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Can we predict the future food production? A sensitivity analysis

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Abstract

An attempt is made to assess the sensitivity of food production to various aspects of global change and environmental degradation during the next few decades. As a tool for this study a spreadsheet accounting system for food demand and supply is used. Taking into account the uncertainties of the various influencing factors, such as new technologies, improved management, increased fertilizer use, climatic change, expansion of irrigation, soil degradation and loss of agricultural land, the study indicates that one cannot say with any certainty whether or not food supply will meet expected demand in 2025, especially in Less Developed Countries. Bringing into use 10% of available potential cropland will make little difference. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Many attempts have been made to predict the future capacity of the global food production system. The reason for the considerable interest in this problem is obvious. Due to the rapidly growing world population and the increasing stresses on the environment it cannot be taken for granted it will be possible to increase food production to keep pace with demand.

During the past three centuries a multitude of estimates have been made of how many people can be fed on Earth, for example by Heilig (1993) and Cohen (1995), and the range of these estimates is tremendous, from less than a billion to more than a trillion. It is also interesting to note that the estimates made in previous centuries were all of a reasonable order of magnitude, about 5 to 15 billions. For example, Antoni van Leeuwenhook (1948) estimated in 1669 that the maximum number of people on Earth can support is 13.4 billion.

The more extreme estimates have been made after 1900. Thus, in an FAO study undertaken by Higgins et al. (1983), it was concluded that on Third World soils alone, between 3.9 and 32.4 billion people could be fed, depending on the agricultural input. Estimates published in 1994 alone ranged from less than 3 to 44 billion (Cohen, 1995).

To some extent it is possible to explain why the various estimates of the Earth's carrying capacity vary within such wide limits, for example:

(i) Many, or most, of the factors having an influence on food production have very limited predictability.
(ii) Many of the estimates are based on very subjective and qualitative assessments of the factors having an influence on food production.
(iii) In many cases it appears that, for one reason or another, either the positively or the negatively influencing factors have been deliberately exaggerated.
(iv) Very few models of global food production take into account all the major influencing factors.
(v) The data bases related to the various components of the global food production system are insufficient and often inaccurate.
(vi) There are difficulties in distinguishing between what is theoretically possible in improving food production, and what can be achieved realistically.

Thus, the predictions of the future global food production often give the impression of "wishful thinking", or of spreading unnecessary alarm. As an example of a very

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optimistic outlook we may cite a statement made by FAO (1995): "Yields will be higher, more land will be brought into cultivation and irrigated, and the existing land will be used more extensively through multiple cropping and reduced fallow periods". Another optimistic view of what is theoretically possible is presented by Waggoner (1994). He comes to the conclusion it is possible to produce far more food than ten billion need, and at the same time sparing some of today's cropland for nature.

As a contrasting view we may cite a statement by the Worldwatch Institute (Brown, 1995) in which emphasis is put on the negative impacts on the world food production: "The combination of continuously rising demand and a shrinking resource base can lead from stability to instability and to collapse almost overnight".

We may also mention that in the report of the results of the IFPRI 2020 Project it was concluded that in many developing countries food production is unlikely to keep pace with increases in demand for food — "the food gap" could be more than double in the next 25 years (Pinstrup-Andersen et al., 1997).

2. Scope of the paper

Given the above conflicting views, the aim of this paper is to attempt to quantify the sensitivity of food production to uncertainties in factors such as crop yields and agricultural land area, and to then make a judgement whether future food demands are likely to be met or not.

Thus, we will not be concerned with what is theoretically possible, rather we will be concerned with whether or not we can make meaningful predictions. Our approach will be to make the best possible estimates we can of the impacts (and their uncertainties) of the various factors affecting food production, and then to use *these* as input to a spreadsheet-based accounting system for food demand and production to assess the overall predictability of food production.

3. A tool for sensitivity analysis

In attempting to predict the future global food demand and production we are confronted with three types of constraints:

- Our knowledge of the numerous physical, chemical, biological and socio-economic factors that have an influence on food demand and production is very limited.
- Our lack of knowledge is even more pronounced with regard to the many interactive processes that take place among the above factors.
- There is an insufficient number of reliable observations.

With regard to the various socio-economic factors, it has to be recognized that economic development has a very low predictability. Even the most sophisticated models can be expected to predict economic development for more than a few years into the future.

To assess the sensitivity of future food demand and production to various factors, we will make use of a spreadsheet-based accounting system for food that was developed at the Stockholm Environment Institute (SEI). A flow chart for this system is shown in Fig. 1, and a detailed description is given in Bartholomew et al. (1995a,b) and Shaw (1997).

Given the constraints on predictability discussed above, we decided to adopt an accounting system which is linear in nature. It should not be considered to be a full-fledged model that includes non-linearities and feedbacks such as IMAGE (Alcamo et al., 1998). In this connection it should be emphasized it is not always true that the more equations you add to describe a system, the more accurate will be the eventual forecast (Lorenz, 1995).

In this paper the accounting system will be used as device to assess the effects of uncertainties in the input factors shown in the boxes in Fig. 1. A detailed discussion of the uncertainties in the input factors will be given in Sections 4 and 5.

3.1. The demand for food

As shown in Fig. 1, the demand (D_{ij}) for each crop commodity category (i) in a given region (j) to be produced can be expressed by the equation:

$$D_{ij} = H_{ij} + F_{ij} + I_{ij} + L_{ij} + S_{ij} + E_{ij} + C_{ij} \tag{1}$$

where

H_{ij} = the human food consumption,
F_{ij} = the feed for livestock production,
I_{ij} = industrial uses,
L_{ij} = processing and distribution losses,
S_{ij} = seed use,
E_{ij} = net export,
C_{ij} = stock change.

In this accounting system we express the processing and distribution losses as a fraction of the crop production used for food, feed and industrial purposes, i.e.

$$L_{ij} = \mu_{ij}(H_{ij} + F_{ij} + I_{ij}). \tag{2}$$

The amount of seed required is expressed as a fraction (v_{ij}) of the production, i.e.

$$S_{ij} = v_{ij} D_{ij}. \tag{3}$$

Introducing the expressions for these two terms in (1) we obtain

$$D_{ij} = \frac{(1 + \mu_{ij})(H_{ij} + F_{ij} + I_{ij}) + E_{ij} + C_{ij}}{1 - v_{ij}}. \tag{4}$$

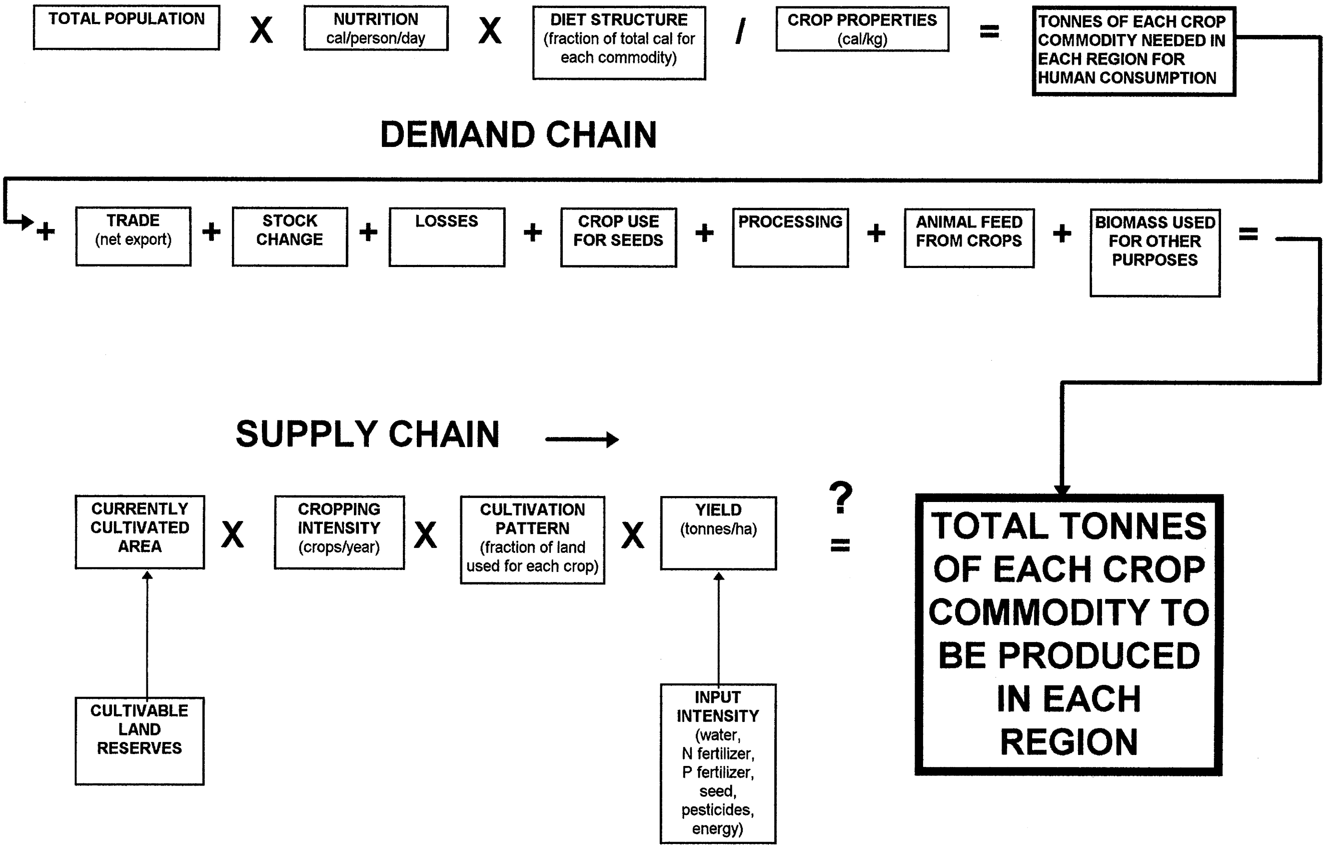


Fig. 1. A schematic illustration of the Stockholm Environment Institute accounting system of the production and consumption of crop commodities (from Shaw, 1997).

The value of the human food consumption of crop category i in region j may be written as

$$H_{ij} = n_j N_j \sigma_{ij} / \varepsilon_i \tag{5}$$

where

n_j = the number of people in region j

N_j = the number of kcal/capita/day in region j

σ_{ij} = the fraction of total caloric intake provided by crop category i

ε_i = the energy per kilo for crop category i

3.2. *The production of food*

For the derivation of the formula for computation of the production (P_{ij}) of crop category i in region j we introduce the following quantities (see Fig. 1):

A_j = the total cultivated area in region j,

ϕ_{ij} = the average cropping intensity of crop category i in region j (number of harvests per year),

η_{ij} = the fraction of area A_j assigned to crop category i (the cultivation pattern),

Y_{ij} = the average yield of crop i in region j,

and obtain the following expression for P_{ij}:

$$P_{ij} = A_{ij} \phi_{ij} \eta_{ij} Y_{ij}. \tag{6}$$

It can be seen from Eq. (6) that the output of the spreadsheet accounting system is merely a product of several input variables such as cultivated area, yield, etc. Therefore, an uncertainty analysis of calculated production will depend upon the uncertainties in each factor in Eq. (6), acting singly and in combination. This will be the approach followed in Section 5. It is recognized that uncertainties in the various factors may be interrelated but, since it was difficult enough to estimate the uncertainties in the individual factors, we did not attempt to estimate any covariances.

