649	189	143	270
	2050	1 086	99	1078	864	87	753	222	147	325
excluding China and India	2005/2007	666	82	547	582	76	442	84	124	105
	2050	785	89	697	680	83	562	106	129	136
Developed countries	2005/2007	635	74	473	584	72	422	51	100	51
	2050	587	81	478	536	80	426	51	100	51
World	2005/2007	1 602	87	1 392	1 361	79	1 070	240	134	321
	2050	1 673	93	1 556	1 400	84	1 179	273	138	377

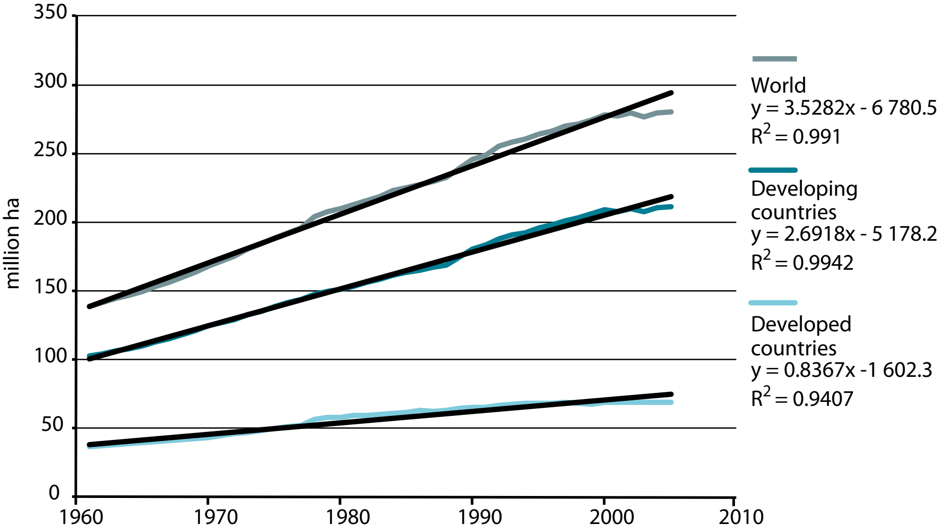
[a] Irrigated area in use, rather than "area equipped for irrigation" (Table 6.9).
Source: Author.

Table 6.9
Area equipped for irrigation

Region	Area *(million ha)*					Annual growth *(%)*			
	1961/1963	1989/1991	2005/2007	2030	2050	1961–2005	1990–2005	1996–2005	2005–2050
Developing countries	103	178	219	242	251	1.76	1.05	0.63	0.31
excluding China and India	47	84	97	111	117	1.91	1.06	0.89	0.42
Sub-Saharan Africa	2.5	4.5	5.6	6.7	7.9	2.07	1.49	0.98	0.67
Latin America and Caribbean	8	17	18	22	24	2.05	0.62	0.27	0.72
Near East and North Africa	15	25	29	34	36	1.86	1.21	1.30	0.47
South Asia	37	67	81	84	86	1.98	1.10	0.28	0.14
East Asia	40	64	85	95	97	1.42	1.00	0.80	0.30
Developed countries	38	66	68	68	68	1.57	0.38	0.20	0.00
World	141	244	287	310	318	1.71	0.87	0.52	0.24

Source: Author.

Figure 6.7
Area equipped for irrigation, past developments



Source: Author.

The aggregate result shows that the area equipped for irrigation could expand by 32 million ha (11 percent) over the projection period (Table 6.9), all in developing countries. This means that 16 percent of the land with irrigation potential and not yet equipped in this group of countries could be brought under irrigation, and by 2050 some 60 percent of all land with irrigation potential[12] (417 million ha) would be in use.

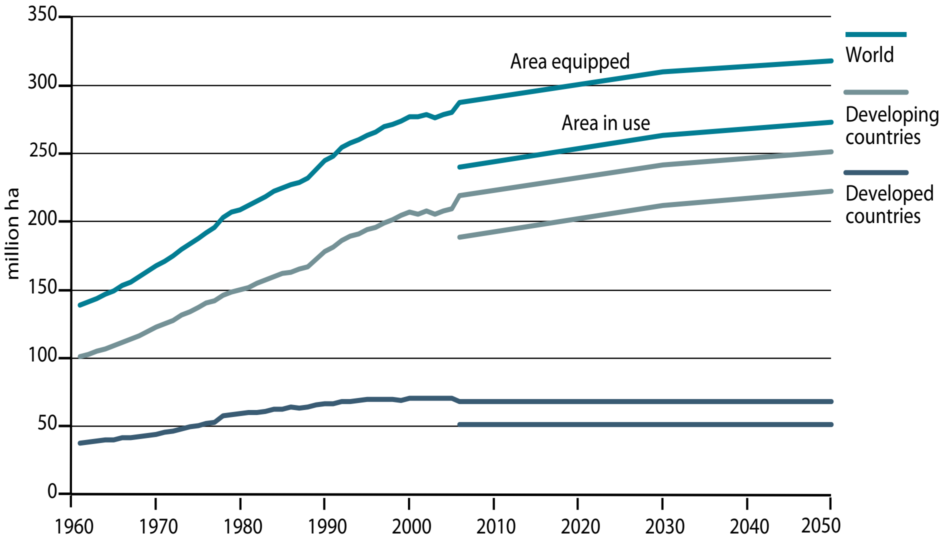
The expansion of irrigation would be strongest (in absolute terms) in the more land-scarce regions that are hard-pressed to raise crop production through more intensive cultivation practices, such as East Asia (an expansion of 12 million ha), South Asia (8 million ha) and the Near East and North Africa (6 million ha), although further expansion in the Near East and North Africa will become increasingly difficult as water scarcity increases and competition for water from households and industry continues to reduce the share available to agriculture. China and India alone account for more than half (56 percent) of the irrigated area in developing countries. Although the overall arable area in China is expected to decrease further, the irrigated area would continue to expand through conversion of rainfed land.

12. Estimates of land with irrigation potential are difficult to make, and should be taken as only rough indications.

Developed countries account for almost a quarter of the world's irrigated area, with 68 out of 287 million ha (Table 6.9). Annual growth of these countries' irrigated area reached a peak of 3.0 percent in the 1970s, dropping to 1.1 percent in the 1980s and to only 0.2 percent in the last decade for which data are available (1996 to 2005). For the developed countries as a group, only a marginal expansion of the irrigated area (supplemented with improvements on existing areas) is foreseen over the projection period, so the world irrigation scene will remain dominated by events in developing countries.

For this study, a distinction was made between the area equipped for irrigation and the irrigated area actually in use (which is the area used in the production analysis). Areas equipped might be temporarily or even permanently out of use, for various reasons, including maintenance, degradation of irrigation infrastructure or lack of need in a particular year. The percentage of the area equipped actually in use differs from country to country, ranging from 60 to 100 percent and averaging 86 percent over all countries. (This is expected to increase very slightly to 88 percent in 2050.) Of the 219 million ha equipped for irrigation in the developing countries in 2005/2007, some 189 million ha was assumed to be in use, increasing to 222 million ha in 2050 (out of 251 million ha equipped; Figure 6.8).

Figure 6.8
Arable irrigated area, past and future



Source: Author.

The importance of irrigated agriculture was discussed in the preceding section. Owing to continuing increases in multiple cropping on both existing and newly irrigated areas, the harvested irrigated area could expand by 56 million ha (17 percent), to account for well over a third of the total increase in harvested land (Table 6.8).

