THE RESOURCE OUTLOOK TO 2050

By How Much Do Land, Water Use and Crop Yields Need to Increase by 2050?

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Contents

List of Tables

List of Figures

List of Boxes

The resource outlook to 2050[1]

By how much do land, water and crop yields need to increase by 2050?

Jelle Bruinsma[2]

Summary and conclusions

This paper discusses the natural resource implications of the latest FAO food and agriculture base line projections to 2050 (FAO, 2006a). These projections offer a comprehensive (food and feed demand, including all foreseeable diet changes, trade and production) and consistent picture of the food and agricultural situation in 2030 and 2050. The main purpose of this paper is to provide an indication of the additional demands on natural resources derived from the crop production levels in 2030 and 2050 as foreseen in the FAO 2006 projections. It does not deal with additional demand for agricultural products used as feedstock in bio-fuel production or the impacts of climate change (these are dealt with in another paper, Fischer 2009, for this expert meeting), nor the additional production needed to eliminate (or to accelerate the elimination of) the remaining undernourishment in 2050.

Growth in agricultural production will continue to slowdown as a consequence of the slowdown in population growth and of the fact that 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 (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 3130 kcal per person per day by 2050. This translates into an additional billion tonnes of cereals and 200 million tonnes of meat to be produced annually by 2050 (as compared with production in 2005/07).

Ninety 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 some 70 million ha (or less then 5 percent), the expansion of land in developing countries by about 120 million ha (or 12 percent) being offset by a decline of some 50 million ha (or 8 percent) in the developed countries. Almost all of the land expansion in developing countries would take place in sub-Saharan Africa and Latin America.

Land equipped for irrigation would expand by some 32 million ha (11 percent) while the harvested irrigated land would expand by 17 percent. All of this increase would be in the developing countries. Mainly (but not only) due to slowly improving water use efficiency, water withdrawals for irrigation would grow at a slower pace but still increase by almost 11 percent (or some 286 cubic km) 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 underway for some time. On average, annual growth

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[2] Consultant with the Global Perspective Studies Unit at FAO. Substantial contributions by Gerold Boedeker, Jean-Marc Faures, Karen Frenken and Jippe Hoogeveen as well as comments on an earlier draft by FAO staff are gratefully acknowledged. The author alone is responsible for any remaining errors. The opinions expressed in this paper are the author’s and do not necessarily reflect those of FAO.

over the projection period would be about half (0.8 percent) of its historical growth rate (1.7 percent; 0.9 and 2.1 percent for the developing countries). Cereal yield growth would slowdown to 0.7 percent per annum (0.8 percent in developing countries), and average cereal yield would by 2050 reach some 4.3 tonne/ha, up from 3.2 tonne/ha at present.

Are the projected increases in land, water use and yields feasible? The Agro-Ecological Zone study shows that there are still ample land resources with some potential for crop production left, but this result 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, i.e. not necessarily where it is most needed, and much of the potential land is suitable for growing only a few crops not necessarily the crops for which there is the highest demand. Also much of the land not yet in use suffers from constraints (chemical, physical, endemic diseases, lack of infrastructure, etc.) which cannot easily be overcome (or it is economically not viable to do so). Part of the land is under forests, protected or under urban settlements, and so on. Overall however it is fair to say that, although there are a number of countries (in particular in the Near East/North Africa and South Asia) that have reached or are about to reach the limits of land available, on a global scale there are still sufficient land resources left to feed the world population for the foreseeable future.

The availability of fresh water resources shows a very similar picture as land availability, i.e. globally more than sufficient but very unevenly distributed with an increasing number of countries or regions within countries reaching alarming levels of water scarcity. This is often the case in the same countries in the Near East/North Africa and South Asia that have no land resources left. A mitigating factor could be that there are still ample opportunities to increase the water use efficiency (e.g. through providing the right incentives to use less water).

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

Towards the end of the projection period there are signs of an increasing number of countries (and not only what at present are termed 'developed countries') reaching 'saturation' levels, i.e. agricultural production hardly grows anymore and arable land is taken out of production. Likewise, although land allocated to crops such as maize and soybeans would 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 with more land allocated to crops used for feeding purposes.

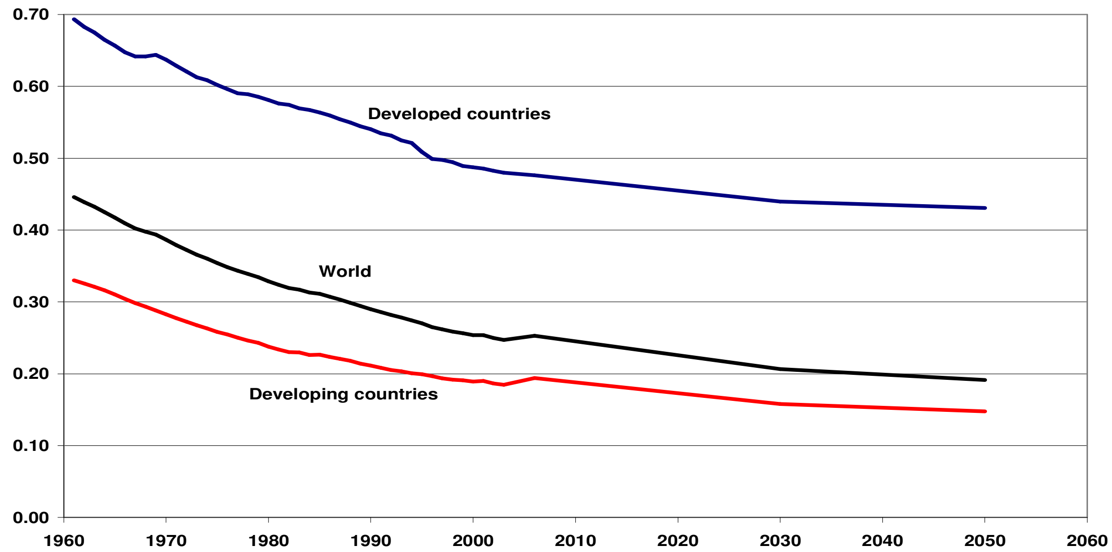
Does this mean that all is well? Certainly not. The conclusion that the world as a whole produces or could produce enough food for all is small consolation to the persons and countries (or regions within countries) that continue to suffer from undernourishment. The projected increases in yields, land and irrigation expansion will not entirely come about spontaneously (i.e. driven by market forces) but 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 on the one hand to develop agriculture and to adapt agriculture to local circumstances and on the other hand to establish social safety nets.

Introduction

The recent food crisis, characterized by sharp food price surges and in part caused by new demands on agriculture such as demand for bio-mass as feedstock in bio-fuel production (see Alexandratos, 2008), made fears that the world is running out of natural resources (foremost among them land and fresh water resources) come back with a vengeance (see for example 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 keep continually coming back prompting a series of studies and statements concerning the question how many people the earth can support. The continuing decline of arable land per person (Figure 1) is often cited as an indicator of impending problems[3]. 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 demands for them originating in urbanization, industrial uses and use in bio-fuel production, by forces that would change their availability such as climate change and the need to preserve resources for future generations (environmentally responsible and sustainable use).

Figure 1. Arable land per caput (ha in use per person)



This paper will address a few of the above-mentioned issues by unfolding the resource use implications of the crop production projections underlying the latest FAO perspective study (FAO, 2006a, "World agriculture: towards 2030/2050 – Interim report"[4]).

The FAO (2006a) projection results are also briefly presented in a companion paper[5]. They can be considered to represent a baseline scenario but do not take into account additional demand for agricultural products and for land needed in bio-fuel production nor do they explicitly account for land use changes due to climate change. This is not to say that such demands on

[3] Of course, one could interpret declining land per person combined with increasing average food consumption as a sign of ever increasing agricultural productivity.

[4] Unlike the preceding study (Bruinsma, 2003), the 2006 interim study did for a number of reasons not deal with resource use issues such as of land and yield expansion and water use in irrigation.

[5] Alexandratos, N. (2009), "World food and agriculture to 2030/2050: Highlights and views from mid-2009".

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 will be discussed in another paper for this meeting by Fischer[6].

In discussing the natural resource implications, this paper will mainly focus 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, due to space and time constraints these will not be explicitly dealt with in this paper.

The 2006 study had as base year the three-year average 1999/2001 based on FAOSTAT data as known in 2002-04. At present, FAOSTAT offers published data up to 2003 for supply-utilization accounts and up to 2007 for land use and production by crop, and although due to time constraints and the non-availability of published food balance sheet data after 2003, no new base year and projections could be derived, production and land use data for the latest three-year average 2005/07 were taken into account in the work underlying this paper.

Another limitation is that at the time of preparation of this paper the results of the 2009 Global Agro-Ecological Zone (GAEZ) study were not yet available so that resort had to be taken to the results of the 2002 GAEZ study (as reported in Fischer *et al.*, 2002).

This paper is based on analytical work for 146 countries (93 developing and 53 developed countries[7], 42 of the latter grouped into 4 country groups. See the Appendix). These countries cover at present almost 98 and 100 percent of the world's population and arable land respectively.

How much more needs to be produced?

FAO's 2006 base line projections (FAO, 2006a) show that by 2050 the world's average daily calorie availability could rise to 3130 kcal per person, an 11 percent increase over its level in 2003. This would by 2050 still leave some 4 percent of the developing countries' population chronically undernourished[8].

For these projections to materialize, world agricultural production would need to increase by some 70 percent over the period from 2005/07 to 2050 (see Table 1). World population is projected to rise by some 40 percent over this period, meaning that per caput production would rise by some 22 percent. The fact that this would translate into an only 11 percent increase of per caput calorie availability is mainly[9] due to the expected changes in diet, i.e. a shift to higher value foods of often lower calorie content (e.g. vegetables and fruits) and to livestock products which imply an inefficient conversion of calories of the crops used in livestock feeds.