3.3. *Resolution of the accounting system*

In designing models for carrying out quantitative analyses and predictions of total demand and production for shorter term periods (years to about a decade), it is desirable to simulate changes in great detail (FAO, 1995). However, for longer term predictions, the demand for detail can most likely be relaxed considerably. Actually, it may even be desirable to reduce the level of detail to a somewhat lower level in order to avoid a false impression of accuracy.

3.3.1. Commodity categories

For estimations of the sensitivity of the capacity of the global food production system to the various influencing factors it might be sufficient to use a relatively coarse subdivision of the various food commodities. Thus, in our analysis we will restrict ourselves to the following two crop categories:

$i = 1$, Cereals
$i = 2$, All other crops.

3.3.2. Geographical resolution

With regard to the geographical resolution it was decided for purposes of our analysis to divide the world into two regional groups: Less Developed Countries (LDCs), and More Developed Countries (MDCs). These two groups include the following regions:

$j = 1$, LDCs:	$j = 2$, MDCs:
• Africa	• North America
• Centrally planned Asia	• Western Europe
• Latin America	• Former USSR
• Middle East	• Eastern Europe
• South and Southeast Asia	• Japan, Australia and New Zealand

3.4. Calculations of 1990 food demand and production

Table 1 shows calculations of the accounting system of the demand and production of cereals and other crops in 1990, and the ratio of supply to demand (S/D). The table does break down LDC and MDC regions into subregions to give an indication of the variation within LDC and MDC regions. However, the results to be described later in this paper will be expressed in terms of the two major global regions (LDCs and MDCs).

For input data on diet and production factors, as well as the parameters in Eqs. (1)–(6), our accounting system is linked to the AGROSTAT-PC data base (FAO, 1990), as described in Bartholomew et al. (1994). The AGROSTAT database was provided by the United Nations Food and Agricultural Organization and contains a wide variety of databases on food production and consumption in all countries of the world.

For cereals, Table 1 shows that the demand in 1990 in LDCs slightly exceeds that in MDCs, while for other crops the demand is much greater in LDCs. The global S/D ratio is within 4% of unity for both cereals and other crops, giving one some confidence in the spreadsheet accounting system. (The small deviation of the ratio from unity is due to the fact that the demand and supply parts of the model are linked to different parts of the AGROSTAT-PC data base).

The results summarized in Table 1 will be used as a starting point for the analysis of the uncertainties of food production brought about by global change. These will be discussed in Section 5. As will be seen in Section 5.5, the ranges in the S/D ratio will be used as an indicator of the effects of these uncertainties.

4. The future global food demand

It can safely be stated that the accuracy with which food demand can be predicted is primarily dependent on

Table 1
Demand and supply of cereals and other crops in 1990 (millions of tons) as calculated by the SEI spreadsheet accounting system (see Section 3.4)

Region	Cereals			Other crops		
	Demand	Supply	S/D	Demand	Supply	S/D
Africa	95	75	0.79	301	268	0.89
C.P. Asia	364	401	1.10	407	369	0.91
L. America	104	100	0.96	681	678	1.00
Middle East	21	25	1.18	41	39	0.94
S and SE Asia	325	303	0.93	651	649	1.00
Total LDCs	909	904	0.99	2082	2002	0.96
N. America	327	329	1.01	198	185	0.93
W. Europe	213	228	1.07	367	348	0.95
Former USSR	156	199	1.28	230	235	1.02
E. Europe	72	75	1.03	107	106	1.00
Japan, Aus. and New Z.	31	34	1.10	73	65	0.89
Total MDCs	799	866	1.08	976	939	0.96
World	1709	1770	1.04	3057	2942	0.96

Note: S/D = Supply/Demand.

Table 2
The projected population (n_j) during the period 1990–2050, and the annual rate of population increase, (Δn_j) in millions

Region	n_j			Δn_j	
	1990	2025	2050	1990–2025	2025–2050
Africa	640	1519	2204	25.1	27.4
Centrally Planned Asia	1234	1587	1867	10.1	11.2
Latin America	442	669	812	6.5	5.7
Middle East	143	384	557	6.9	6.9
S and SE Asia	1553	2634	3214	30.9	23.2
Total LDCs	4012	6969	8674	79.5	68.2
North America	276	330	322	1.54	− 0.3
Western Europe	456	489	477	0.9	− 0.5
Former USSR	289	332	349	1.2	0.7
Eastern Europe	100	115	121	0.4	0.2
Japan, Australia, New Zealand	145	161	157	0.5	− 0.2
Total MDCs	1265	1427	1426	4.6	0
World	5277	8396	10,080	84.1	67.4

Sources: For the period 1990–2025 (UN, 1992) and for the period 2025–2050 (Bulatao et al., 1989).

the reliability of projections of the rate of growth of the population in the less developed countries.

It will here be assumed that the population in the different world regions will change according to the UN Medium Variant Projection, which specifies an increase of the global population from about 5.3 to 8.4 billion during the period 1990–2025, i.e. by about 84 million per year (see Table 2). This is the same population used by Leach (1995) in his analysis of food demand and production through 2025 to the year 2050. The United Nations Population Programme estimates for the 2025 global population range from a low value of about 5 billion to a high estimate of about 9 billion (UN, 1992).

It may also be considered safe to assume that the need for an improved diet in many of these countries, both with regard to quantity and quality, is the second most important factor, and that this is basically governed by their economic development. However, Leach (1995) concludes that data limitations rule out economic models which rely upon driving variables such as prices and incomes. Therefore, we have been taken an approach in assessing future diets as follows:

- *Level 1. Sufficient to maintain the present per capita food consumption.* At present (1990), the daily intake is about 2500 kcal/cap in the LDCs and 3400 kcal/cap in the MDCs (see Table 3).
- *Level 2. Sufficient to ensure food security.* This level of food demand requires an increase of the food production to permit raising the daily intake in the LDCs from 2500 to a minimum of 3000 kcal/cap.

> Leach (1995) assumed a daily caloric intake in 2025 of 3450 kcal in MDCs and 2700 kcal in LDCs, based upon a leveling off of caloric intake in MDCs and a continuation of recent trends in LDCs.

Table 4 shows the calculated demand in 2025 for cereals and other crops, assuming Level 1 and Level 2 diets. The model calculations show that projected population increases, especially in the LDCs, and not improvements in diet, contribute most to the change of meeting future food demand. For example, the SEI accounting system calculates that, in 1990, demand for cereals was about 909 million tons (See Table 1). The calculated Level 1 demand in 2025, which assumes only the projected population increases in Table 2 and no change in diet, is about 1808 million tons, an increase of 899 million tons over the 1990 value. The calculated Level 2 demand in 2025 in LDCs, which assumes both population increases and an improvement in diet, is 2071 million tons, an additional increase of about 263 million tons over the 2025 Level 1 demand.

The demand projections of Leach (1995) for cereals in 2025 of 1852 million tons for LDCs, 952 million tons for MDCs and 2834 million tons worldwide are close to our Level 1 projections; this implies that our Level 2 diet may be somewhat optimistic.

If the diet in LDCs were to be further improved beyond Level 2 such that the calorific percentage of animal products were to be increased to a minimum of 15%, and the crop feed per unit livestock production in LDCs increased by 30% (indicating a change to the MDC-type

Table 3
Human dietary consumption in 1989 in kcal/cap/day and fraction of kcal provided by animal products, and their annual growth rates in per cent per year during the decade 1980–1989

Region	1989	Growth rate (%/yr)	From animal products	
			1989 %	Growth rate (%/yr)
Africa	2351	0.09	7.4	−0.70
Latin America	2729	0.05	17.3	−0.20
Middle East	2869	0.72	10.3	−1.88
China	2618	1.34	10.5	4.42
S and SE Asia	2307	0.64	7.2	1.70
Less Developed Countries	2477	0.71	9.7	1.62
North America	3641	0.54	33.5	−0.58
W. Europe	3426	0.20	30.5	−0.13
E. Europe	3450	−0.10	30.6	0.11
OECD Pacific	2971	0.52	23.4	0.69
Former USSR	3372	−0.01	28.5	1.18
More Developed Countries	3410	0.24	30.0	0.12
World	2703	0.46	15.9	0.42

Source: Leach (1995).

Table 4
Estimated demand in 2025 of cereals and other crops for Level 1 and Level 2 diets (million of tons)

Region	Cereals		Other crops	
	Level 1	Level 2	Level 1	Level 2
Africa	317	376	779	912
Centrally planned Asia	527	596	610	687
Latin America	189	209	1125	1188
Middle East	143	148	2003	2083
S. and SE Asia	631	742	1189	1392
Total LDCs	1808	2071	3902	4387
North America	307	308	256	256
Western Europe	262	262	516	516
Former USSR	268	261	368	360
Eastern Europe	91	91	149	149
Japan, Australia, New Zealand	65	58	116	104
Total MDCs	991	980	1404	1385
World	2799	3051	5306	5772

Note: Totals may not add up exactly due to rounding.

feedlot production), the accounting system calculated that demand for cereals in LDCs would increase to about 2300 million tons, a further increase of only about 230 million tons over that for Level 2.

5. Sensitivities of the global food production to influencing factors

In Fig. 2, attempts have been made to identify the factors that can have a significant influence on the global food production.

5.1. Factors affecting crop yields

In the following, attempts are made to derive expressions for changes in crop yields due to various factors. In doing so, the following simplifying assumptions have been made:

- For each category of influencing factors, the variation with time of the yield of crop commodity i in a region j can be expressed by an elementary function of time.
- The rate of change with time of the yield is assumed to be the same for both cereals and other crops.
- The parameters determining the magnitude of the rate of change of the yield with time will be permitted to be different for LDC and MDC regions.