The projected expansion of irrigated land, by 32 million ha, is an increase in net terms. The projection assumes that losses of existing irrigated land, such as those due to water shortages or degradation resulting from salinization and waterlogging, will be compensated for by rehabilitation or substitution of other areas. The few existing historical data on such losses are too uncertain and anecdotal to provide a reliable basis for drawing inferences about the future. Regarding investments, the rehabilitation of existing irrigation schemes will represent the bulk of future expenditure on irrigation: if it is assumed that 2.5 percent of existing irrigation must be rehabilitated or substituted by new irrigation each year – in other words, the average life of an irrigation scheme is 40 years – the total irrigation investment activity in developing countries must encompass some 173 million ha over the projection period, of which more than four-fifths (141 million ha) would be for rehabilitation or substitution, and the balance for net expansion.

The projected net increase in land equipped for irrigation (32 million ha) is less than a quarter of the increase over the preceding 44 years (145 million ha). This implies an annual growth of only 0.24 percent, well below the 1.7 percent of the historical period. The slowdown projected for most countries and regions reflects the projected lower growth rate of crop production, combined with the increasing scarcity of suitable areas for irrigation and of water resources in some countries, and the rising costs of irrigation investment.

Most of the expansion in irrigated land will be achieved by converting land in use in rainfed agriculture into irrigated land. However, irrigation also takes place on arid and hyper-arid (desert) land, which is not suitable for rainfed agriculture. Of the 219 million ha currently irrigated in developing countries, an estimated 40 million ha is on arid and hyper-arid land, which could increase to 43 million ha in 2050. In some regions and countries, irrigated arid and hyper-arid land forms an important part of the total irrigated land currently in use: 19 million out of 28 million ha in the Near East and North Africa, and 15 million out of 70 million ha in South Asia.

Water use in irrigation and pressure on water resources

A major question concerning the future is whether there will be sufficient freshwater to satisfy the growing needs of agricultural and non-agricultural users. Agriculture already accounts for about 70 percent of freshwater withdrawals in the world, and is usually seen as a major factor behind the increasing global scarcity of freshwater.

The estimates of expansion of land under irrigation presented in the preceding subsection provide a partial answer to this question, because the assessment of irrigation potential takes water limitations into account, and the projections to 2050 assume that agricultural water demand will not exceed available water resources.[13]

Renewable water resources available for irrigation and other uses are commonly defined as that part of precipitation that is not evaporated or transpired by plants, including grasses and trees, and that flows into rivers and lakes or infiltrates into aquifers. Under natural conditions, without irrigation, the annual water balance for a given area can be defined as the sum of annual precipitation and net incoming flows (transfers through rivers from one area to another) minus evapotranspiration and runoff.

shows the renewable water resources for the world and major regions. Average annual precipitation varies from 160 mm per year in the most arid region (the Near East and North Africa) to about 1 530 mm per year in Latin America. These figures give an impression of the wide range of climatic conditions facing developing countries, and the resulting differences in water scarcity: countries with low precipitation, and therefore most in need of irrigation, are also those where water resources are naturally scarce. In addition, the water balance is expressed in yearly averages and does not reflect seasonal and intra-annual variations. Unfortunately, such variations tend to be more pronounced in arid than in humid climates.

The first step in estimating the pressure of irrigation on water resources is to assess irrigation water requirements and withdrawals. Precipitation provides part of the water that crops need to satisfy their transpiration requirements. Acting as a buffer, the soil stores part of the precipitation water, and returns it to the crops in times of deficit. In humid climates, this mechanism is usually sufficient to ensure satisfactory growth in rainfed agriculture. In arid climates or during dry seasons, irrigation is required to compensate for the deficit due to insufficient or erratic precipitation. Consumptive water use in irrigation is therefore defined as the volume of water needed to compensate for the deficit between potential evapotranspiration and effective precipitation over the crop's growing period. It varies considerably with climatic conditions, season, crop and soil type. In this

13. The concept of irrigation potential has severe limitations, and estimates can vary over time, according to the country's economic situation, or as a result of competition for water for domestic and industrial use. Estimates of irrigation potential are based on estimates of renewable water resources, i.e., the resources replenished annually through the hydrological cycle. In arid countries where mining of fossil groundwater represents an important part of water withdrawal, the area under irrigation is usually larger than the irrigation potential.

study, consumptive water use in irrigation has been computed for each country, based on the irrigated and harvested areas, by crop, estimated for the base year (2005/2007) and projected for 2050 (see Box 6.2 for a brief explanation of the methodology applied).

Box 6.2 - Estimating irrigation water requirements

Estimation of the water balances for any year is based on five sets of data: four digital geo-referenced data sets – for precipitation (New *et al.*, 2002), reference evapotranspiration (FAO, 2004), soil moisture storage properties (FAO, 1998) and areas under irrigation (Siebert *et al.*, 2007) – and irrigated areas for all major crops for 2005/2007 and 2050. Water balances are computed by grid cell (of 5 arc minutes, 9.3 km at the equator) and in monthly time steps. The results can be presented in statistical tables or digital maps at any level of spatial aggregation (country, river basin, etc.). They consist of annual values by grid cell for actual evapotranspiration, water runoff and consumptive water use in irrigation.

For each grid cell, actual evapotranspiration is assumed to be equal to reference evapotranspiration (ET_0, in millimetres; location-specific and calculated with the Penman-Monteith method; FAO, 1998; New *et al.*, 2002) in periods of the year when precipitation exceeds reference evapotranspiration or when there is enough water stored in the soil to allow maximum evapotranspiration. In drier periods of the year, lack of water reduces actual evapotranspiration to an extent that depends on the available soil moisture. Evapotranspiration in open water areas and wetlands is considered equal to a fixed fraction of the reference evapotranspiration.

For each grid cell, runoff and groundwater recharge is calculated as that part of the precipitation that does not evaporate and that cannot be stored in the soil. In other words, the sum of the runoff and groundwater recharge is equal to the difference between precipitation and actual evaporation. Runoff is always positive, except for areas identified as open water or wetland, where actual evapotranspiration can exceed precipitation.

Consumptive use of water in irrigated agriculture is defined as the water required in addition to water from precipitation (soil moisture) for optimal plant growth during the growing season. Optimal plant growth occurs when the actual evapotranspiration of a crop is equal to its potential evapotranspiration.

Potential evapotranspiration of irrigated agriculture is calculated by converting data or projections of irrigated (sown) area by crop (at the national level) into a cropping calendar, with monthly occupation rates of the land equipped for irrigation.[1] The following table gives an example of the cropping calendar for Morocco in the base year 2005/2007.[2]

The (potential) evapotranspiration (ET_c in millimetres) of a crop under irrigation is obtained by multiplying the reference evapotranspiration with a crop-specific coefficient ($ET_c = K_c * ET_0$). This coefficient has been derived (FAO, 1998) for four different growing stages: the initial phase, just after sowing; the development phase; the mid-phase; and the late phase, when the crop is ripening to be harvested. In general, these coefficients are low during the initial phase, high during the mid-phase and lower again in the late phase. It is assumed that the initial, development and late phases each take one month for any crop, while the mid-phase lasts several months. For example, the growing season for wheat in Morocco starts in October and ends in April: initial phase, October ($K_c = 0.4$); development phase, November ($K_c = 0.8$); mid-phase, December to March ($K_c = 1.15$); and late phase, April ($K_c = 0.3$).

