# Natural resources and limits of food production in 2040

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**Abstract.** Food demand is estimated for the 15 major regions of the world for the year 2040. It is compared with the potential food production in these regions, which is derived from the area with soils suitable for cropping and grazing, the amount of irrigation water available, and the farming system used. All farmers are assumed to employ the best known techniques for sustainable farming. Two alternative production systems are explored: optimum productivity per unit of land, with intensive use of chemical inputs and energy to produce top yields ('HEI'), and agriculture in which environmental damage per unit area is minimised ('LEI'). In the latter system, legumes provide all nitrogen, agriculture is more diverse, and hectare yields are lower. Farming could occur at a smaller scale than in HEI-farming, with strong integration of arable farming and animal husbandry, but these aspects play no role in this study.

Comparing 2040 scenarios of demand and supply of food shows that most regions can avoid to run into food security problems, but that in Asia situations could develop where a moderate or affluent diet is out of reach of its population, even when maximum use is made of all natural resources.

When HEI-agriculture is practised, all regions can produce food required for an affluent diet, except for East, South and West Asia. Also Southeast Asia and West and North Africa come close to the lower limit. A diet much less expensive provides the only option for escape. The three regions with the least leeway will carry almost half of the global population. Europe, the former USSR, the American regions and Central Africa are well off and need only a part of the suitable land to feed their populations.

Practising LEI-agriculture, only South Asia will have food shortage. In this heavily populated region, there is no way out via less expensive diets or lower population growth (both already at a minimum). Europe could grow all its food on less than half of its suitable soils if the LEI system goes with the low food demand scenario. Only the former USSR, North and South America, Central Africa and Oceania can consider to offer its population an affluent diet.

## Introduction

The UN projected population growth into the next century and expects the global population to stabilise around 2040. The world will then carry 1.5 to

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2.2 times more human beings than in 1990, many of whom will require 2–3 times more food. Can the earth provide enough food by socially acceptable ways of farming, without sacrificing its natural resources?

Two decades ago, the maximum global food production was estimated to be 50 billion ton (Buringh *et al.* 1975), enough to feed at least 30 billion persons. Better knowledge of soils, fresh water resources, and crop performance allows us to improve this estimate. We added also rangelands as a potentially major source of food. Global changes in soil and climate make people wonder whether food production is threatened. Furthermore, questions are posed whether top yields achieved at experiment stations can be achieved at large scale and maintained (World Resources Institute, 1994). Recent reports suggest a ceiling to global food supply that support populations much below 30 billion, some even as low as the current population of just 5 billion (Pinstrup-Andersen 1993; World Resources Institute 1994; Brown and Kane 1994).

Our objective is to investigate in a quantitative manner whether the natural resources allow food security for the future populations in 15 major regions. We will discuss the results of computations for alternative production and demand scenarios, compare them with other reports, and comment on implications. Both production systems considered are agro-ecologically sustainable. How to stimulate farming communities to adopt the production systems proposed is not discussed here.

We do not address effects of global changes in climate or soil because of lack of sufficiently reliable information and because farming is likely to be sufficiently flexible to adapt to possible changes.

A full technical report on methods and basic data is published by Luyten (1995); highlights were presented in the wider context of use of natural resources for industry, transportation, and recreation (Wetenschappelijke Raad Regeringsbeleid 1994). In other articles, we explored implications for soil science (Penning de Vries *et al.* 1995) and zoomed in on China (Luyten *et al.* 1995).

## Outline of the approach

We compute the amount of plant biomass required to feed the future population in each of 15 regions, and compare that with the amount of food that could be produced from an agro-technical point of view in those regions in a sustainable manner, while using the natural resources efficiently. Our 15 regions (figure 1) are those distinguished in the UN population study (we have added the very small region of the Caribbean to Central America, and grouped the four European regions into one). These regions differ significantly in many respects (table 1).