5.1.1. Management improvement and new technologies

Considerable opportunities do exist to improve the efficiency of all phases of the food production system, including the development of new crop varieties with better harvest indices and crops that have improved resistance to insect and plant pathogen attacks, together with efforts to conserve genetic diversity (Kendall and

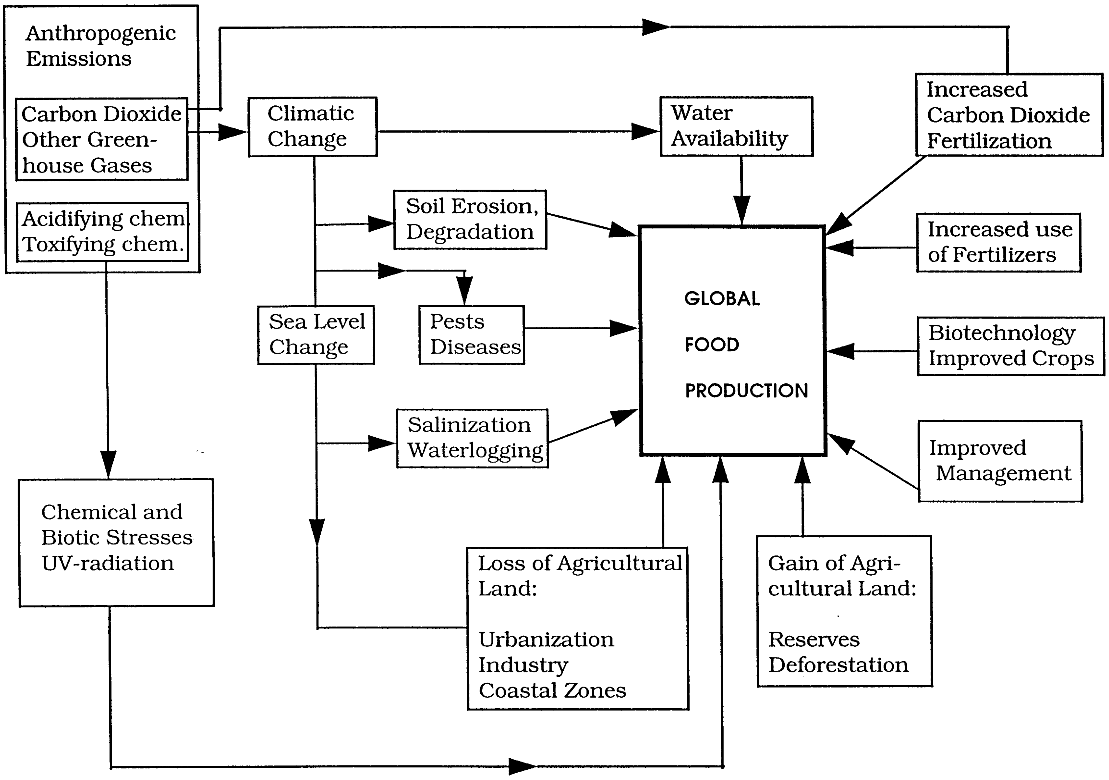


Fig. 2. Schematic illustration of the main factors having an influence on the global food production (Source: Döös, 1997).

Pimentel, 1994). However, the rate at which such improvements can be implemented in LDCs is comparatively slow and is dependent on the willingness of the more developed world to provide the required technology transfers and financial resources.

It should also be recognized that, within about one to two decades, application of biotechnology may make it possible to improve the yield of certain crops, and also decrease the dependency upon pesticides, resulting in more sustainable land use. However, it will mainly be the richer nations that will benefit from agricultural biotechnology. As pointed out by Chen and Kates (1994), it is unlikely that biotechnology will contribute to the alleviation of hunger in the developing nations during the next decade.

It is assumed that the improvement of yield through making use of opportunities relating to

- new technologies,
- resource management,
- biotechnology

may be expressed by

$$Y_{mij}(t) = (1 + m_j t) Y_{mij}(0). \tag{7}$$

Here the parameter m_j represents the annual rate of change of the yield. Although it is clear that there are numerous opportunities to improve yields through "smarter farming" (Waggoner, 1994) in both MDCs and LDCs, it is difficult to judge at what rate at which this is possible. According to Kendall and Pimentel (1994), during the Green Revolution the world grain yield expanded by 2.8% per year but this rate of expansion has slowed down and is not likely to be resumed. For this reason we have assumed a rate of increase of yield in both MDCs and LDCs of 1% per year, although this estimate must be considered to be very uncertain. The reason for assuming the same rate of increase in both MDCs and LDCs is that, although there is more room for improvement of yields in LDCs, the economic situation in LDCs may lead to a slower implementation of yields in LDCs than in MDCs. The following value assumed for this parameter must therefore be considered to be very uncertain:

For LDCs: $0.01 \pm 0.005\ \mathrm{yr}^{-1}$,
For MDCs: $0.01 \pm 0.005\ \mathrm{yr}^{-1}$.

We obtain the following values for the change of the yield by 2025 relative to 1990:

For LDCs: $+35.0 \pm 17.5\%$,
For MDCs: $+35.0 \pm 17.5\%$.

5.1.2. Application of fertilizers

In the past the application of more and more fertilizers has been one of the most efficient driving forces in increasing food production, and this is still the case in many developing countries with low to middle yields and in areas not subject to severe water constraints. However, the scope for further increases in yields by applying more and more fertilizers is much less than in the past (Waggoner, 1994; FAO, 1995). For example, on much of Asia's riceland, applying more fertilizer has had little, if any, effect on the yield (Brown, 1995).

In estimating the expected future increase of crop yields through an increased use of fertilizers, account also needs to be taken of demands for a more restrictive use in view of their potential for environmental change.

For the above reasons, we will here make use of a function which is approaching asymptotically a maximum value:

$$Y_{fij}(t) = Y^{*}_{fij}[1 - \exp(-\varphi_j t)] + Y_{fij}(0)\exp(-\varphi_j t) \quad (8)$$

where Y^{*}_{fij} represents the maximum yield by applying more fertilizers and φ_j the rate at which this maximum value can be reached. Although it is clear there are still substantial opportunities to improve the yield by applying more fertilizers (in particular in LDCs), it is difficult to judge to what extent it will be possible to increase the yield in this way. However, making use of information available (for example: Waggoner, 1994; Leach, 1995; FAO 1995) the following assumed estimates of the maximum yields (reflecting the opportunities for increased yields in the LDCs) might be considered plausible:

For LDCs: $(1.30 \pm 0.15)Y_{fij}(0)$ ton/ha,

For MDCs: $(1.10 \pm 0.10)Y_{fij}(0)$ ton/ha.

We will also assume that 80% of the maximum value of the yield can be attained after 20 yr in both LDCs and MDCs. Given these assumptions we obtain the following values for the percentage change of yields by 2025 relative to 1990:

For LDCs: $+28.2 \pm 14.1\%$,

For MDCs: $+9.4 \pm 9.4\%$.

5.1.3. Climatic change and 'CO$_2$-fertilization'

Due to the increasing atmospheric concentration of carbon dioxide and other greenhouse gases, and the accompanying expected change of climate, crop yields can be expected to be affected in different ways.

5.1.3.1. Climatic change. There exist considerable difficulties in predicting future climatic changes, both due to the complexity of the climate system and because some of the forces that drive long-term climatic change are not known with sufficient accuracy to define future climatic change. This is particularly true with regard to changes of atmospheric aerosols and land-use patterns that cause a negative forcing that and thereby offset changes caused by an increased atmospheric concentration of greenhouse gase (Hansen et al., 1998).

Although it can be claimed that there exists a certain skill in predicting large-scale changes of temperature, it has to be admitted that a comparatively low-level of confidence must be given to the predicted changes of precipitation patterns (IPCC, 1996b).

5.1.3.2. The carbon dioxide 'fertilization effect'. In controlled experiments with optimum environmental conditions, C_3 plants (such as wheat, rice, soybean, and some weeds) show a significant improvement in yield with an increased atmospheric concentration of carbon dioxide (due to increased photosynthesis), while C_4 plants (such as maize, millet, sorghum and many of the major weeds) exhibit relatively little benefit. Actually, some C_4 crops may experience yield reductions due to competition with C_3 weeds. Moreover, as has been pointed out by Wolfe and Erickson (1993), the benefits of a carbon dioxide enrichment are seldom, if ever, maintained when plants grow in field situations. Therefore, they suggest a conservative policy of assuming no "carbon dioxide fertilization" effect.

5.1.3.3. Adaptation of agriculture to climatic change. The negative effects of climatic change may be reduced to a large extent through adaptation methodologies. However, as stressed by the IPCC (1996a), to what extent this is possible depends on the affordability of such measures, particularly in developing countries.

Although the results obtained recently from numerous studies of the impacts of a climatic change, increased carbon dioxide fertilization and adaptation to climatic change vary within wide limits, they do support the overall assessment of the first IPCC assessment that global agricultural production can be maintained relative to the baseline production (Reilly, 1996).

For projections over a limited period of time (a few decades) it may be considered realistic to assume that the variation of the yield caused by the combined effect of the three climate related processes discussed above can be expressed by the following linear function of time:

$$Y_{cij}(t) = (1 + c_j t)Y_{cij}(0) \quad (9)$$

where c_j represents the annual rate of change of the yield.

By making use of results from three climate simulation models, Rosenzweig and Parry (1994) have made an attempt to estimate the change in cereal production taking into account not only of the effect of climatic change and the carbon dioxide "fertilization effect", but also of existing opportunities to adapt to a climatic change. The result of this study is presented in Table 5. Extensive studies have also been undertaken of the vulnerability of a climatic change on a regional basis, and reported by IPCC (1998).

Table 5
Change in cereals production in 2060 using three different general circulation models (GCMs) for simulation of a greenhouse gas induced climatic change

Region	GISS	GFDL	UKMO
World total			
Climate effects only	− 10.9	− 12.1	− 19.6
Plus physiological effect of CO_2	− 1.2	− 2.8	− 7.6
Plus adaptation level 1	0.0	− 1.6	− 5.2
Plus adaptation level 2	1.1	− 0.1	− 2.4
Developed countries			
Climate effects only	− 3.9	− 10.1	− 23.9
Plus physiological effect of CO_2	11.3	5.2	− 3.6
Plus adaptation level 1	14.2	7.9	3.8
Plus adaptation level 2	11.0	3.0	1.8
Developing countries			
Climate effects only	− 16.2	− 13.7	− 16.3
Plus physiological effect of CO_2	− 11.0	− 9.2	− 10.9
Plus adaptation level 1	− 11.2	− 9.2	− 12.5
Plus adaptation level 2	− 6.6	− 5.6	− 5.8

Sources: Rosenzweig and Parry (1994) and Reilly (1996).

Note: The changes are expressed in per cent from a base estimated for 2060 without climatic change.

GISS Goddard Institute for Space Studies

GFDL Geophysical Fluid Dynamics Laboratory

UKMO United Kingdom Meteorological Office

Note, the two levels of adaptation are defined in the following way:

Level 1 adaptation included changes in crop variety but not the crop, the planting date less than 1 month, and the amount of water applied for areas already irrigated.

Level 2 adaptation additionally included changes in the type of crop grown, changes in fertilizer use, changes in the planting date of more than 1 month; and extension of irrigation to previously unirrigated areas.

Taking these results, and assuming that fairly extensive measures aimed at adapting to a climatic change will be implemented in MDCs but to a lesser extent in the LDCs, the following values have been assigned to the parameter c_j:

For LDCs: $-0.001 \pm 0.001\ \mathrm{yr}^{-1}$,

For MDCs: $+0.001 \pm 0.001\ \mathrm{yr}^{-1}$.

We thus obtain the following values for the percentage change of the yield of crop categories $i = 1$ and 2 by 2025. relative to 1990:

For LDCs: $-3.5 \pm 3.5\%$,

For MDCs: $+3.5 \pm 3.5\%$.

5.1.3.4. Changes in climate variability. In the past, climate variability has been the cause of the most severe disturbances of agricultural production, and it cannot be excluded it will cause even greater problems in the future. For example, during the last couple of decades droughts have occurred in most continents and resulted in severe food shortages, particularly in Africa.

Despite our increased understanding of the functioning of the climate system we have to admit that we cannot yet predict with any accuracy the natural occurrences of droughts. Neither do we know to what extent the expected greenhouse gas induced climatic change might result in an increased climate variability and frequency of droughts. We can only state with confidence that the consequences of droughts, and other weather extremes having an influence on the agricultural production, will have more severe consequences in the future due to the increasing population. Although we were not able to consider increased climate variability in our analysis there is a need for improved knowledge about their possible frequency and magnitude in the future in order to ensure that sufficient reserves of food commodities are available.