The surface equipped for irrigation of each grid cell is then multiplied by the sum of all crops' evapotranspiration and the cropping intensity per month, to result in the potential evapotranspiration of the irrigated area in that grid cell. The difference between the calculated evapotranspiration of the irrigated area and actual evapotranspiration under non-irrigated conditions is equal to the consumptive use of water in irrigated agriculture in the grid cell.

Crop under irrigation	Irrigated area ('000 ha)	Crop area as share of total area equipped for irrigation, by month (%)											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Wheat	618	46	46	46	46						46	46	46
Maize	119			9	9	9	9	9					
Potatoes	61					5	5	5	5	5			
Sugar beet	36				3	3	3	3	3	3			
Sugar cane	14	1	1	1	1	1	1	1	1	1	1	1	1
Vegetables	145					11	11	11	11	11			
Citrus	80	6	6	6	6	6	6	6	6	6	6	6	6
Fruits	89	7	7	7	7	7	7	7	7	7	7	7	7
Groundnut	6					1	1	1	1	1			
Other crops	124	9	9							9	9	9	9
Sum over all crops[a]	1 292	69	69	69	72	42	42	42	32	41	69	69	69

[a] Including crops not listed in the table.

The method has been calibrated by comparing calculated values for water resources per country (i.e., the difference between precipitation and actual evapotranspiration under non-irrigated conditions) with data on water resources for each country as given in FAO AQUASTAT.[3] In addition, the discharge of each major river, as given in the literature, was compared with the calculated runoff for the drainage basin of that river. If the calculated runoff value did not match the value as stated in the literature, correction factors were applied to one or more of the basic input data on soil moisture storage and open waters.

The water balance for each country and year is defined as the difference between the sum of precipitation and incoming runoff on the one hand, and the sum of actual evapotranspiration and consumptive use of water in irrigated agriculture in that year on the other hand. This water balance therefore does not account for water withdrawals for other needs (industry, household and environmental purposes).

[1] India, China, Indonesia, the United States of America and the EU15 have been subdivided into two to four subregions with different cropping calendars, to distinguish different climate zones in these countries.

[2] For example, wheat is grown from October to April and occupies 46 percent (618 000 ha) of the 1 292 000 ha of irrigated land in use.

[3] www.fao.org/nr/aquastat.phase, October (Kc = 0.4); development phase, November (Kc=0.8); mid-phase, December to March (Kc = 1.15); and late phase, April (Kc = 0.3).

However, *water withdrawal for irrigation* – the volume of water extracted from rivers, lakes and aquifers for irrigation purposes – should be used to measure the impact of irrigation on water resources. Irrigation water withdrawal normally far exceeds consumptive water use in irrigation because of the water lost during transport and distribution from its source to the crops. In rice irrigation, additional water is used for paddy field flooding, to facilitate land preparation, protect the plants and control weeds.

Water-use efficiency is defined as the ratio between the estimated consumptive water use in irrigation and irrigation water withdrawal. Data on country water withdrawal for irrigation were collected within the framework of the AQUASTAT programme (e.g., FAO, 2005a; 2005b). These data were compared with the consumptive use of irrigation to estimate water-use efficiency[14] at the country level. For the world, average water-use efficiency was estimated at about 44 percent in 2005/2007, varying from 22 percent in areas of abundant water resources (sub-Saharan Africa) to 54 percent in South Asia, where water scarcity calls for higher efficiencies (Table 6.10).

To estimate the irrigation water withdrawal in 2050, assumptions were made about possible developments in the water-use efficiency in each country. Unfortunately, there is little empirical evidence on which to base such assumptions. However, two factors have an impact on the development of water-use efficiency: the estimated level of water-use efficiency in the base year, and water scarcity.[15] A function was designed to capture the influence of these two parameters, bearing in mind that improving water-use efficiency is a very slow and difficult process. The overall result is that efficiency could increase by 2 percentage points, from 44 to 46 percent (Table 6.10). Such an increase in efficiency would be more pronounced in water-scarce regions (e.g., a 10 percentage point increase in the Near East and North Africa) than in regions with abundant water resources (e.g., increases of 3 percentage points or less in Latin America and sub-Saharan Africa). It is expected that under pressure from limited water resources and competition from other uses, demand management will play an important role in improving water-use efficiency in water-scarce regions. In contrast, in humid areas, the issue of water-use efficiency is much less relevant and is likely to receive little attention.

At the global level, irrigation water withdrawal is expected to grow by about 11 percent, from the current 2 620 km^3 per year to 2 906 km^3 in 2050 (Table 6.10), with an increase in developing countries of 14 percent (or 298 km^3)

14. It should be noted that although the term "water-use efficiency" implies losses of water between source and destination, not all of this water is actually lost as much flows back into the river basin and aquifers and can be reused for irrigation.

15. Or "stress", measured as consumptive water use in irrigation as a percentage of renewable water resources.

being offset by a decline in developed countries of more than 2 percent (12 km^3). This increase in irrigation water withdrawal should be seen against the projected 17 percent increase in harvested irrigated area (from 321 million ha in 2005/2007 to 377 million ha in 2050; Table 6.8). The difference is due in part to the expected improvement in water-use efficiency, leading to a reduction in irrigation water withdrawal per irrigated hectare, and in part to changes in cropping patterns for some countries such as China, where a substantial shift in the irrigated area from rice to maize production is expected: irrigation water requirements for rice production are usually twice those for maize.

Table 6.10
Annual renewable water resources and irrigation water withdrawal

	Precipitation	Renewable water resources[a]	Water-use efficiency ratio		Irrigation water withdrawal		Pressure on water resources due to irrigation	
			2005/2007	2050	2005/2007	2050	2005/2007	2050
Region	*(mm/year)*	*(km^3)*	*(%)*		*(km^3)*		*(%)*	
Developing countries	990	28 000	44	47	2 115	2 413	8	9
Sub-Saharan Africa	850	3 500	22	25	55	87	2	2
Latin America and Caribbean	1 530	13 500	35	35	181	253	1	2
Near East and North Africa	160	600	51	61	347	374	58	62
South Asia	1 050	2 300	54	57	819	906	36	39
East Asia	1 140	8 600	33	35	714	793	8	9
World	800	42 000	44	46	2 620	2 906	6	7
Developed countries	540	14 000	42	43	505	493	4	4

[a] At the regional level, includes incoming flows.
Source: Author.

Irrigation water withdrawal in 2005/2007 was estimated to account for only 6 percent of total renewable water resources in the world (Table 6.10). However, there are wide variations among countries and regions, with the Near East and North Africa using 58 percent of its water resources in irrigation, while Latin America uses barely 1 percent of its. At the country level, variations are even higher. In the base year (2005/2007), 11 countries used more than 40 percent of their water resources for irrigation, creating a situation that can be considered critical. Another eight countries consumed more than 20 percent of their water resources, a threshold sometimes used to indicate impending water scarcity. The situation is expected to worsen by 2050, with two more countries crossing the 40 percent and four the 20 percent thresholds. If the expected additional water withdrawals needed for non-agricultural use are added, the picture does not change much, as agriculture represents the bulk of water withdrawal.

Nevertheless, for several countries, relatively low national figures may give an overly optimistic impression of the level of water stress: for example, China is facing severe water shortage in the north, while the south still has abundant water resources. In 2005/2007, four countries – the Libyan Arab Jamahiriya, Saudi Arabia, Yemen and Egypt – used volumes of water for irrigation that were larger than their annual renewable water resources. Groundwater mining also occurs in parts of some other countries in the Near East, and in South and East Asia, Central America and the Caribbean, even if the water balance at the national level may still be positive.