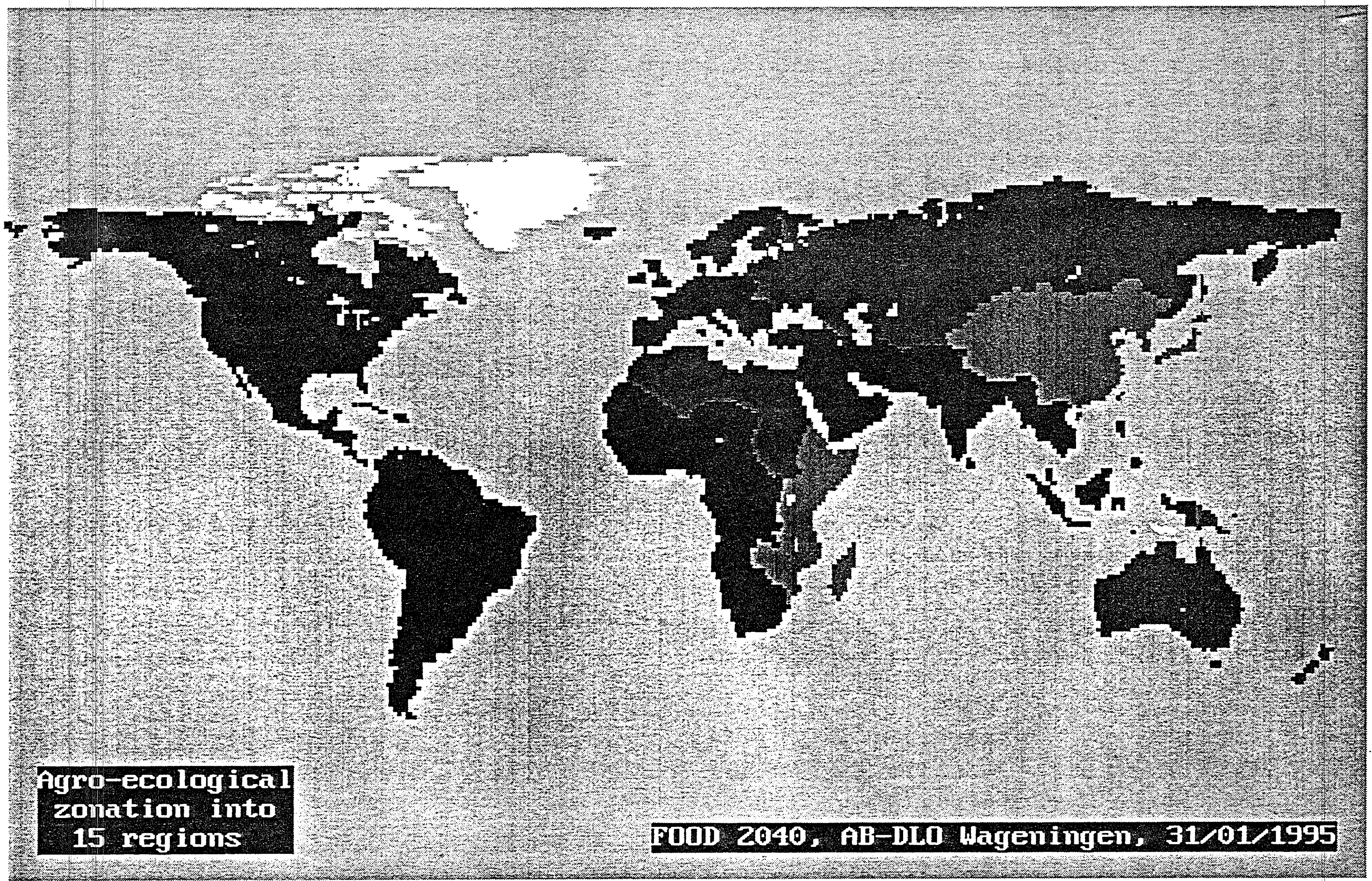


*Fig. 1.* World map of the 15 regions considered in the paper. Other data in table 1.

*Table 1.* Key characteristics of the 15 regions.

| # | Region | Total land area [M km$^2$] | Avrg. land suitability [frac.] | Avrg. crops per year [#] | Available irrig. water [km$^3$ yr$^{-1}$] | Popul. in 1990 [million] | GNP per capita [k US$] |
|---|---|---|---|---|---|---|---|
| 1 | South America | 16.8 | 0.82 | 2.3 | 3150 | 297 | 1.6 |
| 2 | Central America | 2.3 | 0.69 | 2.4 | 410 | 151 | 1.5 |
| 3 | Northern America | 15.9 | 0.56 | 1.3 | 730 | 276 | 18.3 |
| 4 | Northern Africa | 7.9 | 0.70 | 2.2 | 150 | 141 | 1.1 |
| 5 | Western Africa | 5.9 | 0.74 | 2.9 | 550 | 194 | 0.5 |
| 6 | Central Africa | 6.3 | 0.86 | 2.2 | 1380 | 70 | 0.4 |
| 7 | Eastern Africa | 5.9 | 0.80 | 1.9 | 1250 | 197 | 0.2 |
| 8 | Southern Africa | 2.6 | 0.74 | 1.5 | 270 | 41 | 1.5 |
| 9 | Oceania | 7.9 | 0.77 | 2.4 | 390 | 27 | 8.7 |
| 10 | Southeast Asia | 3.5 | 0.58 | 2.7 | 290 | 445 | 0.6 |
| 11 | Easthern Asia | 11.0 | 0.52 | 1.4 | 430 | 1336 | 2.6 |
| 12 | Southern Asia | 6.5 | 0.60 | 2.4 | 620 | 1201 | 0.3 |
| 13 | Western Asia | 4.1 | 0.66 | 2.4 | 170 | 132 | 2.4 |
| 14 | (former) USSR | 20.9 | 0.38 | 1.1 | 480 | 289 | 8.7 |
| 15 | Europe | 4.6 | 0.72 | 1.5 | 160 | 98 | 11.1 |
| | World | 122.0 | 0.64 | 2.0 | 10430 | 5293 | 3.6 |

Six features have been combined in this approach: Demand for food is the product of population size (1) and per capita consumption of carbohydrates and proteins (2). Medium and the extreme of projected values of demand for food are been used in our analyses.