5.1.4. *Irrigation, salinization and waterlogging*

Under this heading we will include the following water related items:

- changes in the area of irrigated land,
- water shortages,
- improvement of irrigation technologies,
- salinization and waterlogging.

The results of a study by Doorenbos and Kassam (1979) suggests that irrigation could result in roughly a doubling of yields for many crops. Indeed, through expansion of irrigated land on all continents (particularly in Asia) it has been possible in the past to increase global food production significantly.

Thus, at present about 250 million ha (circa 17% of the global cropland) are now being irrigated, and it is estimated that an additional 140 million ha have the potential to be irrigated (FAO, 1993; IPCC, 1996a).

Although it can be expected that the expansion of irrigated land will continue, it will probably be at a considerably slower rate. Thus, FAO predicts that irrigated land in the MDCs (excluding China) will expand at a rate of only 0.8% annually which is much slower than the 2.2% in the 1970s and the 1.9% in the 1970s (WRI, 1996). The main reasons for this decline are the increasing cost of irrigation, and competition with other demands for water. Another reason is (as pointed out by Kendall and Pimentel (1994)) that, in many parts of the world, water is drawn from underground water resources at rates much in excess of the natural recharge rate.

If we then also consider the negative effect as represented by the increasing salinization and water logging in all world regions, it cannot be judged likely that the net positive effect will be substantial. Thus FAO (1993) reports that 30 million ha of irrigated land have become severely affected by salinity, and an additional 60–80 million ha are affected to some extent.

Actually, Kendall and Pimentel (1994) claim that the current annual loss of farmland due to salinization alone is about 1.5 million ha and exceeds the present expansion of irrigation. They conclude that, if this damage continues, 30% of the world's presently irrigated acreage will be lost by 2025.

In a longer time perspective (beyond 2025), account also needs to be taken of the expected rise of the sea level. Since a significant part of the arable land is along low-lying coastal zones, salinization by sea water intrusion is likely to be an increasingly important problem. In particular this will be the case in areas with strong subsidence of land (for example in Bangladesh, Egypt, and Mississippi, USA).

Based on these considerations we will adopt the following function for the variation with time of the yield which provides an upper limit for the improvement that can be achieved by irrigation:

$$Y_{wij}(t) = Y^{*}_{wij}[1 - \exp(-\varpi_j t)] + Y_{wij}(0)\exp(-\varpi_j t) \tag{10}$$

where Y^{*}_{wij} represents the maximum yield and ϖ_j the rate at which this maximum value can be reached. Despite the potential doubling of yields implied by the results of Doorenbos et al. (1979), and given the information available in the literature on the potential negative effects of irrigation referred to above, the following cautious values assigned to the expected maximum yield Y^{*}_{wij}:

For LDCs: $(1.04 \pm 0.02)Y_{wij}(0)$ ton/ha,

For MDCs: $(1.06 \pm 0.02)Y_{wij}(0)$ ton/ha.

For determining ϖ we will assume that 80% of the maximum value of the yield can be attained after 20 yr in both LDCs and MDCs. We then obtain the following values of the percentage change of the yields by 2025 relative to 1990:

For LDCs: $+3.8 \pm 1.9\%$,

For MDCs: $+5.7 \pm 1.9\%$.

5.1.5. *Biotic stresses*

This category of environmental stresses on agriculture includes:

- pests and diseases,
- ultraviolet B-radiation,
- groundlevel ozone.

According to Norse et al. (1992) huge losses occur from insects, diseases, weeds and nematodes at both pre- and post-harvest stages. Pre-harvest losses due to pests have been estimated at up to one billion tons of food, feed and fiber. There are also significant losses in livestock productivity due to infectious and non-infectious diseases of animals. It should also be recognized that the use of pesticides might become less and less effective as pest populations become increasingly resistant and their predators are killed off (Leach, 1995). Moreover, it cannot be excluded that biotic stresses might become more severe in connection with the expected greenhouse gas induced global warming.

The rate of increase of these stresses and the magnitude of their impacts can only be estimated with moderate accuracy. Thus, also with regard to the expected change of the yield with time caused by these environmental stresses we will make use of a linear function:

$$Y_{bij}(t) = (1 + b_j t)Y_{bij}(0) \tag{11}$$

Based on the limited information available (including Norse et al., 1992; IGBP, 1997), the following values have been assumed for the parameter b_j expressing the rate of change of the yield:

For LDCs: $-0.002 \pm 0.001\ \mathrm{yr}^{-1}$,

For MDCs: $-0.001 \pm 0.0005\ \mathrm{yr}^{-1}$.

We thus obtain the following values for the percentage change of the yield of crop categories $i = 1$ and 2 by 2025. relative to 1990:

For LDCs: $-7.0 \pm 3.5\%$,

For MDCs: $-3.5 \pm 1.75\%$.

5.2. *Factors contributing to loss of agricultural land*

In the following an attempt is made to quantify the various factors that have, or can be expected to cause, significant losses of presently used agricultural land and land reserves.

5.2.1. *Soil degradation*

In Table 6 estimates are presented of the present extent of moderate to excessive soil degradation caused by various factors (Oldeman et al., 1991). According to this study people have degraded 25% of the occupied land, and much of this damage has been caused during the last 150 yr. Although the figures given in this table must be considered to be very approximate, it is apparent that soil degradation represents a major threat to future food production. As reported by Swaminathan (1991), the rate of soil erosion is almost imperceptible and significantly exceeds its floor renewal rate (0.5 cm in 100 yr), in the temperate countries by 10 to 20 times and in the tropics by 20 to 40 times.

As shown in Table 6, the most serious degradation worldwide is caused by water erosion. Norse (1992) has pointed out that this is in turn the result of deforestation (43%), overgrazing (29%) and mismanagement of arable land (24%).

Table 6
Extent of soil degradation classified as moderately to excessively affected (in million ha)

Region	Water erosion	Wind erosion	Chemical degrad.	Physical degrad.	Total
Africa	170	98	36	17	321
Asia	315	90	41	6	452
South America	77	16	44	1	138
North and Central America	90	37	7	5	139
Europe	93	39	18	8	158
Australasia	3		1	2	6
Total	748	280	147	39	1214

Source: Oldeman et al. (1991).

The values presented in this table provide fairly detailed information about the geographical distribution of soil degradation, but the actual magnitude of the degradation is very qualitatively given (modestly to severely). Regardless of what the present loss is, it cannot be excluded that this type of loss of agricultural land will be increasing with time due to: (a) the growing population in the developing countries which will result in an increasing rate of overcultivation and overgrazing of drylands, and (b) an increasing occurrence of droughts and floods in conjunction with the projected climatic change.

The annual global loss of cropland has been estimated by Lal and Stewart (1990) to be 12 million ha/yr, and by Kendall and Pimentel (1994) to be 5–7 million ha/yr by erosion alone. More recently Crosson (1997), making use of data from the Global Assessment of Soil Degradation (Oldeman, 1994), calculated a 17% cumulative production loss by the year 2030.

Taking account this information, we will assume the loss of cropland in region j during the time period t can be expressed by

$$\Delta A_{dj}(t) = \lambda_j t \tag{12}$$

where λ_j represents the time and space averaged value of the annual loss of cropland in region j. The values of this parameter are estimated to be

For LDCs: $\lambda_1 = -6 \pm 3$ million ha/yr,

For MDCs: $\lambda_2 = -2 \pm 1$ million ha/yr.

During a 35-year period the loss of cropland would thus be:

In LDCs: $\Delta A_{d1}(35) = -210 \pm 105$ million ha,

In MDCs: $\Delta A_{d2}(35) = -70 \pm 35$ million ha.

This corresponds to a change of the extent of the 1990 cropland area:

in LDCs by: $-26.2 \pm 13.1\%$,

in MDCs by: $-17.0 \pm 8.5\%$.

As an alternative to assuming a constant annual absolute loss of cropland per year, we could of course assume the decrease to be a constant annual fractional loss. However, this would not result in a significantly different estimate of the resulting total loss over a 35 yr period.

With regard to the drylands it should be pointed out that according to the UN Convention to Combat Desertification, the problem of land degradation in dryland regions has continued to worsen during the last two decades, and that 70% of drylands used for agriculture around the world are already degraded (CCD, 1995).

In sharp contrast to this pessimistic assessment is the statement made by FAO (1995): "… recent thinking on desertification points to a growing consensus that the past estimates of areas affected were greatly exaggerated". In view of these conflicting opinions about the present and future rate of desertification, reflecting a very insufficient knowledge about this environmental problem, no attempt has been made in our analysis to estimate to what extent desertification may contribute to loss of agricultural land during the next few decades.

5.2.2. Urban and industrial development

Due to the increasing world population there is an increasing demand on land for habitation, industry, infrastructure, etc. A significant portion of this demand for land is likely to be at the expense of high-quality agricultural land because the major urban centers are commonly located in river valleys and coastal plains, as are high-quality agricultural lands. For the annual loss of agricultural land $\Delta A_j(t)$ in region j during the time period t we will use the following formula:

$$\Delta A_{uj}(t) = \alpha_j \beta_j \, \Delta n_j t \tag{13}$$

where

α_j = the area required per capita,

β_j = the portion of this area having productive agricultural potential,

Δn_j = the annual rate of increase of population.

Table 7
Estimates of areas of non-agricultural uses of land per capita for selected regions

Region	area/cap m^2	References
United States	600	Waggoner (1994)
New England, USA	2500	Spaulding and Heady (1977)
Mid-Atlantic, USA	300	Spaulding and Heady (1977)
New Zealand	780	Zarka (1981)
Columbia[a]	800	Zarka (1981)
Uganda[a]	440	Zarka (1981)
Bangladesh	180	FAO/UNDP (1981)
Malaysian irrigation area	500	Wong (1980)
China	280	Prosterman et al. (1996)

Source: Waggoner (1994).

[a] The values for Columbia and Uganda are the high and low values obtained in a study covering 41 countries.

The main source of uncertainty in the estimation of this type of loss of arable land is related to the difficulties in assigning a reliable value for the parameter α_j. In a study by FAO relating to developing countries, an average value of $210\,m^2$ per capita has been used (FAO, 1995). However, as can be seen in Table 7, which provides a range of estimates relating to several countries, this value appears to be an underestimate. At the same time it has to be recognized that the value of α_j can be expected to decrease with an increasing shortage of agricultural land.

With regard to the parameter β_j the estimates exhibit fewer discrepancies. According to the US Department of Agriculture (1990), the expansion of cities in the United States is to a large extent at the expense of productive agricultural land, and more than 60% of this land is taken from cropland. During the next 50 yr it is expected that 90% of the cropland likely to be converted to other uses will be taken from prime farmland. Norse et al. (1992) also emphasizes that much of this land lost in competition with urban/industrial development is taken from high-quality land.