In conclusion, for the developing countries as a whole, water use in irrigation currently represents a relatively small part of their total water resources and there remains significant potential for further irrigation development. With the relatively small increase in irrigation water withdrawal expected between 2005/2007 and 2050, this situation will not change much at the aggregate level. However, locally and in some countries, there are already very severe water shortages, particularly in the Near East and North Africa.

By how much do crop yields need to rise?

As discussed, it is expected that growth in crop yields will continue to be the mainstay of crop production growth, accounting for some 70 percent of production growth in developing countries, and for 100 percent in developed countries. Although the marked deceleration in crop production growth foreseen for the future (Table 6.2) could point to a similar deceleration in growth of crop yields, such growth will continue to be needed. Questions often asked are: Will yield increases continue to be possible? and What is the potential for continuing such growth? There is a realization that a new green revolution or one-off quantum jumps in yields are unlikely to occur, and some believe that yield ceilings for some major crops have been, or are rapidly being, reached. Empirical evidence shows that the accumulation of slower, evolutionary annual increments in yields has been far more important than quantum jumps in yields, for all major crops (e.g., Byerlee, 1996).

Harvested land and yields for major crops

As mentioned, the production projections for the 34 crops covered in this chapter are unfolded into and tested against FAO experts' perceptions of feasible land-yield combinations, based on whatever knowledge is available for each agro-ecological rainfed and irrigated environment. Major inputs into this evaluation are the GAEZ-based (Fischer *et al.*, 2002) estimates regarding the availability of land suitable for growing crops, and the yields attainable in each country and each agro-ecological environment. In practice, such estimates are introduced as constraints to land and yield expansion, but they also act as a guide to what can be grown where. The resulting land and yield projections, although partly based on past performance, are not mere extrapolations of historical trends, as they take into account current knowledge about changes expected in the future.

The overall result for yields of all the crops covered in this study (aggregated with standard price weights) is that the global average annual rate of growth over the projection period will be roughly half that of the historical period: 0.8 percent per annum from 2005/2007 to 2050, against 1.7 percent per annum from 1961 to 2007. For developing countries, the equivalent annual growth rates are 0.9 and 2.1 percent. This slowdown in yield growth is a gradual process that has been under way for some time; for example, yield growth from 1997 to 2007 was 1.3 percent per annum for the world, and 1.6 percent for developing countries. The slowdown reflects the deceleration in crop production growth explained earlier.

Table 6.11
Areas and yields for major crops in the world

	Production (million tonnes)			Harvested area (million ha)			Yield (tonnes/ha)		
Crop	1961/ 1963	2005/ 2007	2050	1961/ 1963	2005/ 2007	2050	1961/ 1963	2005/ 2007	2050
Wheat	235	611	907	206	224	242	1.14	2.72	3.75
Rice (paddy)	227	641	784	117	158	150	1.93	4.05	5.23
Maize	210	733	1 153	106	155	190	1.99	4.73	6.06
Soybeans	27	218	514	24	95	141	1.14	2.29	3.66
Pulses	41	60	88	69	71	66	0.59	0.84	1.33
Barley	84	138	189	59	57	58	1.43	2.43	3.24
Sorghum	44	61	111	48	44	47	0.93	1.39	2.36
Millet	25	32	48	43	36	34	0.58	0.86	1.43
Seed cotton	30	71	90	32	36	32	0.92	1.95	2.80
Rape seed	4	50	106	7	31	36	0.56	1.61	2.91
Groundnuts	15	36	74	17	24	39	0.86	1.49	1.91
Sunflower	7	30	55	7	23	32	1.00	1.29	1.72
Sugar cane	417	1 413	3 386	9	21	30	48.34	67.02	112.34

Crops selected and ordered according to (harvested) land use in 2005/2007.
Source: Author.

Although discussing yield growth at this level of aggregation is not very helpful, the overall slowdown reflects a pattern common to most of the crops covered in this study. Exceptions include citrus and sesame, for which strong demand growth is foreseen in the future, or which are grown in land-scarce environments. The remarkable growth in soybean area and production in developing countries (Table 6.11) has been mainly due to explosive growth in Brazil and Argentina. Soybean is expected to continue to be one of the most dynamic crops, albeit with a more moderate rate of production increase than in the past, bringing the developing countries' share in world soybean production to more than 70 percent by 2050, with four countries – Brazil, Argentina, China and India – accounting for 90 percent of total production in developing countries.

Table 6.12
Cereal yields, rainfed and irrigated

		World						Developing countries					
		Average yield *(tonnes/ha)*			Annual growth *(%)*			Average yield *(tonnes/ha)*			Annual growth *(%)*		
Crop		1961/ 1963	2005/ 2007	2050	1961– 2007	1987 –2007	2005/ 2007– 2050	1961/ 1963	2005/ 2007	2050	1961– 2007	1987 –2007	2005/ 2007– 2050
Wheat	total	1.14	2.72	3.75	2.1	1.0	0.7	0.87	2.69	4.00	2.9	1.5	0.9
	rainfed		2.37	3.17			0.7		1.67	2.57			1.0
	irrigated		3.50	5.08			0.8		3.41	5.06			0.9
Rice	total	1.93	4.05	5.23	1.8	1.1	0.6	1.82	3.98	5.18	1.9	1.1	0.6
(paddy)	rainfed		2.54	3.26			0.6		2.54	3.26			0.6
	irrigated		5.10	6.40			0.5		5.04	6.37			0.5
Maize	total	1.99	4.72	6.06	2.0	1.9	0.6	1.16	3.22	4.56	2.5	2.1	0.8
	rainfed		4.26	5.58			0.6		2.70	3.69			0.7
	irrigated		6.74	7.43			0.2		5.27	6.53			0.5
All	total	1.40	3.23	4.34	1.9	1.4	0.7	1.17	2.91	4.08	2.2	1.5	0.8
cereals	rainfed		2.64	3.58			0.7		1.97	2.80			0.8
	irrigated		4.67	6.10			0.6		4.39	5.90			0.7

Base year data for China adjusted.
Source: Historical data from FAOSTAT.

For cereals, which occupy half (51 percent) of the harvested area in the world and in developing countries, the slowdown in yield growth would be particularly pronounced: from 1.9 percent per annum in the historical period to 0.7 percent over the projection period for the world; and from 2.2 to 0.8 percent in developing countries (Table 6.12). This slowdown too has been under way for some time.

The differences in sources of growth among regions have been discussed. It should be noted that irrigated land is expected to play a more important role in the increase of maize production, almost entirely owing to China – which accounts for more than 40 percent of developing countries' maize production – where irrigated land allocated to maize could more than double. Part of the continued, albeit slowing, growth in yields is due to a rising share of irrigated production (normally with much higher cereal yields) in total production. This would lead to yield increases even if rainfed and irrigated cereal yields did not grow at all.