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[6] Fischer, G. (2009), "How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability?".

[7] The developed countries include the industrialized countries and the 'countries in transition'.

[8] A partial update of the projections presented in Alexandratos (2009) shows a lower average calorie availability by 2050 of 3050 kcal per person per day and a slightly higher share of the developing countries' population chronically undernourished, namely 5 percent.

[9] Since 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 aggregates expressed in physical units or using a calorie-based index as diets change away from staples to higher value commodities (see Box 3.1 in FAO, 2006a).

Meat consumption per caput for example would rise from 37 kg at present to 52 kg in 2050 (from 26 to 44 kg in the developing countries) implying that much of the additional crop (cereal) production will be used for feeding purposes in livestock production.

Table 1. Increases in agricultural production, past and future

	1961/63	2005/07	2050	1961/63 to 2005/07	2005/07 to2050
	million tonnes / persons			increment in percent	
World (146 countries)					
population#	3133	6372	8796	103	38
total production*				148	70
crop production*				157	66
cereals**	843	2012	3009	139	49
livestock production*				136	76
meat production	94	249	461	165	85
(93) Developing countries					
population	2139	5037	7433	135	48
total production				255	97
crop production				242	82
cereals	353	1113	1797	215	61
livestock production				284	117
meat production	42	141	328	236	132
(53) Developed countries					
population	994	1335	1362	34	2
total production				63	23
crop production				64	30
cereals	490	900	1212	84	35
livestock production				62	17
meat production	52	108	133	108	23

2005/07 = 2005; 2050 from the UN 2002 Assessment; the 2050 projection from the UN 2008 Assessment amounts to 9056 million for the 146 countries covered.
* in value terms. ** including rice in milled form. The latest (CCBS) data show a world cereal production of 2138 million tons for 2006/08 implying an increment to 2050 of less than 900 million ton if measured from the 2006/08 average.

Table 1 shows the increments in production for the past and future 44-year periods. It clearly brings out the drastic slowdown in expected production growth as compared with the past for the country and commodity groups shown. This of course mirrors the projected deceleration in demand for agricultural products which in turn is a reflection of the decelerating growth of population and of the fact that an ever increasing share of population gradually attains mid to high levels of food consumption (FAO, 2006a).

This slowdown is particularly pronounced for the group of developed countries, but the group of better-off developing countries (defined as having a 2005 daily calorie supply of over 3000 kcal per person) is expected to follow a similar pattern.

Table 2. Annual crop production growth (percent p.a.)

	1961-07	1987-07	1997-07	2005/07-30	2030-50	2005/07-50
Developing countries	3.0	3.0	2.9	1.5	0.9	1.2
idem, excl. 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 / 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
memo item 14 developing countries with over 3000 kcal/person/day in 2005*	3.3	3.3	3.2	1.3	0.7	1.0

* these countries account for 40 percent of the population in developing countries

Although the annual growth of world agricultural production is projected to fall from 2.2 percent over the last decade to 1.5 percent over the period to 2030 and 0.9 percent over the period 2030 to 2050 (Table 2), one should not loose sight of the fact that the incremental quantities involved are still very considerable: an additional billion tonnes of cereals and an another 200 million tonnes of meat would need to be produced annually by 2050. The latter would require ample increases in the production of concentrate feeds. For example, some 80 percent of the additional 480 million tons of maize produced annually by 2050 would be for animal feeds and soybean production would need to increase by a hefty 140 percent to 515 million tons in 2050. As mentioned before, these increments do not account for additional production needed as feedstock in bio-fuel production.

With a view to natural resource use in agricultural production, one should bear in mind that the bulk of the foods consumed are produced locally. On average at present only 16 percent[10] (15 percent for cereals and 12 percent for meats) of world production enters international trade, with of course a wide variation among individual countries and commodities.

What are the sources of growth in crop production?

Growth in crop production comes on account of growth in crop yields and/or expansion in the physical area (arable land) allocated to crops which, together with increases in cropping intensities (i.e. by increasing multiple cropping and/or shortening of fallow periods), leads to an expansion in the actually harvested area.

For the purposes of this study, a detailed investigation was made of present and future land/yield combinations for 34 crops under rainfed and irrigated cultivation conditions, for 108 countries and country groups. The informal method applied took into account whatever information was available but is in the main based on expert-judgment (see Box 1 for a brief description of the approach followed).

The summary results shown in Table 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, 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.

[10] Measured as ((gross imports + gross exports) / 2) / production.

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 3). The share due to intensification goes up to 95 percent in the land-scarce region South Asia and to over 100 percent in Near East/North Africa where increases in yield would have to also compensate for the foreseen decline in the 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.

Table 3. Sources of growth in crop production (percent)

	Arable land expansion		Increases in cropping intensity		Yield increases	
	1961 - 2005	2005/07 -2050	1961 - 2005	2005/07 -2050	1961 - 2005	2005/07 -2050
All developing countries	23	21	8	8	70	71
sub-Saharan Africa	31	25	31	6	38	69
Near East/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
memo items						
developing countries with less then 40 percent of their potentially arable land in use in 2005*		30		15		55
developing countries with over 80 percent of their potentially arable land in use in 2005**		2		9		89

* 42 countries accounting for 15 percent of the population in developing countries.
** 19 countries accounting for 35 percent of the population in developing countries.

These summary results mask of course a wide variation among countries. The actual combination of the factors used in crop production (e.g. land, labour and capital) in the different countries will be determined by their relative prices. Taking the physical availability of land as a proxy for its relative scarcity and hence price, one would expect land to play a greater role in crop production the less scarce it is. For the 42 developing countries, which at present use less than 40 percent of their land estimated to have some rainfed crop production potential, arable land expansion is projected to account for almost one-third of their crop production growth. At the other end of the spectrum, in the group of 19 land-scarce countries (defined here as 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 (2 percent – see Table 3).

In the 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. Hence growth in crop yields accounted for all of their growth in crop production and in addition compensated for declines in their arable land area. This trend is foreseen to continue also for the period to 2050 (see below). As a result, intensification (higher yields and more intensive use of land) is seen to contribute over the projection period more than 90 percent to growth in crop production at the world level.

It is interesting to see that growth in rice production in the developing countries increasingly will have to come (at least on average) entirely from gains in yield (Table 4), with yield increases even compensating for a slight decline in harvested land allocated to rice. This could be a sign of consumption of certain food commodities in some countries reaching saturation levels by 2050.

In the developing countries, the bulk of wheat and rice is produced in the land-scarce regions of Asia and the Near East/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 therefore will continue to be major contributor to production growth of maize.

Table 4. Sources of growth for major cereals in developing countries

		annual growth (percent p.a.)			contribution to growth (percent)	
		production	harvested land	yield	harvested land	yield
Wheat	1961-2007	3.77	1.04	2.70	28	72
	2005/07-2050	1.05	0.29	0.75	28	72
Rice, paddy	1961-2007	2.32	0.51	1.80	22	78
	2005/07-2050	0.48	-0.11	0.59	-23	123
Maize	1961-2007	3.43	0.99	2.42	29	71
	2005/07-2050	1.41	0.63	0.78	44	56

As discussed in FAO (2006a), an increasing share of the increment in the production of cereals, mainly coarse grains, will be used in livestock feed. As a result, maize production in the developing countries is projected to grow at 1.4 percent p.a. 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 actually falling over the projection period, while maize production is expected to grow by some 60 percent. Hence there will be a corresponding decline in the areas allocated to wheat and rice but a considerable increase in the maize area.

Table 5. Shares of irrigated land and production in total

	All crops			Cereals	
shares (in percent)	arable land	harvested land	production	harvested land	production
World					
share in 2005/07	15	23	42	29	42
share in 2050	16	24	43	30	43
Developing countries					
share in 2005/07	19	29	47	39	59
share in 2050	20	30	47	41	60

This study made an attempt to unfold crop production by rainfed and irrigated land in order to analyse the contribution of irrigated crop production to total crop production. It is estimated that at present in the developing countries, irrigated agriculture, with about a fifth of all arable land, accounts for 47 percent of all crop production and almost 60 percent of cereal production (Table 5). It should be emphasized that except for some major crops in some countries, there is only limited data on irrigated land and production by crops and the results presented in Table 5 are in part based on expert-judgment (see Box 1). Nevertheless, the results suggest a continuing importance of irrigated agriculture.

Box 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.

These projections took as a starting point the crop production projections for 2030 and 2050 from the 2006 FAO study "World agriculture: towards 2030/2050" (FAO, 2006a). The crop production projections are based on demand and trade projections (including for livestock and feed commodities) which together make up consistent commodity balances and clear the world market. The base line scenario presents a view how the key food and agricultural variables may evolve over time, not how they should evolve from a normative perspective to solve problems of nutrition and poverty. An effort was made to draw to the maximum extent possible on FAO's in-house knowledge available in the various disciplines present in FAO. The quantitative analysis and projections were therefore carried out in considerable detail, also in order to provide a basis for making statements about the future concerning individual commodities and groups of commodities as well as agriculture as a whole, and for any desired group of countries. The analysis was carried out for as large a number of individual commodities and countries as practicable (108 countries and country groups covering some 146 countries in total , 34 crops - see the Appendix - and two land classes, rainfed and irrigated agriculture).

A major part of the data preparation work is the unfolding of the data for production (i.e. the FAOSTAT data for area harvested and average yield for each crop and country for the three-year average 2005/07, 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 any standard database. It became therefore necessary to piece them together from fragmentary information, from both published (e.g. from EUROSTAT for the EU countries) and unpublished documents giving, for example, areas and yields by irrigated and rainfed land at the national level or by administrative districts, supplemented by a good deal of guesstimates. For a number of countries (e.g. for the USA, China, EU15, India and Indonesia) the data for irrigated agriculture were assembled at the sub-national level.