Taking this information into account, it may be considered realistic to use the following values for α_j and β_j for both LDCs and MDCs:

$$\alpha_1 = \alpha_2 = 500 \pm 250\,m^2 \text{ per capita},$$

$$\beta_1 = \beta_2 = 0.5 \pm 0.1.$$

Using these values and the values for the annual rate of population increase $\Delta n_j(t)$, given in Table 2, the annual loss of productive cropland may be estimated to be about:

In LDCs: 2 ± 1 million ha/yr,

In MDCs: 0.1 ± 0.1 million ha/yr.

Other studies of this problem have arrived at similar, or higher, values for the annual loss of arable land. For example, Kendall and Pimentel (1994) assumes it to be 2–4 million ha, and Norse et al. (1992) 5 million ha.

Thus, during a 35 yr period, the loss will be:

In LDCs: $\Delta A_{u1}(35) = -70 \pm 35$ million ha,

In MDCs: $\Delta A_{u2}(35) = -3.5 \pm 3.5$ million ha.

This corresponds to a loss of cropland relative to the cropland areas in 1990 (1990 area in LDCs: 802 million ha; MDCs: 412 million ha):

In LDCs by: $-8.70 \pm 4.35\%$,

In MDCs by: $-0.85 \pm 0.85\%$.

5.2.3. Sea level rise

In a longer time perspective, the rise of the global sea level caused by a climate warming in combination with local subsidence of land, may result in extensive loss of agricultural land in low-lying coastal areas. By the end the 21st century the rise of the global sea level is expected to be within the range 20–86 cm (IPCC, 1996b). Thus, between now and the year 2025, it is not likely it will lead to a significant loss of land. Nevertheless, this does not exclude the possibility that sea level rise can within the next three decades contribute significantly to salinization in many coastal zones.

5.3. Change of cropping intensity

In many regions there is a potential for a substantial increase of crop production by increasing the cropping intensity, provided there are appropriate inputs of fertilizer, pesticide and water, and perhaps mechanization. Thus, based on information available (for example Hoque, 1984; FAO, 1995; Leach, 1995) it is estimated that the cropping intensity factor can be increased in LDCs by about $10 \pm 5\%$ during the next 35 yr for both cereals and other crops, while no significant changes can be expected in the MDCs.

5.4. Summary of the sensitivity of food production in 2025 to various aspects of global change

Table 8 summarizes the effect on food production in 2025 to various aspects of global change, and to uncertainties therein. The effects on yield, cropland and cropping intensity could act either individually or in combination. To illustrate how the uncertainty of combined effects were estimated for each of these factors, let us take the combined effects upon yield as an example. It was assumed that:

(i) The five factors affecting yield are independent of one another. Although this cannot be a realistic assumption, it was difficult enough to estimate the individual affects of factors, let alone the interactions among them.

(ii) For each factor affecting yield, the possible changes in yield are uniformly distributed between the mean value x in Table 8 plus or minus the uncertainty Δx, and that the mean values of the errors is zero.

(iii) The five factors affecting yield combine in an additive way such that the combined percentage change has an approximately normal distribution with mean value equal to $\sum x$ and standard deviation equal to:

$$\sigma = [1/3\sum(\Delta x)^2]^{1/2}$$

(iv) The probability is that about 95% of the combined change in yield is within plus or minus twice the standard deviation.

The combined effects on loss of cropland and increased cropping intensity were calculated in the same way.

Because production is calculated by multiplying yield, cropland area and cropping intensity, the uncertainty in calculated production was calculated assuming that the relative error in the ratio of 2025 production due to all effects in Table 8 acting in combination was the sum of the relative errors in the combined effects on yield, cropland area and cropping intensity. (It was also assumed that the effects of these three factors were independent of one another.)

What effect would the changes in food production in Table 8 have upon predicting supply/demand ratios for cereals and other crops in LDCs and MDCs in 2025? The ratios due to global change in Table 8 were applied to the 1990 production values calculated by the spreadsheet accounting tool (see Table 1). These ratios were applied to the production of both cereals and other crops. The demands for cereals and other crops were calculated according to the assumption for population increase to 2025, and the assumptions for Level 1 and Level 2 diets that were described in Section 4.

The resulting ratios of supply to demand in 2025 will be discussed in the next section.

Table 8
Sensitivity of food production in 2025 to various aspects of global change, and uncertainties therein

Influencing factors	Region	Change in per cent		Range in production 2025 relative to 1990		
		x	Δx	Min.	Mean	Max.
I. Impacts on yield						
Improvement of management and new technologies	LDCs	+ 35.0	± 17.5	1.18	1.35	1.53
	MDCs	+ 35.0	± 17.5	1.18	1.35	1.53
Increased use of fertilizers	LDCs	+ 28.2	± 14.1	1.14	1.28	1.42
	MDCs	+ 9.4	± 9.4	1.00	1.09	1.19
Climatic change, adaptation and CO_2 fertilization	LDCs	− 3.5	± 3.5	0.93	0.97	1.00
	MDCs	+ 3.5	± 3.5	1.00	1.04	1.07
Irrigation, salinization and waterlogging	LDCs	+ 3.8	± 1.9	1.02	1.04	1.06
	MDCs	+ 5.7	± 1.9	1.04	1.06	1.08
Pests, diseases, UV-radiation, low-level O_3, etc.	LDCs	− 7.0	± 3.5	0.89	0.93	0.97
	MDCs	− 3.5	± 1.75	0.95	0.97	0.98
Combined effects upon yield	LDCs	+ 57	± 27	1.30	1.57	1.84
	MDCs	+ 50	± 23	1.27	1.50	1.73
II. Loss of cropland						
Soil degradation processes: Erosion, etc.	LDCs	− 26.2	± 13.1	0.61	0.74	0.87
	MDCs	− 17.0	± 8.5	0.75	0.83	0.92
Human habitation, industries, infrastructure, etc.	LDCs	− 8.7	± 4.35	0.87	0.91	0.96
	MDCs	− 0.9	± 0.9	0.98	0.99	1.00
Global sea level rise and local subsidence of land	LDCs	0	0	1.00	1.00	1.00
	MDCs	0	0	1.00	1.00	1.00
Combined effects upon cropland	LDCs	− 35	± 16	0.49	0.65	0.81
	MDCs	− 18	± 10	0.72	0.82	0.92
III. Change of cropping intensity	LDCs	+ 10	± 5	1.05	1.10	1.15
	MDCs	0	0	1.00	1.00	1.00
Combined effects of changes in yield, cropland area and cropping intensity	LDCs	+ 12	± 52	0.60	1.12	1.64
	MDCs	+ 23	± 34	0.89	1.23	1.57

5.5. Uncertainties in the ratio of supply to demand in 2025

5.5.1. Level 1 food demand

Table 9 shows the mean, minimum and maximum values of the ratio of supply to demand (S/D) for cereals and other crops for Level 1 demand in 2025. To begin, the accounting system was first run for the year 2025 for a Base Case in which the demand was calculated using the population projections and the Level 1 diet discussed in Section 4. The food production was calculated using

Table 9
Estimated ranges in the ratio of supply (using present cropland) to level 1 demand for cereals and other crops in 2025 due to uncertainties in various factors influencing production (see Table 8)

Influencing factors	Region	Range in supply/demand					
		Cereals			Other crops		
		Min.	Mean	Max.	Min.	Mean	Max.
Base Case No impacts of factors listed below	LDCs	0.56	0.56	0.56	0.53	0.53	0.53
	MDCs	0.87	0.87	0.87	0.67	0.67	0.67
	World	0.67	0.67	0.67	0.56	0.56	0.56
I. Impacts on yield							
Improvement of management and new technologies	LDCs	0.66	0.76	0.86	0.62	0.71	0.80
	MDCs	1.03	1.18	1.33	0.79	0.90	1.02
	World	0.79	0.91	1.02	0.66	0.76	0.86
Increased use of fertilizers	LDCs	0.64	0.72	0.80	0.60	0.67	0.75
	MDCs	0.87	0.96	1.04	0.67	0.73	0.79
	World	0.72	0.80	0.88	0.62	0.69	0.75
Climatic change, adaptation and CO_2 fertilization	LDCs	0.52	0.54	0.56	0.49	0.51	0.53
	MDCs	0.87	0.90	0.93	0.67	0.69	0.72
	World	0.65	0.67	0.69	0.54	0.56	0.58
Irrigation, salinization and waterlogging	LDCs	0.57	0.58	0.59	0.54	0.55	0.56
	MDCs	0.91	0.92	0.94	0.69	0.71	0.72
	World	0.69	0.70	0.72	0.58	0.59	0.60
Pests, diseases, UV-radiation, low-level O_3, etc.	LDCs	0.50	0.52	0.54	0.47	0.49	0.51
	MDCs	0.83	0.84	0.86	0.63	0.65	0.66
	World	0.62	0.64	0.65	0.51	0.53	0.55
Combined effects upon yield	LDCs	0.73	0.88	1.03	0.68	0.83	0.97
	MDCs	1.11	1.31	1.51	0.73	0.87	1.02
	World	0.86	1.03	1.20	0.73	0.87	1.02
II. Loss of cropland							
Soil degradation processes: Erosion, etc.	LDCs	0.34	0.41	0.49	0.32	0.39	0.46
	MDCs	0.65	0.73	0.80	0.50	0.56	0.61
	World	0.45	0.52	0.60	0.37	0.43	0.50
Human habitation, infrastructure, industries etc. LDCs	LDCs	0.49	0.51	0.54	0.46	0.48	0.50
	MDCs	0.86	0.87	0.87	0.66	0.66	0.67
	World	0.62	0.64	0.66	0.51	0.53	0.55
Global sea level rise and local subsidence	LDCs	0.56	0.56	0.56	0.53	0.53	0.53
	MDCs	0.87	0.87	0.87	0.67	0.67	0.67
	World	0.67	0.67	0.67	0.56	0.56	0.56
Combined effects upon cropland	LDCs	0.27	0.36	0.45	0.26	0.34	0.43
	MDCs	0.63	0.72	0.80	0.48	0.54	0.62
	World	0.40	0.49	0.59	0.32	0.40	0.48
III. Change of cropping intensity	LDCs	0.59	0.62	0.65	0.56	0.58	0.60
	MDCs	0.87	0.87	0.87	0.67	0.67	0.67
	World	0.69	0.71	0.73	0.58	0.60	0.62
Combined effects of changes in yield, cropland area and cropping intensity	LDCs	0.34	0.63	0.82	0.32	0.59	0.86
	MDCs	0.78	1.07	1.37	0.60	0.82	1.05
	World	0.49	0.79	1.08	0.39	0.65	0.91

the same values for yield, agricultural area and cropping intensity as in 1990. In other words, the Base Case assumes that, for production, there are no differences from 1990 due to global change, and there are no uncertainties.

The results for the Base Case are shown in the top part of Table 9. Because there are no uncertainties involved, the minimum, mean and maximum values for the S/D ratios are the same for the Base Case. Not surprisingly, the world supply of cereals meets only about two-thirds of the calculated demand while the world supply of other crops is slightly over one-half of demand. The calculated shortfall is, as to be expected, from the relatively large increase in population whilst keeping the production to 1990 levels.

The remainder of Table 9 deals with the effects of uncertainty in global change on the supply/demand ratio for cereals and other crops. For example, uncertainty in the use of fertilizers could by itself cause the S/D ratio for cereals in LDCs to vary between 0.64 and 0.80; if this uncertainty were to act in combination with those others affecting yield, the S/D ratio could fluctuate over a wider range: from 0.73 to 1.03.