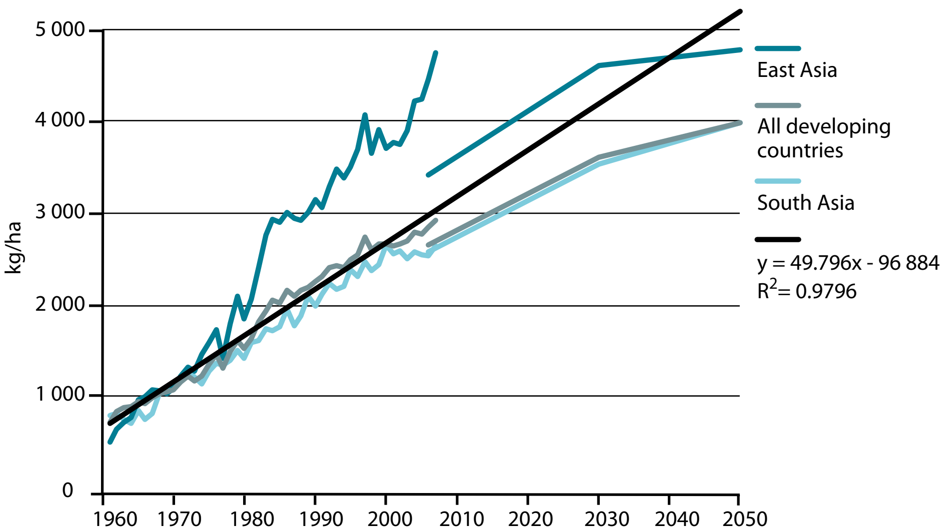
Yield increases are often credited (e.g., Borlaug, 1999) with saving land and thus diminishing pressure on the environment, such as by reducing deforestation. Using cereals as an example, the reasoning is as follows: if the average global cereal yield had not grown since 1961/1963, when it was 1 405 kg per hectare, 1 620 million ha would have been needed to grow the 2 276 million tonnes of cereals the world produced in 2005/2007; this amount was actually obtained from an area of only 705 million ha, at an average yield of 3 230 kg/ha; therefore, 915 million ha were saved because of yield increases for cereals alone. This conclusion should be qualified however, because if there had been no yield growth, the most probable outcome would have been much lower production, owing to lower demand resulting from higher cereal prices, and somewhat more land under cereals. Furthermore, in many countries, the alternative of land expansion instead of yield increases does not exist.

The scope for yield increases

Despite the increases in land under cultivation in land-abundant countries, much agricultural production growth has been based on the growth of yields, and will need increasingly to be so. What is the potential for continuing yield growth? In countries and localities where the potential of existing technology is being exploited fully, subject to the agro-ecological constraints specific to each locality, further growth – or even maintenance – of current yield levels will depend on further progress in agricultural research. In places where yields are nearing the ceilings obtained on research stations, the scope for raising them further is far more limited than in the past (Sinclair, 1998). Nevertheless, yields have continued to increase, albeit at a decelerating rate. For example, wheat yields in South Asia, which accounts for about a third of the developing countries' area under wheat, increased by 40 kg/ha per year between 1961 and 2007 (27 kg/ha over the last decade), and are projected to grow by 32 kg/ha per year over the period 2005/2007 to 2050. The equivalent increases for the developing countries overall are 50 kg/ha (past; Figure 6.9) and 30 kg/ha (future) per annum.

The variation in yields among countries remains very wide. Table 6.13 illustrates this for wheat, rice and maize in developing countries. Current yields in the 10 percent of countries with the lowest yields (the bottom decile, excluding countries with less than 50 000 ha under the crop) are generally less than one-fifth (24 percent for maize) of the yields of the best performers (top decile), and this gap has been worsening over time. If sub-national data were available, a similar pattern would probably be seen for within-country differences as well. For wheat and maize, the gap between worst and best performers is projected to persist until 2050, while for rice it may be somewhat narrowed by 2050, with yields in the bottom decile reaching 25 percent of those in the top. This may reflect the more limited scope for raising the yields of top rice performers than in the past. However, countries included in the bottom and top deciles account for only a minor share of total wheat and rice production; it is more important to examine what will happen to yield levels in the countries that account for the bulk of production. Current (unweighted) average yields of the largest producers[16] are about half those (40 percent for maize) achieved by the top performers (Table 6.13). In spite of continuing yield growth in these largest producing countries, this situation is expected to remain essentially unchanged by 2050.

Figure 6.9
Wheat yields



The break in the series for East Asia (and thus for all developing countries) is due to a downwards adjustment of the base year data for yields in China.
Source: Historical data from FAOSTAT.

16. The top 10 percent of countries ranked according to area allocated to the crop examined. For 2005/2007 these countries are China, India and Turkey for wheat; India, China, Indonesia, Bangladesh and Thailand for rice; and China, Brazil, India, Mexico, Nigeria, Indonesia and the United Republic of Tanzania for maize.

Table 6.13
Average wheat, rice and maize yields in developing countries

Crop	1961/1963 (tonnes/ ha)	1961/1963 (% of top decile)	2005/2007 (tonnes/ ha)	2005/2007 (% of top decile	2050 (tonnes/ ha)	2050 (% of top decile)
Wheat						
Number of developing countries included	31		32		33	
Top decile	2.15		5.65		9.02	
Bottom decile	0.40	18	0.83	15	1.50	17
Decile of largest producers (by area)	0.87	40	3.13	55	4.65	52
All countries included	0.98	46	2.35	42	3.77	42
World	1.48		2.85		3.60	
Rice (paddy)						
Number of developing countries included	44		53		56	
Top decile	4.66		7.52		9.84	
Bottom decile	0.67	14	1.06	14	2.48	25
Decile of largest producers (by area)	1.84	39	4.16	55	5.19	53
All countries included	1.90	41	3.70	49	5.15	52
World	2.19		3.74		5.33	
Maize						
Number of developing countries included	58		69		67	
Top decile	2.16		7.77		9.82	
Bottom decile	0.52	24	0.53	7	1.54	16
Decile of largest producers (by area)	1.21	56	3.15	41	4.92	50
All countries included	1.07	50	2.49	32	3.87	39
World	1.47		3.77		4.40	

Only countries with more than 50 000 ha of harvested area are included.
Countries included in each decile are not necessarily the same for all years.
Average yields are simple averages, not weighted by area.
Source: Author.

Based on this analysis, a prima facie case could be made that there has been, and still is, considerable slack in the crop yields of different countries, which could be exploited if the economic incentives are sufficient. However, the wide differences in yields among major cereal producing countries do not necessarily imply that the lagging countries have scope for yield increases equal to the inter-country yield gaps. Part of these yield differences simply reflect differing agro-ecological conditions, although not all, and perhaps not even the major part, can be ascribed to such conditions, as there are wide yield differences even among countries with fairly similar agro-ecological environments. In these cases, differences in the socio-economic and policy environments probably play a major role. The literature distinguishes two components of yield gaps: agro-environmental and other non-transferable factors, which create gaps that cannot be narrowed; and crop management practices, such as suboptimal use of inputs and other cultural practices. This second component can be narrowed – provided it makes economic sense to do so – and is therefore termed the "exploitable" or "bridgeable yield gap".

Duwayri, Tran and Nguyen (1999) state that the theoretical maximum yields for both wheat and rice are probably in the order of 20 tonnes/ha. On experimental stations, yields of 17 tonnes/ha have been reached in subtropical climates and of 10 tonnes/ha in the tropics. FAO (1999) reports that concerted efforts in Australia to reduce the exploitable yield gap increased rice yields from 6.8 tonnes/ha in 1985/1989 to 8.4 tonnes/ha in 1995/1999, with many individual farmers obtaining 10 to 12 tonnes/ha.