No data exist on total harvested land, but a proxy can be obtained by summing up the harvested areas reported for the 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. Indeed, for several countries (in particular for sub-Saharan countries but not only) the implicit values of the cropping intensities did not seem to be realistic. In such cases the harvested area data resulting from the crop statistics were accepted as being the more robust (or the less questionable) ones and those for arable area were adjusted (see Alexandratos, 1995 for a discussion of these problems) .

Data reported in FAOSTAT on arable irrigated land refer to 'area equipped for irrigation'. What is needed is the 'irrigated land actually in use' which is often between 80 and 90 percent of the area equipped. Data for the 'area in use' were taken from FAO's AQUASTAT data base.

The bulk of the projection work concerned the unfolding of 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.

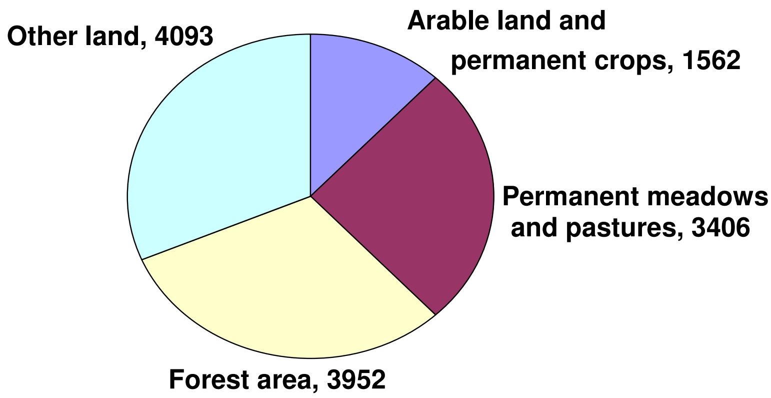
An initial mechanically derived projection for rainfed and irrigated harvested area and yield by crop (constrained to arrive at exactly the projected production) was evaluated against such information as recent growth in land and yield (total by crop) and the 'attainable yield' levels for most crops from the Global Agro-Ecological Zone (GAEZ) study (Fischer et al., 2002), and adjusted were needed. A similar projection was made for total arable rainfed and irrigated area which were then evaluated against estimates for the (maximum) potential areas for rainfed agriculture (from the GAEZ) and for irrigated agriculture (from AQUASTAT) and adjusted where needed. In addition, for irrigated area cropping patterns were checked against 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 over all crops with the arable area) and again adjusting areas (and yields) where needed. Normally it required several iterations before arriving at an 'acceptable' picture of the future.

Since the whole exercise is dependent on expert-judgement and requires an evaluation of each and every number, it is a time-consuming exercise. The projections presented in this study are not trend extrapolations as they take into account all knowledge available at present as to expected developments that might make evolutions in major variables deviate from their trend path.

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

At present some 12 percent (over 1.5 billion ha. Figure 2) of the globe's land surface (13.4 billion ha) is used in crop production (arable land and land under permanent crops). This area represents slightly over a third (36 percent) of the land estimated to be to some degree suitable for crop production. The fact that there remain some 2.7 billion ha with crop production potential suggests that there is still scope for further expansion of agricultural land. However, there is also a perception, at least in some quarters, that there is no more, or very little, land to bring under cultivation. In what follows, an attempt is made to shed some light on these contrasting views by first briefly discussing some estimates of land with crop production potential and some constraints to exploiting such suitable areas, where after the projected expansion of the agricultural area over the period up to 2050 will be presented.

Figure 2. World land area (million ha in 2005)



Source: FAOSTAT

How much land is there with crop production potential[11]?

Notwithstanding the predominance of yield increases in the growth of agricultural production, land expansion will continue to be a significant factor in those developing countries and regions where the potential for expansion exists and the prevailing farming systems and more general demographic and socio-economic conditions favour it. One of the frequently asked questions 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?

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

Summing over all crops (covered in the GAEZ) and technology levels considered, it is estimated that about 30 percent of the world's land surface, or 4.2 billion ha[12] is suitable to

[11] This section is an adaptation of a similar section in Bruinsma (2003). It is based on the Global Agro-Ecological Zone (GAEZ) published in 2002 (Fischer *et al*., 2002). During the past few years the GAEZ study was completely revisited results of which will be published during 2009, unfortunately too late to be taken into account in the work for this paper.

some extent for rainfed agriculture (Table 6). Of this area some 1.6 billion ha are already under cultivation (Table 7). The developing countries have some 2.8 billion ha of land of varying qualities which have potential for growing rainfed crops at yields above an "acceptable" minimum level, of which nearly 970 million ha are already under cultivation. The gross land balance of 2.6 billion ha (4.2 – 1.6 billion; 1.8 billion ha for the developing countries) would therefore seem to provide significant scope for further expansion of agriculture. However, this favourable impression must be much qualified if a number of considerations and constraints are taken into account.

Table 6. Land with rainfed crop production potential (million ha)

	Total land surface	Share of land suitable (%)	Total land suitable	Very suitable (VS)*	Suitable (S)	Moderately suitable (MS)	Marginally suitable (mS)	Not suitable (NS)
Developing countries	7302	38	2782	1109	1001	400	273	4520
Sub-Saharan Africa	2287	45	1031	421	352	156	103	1256
Near East/North Africa	1158	9	99	4	22	41	32	1059
Latin America	2035	52	1066	421	431	133	80	969
South Asia	421	52	220	116	77	17	10	202
East Asia	1401	26	366	146	119	53	48	1035
Industrial countries	3248	27	874	155	313	232	174	2374
Transition countries	2305	22	497	67	182	159	88	1808
World**	13400	31	4188	1348	1509	794	537	9211

* VS = yield attainable is 80 to 100% of the maximum constraint-free yield; S = 60-80%; MS = 40-60%; mS = 20-40%; NS = <20%.
** Including some countries not covered in this study.

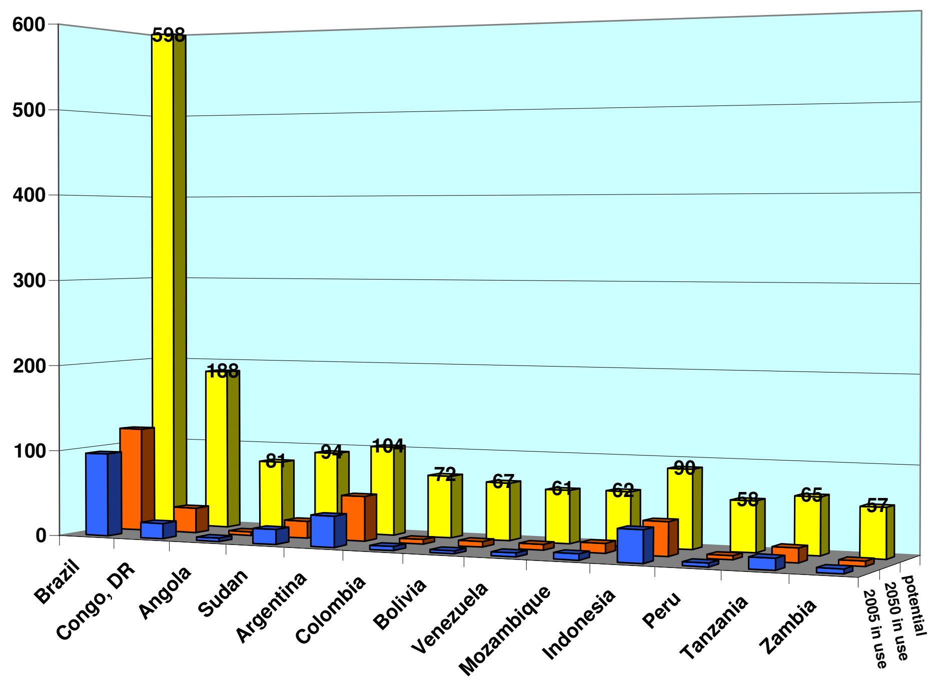
First it ignores land uses other than for growing the crops for which it was evaluated. Thus, forest cover, protected areas and land used for human settlements and economic infrastructure are not taken into account. Alexandratos (1995) estimated that forests cover at least 45 percent, protected areas some 12 percent and human settlements some 3 percent of the gross land balance so that 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 but 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 a significant factor 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 some 60 million ha of the gross land balance, protected areas 200 million ha and forests 800 million ha, so that the net land balance would be some 1.5 billion ha.

Second and probably more important than allowing for non-agricultural use of land with crop production potential is the nature of the estimates itself, i.e. the method of deriving the land suitability 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 permit cultivation of only olive trees (and a few other minor crops). These areas therefore are

[12] Fischer (2002) reports a lower 3.56 billion ha (Table 5.15) for the gross extent of land with rainfed crop production potential which is based on a different version of the GAEZ 2002 as used in Bruinsma (2003). Likewise OECD/FAO (2009) also basing itself on the GAEZ 2002, reports a total of 4.3 billion ha for the gross extent of land with rainfed crop production potential.

counted as 'suitable' although one might have little use for them in practice. It is therefore more sensible to discuss suitability for individual crops and the notion of an overall land suitability is of limited meaning.

Figure 3. Developing countries with the highest (gross) land balance



Note: thirteen countries with a gross land balance of over 50 million ha in 2005 and accounting for two-thirds of the total gross land balance in developing countries.

Third, the land balance (land with crop production potential not in agricultural use) is very unevenly distributed between 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 of the total is concentrated in just seven countries (Brazil, Congo DR, Angola, Sudan, Argentina, Colombia, Bolivia. See Figure 3). At the other extreme, there is virtually no spare land available for agricultural expansion in South Asia and the Near East/North Africa. In fact, in a few countries in these latter two regions, the land balance is negative, i.e. land classified as not suitable, is made productive through human intervention such as terracing of sloping land, irrigation of arid and hyper-arid land, etc., and is in 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 sub-regions.