The main results in Table 9 are summarized for the world in Fig. 3 (for cereals) and Fig. 4 (for other crops). The difference in the height of the minimum and maximum bars in the figures show the uncertainty in the S/D ratio that results from each of the factors indicated. Fig. 4a shows that the combined uncertainties in yield, cropland and cropping intensity could result in a global

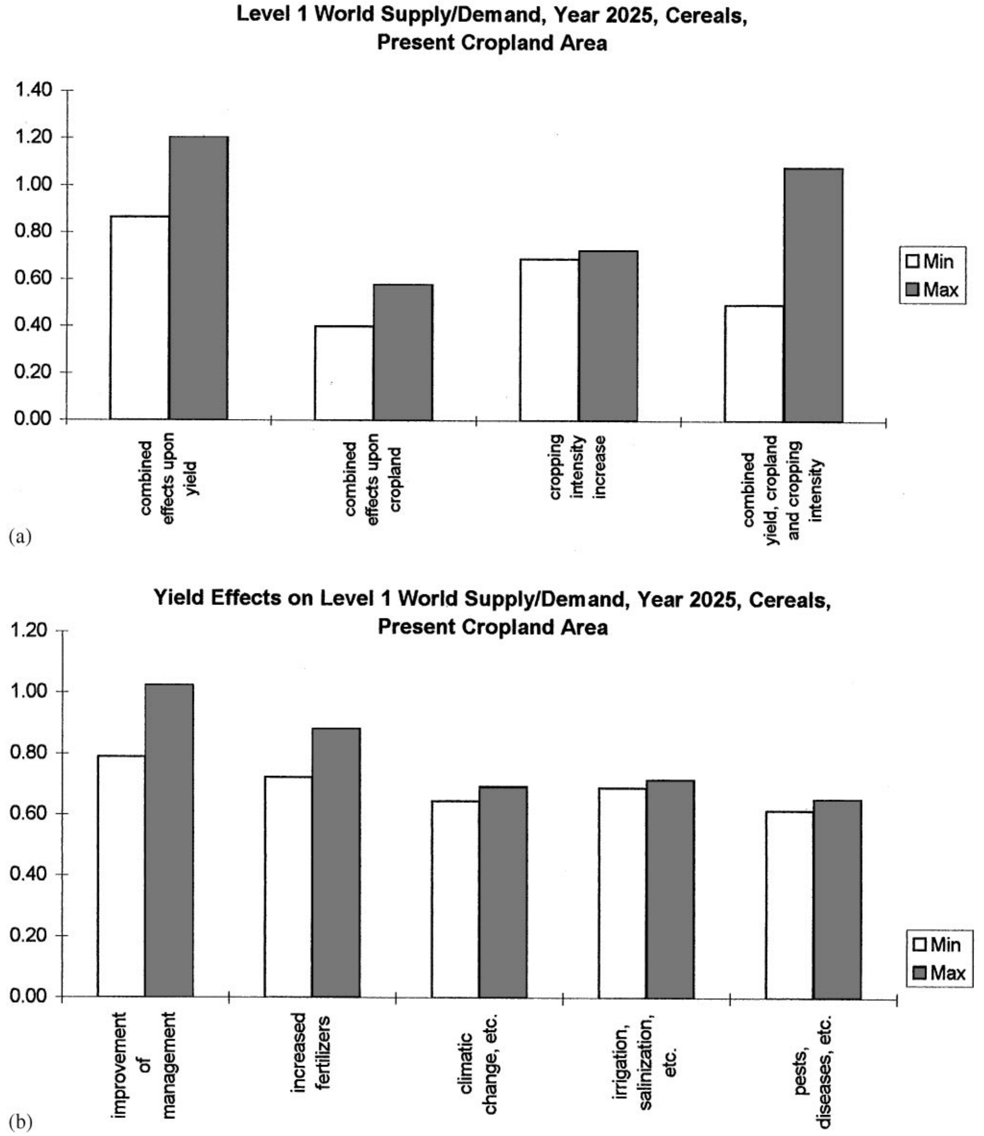


Fig. 3. Ranges in the ratio of world supply to Level 1 demand for cereals in 2025, given the present extent of cropland, caused by uncertainties in:
(a) the combined influences on the crop yield and cropland area and changes of the cropping intensity,
(b) the various factors having an influence only on the crop yield.

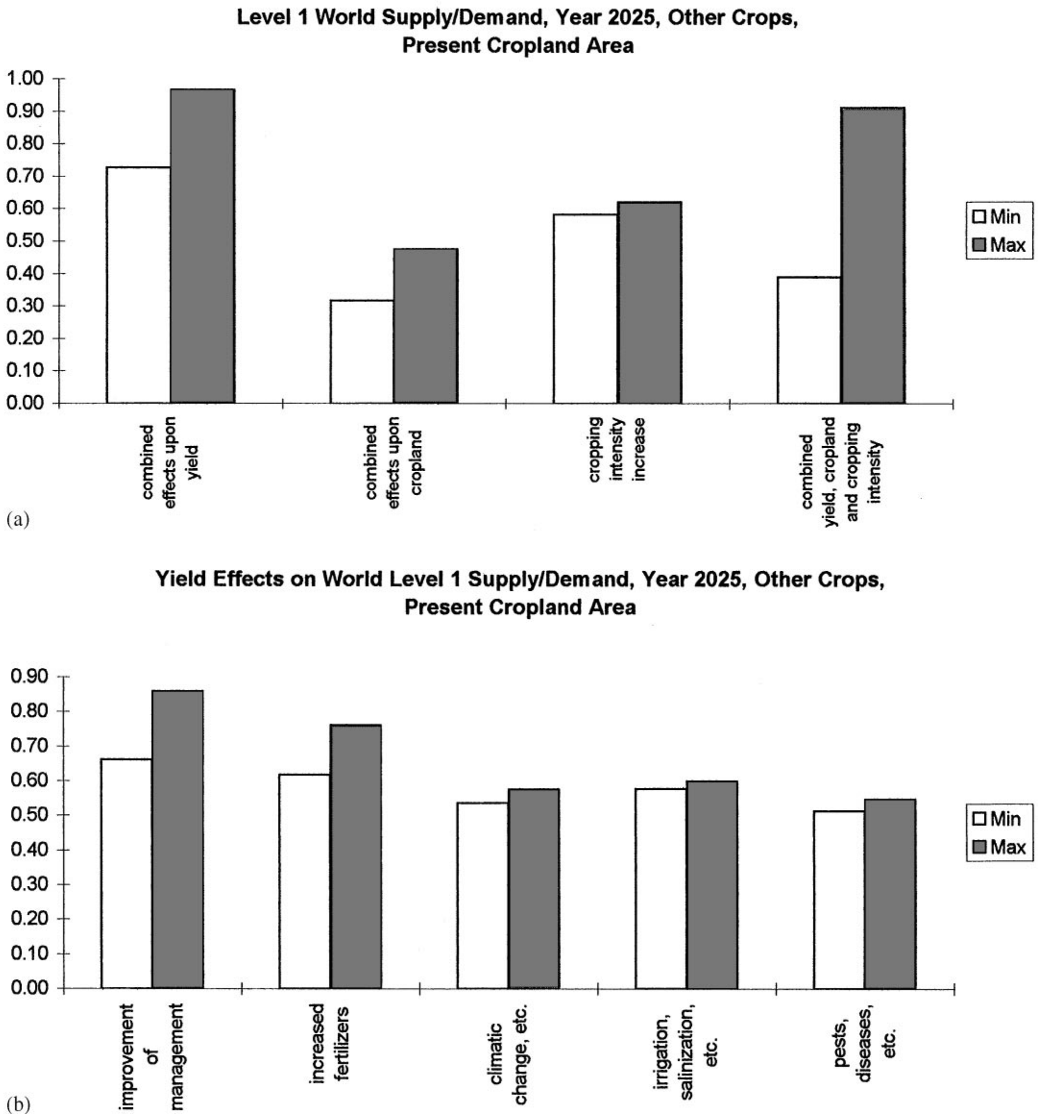


Fig. 4. Same as Fig. 3, but for other crops.

S/D ratio for cereals in 2025 as low as about 0.5 (supply only about one half that of demand), or as high as about 1.1 (supply about 10% greater than demand). Table 9 shows that calculated shortfalls in LDCs (minimum $S/D = 0.34$) contribute the most to the global minimum S/D value, while calculated production excesses in MDCs (maximum $S/D = 1.37$) contribute the most to the calculated global maximum S/D value.

Fig. 3a also shows that most of the combined uncertainty in the Level 1 S/D ratio is due to the uncertainties in our estimates of the effect of global change upon yield, rather than on cropland or cropping intensity. The effects of uncertainties in the various factors influencing yield are shown in more detail in Fig. 3b. It can be seen that the uncertainties in the future effects of possible improvement in management and in the increased use of fertilizers, and not the effects of climatic change, irrigation or pests, may contribute the most to the uncertainties in future yield and, therefore, in our ability to meet future food demand.

Fig. 4a and b show similar results for the other crops. Again, the uncertainties due to future management and the use of fertilizers, and not climatic change and other factors, are the biggest cause of uncertainty in our ability to meet future global demand.

5.5.2. *Level 2 food demand*

Figs. 5 and 6 show results for Level 2 demand analogous to those in Figs. 3 and 4 for Level 1 demand. Although the S/D ratios in Figs. 5 and 6 are slightly less than they are in Figs. 3 and 4 (due to the increase of caloric input in LDCs to a minimum of 3000 kcal/cap for Level 2 demand), the figures give the same message as