To draw conclusions on the scope for narrowing the yield gap, it is necessary to separate the "non-transferable" part of the gap from the "exploitable" part. One way of doing so is to compare the yields obtained from the same crop varieties grown in different locations with similar physical characteristics (climate, soil, terrain); this eliminates the non-transferable part of the comparison. This can start with an examination of data from the GAEZ analysis on the suitability of land in different countries for producing the given crop under specific technology packages. These data make it possible to derive a national maximum obtainable yield by weighting the yield obtainable in each suitability class with the estimated land area in that class. The derived national obtainable yield can then be compared with data on actual national average yields. The findings presented in Table 6.14 seem to confirm the hypothesis that a good part of the yield gap is of the exploitable type.

Countries with similar attainable averages 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; for example, 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 among countries for producing that crop under the specified conditions.

Table 6.14 shows the agro-ecologically attainable national average wheat yields for 16 countries,[17] and compares them with actual prevailing yields.[18] These countries span a wide range of agro-ecological endowments for wheat

17. Countries with more than 4 million tonnes of wheat production in 2003/2007 and rainfed agriculture accounting for more than 90 percent of total wheat production (except for Turkey, with 80 percent).

18. This comparison is somewhat distorted, as the results of the GAEZ analysis (Fischer, van Velthuizen and Nachtergaele, 2009) available at the time of writing deal with rainfed agriculture only, while the national statistics also include irrigated agriculture.

production, with some having a high proportion of their wheat land in the very suitable category (e.g., France and Poland), and others having high proportions in the suitable and moderately suitable categories (e.g., Kazakhstan and Canada). Attainable average yields in these countries range from more than 7 tonnes/ha in Hungary, Romania, France and Ukraine to less then 4 tonnes/ha in the Russian Federation, Kazakhstan and Canada.

Table 6.14
Agro-ecological suitability for rainfed wheat production, selected countries

	Area				Yield attainable				Actual average 2003/2007	
	Total	Very suitable	Suitable	Moderately suitable[a]	Very suitable	Suitable	Moderately suitable[a]	Average	Area	Yield
Country	*(million ha)*				*(tonnes/ha)*				*(million ha)*	*(tonnes/ ha)*
Romania	14.4	8.3	4.2	1.9	9.0	6.9	5.2	7.9	2.0	2.6
Hungary	7.9	3.6	2.8	1.4	8.8	7.1	4.8	7.5	1.1	4.0
France	27.6	17.1	7.8	2.7	8.0	6.6	4.6	7.3	5.2	6.8
Ukraine	53.7	21.6	25.6	6.5	8.5	6.5	5.2	7.1	5.3	2.5
Poland	28.6	13.7	6.3	8.6	8.5	6.8	4.9	7.0	2.2	3.8
Germany	18.3	6.7	6.1	5.4	8.3	6.7	4.9	6.7	3.1	7.3
Italy	5.8	1.9	2.6	1.3	8.1	6.1	4.0	6.3	2.1	3.5
USA	357.8	124.9	132.2	100.7	8.4	6.0	4.1	6.3	20.3	2.8
UK	11.2	2.4	4.9	3.9	7.7	6.5	4.4	6.0	1.9	7.8
Turkey	24.8	2.5	9.4	13.0	6.6	5.8	4.7	5.3	8.9	2.2
Denmark	4.3	1.3	1.1	1.9	6.7	5.7	4.1	5.3	0.7	7.0
Argentina	87.6	8.3	36.0	43.3	6.6	5.2	3.7	4.6	5.6	2.6
Australia	47.4	3.7	15.5	28.2	6.7	5.2	3.6	4.4	12.7	1.5
Russian Federation	406.1	91.9	168.0	146.2	5.9	3.9	2.4	3.8	23.0	1.9
Kazakhstan	20.6	0.2	3.3	17.0	5.7	4.9	2.9	3.3	11.9	1.1
Canada	158.9	12.8	43.0	103.2	5.8	3.3	2.2	2.8	9.5	2.5

[a] Moderately suitable under high inputs. The data on potentials exclude marginally suitable land that in the GAEZ analysis is not considered appropriate for high-input farming.

Sources: Fischer, van Velthuizen and Nachtergaele, 2009; FAOSTAT.

The divergence between economically efficient and agro-ecologically attainable yields can be very wide. For example, the United Kingdom and the United States of America have nearly equal attainable yields (6.0 to 6.3 tonnes/ha, although the United States has much more land suitable for wheat than the United Kingdom), but actual yields are 7.8 tonnes/ha in the United Kingdom (exceeding what the GAEZ evaluation suggests as attainable on average) and 2.8 tonnes/ha in the United States. Although the United States' yields are only a fraction of those that are agro-ecologically attainable and those that prevail in the United Kingdom, the United States is not necessarily a less efficient wheat producer than the United Kingdom in terms of production costs. Other examples of economically efficient wheat producers with low yields in relation to their agronomic potentials include Argentina (2.6 tonnes/ha actual versus 4.6 tonnes/ha attainable) and Ukraine (2.5 versus 7.1 tonnes/ha).

The yield gap in relation to agronomic potential is an important element when discussing agronomic potentials for yield growth. In countries with large differences between actual and attainable yields, it seems probable that factors other than agro-ecology are responsible. Yields in these countries could grow some way towards bridging the gap if some of these factors were changed, for example, if prices rose. Once the countries with a sizeable bridgeable gap have been identified, their aggregate weight in world production of a particular crop can be assessed. If this weight is significant, 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.).

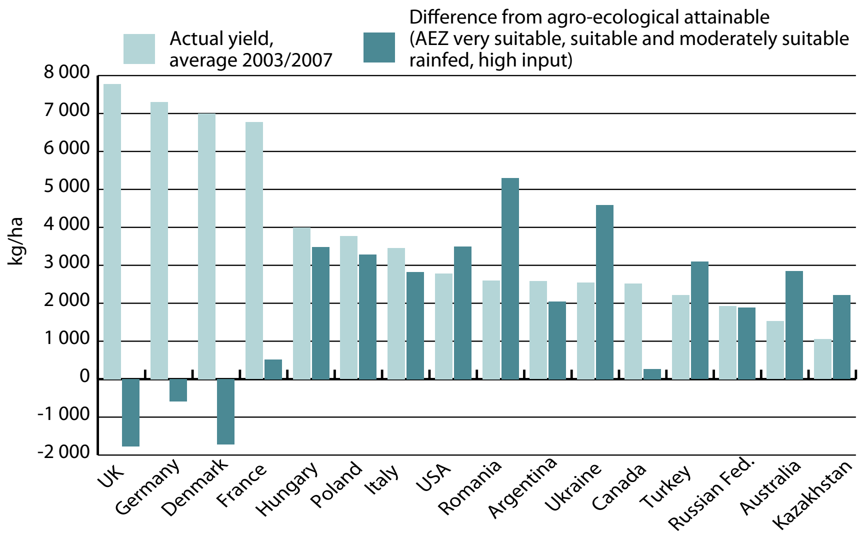
Among the major wheat producers, only some EU countries (the United Kingdom, Denmark, France and Germany) have actual yields close to, or even higher than,[19] those attainable for their agro-ecological endowments under rainfed high-input farming. In all other major producers with predominantly rainfed wheat production, the gaps between actual and attainable yields are significant (Figure 6.10). Even assuming that only half of these yield gaps (attainable minus actual) are bridgeable, the production of these countries could increase considerably without any increase in their area under wheat. As discussed, yield growth would also occur in the countries accounting for the rest of world production, including the major producers of irrigated wheat that are not included in Figure 6.10, such as China, India, Pakistan and Egypt. None of this discussion has considered the potential yield gains that could come from further improvement in varieties, as the attainable yields in GAEZ reflect the yield potential of existing varieties.