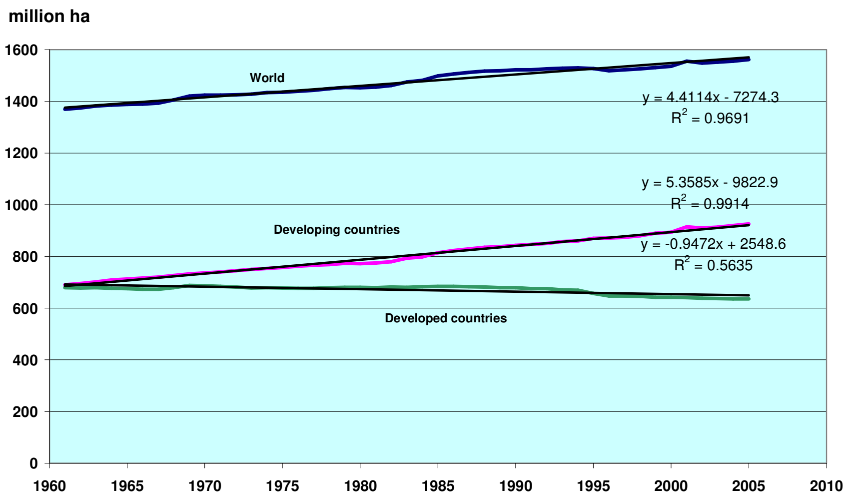
Fourth, much of the remaining land also suffers from constraints such as ecological fragility, low fertility, toxicity, high incidence of disease or lack of infrastructure. These reduce its productivity, require high input use and management skills to permit its sustainable use, or require prohibitively high investments to be made accessible or disease-free. Fischer (2002) shows that over 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 as well as human intervention can also lead to deterioration of the productive potential of the resource for example through soil erosion or salinization of irrigated areas. Hence the evaluation of suitability may contain elements of overestimation (see also Bot *et al.*, 2000) and much of the land balance cannot be considered to be a resource that is readily usable for food production on demand.

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 estimates made 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 over-estimates.

Expansion of land in crop production

The perception that there is no more, or very little, new land to bring under cultivation might be well grounded in the specific situations of land-scarce countries and regions such as South Asia and the Near East/North Africa but may not apply, or may apply with much less force, to other parts of the world. As discussed above, 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, be partly under forest cover or in wetlands which 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 4. Arable land and land under permanent crops: past developments



In reality, expansion of land in agricultural use continues to take place (Figure 4). It does so mainly in countries which combine growing needs for food and employment with limited access to 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 7). This includes countries with ample land resources with potential for crops facing fast demand growth, particularly for exports and for non-food uses, e.g. soybeans in South America and the oilpalm in South-East Asia. Indeed, oilcrops have been responsible for a good part of the increases in total cultivated land in the developing countries and the world as a whole (FAO, 2006a), albeit often at the expense of deforestation.

The projected expansion of arable land in crop production shown below in Tables 7, 8 and 9, has been derived for rainfed and irrigated land separately. As explained in Box 1, starting with the production projections for each crop, the land and yield projections were derived drawing on expert judgement and taking into account: (a) base year (2005/07) data on total harvested land and yield by crop; (b) data or often estimates for harvested land and yield by crop for rainfed and irrigated land; (c) data on total arable rainfed and irrigated land and their expected increases over time; (d) likely increases in yield by crop and land class; (e) plausible increases in cropping intensities, and (g) the land balances for rainfed and irrigated agriculture. As mentioned in Box 1, base year data for total arable land were for several developing countries adjusted (in particular for China[13]) to, among other things, arrive at cropping intensities that seemed more meaningful. This is reflected in column '2005 adj.' in Table 7.

Table 7 Total arable land: data and projections

	arable land in use						annual growth			balance	
	1961 /63	1989 /91	2005	2005 adj.	2030	2050	1961-2005	1990-2005	2005-2050	2005	2050
	(million ha)						(percent p.a.)			(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/ 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
excl. China	73	94	102	105	109	112	0.85	0.71	0.15	78	75
Developing countries	693	837	920	966	1040	1086	0.67	0.65	0.27	1805	1684
excl. China and India	426	536	594	666	740	789	0.75	0.66	0.39	1730	1609
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	1375	1521	1562	1602	1648	1673	0.30	0.17	0.10	2576	2503

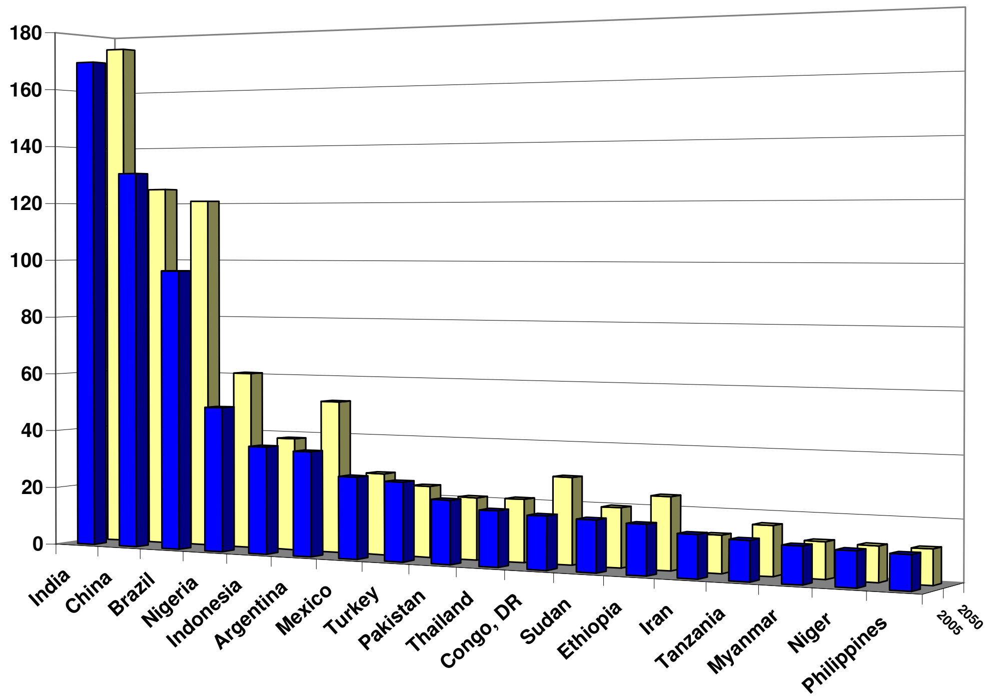
Source for historical data: FAOSTAT, January 2009. "World" includes a few countries not included in the other country groups shown.

The overall result for developing countries is a projected net increase in the arable area of some 120 million ha (from 966 in the base year to 1086 in 2050), an increase of 12.4 percent (see Table 7). Not surprisingly, the bulk of this projected expansion is expected to take place in sub-Saharan Africa (64 million) and Latin America (52 million), with almost no land expansion in East and South Asia, and even a small decline in Near East/North Africa. The slowdown in the 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 small number of developing countries (Figure 5). A number of developing countries would towards the end of the projection period witness a decline in the arable land area (e.g. China and the Republic of Korea, but not only) and embark on a pattern already seen for most developed countries (with production only increasing very slowly and increases in yield permitting a reduction in crop area).

[13] Data on arable land for China are unreliable. FAOSTAT data show an (unlikely) upward trend from 1983 onwards, which distorts the historical growth rates in Table 7 for East Asia (and for the total of developing countries).

Figure 5. Developing countries with over 10 million ha of arable land in use*



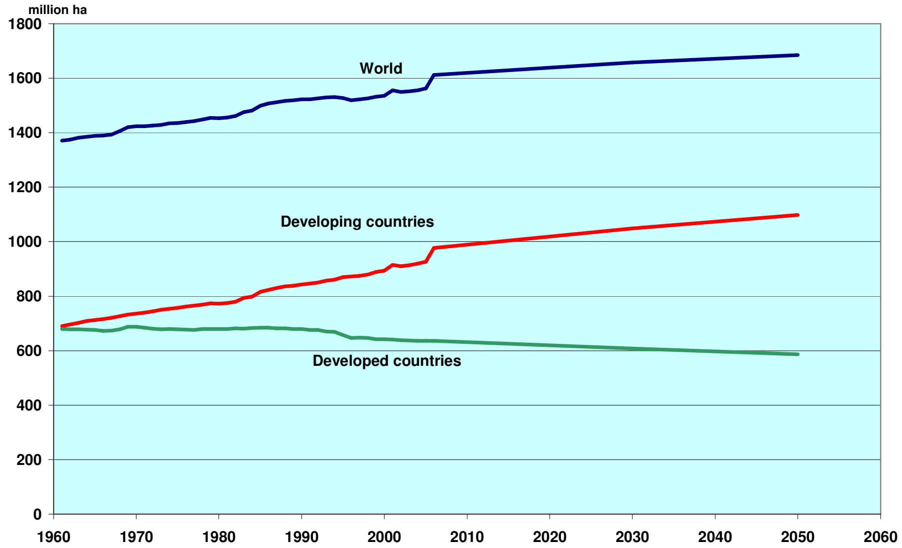
* These 18 countries account in 2005 for 75 percent of the total arable land in use in developing countries

The arable area in the world as a whole expanded between 1961/63 and 2005 by 187 million ha, the result of two opposite trends: an increase of 227 million ha in the developing countries and a decline of 40 million ha in the developed countries. The arable land area in the latter group of countries peaked in the mid-1980s (at 684 million ha) and declined ever since. This decline in the arable area has been accelerating over time (Table 7). The longer-term forces determining such declines are sustained yield growth combined with a continuing slowdown in the growth of demand for their agricultural products. The projections of this study foresee a further slow decline in their arable area to 587 million ha in 2050 (it is again noted that this may change under the impact of an eventual fast growth in biofuels). The net result for the world is an increase in the arable land area of 71 million ha, consisting of an increase by 120 million ha in the developing countries and a decline by 48 million ha in the developed countries (Table 7 and Figure 6).