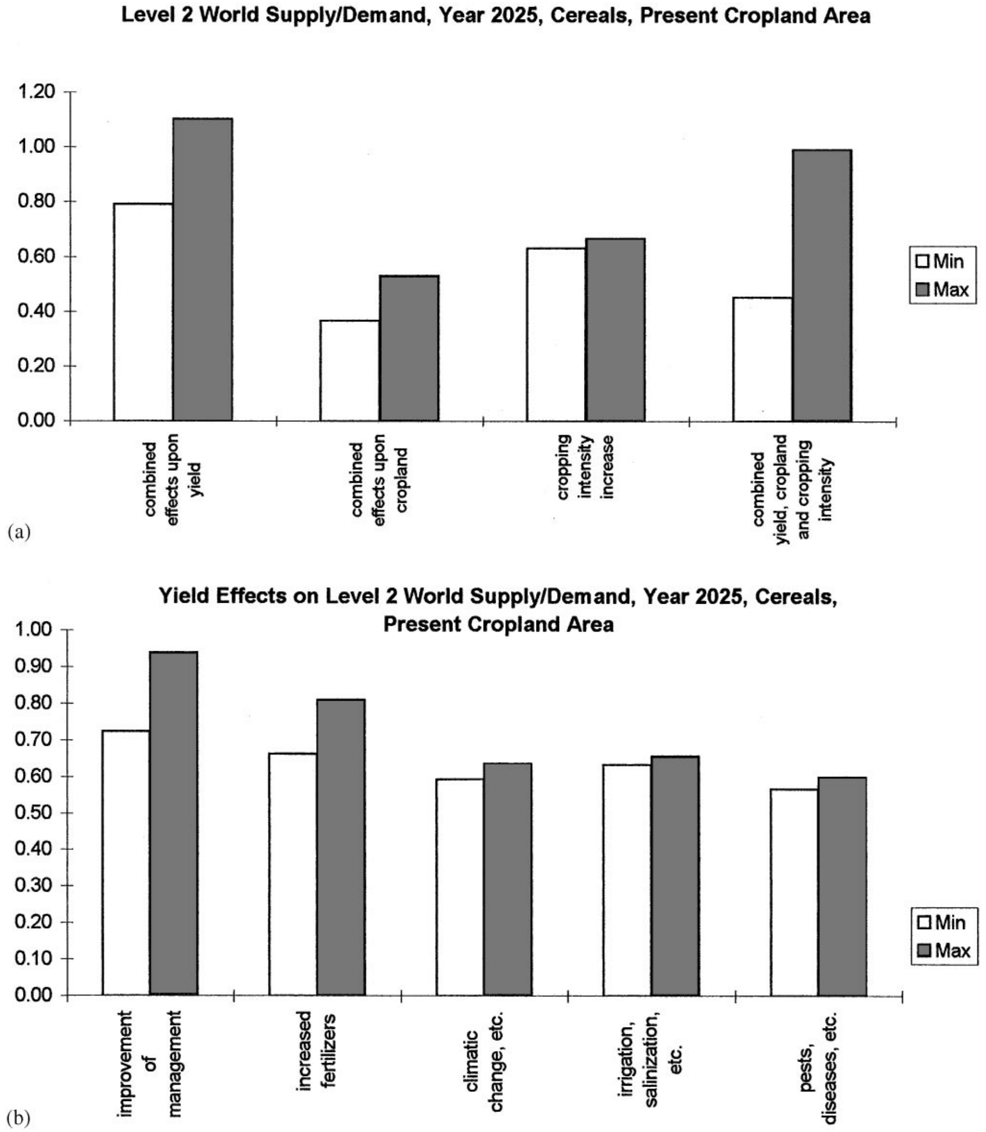


Fig. 5. Same as Fig. 3, but for Level 2 demand.

Figs. 3 and 4: uncertainties in the future agricultural management and the use of fertilizers may contribute the most on the supply side to the uncertainty as to whether or not future food demand can be met.

6. The need for expansion of cropland

6.1. Supply of crop commodities with present cropland

The Base Case in the top section of Table 9 shows that the mean S/D ratio for cereals in the world and Level 1 demand in the absence of global change could be 0.67.

The bottom section of the table shows that, on average, global changes in all aspects of production would cause the calculated value to meet only about 63% of calculated cereal demand in LDCs; in contrast it would exceed calculated demand in MDCs by a small margin of 7%. However, uncertainties in global change might cause it to meet only 34% of demand in LDCs or, alternatively, to meet as much as 82%. In MDCs, the S/D ratio could vary between 0.78 and 1.37.

Similar uncertainties are obvious when looking at other crops. This means that, depending upon how the uncertainties combine, a large increase in food production might be required by 2025 to compensate for global change and give us a reasonable chance of meeting the expected demand, especially in LDCs.

Would it be possible to accomplish this through an expansion in cropland, allowing for the uncertainties in the effects of global change? It is necessary, therefore, to examine the availability of additional cropland.

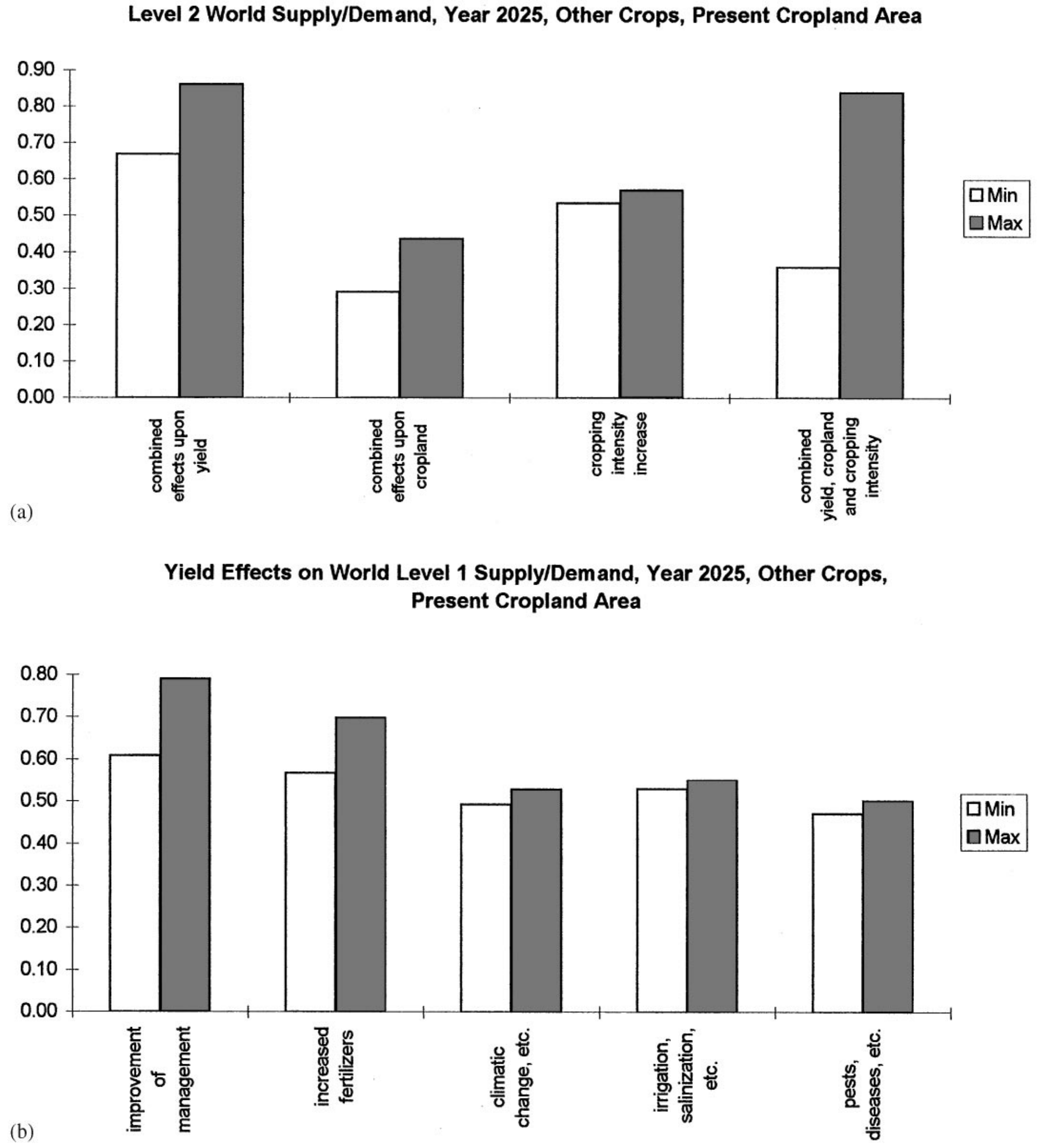


Fig. 6. Same as Fig. 5, but for other crops.

6.2. *The availability of additional cropland*

According to data presented by Crosson and Andersson (1992,1994) and FAO (1995), and shown in Table 10, the availability of land reserves with crop production potential is quite impressive. However, it is also pointed out that, as can be seen in this table, that the land reserves are almost entirely concentrated in the sub-Saharan Africa and Latin America regions. Moreover, in estimating the future availability of agricultural land, it should be recognized that

- A high portion of the present land reserves are only marginally suited for crop production. Thus, according to FAO (1995), three quarters of the two regions (sub-Saharan Africa and Latin America), which have

Table 10
Estimates of the present area of cropland, and expected losses and expansion during the period 1990–2025 in LDCs

Region	Area 1990	Estimated losses 1990–2025	Potential expansion	10% of potential expansion
Africa	168	53	621	62
CP Asia	151	48	320	32*
L. america	160	50	734	73
M. East	42	13	0	0
S. + SE Asia	274	86	23	2
LDCs	795	250	1698	169

Sources: Crosson and Anderson (1992) and FAO (1990). See Section 5 for estimated losses.

Note: Additional potential calculated from using 10% of 320 million ha of permanent pasture in AGROSTAT database for Centrally Planned Asia.

92% of the global "reserve", suffer from soil and terrain constraints.

- Most reserves are currently under forest or permanent pastures or range land, and the demand for both forests and pastures is growing (Norse et al., 1992). It should be pointed out that deforested land is not well suited for agriculture. It is often put into use before it has had time to regenerate and replenish its soil nutrients.
- Another constraint in making use of the main land reserves is that they are located far from domestic and foreign markets, and that they are poorly connected by road, rail and air to these markets (Crosson and Anderson, 1992,1994).

For the above reasons, it is assumed as indicated in Table 10 that only 10% of the potential cropland will be used in 2025.

6.3. *Supply of crop commodities with expanded cropland*

6.3.1. *Level 1 food demand*

Fig. 7a, b, Fig. 8a and b, show the calculated ranges of supply to demand for cereals and other crops, respectively, for Level 1 demand in 2025 assuming the expanded cropland indicated in Table 10. It can be seen that the ranges have been shifted upwards from those shown in Figs. 3 and 4. This means that, on the average, increasing the cultivated area by utilizing 10% of the potential