Some states in India, such as Punjab, are often quoted as examples of areas where wheat and rice yields have been slowing or are even reaching a plateau. Fortunately, India is one of the few countries for which data are available at the subnational level and distinguished by rainfed and irrigated area. Bruinsma (2003: Table 11.2) compares wheat and rice yields in major growing states with the agro-ecologically attainable yields (estimated in Fischer *et al.*, 2002), taking

19. That actual yield levels in the United Kingdom, Germany and Denmark exceed the average agro-ecological zone attainable yields from all suitable land can in part be explained if it is assumed that all wheat is grown only on very suitable areas (Table 6.14).

into account irrigation. This shows that, although yield growth has indeed been slowing, most actual yields are still far from the agro-ecologically attainable yield (with a few exceptions, such as wheat in Haryana). This suggests that there are still considerable bridgeable yield gaps in India.

Figure 6.10
Actual and agro-ecologically attainable wheat yields, selected countries



Source: Author.

This discussion gives an idea of the scope for wheat production increases through the adoption of improved technologies and practices to bridge some of the gaps between actual and obtainable yields. Wheat was used as an example, but similar analysis of other crops shows that the conclusions hold for all crops. The broad lesson from experience seems to be that if scarcities develop and prices rise, farmers quickly respond by adopting such technologies and increasing production, at least when they live in an environment with relatively easy access to improved technology, transport infrastructure and supportive policies. However, in countries with land expansion possibilities, the quickest response comes from increasing the land under cultivation, including by shifting land among crops towards the most profitable ones.

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, such land is also suitable for other crops, and is used for them. The point being made here is that the gap between the 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. Although production increases may be obtained by expanding cultivation into land suitable for a particular crop, such land may not be available if it is being used for other crops.

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

This discussion may create the impression that all is well regarding the potential for further production growth based on the use of existing varieties and technologies to increase yields. However, this should be heavily qualified, because: i) the exploitation of bridgeable yield gaps requires the further spread of high-external-input technologies, which might aggravate related environmental problems; and ii) perhaps more important from the standpoint of meeting future demand, the countries where there will be additional demand do not necessarily have potential for yield growth. When the potential demand is in countries with limited import capacity, as is the case of many developing countries, such potential can be expressed as effective demand only if it can be matched predominantly by local production. 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 from 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.

Summary and conclusions

This chapter has discussed the natural resource implications of the latest FAO food and agriculture baseline projections to 2050 (FAO, 2006b). These projections offer a comprehensive and consistent picture of the food and agricultural situation in 2030 and 2050, covering food and feed demand, including all foreseeable diet changes, trade and production. The main purpose of the chapter is to provide an indication of the additional demands on natural resources that will be derived from the crop production levels for 2030 and 2050 as foreseen in the FAO 2006 projections. It does not deal with additional demand for agricultural products used as feedstock in biofuel production, or the impacts of climate change (these are dealt with in Chapter 3), nor does it deal with the additional production needed to eliminate (or accelerate the elimination of) the remaining undernourishment by 2050.

Growth in agricultural production will continue to slow as a consequence of the slowdown in population growth and because an ever-increasing share of world population is reaching medium to high levels of food consumption. Nevertheless, agricultural production would still need to increase by 70 percent (and nearly 100 percent in developing countries) by 2050 to cope with a 40 percent increase in world population and to raise average food consumption to 3 130 kcal per person per day by 2050. This translates into additional production of 1 billion tonnes of cereals and 200 million tonnes of meat a year by 2050 (compared with production in 2005/2007).

Some 90 percent (80 percent in developing countries) of the growth in crop production would be a result of higher yields and increased cropping intensity, with the remainder coming from land expansion. Arable land would expand by 70 million ha (less than 5 percent), an expansion of about 120 million ha (12 percent) in developing countries being offset by a decline of 50 million ha (8 percent) in developed countries. Almost all of the land expansion in developing countries would occur in sub-Saharan Africa and Latin America.

Land equipped for irrigation would expand by 32 million ha (11 percent), while harvested irrigated land would expand by 17 percent. All of these increases would be in the developing countries. Mainly (but not only) as a result of slowly improving water-use efficiency, water withdrawals for irrigation would grow more slowly, but would still increase by almost 11 percent (or 286 km^3) by 2050.

Crop yields would continue to grow, but at a slower rate than in the past. This process of decelerating growth has already been under way for some time. On average, annual growth over the projection period would be about half (0.8 percent; 0.9 in developing countries) of its historical growth rate (1.7 percent; 2.1 percent in developing countries). Cereal yield growth would slow to 0.7 percent per annum (0.8 percent in developing countries), and average cereal yield would reach 4.3 tonnes/ha in 2050, up from 3.2 tonnes/ha at present.

Are the projected increases in land, water use and yields feasible? The GAEZ study shows that ample land resources with some potential for crop production remain, but this needs to be heavily qualified. Much of the suitable land not yet in use is concentrated in a few countries in Latin America and sub-Saharan Africa, not necessarily where it is most needed, and much is suitable for growing only a few crops, not necessarily those for which the demand is highest. In addition, much of the land not yet in use suffers from constraints (chemical, physical, disease, lack of infrastructure, etc.) that cannot be overcome easily (or economically). Part of the land is under forests, protected or under urban settlements, and so on. Overall, however, although a number of countries – particularly in the Near East and North Africa and in South Asia – have reached or are about to reach the limits of their available land, at the global scale there are still sufficient land resources left to feed the world population for the foreseeable future.

The availability of freshwater resources shows a very similar picture to that of land availability, with sufficient resources at the global level being unevenly distributed and an increasing number of countries or parts of countries reaching alarming levels of water scarcity. Many of the water-scarce countries in the Near East and North Africa and in South Asia also lack land resources. A mitigating factor could be that there are still ample opportunities for increasing water-use efficiency, such as through providing the right incentives to use less water.

The potential to increase crop yields (even with existing technology) seems considerable. Provided the appropriate socio-economic incentives are in place, there are still ample bridgeable yield gaps – the differences between agro-ecologically attainable and actual yields – to be exploited. Fears that yields, such as for rice, are reaching a plateau do not seem warranted, except for in a few very special instances.

Towards the end of the projection period there are signs that an increasing number of countries (not all of them among today's "developed countries") will reach saturation levels, when agricultural production ceases to increase and arable land is taken out of production. Likewise, although land allocated to crops such as maize and soybeans could still increase considerably, land allocated to crops such as rice, potatoes and pulses would decline. Naturally, apart from rising yields, this reflects slowing (or even declining) population growth, medium to high food consumption levels, and the shift in diets to livestock products resulting in more land being allocated to crops for animal feed.

Does this mean that all is well? Certainly not. The conclusion that the world as a whole produces or could produce enough food for all is small consolation to the people and countries (or regions within countries) that continue to suffer from undernourishment. The projected increases in yield, land and irrigation expansion will not come about entirely spontaneously (driven by market forces), but will require huge public interventions and investments, particularly in agricultural research and in preventing and mitigating environmental damage. In the problem countries, public intervention will continue to be required, to develop agriculture and adapt it to local circumstances, and to establish social safety nets.

References

Alexandratos, N., ed. 1995. *World agriculture: Towards 2010, an FAO study.* Chichester, UK, J. Wiley and Sons, and Rome, FAO.