Maximum food production is approximated in a series of steps (figure 2), taking into account four natural resources: crops, land, water and climate. For each region, total production results from aggregation of yields from small units characterised by specific combinations of soil and climate. In total, we used data from some 15500 land units, over 700 weather stations and about 100 large river basins, applying the concept that it is better to use all basic data and to aggregate subsequently, than to use averages (De Wit and Van Keulen 1987). We compute potential production for situations where all farming is practised by well-informed, skilled farmers applying the most efficient methods. Crop production per unit area is quantified with a crop growth simulation model, that is applied in both a high (3) and a low external input (4) production system. Potential arable land area is far less than total land area because most of the land surface is unsuitable for modern mechanised agriculture (5). Finally, we take into account that water supply for irrigation is limited (6).

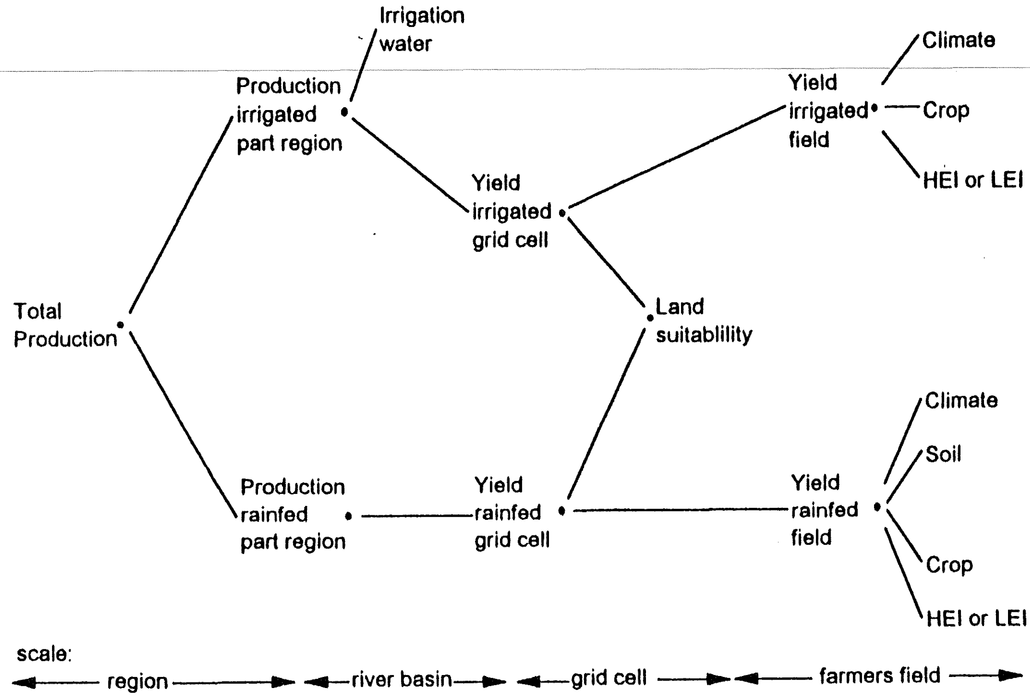


*Fig. 2.* Steps and aggregation level to compute food production by region.

We address two alternative types of farming, based on contrasting views with respect to the 'best' use of land (cf. WRR 1994). Different is these view is the approach to the environment. Similar is that all farmers are assumed to farm using 'best technical means', i.e. the best techniques currently available for each agro-climatic zone (cf. De Koning *et al.* 1992). Different levels of agriculture and use of natural resources result from the contrasting views. In the first view, one aims at optimum productivity of land and it is expected that environmental damage can be limited to acceptable levels. Agricultural practice is characterised by a high degree of mechanisation and heavy use of fossil fuel. The losses of inputs to the environment are minimal per unit of product, so that this high input farming is ecologically sustainable. We call this global and market oriented view of agricultural production systems the 'high external input' scenario (HEI).