Arable land in the group of land-scarce countries[14] would practically remain constant (at between 265 and 268 million ha), but its irrigated land could expand by some 12 million ha of which 9 million ha through conversion of rainfed land. Some of these countries are still highly dependent on agriculture and experiencing an above-average population growth, which 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).

[14] 19 countries with more than 80 percent of their land with rainfed and/or irrigation potential in use in 2005, of which 6 are in the Near East / North Africa, 5 in sub-Saharan Africa and 4 in South Asia.

Figure 6. Arable land and land under permanent crops: past and future



The projected average annual increase in the developing countries' arable area of 2.75 million ha (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, for example due 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 would come from forested areas, this would imply an annual deforestation rate of 0.14 percent, compared with 0.42 percent (or 9.3 million ha p.a.) for the 1990s and 0.36 percent (or 7.5 million ha p.a.) over the period 2000 to 2005 (FAO, 2006b). The latter estimates, of course, include deforestation from all causes, such as informal, non-recorded agriculture, grazing, logging, gathering of fuel wood, etc.

What does the empirical evidence show concerning land expansion for agricultural use in the 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 the experience of Côte d'Ivoire, Lopez (1998) concludes that "the main response of annual crops to price incentives is to increase the area 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). Some of the land expansion however is taking place at the expense of longer rotation periods and shorter fallows, a practice still common to many countries in sub-Saharan Africa, with the result that the natural fertility of the soil is reduced. Since fertilizer use is often uneconomic, the end-result is soil mining and stagnation or outright reduction of yields.

Although the 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, due to increases in cropping intensities (Table 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 continue to rise through shorter fallow periods and more multiple cropping. An increasing share of irrigated land in total agricultural land also contributes to more multiple cropping. Almost one-third of the arable land in South and East Asia is irrigated, a share which is projected to rise to over 36 percent in 2050. This high share of irrigation in total arable land is one of the reasons why the average cropping intensities in these regions are considerably higher 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 the developing countries, are and will continue to be much lower.

Table 8. Arable land in use, cropping intensities and harvested land

		Total land in use			Rainfed use			Irrigated use*		
		A#	CI	H	A	CI	H	A	CI	H
Developing countries	2005/07	966	95	919	777	83	649	189	143	270
	2050	1086	99	1078	864	87	753	222	147	325
excl. China and India	2005/07	666	82	547	582	76	442	84	124	105
	2050	785	89	697	680	83	562	106	129	136
Developed countries	2005/07	635	74	473	584	72	422	51	100	51
	2050	587	81	478	536	80	426	51	100	51
World	2005/07	1602	87	1392	1361	79	1070	240	134	321
	2050	1673	93	1556	1400	84	1179	273	138	377

A = arable land (million ha); CI = cropping intensity in percent; H = harvested land (million ha).
* Irrigated area actually in use as distinguished from 'area equipped for irrigation' (Table 9).

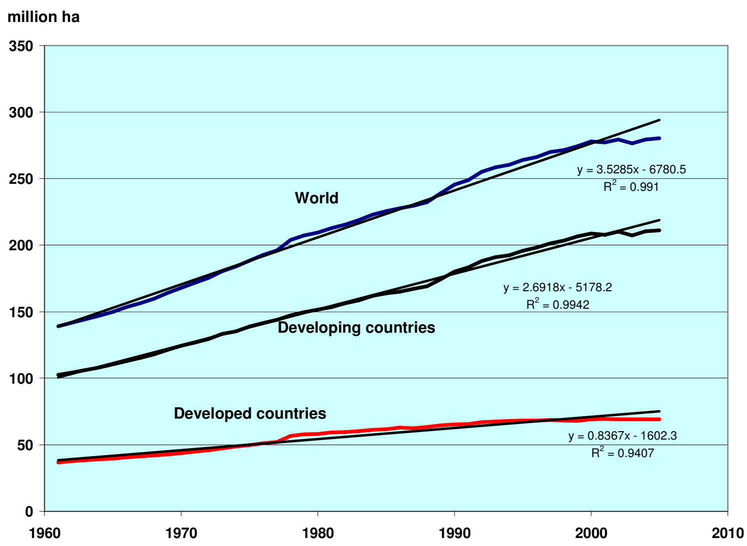
Rising cropping intensities could be one of the factors responsible for increasing the risk of land degradation and thus threatening sustainability, in particular when not accompanied by land conservation measures, including adequate and balanced use of fertilizers to compensate for the removal of soil nutrient by crops. It is expected that this risk will continue to exist because in many cases the socio-economic conditions do not favour the 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 more recently this expansion has considerably slowed down (Figure 7). The projections of irrigation presented below reflect scattered information on existing irrigation expansion plans in the different countries, potentials for expansion (including water availability) and need to increase crop production. The projections include expansion in both formal and informal irrigation, the latter being important in particular in sub-Saharan Africa.

Figure 7. Area equipped for irrigation



The aggregate result shows that the area equipped for irrigation could expand by 32 million ha (11 percent) over the projection period (Table 9) all of it in the developing countries. This means that some 16 percent of the land with irrigation potential in this group of countries not yet equipped at present could be brought under irrigation, and that by 2050 some 60 percent of all land with irrigation potential[15] (417 million ha) would be in use.

The expansion of irrigation would be strongest (in absolute terms) in the more land-scarce regions hard-pressed to raise crop production through more intensive cultivation practices, such as East Asia (+ 12 million ha), South Asia (+ 8 million ha), and the Near East/North Africa (+ 6 million ha), although in the latter region further expansion will become increasingly difficult as water scarcity increases and competition for water from households and industry will continue 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.

Table 9. Area equipped for irrigation

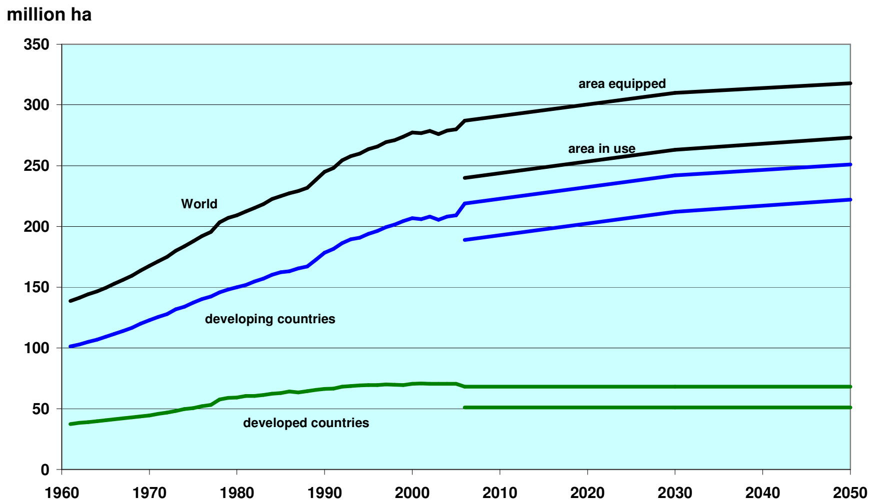
	1961/63	1989/91	2005/07	2030	2050	1961-05	1990-05	1996-05	2005-50
	million ha					annual growth (percent p.a.)			
Developing countries	103	178	219	242	251	1.76	1.05	0.63	0.31
idem, excl. China and India	47	84	97	111	117	1.91	1.06	0.89	0.42
sub-Saharan Africa	2.5	4.5	5.6	6.7	7.9	2.07	1.49	0.98	0.67
Latin America and Caribbean	8	17	18	22	24	2.05	0.62	0.27	0.72
Near East / 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

The developed countries account for almost a quarter of the world's irrigated area, 68 out of 287 million ha (Table 9). Annual growth of their 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 over the last decade for which data are available (1996-2005). 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 that the world irrigation scene will remain dominated by events in the developing countries.

For the purpose of this study a distinction was made between the area equipped for irrigation and the irrigated area actually in use (which is the area to be used in the production analysis). Areas equipped might be temporarily or even permanently out of use for various reasons (including for maintenance, because of degradation of irrigation infrastructure or because the area is not needed in a particular year). The percentage of the area equipped actually in use differs from country to country and could range from a low 60 to a high 100 percent, but on average over all countries is 86 percent (expected to increase very slightly to 88 percent in 2050). So out of the 219 million ha equipped for irrigation in the developing countries in 2005/07, some 189 million ha were assumed to be in use increasing to 222 million ha in 2050 (out of 251 million ha equipped; see also Figure 8).

[15] Estimates of "land with irrigation potential" are difficult to make and such estimates should only be taken as rough indications.

Figure 8. Arable irrigated area: past and future



The importance of irrigated agriculture was already discussed in the preceding section. Due to a continuing increase in multiple cropping on both existing and newly irrigated areas, the harvested irrigated area could expand by 56 million ha (or 17 percent) and would account for well over a third of the total increase in harvested land (Table 8).

The projected expansion of irrigated land by 32 million ha is an increase in net terms. It assumes that losses of existing irrigated land due to, for example, water shortages or degradation because of salinization and waterlogging, will be compensated for through rehabilitation or substitution by new areas for those lost. The few existing historical data on such losses are too uncertain and anecdotal to provide a reliable basis for drawing inferences about the future. In investment terms, 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, that is, if the average life of irrigation schemes were 40 years, then the total irrigation investment activity over the projection period in the developing countries must encompass some 173 million ha, 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 of 32 million ha is less then a quarter of the increase over the preceding 44 years (145 million ha). In terms of annual growth it would be ‘only’ 0.24 percent, well below the 1.7 percent for the historical period. The projected slowdown which applies to 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, as well as the rising costs of irrigation investment.