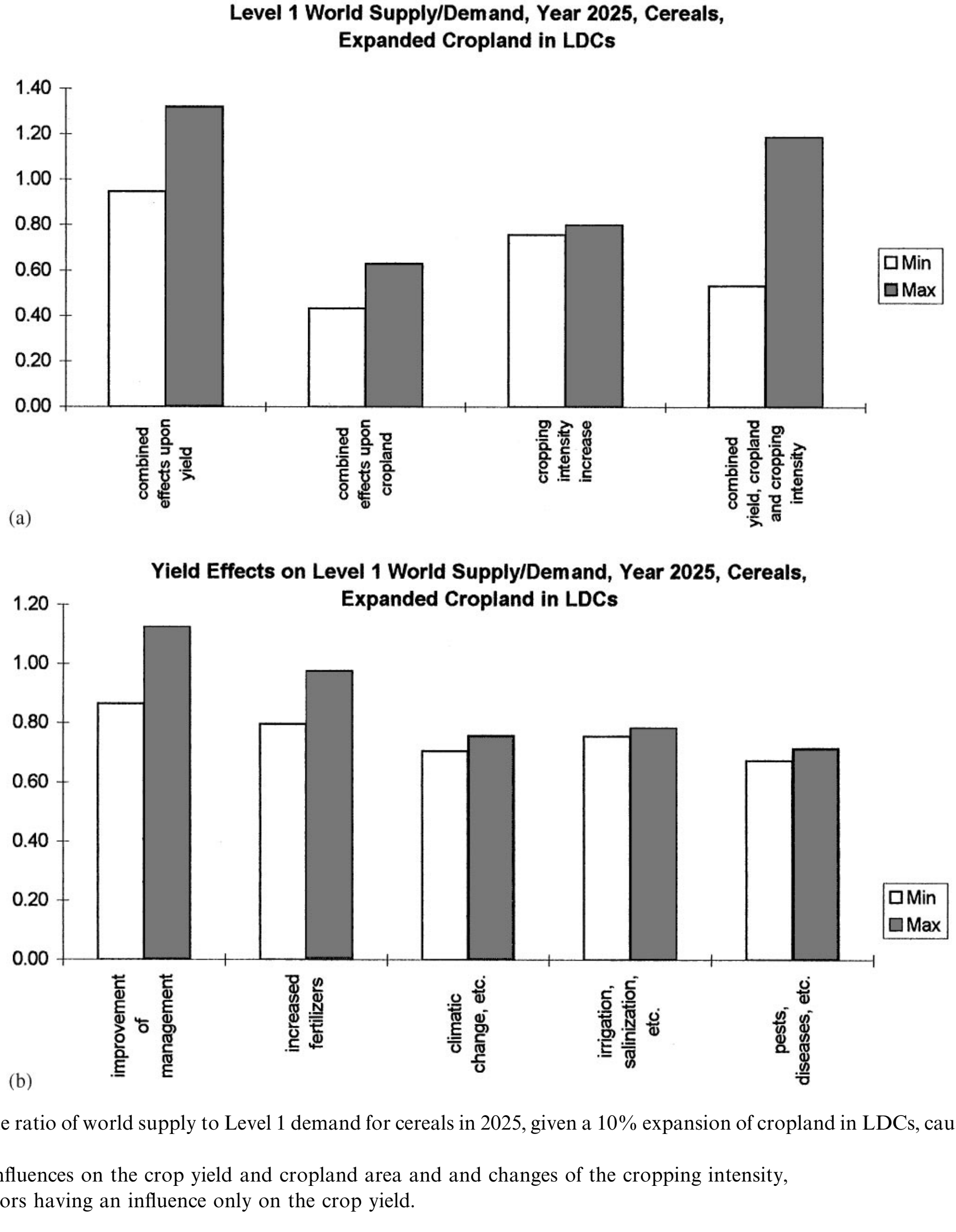
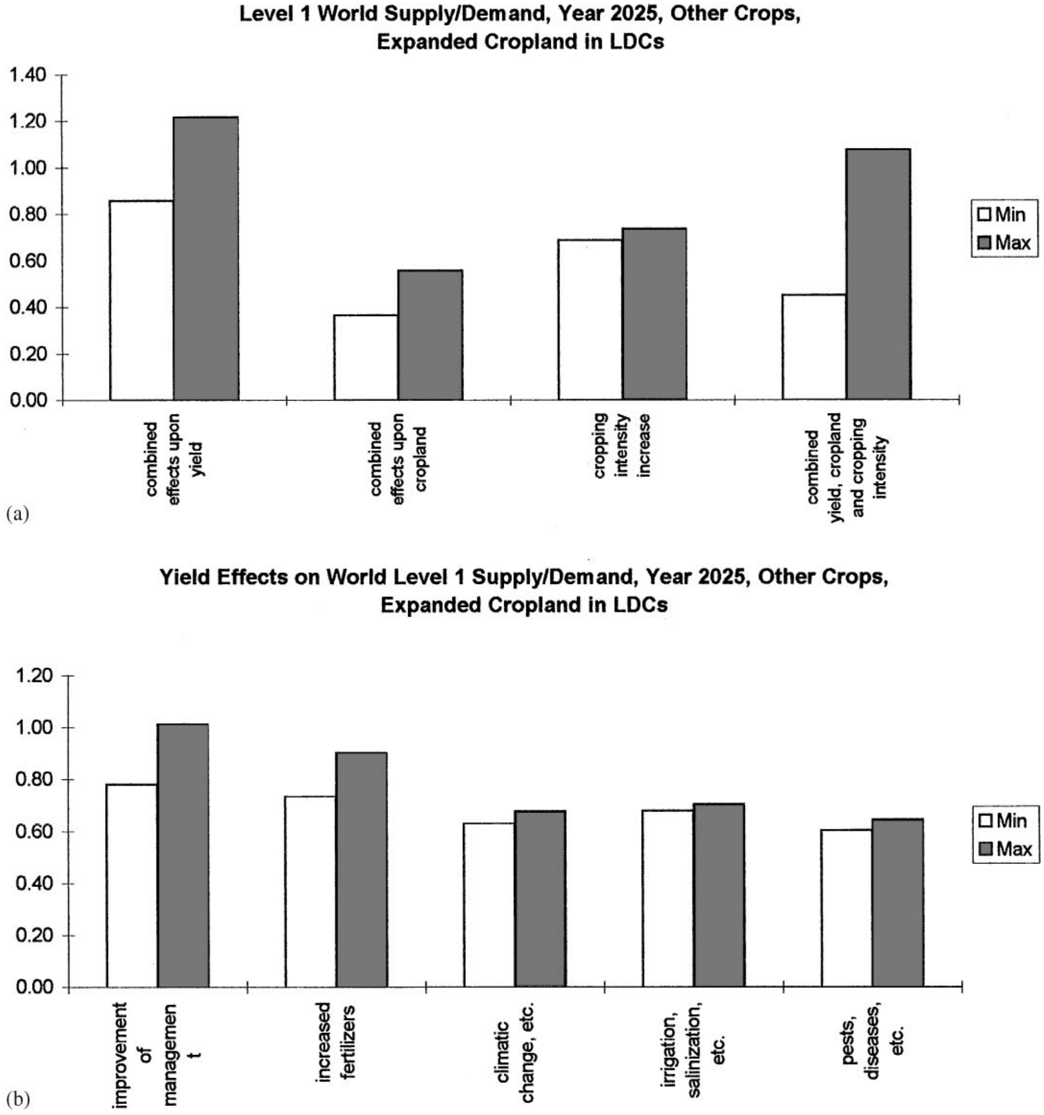


Fig. 7. Ranges in the ratio of world supply to Level 1 demand for cereals in 2025, given a 10% expansion of cropland in LDCs, caused by uncertainties in:

(a) the combined influences on the crop yield and cropland area and and changes of the cropping intensity,

(b) the various factors having an influence only on the crop yield.



Level 1 World Supply/Demand, Year 2025, Other Crops, Expanded Cropland in LDCs

Yield Effects on World Level 1 Supply/Demand, Year 2025, Other Crops, Expanded Cropland in LDCs

Fig. 8. Same as Fig. 7, but for other crops.

cropland would increase our chances of meeting the Level 1 food demand in 2025, especially when yield is increased through improved management and the increased use of fertilizers. Nevertheless, if the uncertainties in the factors affecting production were to combine in a negative fashion, it would be by no means guaranteed that Level 1 demand would be met even with increased cropland.

6.3.2. *Level 2 food demand*

Obviously the increased demand will shift S/D ratios downwards from those for Level 1 demand, indicating that, according to the model calculations, our chances of meeting Level 2 demand are less and may be small if the factors affecting production combine in a negative fashion, even with expanded cropland. As in the case for Level 1 demand, our best chances of meeting the demand are increased through improved management and the increased use of fertilizers.

7. Surprises

The foregoing analysis made use of a set of assumptions (albeit very uncertain) about expected future changes in yields and cultivated areas. However, during the next few decades it cannot be excluded that there could be a number of unexpected developments that might affect the production of food in a positive or negative way. Such developments are:

Sudden shifts in the climate state: It is possible that the response to even a gradual climate forcing factor can be quite irregular, and lead to significant changes in the atmospheric circulation (IPCC, 1996b). This in turn can result in changes of the frequency of the occurrence of droughts and floods. We have already seen examples of this in the havoc caused by the El Niño phenomenon in recent decades.

Volcanic eruptions: Occurrences of major volcanic eruptions can lead to sudden significant cooling of the atmosphere and could cause for example a repeat of the "year without a summer" which occurred in 1816 as a result of the eruption in the previous year of the Tambora volcano in Indonesia (Stommel and Stommel, 1983; Harrington, 1992; Chenworth, 1996). This could result in extensive reductions in agricultural production.

Surge of the West Antarctic ice-sheet: The risk of a collapse of the West Antarctic ice-sheet that could result in a major sea level rise is at present judged to be low. However, due to insufficient knowledge of the complex processes involved, it is difficult to quantify this risk (IPCC, 1966b).

Biotechnology: Undoubtedly biotechnology offers a range of promising applications for improving plant and animal production, and they can be expected to have a positive impact prior to 2025. However, it cannot be totally excluded that some of the these applications may turn out to have undesired side effects.

Pests and diseases: A global warming and a change of the large-scale precipitation patterns will affect the distribution and degree of infestation of insect pests and pathogen-mediated plant and animal diseases. As pointed out by Reilly (1996), the potential changes in crop losses due to climatically driven changes in pests have not been included in most agricultural impact studies.

8. Conclusions

Many statements have been made in the literature about whether or not the world food system will be able to meet the expected increase in food demand in the 21st century. The aim of this paper is not to make another such prediction, but rather to examine the uncertainties in predicting food production in the year 2025, given that there will be aspects of global change such as climatic change, salinization and waterlogging of land, biotic stresses, soil degradation, as well as direct human factors such as improved agricultural management, the increased use of fertilizers and expansion of irrigation.

In attempting to make such an estimate of the uncertainty of a prediction of the future food production it should be recognized that:

- The present and predicted magnitudes of the various environmental and socio-economic factors having an influence on the food production are very uncertain. This is especially the case with regard to socio-economic factors.
- The degree of impact of all these factors on the food production (yield, cropland area and cropping intensity) must also be judged to be very uncertain. By 2025, the ratio of global supply to demand for cereals (taking into account all uncertainties acting together) may be as low as 0.5, or as high as 1.1.

Consequently, the parameters specifying the change with time of the individual influencing factors must by necessity be given a comparatively wide range of uncertainty.

Accepting this unavoidable weakness of the base for this analysis, we may summarize the main results by making the following points:

- Given the present extent of cropland, and the uncertainties in food production brought about by global change,
  - by 2025, the ratio of global supply to demand for cereals may be as low as 0.40, or as high as 1.50, depending upon which uncertainty is being considered.
  - it is likely that it will be possible to meet in 2025 the demand for cereals in the MDC regions,
  - it is highly unlikely that the demand for cereals can be met in the LDC regions, especially when uncertainties brought about by global change are considered,
- A 10% addition of potential cropland by 2025 cannot be expected to increase significantly the possibility that the demand for cereals can be met in the LDC regions.
- It is possible that aquaculture may supply some of the increased demand for protein and thereby reduce the demand for cereals; however, our knowledge of the future aquaculture is even more uncertain than that of landbased agriculture and, therefore, no attempt was made to examine this aspect of the problem.

Although the analysis showed that it is not possible to make a precise prediction of future food production, it also showed that the greatest uncertainties were associated with direct human factors such as improved management and the increased use of fertilizers, rather than natural and/or indirect human factors such as climatic change, irrigation, salinization, waterlogging, or pests. In view of the risk of our not meeting future food demand, especially in LDC regions, it would appear that policies aimed at reducing the uncertainty in agricultural management and the use of fertilizers would be the most robust, and would in any event, represent a precautionary response to limiting the adverse impacts of global change.

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