In the second view, such intensive practices can never be sustainable. Therefore, the production system is designed to minimise loss per unit area and impact on the environment (we will return to this in the discussion). This is realised by replacing all N in chemical fertiliser by biological N fixation, elimination of biocides, restricted use of mechanisation, intensive recirculation of nutrients, and a 'local' consumption of the products. In this scenario, crop yields are lower, but product quality and prices higher, less fossil energy is used, and agriculture can be more integrated with nature development. We call this the 'low external input' scenario (LEI). P and K

*Table 2*. The population size in 1990, and the low, medium and high population estimates for 15 regions of the world for 2040 (United Nations 1992).

| # | Region | Population 1990 | Population estimate 2040 Low | Medium | High |
|---|---|---|---|---|---|
| 1 | South America | 297 | 481 | 558 | 663 |
| 2 | Central America | 151 | 250 | 296 | 347 |
| 3 | Northern America | 276 | 274 | 328 | 398 |
| 4 | Northern Africa | 141 | 277 | 343 | 419 |
| 5 | Western Africa | 194 | 466 | 635 | 798 |
| 6 | Central Africa | 70 | 190 | 240 | 286 |
| 7 | Eastern Africa | 197 | 537 | 679 | 842 |
| 8 | Southern Africa | 41 | 89 | 100 | 123 |
| 9 | Oceania | 27 | 32 | 37 | 45 |
| 10 | Southeast Asia | 445 | 658 | 820 | 1005 |
| 11 | Easthern Asia | 1336 | 1503 | 1770 | 2098 |
| 12 | Southern Asia | 1201 | 1965 | 2408 | 2889 |
| 13 | Western Asia | 132 | 249 | 324 | 399 |
| 14 | (former) USSR | 289 | 323 | 369 | 419 |
| 15 | Europe | 498 | 437 | 498 | 563 |
| | World | 5293 | 7730 | 9404 | 11291 |

fertiliser cannot be replaced biologically, and are assumed to be supplied to allow high rates of N-fixation. Because of this use of inputs, LEI-farming is not identical to LEISA-farming (Reijntjes *et al.* 1993).

To compare expected food consumption and potential production, we express both in grain equivalents (GE). GE is a theoretical food unit. In the production process, it refers to the quantity (in kg) of dry grain that would be produced if only one type of crop were grown (a cereal), plus the amount of grain that needs not to be produced because of feed (grass) harvested from land unsuitable for arable farming; feed requires conversion via animals for human consumption. In the consumption process, GE refers to the amount of cereals (in kg) needed as raw material for the food consumed, plus the 'opportunity cost' to grow food that cannot be produced via 'grain' (e.g. fruit).

## The approach

(1) For the projected size of the regional populations (table 2), we followed a recent UN-report (1992). We have chosen the year 2040 as target date since the low, medium and high projections then stabilise at global level.

*Table 3.* Average relative cost of food, expressed in grain equivalents (GE).

| Food item | kg GE per kg dry mass | kg GE per kg fresh material |
|---|---|---|
| Plant products | 2.0–3.5 | 0.8–1.2 |
| Dairy products | 6.3–7.2 | 2.4–3.3 |
| Meat products | 17.0–19.0 | 8.5–9.5 |

*Table 4.* Food composition in three diets. Note: our data on 'grain use per capita' are different from other authors (e.g. Crosson and Anderson 1992; Brown and Kane 1994). Our definition includes the opportunity cost (in GE) of all other food crops, such as tuber, oil seed and leguminous, fruits and vegetables, while other data refer to cereals *sensu stricto*.

| Diet | GE [kg $cap^{-1}$ $yr^{-1}$] | Energy [kJ $d^{-1}$] | Animal protein [g $d^{-1}$] | Plant protein [g $d^{-1}$] |
|---|---|---|---|---|
| Vegetarian | 475 | 10.0 | 8.6 | 66.7 |
| Moderate | 875 | 10.0 | 31.2 | 50.0 |
| Affluent | 1530 | 11.5 | 63.2 | 28.9 |

(2) Human food is extremely variable in composition, and we cannot address even a fraction of that diversity. Food items vary strongly in energy and water content. Part of the food comes from animal sources, often formed in an inefficient conversion process from plant biomass (table 3). Therefore, the amount of basic food that needs to be grown depends strongly on the composition of our diet. To compare requirements for different populations with the production capacity of the land, we express all consumption in GE (for details, see Luyten 1995). Plant biomass (in GE) needed for a productive life consuming a largely vegetarian diet (grains, tuber crops, pulses, some milk) is only about one third of the quantity needed for a diet with a considerable proportion of animal products, including meat (table 4). We carry out our calculations for three diets: an ample and healthy vegetarian diet, a moderate diet (with some meat, similar to that in Japan or Italy), and an affluent diet (such as that of the USA in the 1970s). The affluent diet will mostly be found in rich societies with many pets, for which the feed is included.

The medium and extreme projections of demand for food per region are given in table 5.