Most of the expansion of irrigated land is achieved by converting land in use in rainfed agriculture into irrigated land. Part of irrigation, however, takes place on arid and hyper-arid (desert) land which is not suitable for rainfed agriculture. It is estimated that of the 219 million ha irrigated at present in developing countries, some 40 million ha are 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 presently in use: 19 out of 28 million ha in the Near East/North Africa, and 15 out of 70 million ha in South Asia.

Water use in irrigation and pressure on water resources

One of the major questions 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 the freshwater withdrawals in the world and is usually seen as one of the main factors behind the increasing global scarcity of freshwater.

The estimates of the expansion of land under irrigation presented in the preceding section provide a partial answer to this question since the assessment of irrigation potential already takes into account water limitations and since the projections to 2050 assume that agricultural water demand will not exceed available water resources[16].

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

Table 10 shows the renewable water resources for the world and major regions. Average annual precipitation varies from a low 160 mm per year in the most arid region (Near East/North Africa) to a high precipitation of about 1530 mm per year in Latin America. These figures give an impression of the extreme variability of climatic conditions facing the developing countries, and the ensuing differences observed in terms of water scarcity: those countries suffering from low precipitation and therefore most in need of irrigation are also those where water resources are naturally scarce. In addition, the water balance presented is expressed in yearly averages and cannot adequately 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 crops need to satisfy their transpiration requirements. The soil, acting as a buffer, 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 the dry season, irrigation is required to compensate for the deficit due to insufficient or erratic precipitation. *Consumptive water use in irrigation* therefore is defined as the volume of water needed to compensate for the deficit between potential evapotranspiration and effective precipitation over the growing period of the crop. It varies considerably with climatic conditions, seasons, crops and soil types. Consumptive water use in irrigation has here been computed for each country on the basis of the irrigated and harvested areas by crop as estimated for the base year (2005/07) and as projected for 2050 (see Box 2 for a brief explanation of the methodology applied).

[16] The concept of irrigation potential has severe limitations and estimates of irrigation potential can vary over time, in relation 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 those 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.

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

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 has been collected in the framework of the AQUASTAT programme (see e.g. FAO, 2005a and 2005b). Comparison of these data with the consumptive use of irrigation was used to estimate water use efficiency[17] at the country level. For the world, it is estimated that the average water use efficiency was around 44 percent in 2005/07, 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 10).

To estimate the irrigation water withdrawal in 2050, an assumption had to be made about possible developments in the water use efficiency in each country. Unfortunately, there is little empirical evidence on which to base such an assumption. Two factors, however, will have an impact on the development of the water use efficiency: the estimated levels of water use efficiency in the base year and water scarcity[18]. 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 percent to 46 percent (Table 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/North Africa region) than in regions with abundant water resources (3 percentage points or less in Latin America and sub-Saharan Africa). Indeed, 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.

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[17] 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 re-used for irrigation.

[18] ‘stress’ measured as consumptive water use in irrigation as a percentage of renewable water resources.

Table 10. Annual renewable water resources and irrigation water withdrawal

	Precipi-tation	Renewable water resources*	Water use efficiency ratio		Irrigation water withdrawal		Pressure on water resources due to irrigation	
			2005 /07	2050	2005 /07	2050	2005 /07	2050
	mm p.a.	cubic km	percent		cubic km		percent	
Developing countries	990	28000	44	47	2115	2413	8	9
sub-Saharan Africa	850	3500	22	25	55	87	2	2
Latin America /Caribbean	1530	13500	35	35	181	253	1	2
Near East / North Africa	160	600	51	61	347	374	58	62
South Asia	1050	2300	54	57	819	906	36	39
East Asia	1140	8600	33	35	714	793	8	9
Developed countries	540	14000	42	43	505	493	4	4
World	800	42000	44	46	2620	2906	6	7

* includes at the regional level 'incoming flows'.

At the global level irrigation water withdrawal is expected to grow by about 11 percent, from the current 2620 km3/yr to 2906 km3/yr in 2050 (Table 10), increasing in the developing countries by 14 percent (or 298 km3), offset by a decline in the developed countries of over 2 percent (or 12 km3). The 11 percent increase in irrigation water withdrawal should be seen against the projected 17 percent increase in the harvested irrigated area (from 321 million ha in 2005/07 to 377 million ha in 2050; Table 8). This difference is in part explained by the expected improvement in water use efficiency, leading to a reduction in irrigation water withdrawal per irrigated hectare, and in part due 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.

Irrigation water withdrawal in 2005/07 was estimated to account for only 6 percent of total renewable water resources in the world (Table 10). However, there are wide variations between countries and regions, with the Near East/North Africa region using 58 percent of its water resources in irrigation while Latin America barely uses 1 percent of its resources. At the country level, variations are even higher. In the base year (2005/07), 11 countries used already more than 40 percent of their water resources for irrigation, a situation which can be considered critical. An additional 8 countries consumed more than 20 percent of their water resources, a threshold sometimes used to indicate impending water scarcity. The situation would worsen over the period to 2050, with two more countries crossing the 40 percent and 4 countries the 20 percent threshold. If one would add the expected additional water withdrawals needed for non-agricultural use, the picture would not change much since agriculture represents the bulk of water withdrawal.

Box 2. Estimating irrigation water requirements

The estimation of water balances for any year is based on five sets of data, namely four digital geo-referenced data sets for precipitation (New *et al.*, 2002), reference evapotranspiration (FAO, 2004), soil moisture storage properties (FAO, 1998), extents of areas under irrigation (Siebert *et al.*, 2007) and irrigated areas for all major crops for 2005/07 and 2050. The computation of water balances is carried out by grid-cell (each 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 the actual evapotranspiration, water runoff and consumptive water use in irrigation.

For each grid-cell, the actual evapotranspiration is assumed to be equal to the reference evapotranspiration (ET_0, in mm; location-specific and calculated with the Penman-Monteith method; Allen *et al.,* 1998, New *et al.,* 2000) in those 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 depending on the available soil moisture. Evapotranspiration in open water areas and wetlands is considered to be equal to be a fixed fraction of the reference evapotranspiration.

For each gridcell, runoff and ground water recharge is calculated as that part of the precipitation that does not evaporate and cannot be stored in the soil either. In other words, the sum of the runoff and ground water 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 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 table below gives as an example, the cropping calendar of Morocco for the base year 2005/07[2].

Crop under irrigation	Irrigated area (1000 ha)	Crop area as share (percent) of the total area equipped for irrigation by month											
		J	F	M	A	M	J	J	A	S	O	N	D
Wheat	618	46	46	46	46						46	46	46
Maize	119			9	9	9	9	9					
Potatoes	61					5	5	5	5	5			
Beet	36				3	3	3	3	3	3			
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[3]	1292	69	69	69	72	42	42	42	32	41	69	69	69

1 India, China, Indonesia, the USA and the EU15 have been subdivided into two to four sub-regions for which different cropping calendars have been made to distinguish different climate zones in these countries.

2 E.g. wheat is grown from October through April and occupies 46 percent (618 thousand ha) of the 1292 thousand ha of irrigated land in use.

3 Including crops not shown above.

The (potential) evapotranspiration (ET_c in mm) 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 (according to 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 again lower in the late phase. It is assumed that the initial, the development and the late phase, all take one month for each crop, while the mid-phase lasts a number of months. For example, the growing season for wheat in Morocco starts in October and ends in April, as follows: initial phase: October ($K_c = 0.4$), development phase: November ($K_c = 0.8$), mid-phase: December – March ($K_c = 1.15$), and late phase: April ($K_c = 0.3$).

Multiplying for each grid-cell its surface equipped for irrigation with the sum over all crops of their evapotranspiration and with the cropping intensity per month, results 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.

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 (www.fao.org/nr/aquastat). In addition, the discharge of major rivers as given in the literature was compared with the calculated runoff for the drainage basin of these rivers. If the calculated runoff values did not match the values 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.

Finally, the water balance for each country and year is defined as the difference between the sum of precipitation and incoming run-off 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 is therefore the balance of water without accounting for water withdrawals for other needs (industry, household and environmental purposes).

Nevertheless, for several countries, relatively low national figures may give an overly optimistic impression of the level of water stress: China, for instance, is facing severe water shortage in the north while the south still has abundant water resources. Already in 2005/07, four countries (Libya, Saudi Arabia, Yemen and Egypt) used volumes of water for irrigation larger than their annual renewable water resources. Groundwater mining also occurs in certain parts of some other countries of the Near East and in South and East Asia, Central America and in the Caribbean, even if at the national level the water balance may still be positive.

In concluding this section on irrigation, 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 a significant potential for further irrigation development. With the relatively small increase in irrigation water withdrawal expected between 2005/07 and 2050, this situation will not change much at the aggregate level. Locally and in some countries, however, there are already very severe water shortages, in particular in the Near East/North Africa region.

By how much do crop yields need to rise?

As discussed above, it is expected that growth in crop yields will continue to be the mainstay of crop production growth, accounting for some 70 percent of the latter in developing countries, and for all of it in the developed countries. Although the marked deceleration in crop production growth foreseen for the future (Table 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 a continuation of such growth? There is a realization that the chances of a new Green Revolution or of one-off quantum jumps in yields, are now rather limited. There is even a belief that for some major crops, yield ceilings have been, or are rapidly being, reached. At the same time, empirical evidence has shown that the cumulative gains in yields over time due to slower, evolutionary annual increments in yields, have been far more important than quantum jumps in yields, for all major crops (for example see Byerlee, 1996).