Alexandratos, N. 2005. Countries with rapid population growth and resource constraints: Issues of food, agriculture, and development. *Population and Development Review*, 31(2): 237–258.

Alexandratos, N. 2008. Food price surges: Possible causes, past experiences, relevance for exploring long-term prospects. *Population and Development Review*, 34(4): 663–697.

Borlaug, N. 1999. Feeding a world of 10 billion people: the miracle ahead. Lecture presented at De Montfort University, Leicester, UK.

Brown, L. 2009. Could food shortages bring down civilization? *Scientific American*, 22 April 2009.

Bruinsma, J., ed. 2003. *World agriculture: Towards 2015/2030, an FAO perspective*. London, Earthscan and Rome, FAO. www.fao.org/es/esd/gstudies.htm.

Byerlee, D. 1996. Modern varieties, productivity and sustainability: Recent experience and emerging challenges. *World Development*, 24(4): 697–718.

Cohen, J. 1995. *How many people can the earth support?* New York, W. Norton.

Deininger, K. & Minten, B. 1999. Poverty, policies and deforestation: the case of Mexico. *Economic Development and Cultural Change,* January 1999.

Duwayri, M., Tran, D. & Nguyen, V. 1999. Reflections on yield gaps in rice production. *International Rice Commission Newsletter*, 48: 13–26.

FAO. 1998. *Crop evapotranspiration: Guidelines for computing crop water requirements,* by R. Allen, L. Pereira, D. Raes and M. Smith. FAO Irrigation and Drainage Paper No. 56. Rome.

FAO. 1999. *Bridging the rice yield gap in the Asia-Pacific region*. FAO Expert Consultation, 5–7 October 1999, Bangkok.

FAO. 2000. *Land resource potential and constraints at regional and country levels,* by A. Bot, F. Nachtergaele and A. Young. World Soil Resources Report No. 90. Rome.

FAO. 2004. *Global map of monthly reference evapotranspiration – 10 arc minutes*. FAO-GeoNetwork. www.fao.org/geonetwork/srv/en/main.home.

FAO. 2005a. *Irrigation in Africa in figures: Aquastat survey – 2005.* FAO Water Report No. 29. Rome.

FAO. 1995. *World agriculture: Towards 2010, an FAO study*, edited by N. Alexandratos. Rome, and Chichester, UK, J. Wiley and Sons.

FAO. 2005b. *Key water resources statistics in Aquastat.* Rome.

FAO. 2006a. *Global Forest Resources Assessment 2005.* FAO Forestry Paper No. 147. Rome.

FAO. 2006b. *World agriculture: towards 2030/2050 – interim report.* Rome.

Fischer, G., van Velthuizen, H., Shah, M. & Nachtergaele, F. 2002. *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and results*. RR-02-002. Laxenburg, Austria, IIASA.

Fischer, G., van Velthuizen, H. & Nachtergaele, F. 2009. *Global Agro-ecological Assessment – the 2009 revision*. Laxenburg, Austria, IIASA.

Lopez, R. 1998. The tragedy of the commons in Côte d'Ivoire agriculture: Empirical evidence and implications for evaluating trade policies. *World Bank Economic Review,* 12(1): 105–131.

Nachtergaele, F. & George, H. 2009. How much land is available for agriculture. Unpublished paper for FAO. Rome.

New, M., Lister, D., Hulme, M. & Makin, I. 2002. A high-resolution data set of surface climate over global land areas. *Climate Research,* 21: 1–25.

OECD/FAO. 2009. *Agricultural Outlook 2009–2018.* Paris and Rome.

Siebert, S., Döll, P., Feick, S., Hoogeveen, J. & Frenken, K. 2007. *Global map of irrigation areas version 4.0.1.* Frankfurt-am-Main, Germany, Johann Wolfgang Goethe University, and Rome, FAO.

Sinclair, T. 1998. Options for sustaining and increasing the limiting yield-plateaus of grain crops. Paper presented at the NAS Colloquium Plants and Population: Is There Time? Irvine, California, USA, 5–6 December 1998.

Young, A. 1999. Is there really spare land? A critique of estimates of available cultivable land in developing countries. *Environment, Development and Sustainability,* 1: 3–18.

Annex 6.1

Countries included in the analysis

Developing countries

Sub-Saharan Africa

Angola	Democratic Republic of the Congo	Madagascar	Sierra Leone
Benin	Eritrea	Malawi	Somalia
Botswana	Ethiopia	Mali	Sudan
Burkina Faso	Gabon	Mauritania	Swaziland
Burundi	Gambia	Mauritius	Togo
Cameroon	Ghana	Mozambique	Uganda
Central African Republic	Guinea	Niger	United Republic of Tanzania
Chad	Kenya	Nigeria	Zambia
Congo	Lesotho	Rwanda	Zimbabwe
Côte d'Ivoire	Liberia	Senegal	

Latin America and the Caribbean

Argentina	Ecuador	Mexico	Suriname
Brazil	El Salvador	Nicaragua	Trinidad and Tobago
Chile	Guatemala	Panama	Uruguay
Colombia	Guyana	Paraguay	Venezuela
Costa Rica	Haiti	Peru	
Cuba	Honduras	Plurinational State of Bolivia	
Dominican Republic	Jamaica		

Near East and North Africa

Afghanistan	Islamic Republic of Iran	Libyan Arab Jamahiriya	Syrian Arab Republic
Algeria	Jordan	Morocco	Tunisia
Egypt	Lebanon	Saudi Arabia	Turkey
Iraq			Yemen

South Asia

Bangladesh	India	Nepal	Pakistan	Sri Lanka

East Asia

Cambodia	Indonesia	Myanmar	Thailand
China	Lao People's Democratic Republic	Philippines	Viet Nam
Democratic People's Republic of Korea	Malaysia	Republic of Korea	

Industrial countries

*European Union 15**

Austria	France	Italy	Spain
Belgium	Germany	Luxembourg	Sweden
Denmark	Greece	Netherlands	United Kingdom
Finland	Ireland	Portugal	

Other industrial countries

Australia	Israel	Norway	United States of America
Canada	Japan	South Africa	
Iceland	New Zealand	Switzerland	

Transition countries

Russian Federation

*Countries in the European Union **

Czech Republic	Latvia	Poland
Estonia	Lithuania	Slovakia
Hungary	Malta	Slovenia

*Central Asia**

Armenia	Georgia	Kyrgyzstan	Turkmenistan
Azerbaijan	Kazakhstan	Tajikistan	Uzbekistan

*Other Eastern Europe**

Albania	Bulgaria	Macedonia	Romania
Belarus	Croatia	Montenegro	Serbia
Bosnia and Herzegovina	Former Yugoslav Republic of	Republic of Moldova	Ukraine

* Country group treated as an aggregate in the analysis.

Annex 6.2

Crops included in the analysis

Wheat	Plantains	Sunflower seed
Rice, paddy	Sugar beet	Palm oil/palm-kernel oil
Maize	Sugar cane	Rapeseed
Barley	Pulses	Other oilseeds
Millet	Vegetables	Cocoa beans
Sorghum	Bananas	Coffee
Other cereals	Other fruits	Tea
Potatoes	Citrus fruits	Tobacco
Sweet potatoes and yams	Soybeans	Seed cotton
Cassava	Groundnuts	Jute and hard fibres
Other roots	Sesame seed	Rubber
	Coconuts	