(3) Food production. The natural resource base is characterised by soil, climate, plant genetic properties and surface water. We do this at as small a scale as soil data permit (i.e. a grid cell of $1° \times 1°$). We base our calculations on two crop types (cereal and grass) for reasons of simplicity, albeit that a temperate variety of the cereal ('wheat') and a tropical one ('rice') are

*Table 5.* The maximum, medium and minimum amount of food required in 2040, by region and total (in GE $yr^{-1}$).

| # | Region | Minimum (veg. diet, low pop.) | Medium (mod. diet, med. pop.) | Maximum (affl. diet, high pop.) |
|---|---|---|---|---|
| 1 | South America | 228 | 489 | 1016 |
| 2 | Central America | 118 | 259 | 532 |
| 3 | Northern America | 130 | 287 | 610 |
| 4 | Northern Africa | 131 | 300 | 642 |
| 5 | Western Africa | 221 | 556 | 1223 |
| 6 | Central Africa | 90 | 211 | 438 |
| 7 | Eastern Africa | 255 | 595 | 1290 |
| 8 | Southern Africa | 42 | 88 | 188 |
| 9 | Oceania | 15 | 33 | 68 |
| 10 | Southeast Asia | 312 | 718 | 1541 |
| 11 | Easthern Asia | 713 | 1551 | 3217 |
| 12 | Southern Asia | 932 | 2109 | 4428 |
| 13 | Western Asia | 118 | 283 | 611 |
| 14 | (former) USSR | 153 | 323 | 642 |
| 15 | Europe | 207 | 436 | 864 |
| | World | 3668 | 8238 | 17309 |

distinguished to account for climatic adaptation. Since all major agricultural crops produce biomass (dry matter) at a rate in the order of 200 kg $ha^{-1}$ $d^{-1}$ at full soil cover, total production is hardly affected by this simplification. A difference between the commodities is in the harvest index (HI, fraction of total biomass harvested), which is 0.4–0.45 for modern varieties of cereal crops, and 0.6–0.7 for permanent grassland. The simplification of using two crop types only is acceptable when conversions between food types produced and food types required for specific diets are possible.

Maximum production for wheat, rice and permanent grassland are computed considering local soil, climate and HEI-management practices. The cereal crops are grown in healthy rotations, with up to three crops per year when climate and soil permit. Varieties grown are similar to the best currently available (HI = 0.45); post harvest losses are set to 10%. Permanent grassland grows on soils unsuitable for arable crops. For grassland, we applied a rather low value of the HI (0.6) to reflect that some of these areas are difficult to reach for animals or have top soils that are easily damaged. Also here we assumed 10% post harvest losses.

For each grid cell, crop yield for the HEI-system is computed with a simple simulation model (SIMFOOD; figure 3). It is based on the well-tested concept