Harvested land and yields for major crops

As mentioned before, the production projections for the 34 crops covered in this report are unfolded into and tested against what FAO experts think are “feasible” land-yield combinations by agro-ecological rainfed and irrigated environment, taking into account whatever knowledge is available. A major input into this evaluation are the estimates regarding the availability of land suitable for growing crops and of yields attainable in each country and each agro-ecological environment which originate in the Agro-Ecological Zones work (Fischer *et al*., 2002). 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 since they take into account present-day 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 roughly a halving of the average annual rate of growth over the projection period as compared to the historical period: 0.8 percent p.a. during 2005/07 to 2050 against 1.7 percent p.a. during 1961-2007 (for the world. For the developing countries the annual growth rates are 0.9 and 2.1 percent respectively). This slowdown in the yield growth is a gradual process which has been under way for some time (for the last ten-year period 1997-07, the annual yield growth was 1.3 and 1.6 percent for the world and the group of developing countries respectively) and is expected to continue in the future. It reflects the deceleration in crop production growth explained earlier.

Table 11. Area and yields for major crops in the world

	Production (million tonnes)			Harvested area (million ha)			Yield (tonnes/ha)		
	1961/63	2005/07	2050	1961/63	2005/07	2050	1961/63	2005/07	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	1153	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
Sugarcane	417	1413	3386	9	21	30	48.34	67.02	112.34

Note: crops selected and ordered according to (harvested) land use in 2005/07.

Discussing yield growth at this level of aggregation however is not very helpful, but the overall slowdown is a pattern common to most crops covered in this study with only a few exceptions such as citrus and sesame. These are crops for which a strong demand growth is foreseen in the future or which are grown in land-scarce environments. The growth in soybean area and production in developing countries (Table 11) has been remarkable mainly due to explosive growth in Brazil and Argentina. Soybean is expected to continue to be one of the most dynamic crops, albeit with its production increasing at a more moderate rate than in the past, bringing by 2050 the developing countries' share in world soybean production to over 70 percent, with four countries (Brazil, Argentina, China and India) accounting for 90 percent of total production in developing countries.

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: at the world level down from 1.9 percent p.a. in the historical period to 0.7 percent p.a. over the projections period (from 2.2 to 0.8 percent p.a. in developing countries. Table 12). Again this slowdown has been underway for some time.

The differences in the sources of growth for the various regions have been discussed before. Suffice it here to note that irrigated land is expected to play a more important role in increasing maize production, almost entirely due to China which accounts for over 40 percent of the developing countries' maize production and 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 (with normally much higher cereal yields) in total production. This fact alone would lead to yield increases even if rainfed and irrigated cereal yields would not grow at all.

Table 12. Cereal yields, rainfed and irrigated

		World						Developing countries					
		Average yield			Annual growth						Annual growth		
		tonnes/ha			% p.a.						% p.a.		
		1961/63	2005/07	2050	1961-07	1987-07	2005/07-2050	1961/63	2005/07	2050	1961-07	1987-07	2005/07-2050
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 (paddy)	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
	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 cereals	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
	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

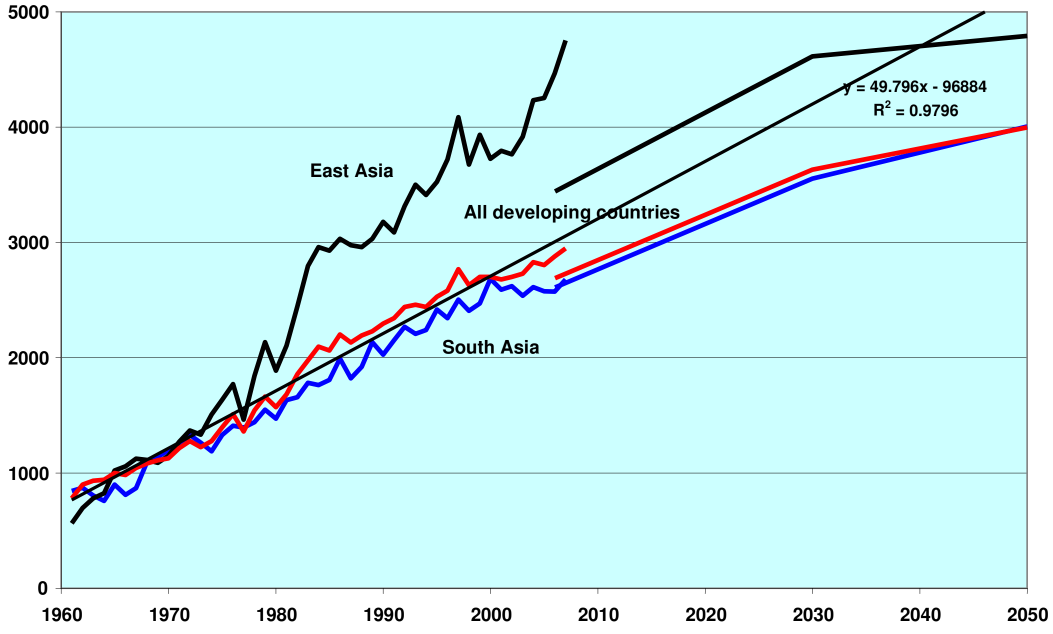
Note: Historical data are from FAOSTAT; base year data for China have been adjusted.

Increasing yields are often credited (see for example Borlaug, 1999) with saving land and thus diminishing pressure on the environment (e.g. less deforestation than otherwise would have taken place). To take cereals as an example, the reasoning is as follows. If the average global cereal yield had not grown since 1961/63 when it was 1405 kg/ha, 1620 million ha would have been needed to grow the 2276 million tonnes of cereals the world produced in 2005/07. This amount was actually obtained on an area of only 705 million ha at an average yield of 3230 kg/ha. Therefore, 915 million ha (1620 – 705) have been saved because of yield increases for cereals alone. This conclusion should be qualified however, since if there had been no yield growth, the most probable outcome would have been much lower production because of lower demand due to higher prices of cereals, and somewhat more land under cereals. Furthermore, in many countries the alternative of land expansion instead of yield increases, does not exist in practice.

The scope for yield increases

Despite the increases in land under cultivation in the land-abundant countries, much of agricultural production growth has been based on the growth of yields, and will increasingly need to do so. What is the potential for a continuation of 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 crucially on further progress in agricultural research. In places where yields are nearing ceilings obtained on research stations, the scope for raising yields is much more limited than in the past (Sinclair, 1998). Despite this, average 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 p.a. over 1961 to 2007 (27 kg p.a. over the last decade), and is projected to grow by 32 kg per year over the period 2005/07 to 2050. Similar increases for the group of developing countries are 50 kg (past. See Figure 9) and 30 kg (future) per annum.

Figure 9. Wheat yields (kg/ha)



Note: historical data from FAOSTAT. The break in the series for East Asia (and thus also for 'all developing countries') is due to a downward adjustment of the base year data for yields in China.

The variation in yields among countries however remains very wide. Table 13 illustrates this for wheat, rice and maize in developing countries. Current yields in the ten percent of countries with the lowest yields (bottom decile, excluding countries with less than 50 000 ha under the crop), are less than one-fifth (or 24 percent in the case of maize) of the yields of the best performers (top decile) and this 'gap' has been worsening over time. If sub-national data were available, probably a similar pattern would be seen for intra-national differences as well. For wheat and maize this gap between worst and best performers is projected to persist until 2050, while for rice the gap between the top and bottom deciles may be somewhat narrowed by 2050, with yields in the bottom decile reaching 25 percent of yields in the top decile. This may reflect the fact that the scope for raising yields of top rice performers is more limited than in the past. However, countries included in the bottom and top deciles account for only a minor share of the total production of wheat and rice. Therefore it is more important to examine what will happen to the yield levels obtained by the countries which account for the bulk of wheat, rice and maize production. Current (un-weighted) average yields of the largest producers[19] are about half the yields (40 percent in the case of maize) achieved by the top performers (Table 13). In spite of continuing yield growth in these largest producing countries, this situation is expected to remain essentially unchanged by 2050.

Table 13. Average wheat, rice and maize yields in developing countries

	1961/63		2005/07		2050	
	tonnes /ha	as % of top decile	tonnes /ha	as % of top decile	tonnes /ha	as % 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	

Notes: (1) only countries with over 50 000 harvested ha are included; (2) countries included in the deciles are not necessarily the same for all years; (3) average yields are simple averages, not weighted by area.

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 the different countries, which could be exploited if the economic incentives so dictate. However, the fact that yield differences among the major cereal producing countries are very wide, does not necessarily imply that the lagging countries have scope for yield increases equal to inter-country yield gaps. Part of these differences of course simply reflects differing agro-ecological conditions. However, not all, or perhaps not even the major part, of yield differences can be ascribed to such conditions as wide yield differences are present even among countries with fairly similar agro-ecological environments. In such cases, differences in the socio-economic and policy environments probably play a major role. The literature on yield gaps distinguishes two components of yield gaps, one due to agro-environmental and other non-transferable factors (these gaps cannot be narrowed), and

[19] Top ten percent of countries ranked according to area allocated to the crop examined. For 2005/07 these are China, India, and Turkey for wheat; India, China, Indonesia, Bangladesh and Thailand for rice; and China, Brazil, India, Mexico, Nigeria, Indonesia and Tanzania for maize.

another component due to differences in crop management practices such as sub-optimal use of inputs and other cultural practices. This second component can be narrowed provided that it makes economic sense to do so and therefore is termed the ‘exploitable yield gap’ or ‘bridgeable gap’.

Duwayri *et al.* (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 1985/89 to 8.4 tonnes/ha in 1995/99, with many individual farmers obtaining 10 to 12 tonnes/ha.