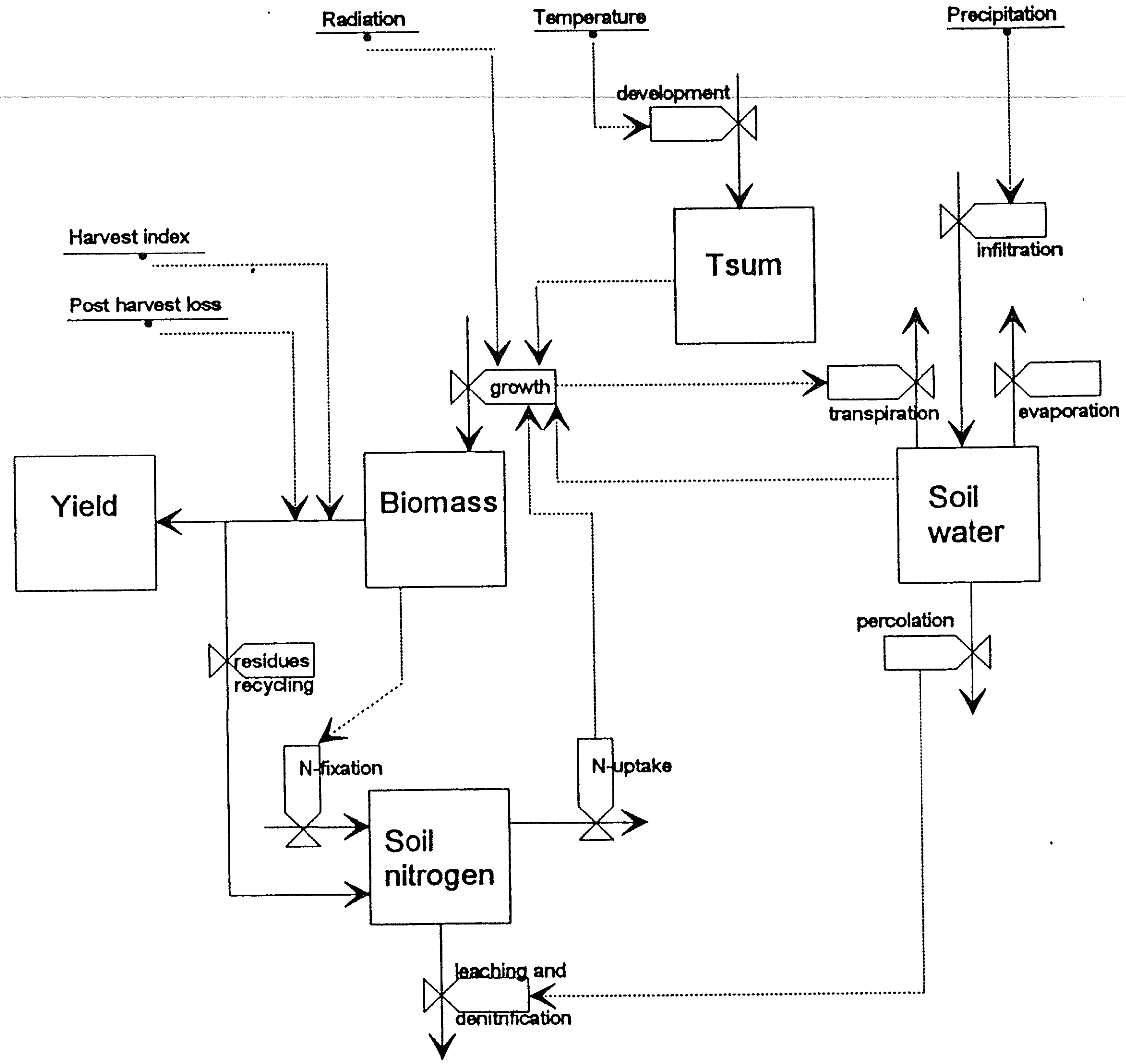


*Fig. 3.* Flowchart of the simulation model SIMFOOD. Rectangles stand for quantities, valve symbols for rates and underlines variables are constants or driving variables. Daily growth of biomass is computed from intercepted radiation for the duration of a growing season, which is monitored as a temperature sum. Final yield equals biomass times the harvest index, minus post harvest losses. The soil water balance model is used in rainfed conditions, and to determine the demand for irrigation water. When the relative water content is low, the growth rate is reduced. For LEI-simulations, the soil N-balance is invoked. Low soil N leads to reduced growth rates. High rates of percolation cause leaching and denitrification.

of conservative efficiencies of use of radiation (about 3 g dry biomass $MJ^{-1}$ absorbed radiation), water (about 2 g biomass $kg^{-1}$ water transpired, Monteith 1990) and nutrients (about 115 kg biomass $kg^{-1}$ N absorbed, Sinclair 1990). For irrigated conditions, inputs are key crop characteristics (development rate, maximum photosynthesis), radiation and temperature; for rainfed conditions we used the same data plus soil data (water holding capacity) plus rainfall and evaporation. The model also computes the amount of supplementary water required to fully irrigate an arable crop (grassland is not irrigated), the amount of fertiliser N required to grow the cereal and grass crop without

*Table 6.* Typical yields of crops and permanent grassland (in GE, t $ha^{-1}$ $yr^{-1}$) in temperate and tropical zones for the HEI and LEI production systems. In tropics, up to three crops per year are grown.

| **GRAIN:** | HEI | LEI |
|---|---|---|
| *zone* | | |
| tropics, irrigated | 16–20 | 4–6 |
| tropics, rainfed | 4-12 | 2–4 |
| temperate, irrigated | 7–11 | 2–4 |
| temperate, rainfed | 4–9 | 2–3 |

| **GRASSLAND:** | HEI | LEI |
|---|---|---|
| *zone* | | |
| tropics, irrigated | 21–26 | 7–11 |
| tropics, rainfed | 5–16 | 4–7 |
| temperate, irrigated | 9–14 | 4–7 |
| temperate, rainfed | 5–12 | 4–5 |

exhausting the soil, the associated $NO_3$-leaching, the required biocide input and the labour requirement. Typical yields for the HEI system are shown in table 6; the large difference between tropical and temperate zones is due to the number of crops per year, while the difference between rainfed and irrigated crops is due to the lower number of crops per year and the effects of temporary drought stress; grass yields exceed cereal yields because a larger fraction of grass is used.

In rainfed situations, the standard duration of the simulated crop does no justice to farmer's practices that fully exploit the growing season. But our model accounts for this discrepancy as it 'initiates' in the rainfed situation as many crops as in the irrigated case, utilising all available water, and adds the yields of all these crops in a year, so that their total yield corresponds with that of an adapted cropping system.

Arable cropping requires better soils and flatter land than grass production. We compute therefore first the production of arable crops on soils suitable for them, and then we compute grass production on remaining soils suitable for agriculture.

(4) In the LEI-system, crop production is ultimately limited by the supply of N in irrigated conditions, and by N or drought in rainfed situations. In SIMFOOD, production in each grid cell is related to the N absorbed. Uptake by the crop is one of the processes by which N is removed from the soil (leaching and denitrification being the other), and these are in balance with the processes by which N is supplied (fixation, recirculation, manure). Under appropriate farming and range management techniques, N-supply equals 270 kg N $ha^{-1}$ $rotation^{-1}$, most of which originates from N-fixation by legumes; crop

residues and animal manure are recycled completely. We assumed arable cropping to be practised in a 2:1 cereal-legume rotation (the legume having the same growth characteristics as the cereal), and the rangeland to contain sufficient N-fixing legumes. N-supply per crop has been taken constant for all soils and climates, but when crop growth is limited by moisture supply, N-supply is reduced accordingly. Though agriculture in LEI-systems is also supposed to be carried out by skilful and knowledgeable farmers, the 'best technical means' are slightly different: HI is a little lower (0.4) and post harvest losses higher (0.2) because biocides are not used, the turn-around time between crops is longer (2 vs. 4 weeks), the N use efficiency is 120 kg $kg^{-1}$ (vs. 112 in HEI). Permanent grassland comprises a mixture of grasses and legumes, and because of the higher quality of the LEI-pastures we assume that they are exploited better (HI = 0.7). Post harvest losses are also set to 20%. The fraction of N lost to denitrification and leaching is related to soil texture and to the precipitation surplus (De Koning *et al.* 1992).

Yield levels in the LEI-system are roughly one third of those in the HEI-system (table 6). The difference between irrigated and rainfed crops and grasslands is small because N-supply is usually the main limiting factor. The use of rangeland for food production is neglected in many studies (e.g. Buringh *et al.* 1975). However, vast amounts of land unsuitable for cropping are potentially valuable resources of animal products.

(5) Not all land is equally suitable for arable cropping. Slopes may be too steep, soils too stony and shallow, too saline, etc. Although LEI-farming may be less demanding than HEI-farming, we have not made a distinction. Arable cropping is more demanding than permanent grassland. Suitability is therefore judged per grid cell for cereal crops and grassland separately. It is expressed as the fraction of the area where crops can be grown without soil-related restriction; the remainder is not cropped, but can be used for other purposes (nature, recreational areas, infrastructure). Suitability for agriculture could not be taken directly from a source, so we used a global database designed for climate impact studies (Zobler 1986). It specifies the relative suitability of grid cells with respect to slope, soil phase and soil texture; by expert judgement we attributed values of 0 to 1 to each characteristic and defined 'suitability' as the product of the three factors. The world's average suitability for arable crops (weighed according to area) is only 0.31. An additional 0.33 is suitable for grassland. Suitability is distributed highly irregular at small and large scales (figure 1, Penning de Vries *et al.* 1995): that of South America stands out as a relatively high value, while that of South East Asia and the former USSR are low.

The soil water holding capacity depends on soil texture: high for clay and loamy soils, low for sandy soils; the texture of the dominant soil type is applied to the entire grid cell. In our simple water balance model, soils are not layered or cracked, well drained, and 0.6 m deep; there is no run off, and no watershed level storage of water.

(6) Irrigation. The irrigable area per river basin was calculated as river discharge and demand of arable crops for full irrigation (we choose not to irrigate grassland). Data were used on the current water discharge of 95 major river basins (those exceeding $3.10^4$ $km^2$) that together occupy about 0.6 of the total land surface and carry currently 0.9 of the global population. River discharge was adjusted to account for unavoidable flood runoff (about half of the total), and corrected for projected household and industrial water use (assuming first priority for these uses) and for current extraction in irrigation schemes (Delft Hydraulics 1992). Of the irrigation water for cropping, only about half is actually used by plants (the 'best technical means' in irrigation schemes (Doorenbos and Pruitt 1977; the current water use efficiency is around 0.35), while 0.25 of the water flows back to the river and is not re-used to prevent salinization. This approach provides a conservative estimate of the quantity of water available for crop growth. Based on the reasoning that water is always used at maximum efficiency, we apply irrigation water first to crops with the lowest demands to attain maximum yields (i.e. in the most humid zones in each basin and on the best soils); only under ample water supply, drier zones are also irrigated.

As a world average in the HEI-scenario, 0.64 of the land suitable for arable cropping can be irrigated. In North Africa and Oceania is water scarce and less than 0.25 of the suitable area is irrigable, but also South and East Asia, West and South Africa have little surface water ($< 0.5$ irrigable). Demand for water for crop production is roughly proportional to yield. Per unit area, LEI-production systems need much less water, and large areas do not even require additional water, so that on a much larger area crops are grown without water shortage: 0.91 of the total area, i.e. all crop land in all regions except for ones mentioned with major shortage in the HEI-system.

## The regional and global food situation

### *The HEI-scenario*

The absolute maximum regional and global quantity of food that can be produced in a sustainable manner would be achieved if water were never in short supply (e.g. when desalinised sea water would be freely available). If all land suitable for arable cropping is irrigated (and no use is made of grassland), the HEI-production system could supply an affluent diet to over 50 billion persons, though even then, food would have to be imported in East and South Asia under the high population scenario.