In order to draw conclusions on the scope for narrowing the yield gap, one needs to separate its ‘non-transferable’ part from the ‘exploitable’ part. One way to do so is to compare yields obtained from the same crop varieties grown on different locations of land that are fairly homogeneous with respect to their physical characteristics (climate, soil, terrain) which would eliminate the 'non-transferable' part in the comparison. One can go some way in that direction by examining the data on the suitability of land in the different countries for producing any given crop under specified technology packages. The required data comes from the GAEZ analysis. These data make it possible to derive a 'national maximum obtainable yield' by weighting the yield obtainable in each of the suitability classes with the estimated land area in each suitability class. The derived national obtainable yield can then be compared with data on the actual national average yields. The findings presented below seem to confirm the hypothesis that a good part of the yield gap is of the second, 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, e.g. in some countries the limiting factors may be temperature and radiation, in others soil and terrain characteristics or moisture availability. Nevertheless, the GAEZ average attainable yields for any crop can be taken as a rough index of agro-ecological similarity of countries for producing that crop under the specified conditions.

Table 14 shows the agro-ecologically (AEZ) attainable national average wheat yields for sixteen countries[20] and compares them with actual prevailing yields[21]. These countries span a wide range of agro-ecological endowments for wheat production, with some countries having a high proportion of their "wheat land" in the Very Suitable category (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 over 7 tonnes/ha in Hungary, Romania, France and Ukraine to less then 4 tonnes/ha in Russia, Kazakhstan and Canada.

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[20] 16 countries with more than 4 million tonnes of wheat production in 2003/07 and where rain-fed agriculture accounts for over 90 percent of total wheat production (except for Turkey: 80 percent).

[21] This comparison is somewhat distorted since the results of the GAEZ-2009 analysis (Fischer *et al.*, forthcoming) available to us at the time of writing deals only with rainfed agriculture, while the national statistics include irrigated agriculture as well.

Table 14. Agro-ecological suitability for rainfed wheat production, selected countries

	Area suitable				Yields attainable				Actual average 2003/07	
	total	VS#	S	MS	VS	S	MS	average	area	yield
	million ha				tonnes /ha				mln. ha	t/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
Russia	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

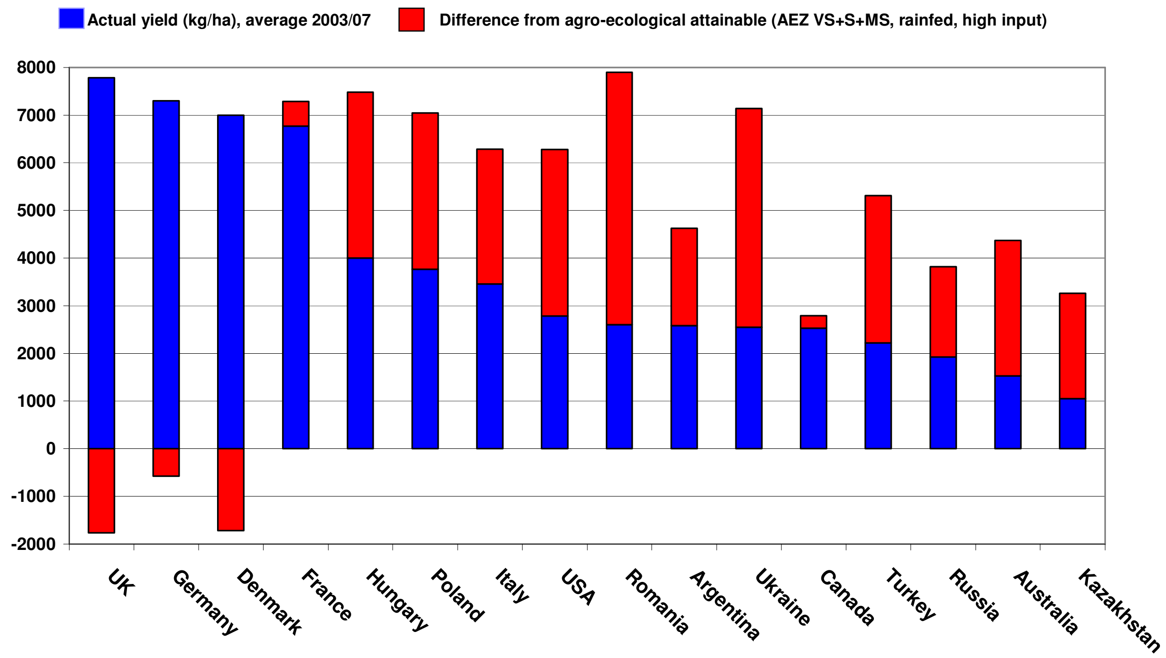
VS = Very Suitable, S = Suitable and MS = Moderately Suitable under high input. The data on potentials exclude marginally suitable land which in the GAEZ analysis is not considered appropriate for high input farming.
Source: Fischer *et al.* (2009, forthcoming) and FAOSTAT.

The divergence between economically efficient and agro-ecologically attainable yields can be very wide. For example, the UK and USA have nearly equal attainable yields (6.0-6.3 tonnes/ha, but with the USA having much more land suitable for wheat growing than the UK) but actual yields are 7.8 tonnes/ha in the UK (in practice exceeding what the GAEZ evaluation suggests as attainable on the average) and 2.8 tonnes/ha in the USA. In spite of USA's yields being a fraction of those that are agro-ecologically attainable and of those prevailing in the UK, it is not necessarily a less efficient wheat producer than the UK in terms of production costs. Other examples of economically efficient wheat producers with low yields in relation to their agronomic potential include Argentina (2.6 tonnes/ha actual versus 4.6 tonnes/ha attainable) and the Ukraine (2.5 tonnes/ha versus 7.1 tonnes/ha).

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

Among the major wheat producers, only the EU countries (the UK, Denmark, France, Germany) have actual yields close to, or even higher than[22], 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 10). Even assuming that only half of their yield gap (attainable minus actual) would be "bridgeable", their collective production could increase considerably without any increase in their area under wheat. As discussed above, yield growth would also occur in the other countries accounting for the rest of world production, including the major producers with irrigated wheat not included in Figure 10 such as China, India, Pakistan, Egypt. All this is without counting the potential yield gains that could come from further improvement in varieties - since the attainable yields of the GAEZ reflect the yield potential of existing varieties.

Figure 10. Wheat: actual and agro-ecologically attainable yields



Some States in India, such as the Punjab, are often quoted as examples of areas were wheat and rice yields have been slowing down or are even reaching a plateau. Fortunately, India is one of the few countries for which data at sub-national level and distinguished by rainfed and irrigated area are available. Bruinsma (2003, Table 11.2) compares wheat and rice yields by major growing State with the agro-ecologically attainable yields (as estimated in Fischer *et al.*, 2002), taking into account irrigation. It shows that, although yield growth has indeed been slowing down, in most cases actual yields are still far from the agro-ecologically attainable yields (with a few exceptions such as wheat in Haryana). This suggests that there are still considerable bridgeable yield gaps also in India.

The discussion above gives an idea of the scope for wheat production increases through the adoption of improved technologies and practices to bridge some of the gap that separates actual yields from obtainable yields. Wheat was used here as an example but similar analysis for other crops shows that the conclusions hold for all crops. The broad lesson of experience

[22] That actual yield levels in the UK, Germany and Denmark exceed the average S+VS+MS AEZ attainable yield can in part be explained if one assumes that all wheat is grown only on VS area (see Table 14).

seems to be that if scarcities develop and prices rise, farmers quickly respond by adopting such technologies and increasing production, at least those living in an environment of not-too-difficult access to improved technology, transport infrastructure and supportive policies. However, in countries with land expansion possibilities, the quickest response comes from increasing land under cultivation, including shifting land among crops towards the most profitable ones.

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 in practice is used for other crops. The point made here is that the gap existing between yields actually achieved and those obtainable under high input technology packages, affords significant scope for production increases through yield growth, given conducive socio-economic conditions, incentives and policies. The point is not that the production increases can be obtained by expanding cultivation into land suitable for a particular crop, because such land may not be available if it is used for other crops.

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

The preceding discussion may create the impression that all is well from the standpoint of potential for further production growth based on the use of existing varieties and technologies to increase yields. This statement should however be heavily qualified since (i) exploitation of bridgeable yield gaps means 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, ready potential for yield growth does not necessarily exist in the countries where the additional demand will be. When the potential demand is in countries with limited import capacity, as is the case in many developing countries, such potential can be expressed as effective demand only if it can be predominantly matched by local production. In such circumstances, the existence of large exploitable yield gaps elsewhere (e.g. in Argentina or Ukraine) is less important than it appears for the evaluation of potential contributions of yield growth to meeting future demand.

It follows that continued and intensified efforts are needed on the part of the agricultural research community to raise yields (including through maintenance and adaptive research) in the often unfavourable agro-ecological and often also unfavourable socioeconomic environments of the countries where the additional demand will be.

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Appendix: Countries and crops included in the analysis

Developing countries

Africa, sub-Saharan

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

Latin America and Caribbean

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

Near East/North Africa

Afghanistan
Algeria
Egypt
Iran, Islamic Rep.
Iraq
Jordan
Lebanon
Libyan Arab Yam.
Morocco
Saudi Arabia
Syrian Arab Rep.
Tunisia
Turkey
Yemen

South Asia

Bangladesh
India
Nepal
Pakistan
Sri Lanka

East Asia

Cambodia
China
Dem. Rep. of Korea
Indonesia
Lao
Malaysia
Myanmar
Philippines
Rep. of Korea
Thailand
Viet Nam

Industrial countries

European Union-15 *

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

Other Industrial Countries

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

Transition countries

Russian Federation

Countries in the European Union*	Central Asia*	Other Eastern Europe*
Czech Republic	Armenia	Albania
Estonia	Azerbaijan	Belarus
Hungary	Georgia	Bosnia and Herzegovina
Latvia	Kazakhstan	Bulgaria
Lithuania	Kyrgyzstan	Croatia
Malta	Tajikistan	Moldova Republic
Poland	Turkmenistan	Montenegro
Slovakia	Uzbekistan	Romania
Slovenia		Serbia
		The Former Yugoslav Rep. of Macedonia
		Ukraine

* Country groups marked with an asterisk (*) were treated in the analysis as one aggregate

Crops covered

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