It is unlikely that availability of water will increase dramatically. With maximum use of all fresh water supplies, 0.51 of the global area suitable for cropping can be irrigated. The distribution of irrigeable land is highly irregular: Asia has already much irrigable land, and major potentials for irrigation

*Table 7.* Maximum and irrigated food production (GE, Mt $yr^{-1}$) and the maximum area irrigated (Mha) in the HEI and the LEI situation. The total food production is the sum of contributions by irrigated and rainfed arable crops, and that of rangeland.

| # | Region | HEI system | | | LEI system | | |
|---|---|---|---|---|---|---|---|
| | | Total prod. [Mt $yr^{-1}$] | Irrigated prod. [Mt $yr^{-1}$] | Irrigated area [Mha] | Total prod. [Mt $yr^{-1}$] | Irrigated prod. [Mt $yr^{-1}$] | Irrigated area [Mha] |
| 1 | South America | 20373 | 11837 | 697 | 6877 | 3804 | 852 |
| 2 | Central America | 1853 | 949 | 55 | 811 | 284 | 55 |
| 3 | Northern America | 6418 | 2396 | 250 | 3252 | 1519 | 480 |
| 4 | Northern Africa | 1798 | 648 | 35 | 1066 | 290 | 58 |
| 5 | Western Africa | 3546 | 1449 | 73 | 1503 | 788 | 138 |
| 6 | Central Africa | 7505 | 4691 | 301 | 2672 | 1467 | 318 |
| 7 | Eastern Africa | 5594 | 3169 | 169 | 1892 | 1057 | 254 |
| 8 | Southern Africa | 1304 | 654 | 35 | 616 | 326 | 89 |
| 9 | Oceania | 4137 | 1020 | 55 | 2238 | 821 | 150 |
| 10 | Southeast Asia | 3670 | 1394 | 78 | 1185 | 368 | 78 |
| 11 | Easthern Asia | 4056 | 1949 | 236 | 2261 | 740 | 236 |
| 12 | Southern Asia | 3442 | 1594 | 98 | 1836 | 931 | 179 |
| 13 | Western Asia | 1245 | 772 | 45 | 658 | 305 | 59 |
| 14 | (former) USSR | 4524 | 1645 | 218 | 2459 | 1113 | 432 |
| 15 | Europe | 2792 | 1011 | 110 | 1348 | 375 | 120 |
| | World | 72256 | 35175 | 2457 | 30673 | 14188 | 3499 |

exist in South America, Central and Eastern Africa, North America and the former USSR. A substantial proportion of the unirrigated land receives sufficient rain to produce a decent rainfed crop. On a global basis, potential irrigated production exceeds rainfed production considerably (35 vs. 8 billion ton GE), whereas maximum grassland production could provide another 29 billion ton. Details are shown in table 7.

In Oceania there is still so much rangeland that the maximum rainfed production equals that of irrigated production. In absolute terms, South America has by far the highest food production potential of all regions: due to its large capacity for irrigation, and it also has the highest rainfed production potential. Obviously, realisation of this potential requires agricultural use of areas currently under rain forest. A second substantial area for irrigated cropping is Central Africa, while East Africa comes third. Clearly: there are enormous potentials in areas with few people (table 1).

Different regions (or indeed, all countries within regions) can simultaneously apply the HEI or the LEI production system (or anything in between). The global sums in the tables 8 and 9 have therefore only a reference value.

*The LEI-scenario*

Maximum hectare-yields in the LEI-scenario are lower than in the HEI-scenario, but this is largely compensated by a larger area that can be irrigated (0.9 of the cropped land). Indeed: N is the limiting production factor in this situation, not water.

If water shortage were completely eliminated, about 20 billion persons could be sustained on a vegetarian diet. With the current water supply, maximum global food production is 31 billion ton, or about one third of the maximum for HEI, using the same natural resources (table 7). Rainfed crop production is 20 × smaller than irrigated production, and only of importance in Oceania, and West and North Africa. Feed production from rangelands (16 billion ton) is still significant. Again, differences among regions are large. Barring food imports, Asia and to a lesser extent Europe, cannot produce the food to provide an affluent (or even a moderate) diet to its population in all but the lowest population scenario. North Africa's production largely originates from rainfed crops and grassland, which is also significant in South and West Asia.

*Supply versus demand*

What picture emerges when future production potentials and future demands are confronted? Excluding large-scale unilateral export of food from regions, the ratio of potential supply over expected demand indicates the potential relative food security (table 8). Ratios vary from values below 1.0 to over 100. Generalisations are risky, as each region has its own balance of resources and food demand.

Under HEI-farming, the projected medium demand can be satisfied in all regions, though in some regions (Asia), all suitable cropping and grazing land is needed. Results of a similar study for Europe also showed that not all land will be needed for agriculture in the future (WRR 1992).

Practising LEI-farming, Asia and to a lesser extent Europe, cannot produce the food to provide an affluent diet (or even a moderate one in Asia) to its population in all but the lowest population scenario, assuming massive food transfers do not take place. North Africa's production largely originates from rainfed crops and grassland, which is also significant in South and West Asia.

Before examining all ratios individually, their number can be reduced by focusing at some scenarios. To do so, we return to the contrasting views on agricultural development that are the basis of the current study. The view

*Table 8a.* Ratio of potential demand and supply of food, by region, and global total. Table 8a gives all ratios, table 8b shows the selection of ratios with values of 2.0 or less, and table 8c shows the most likely scenarios.

| # | Region | HEI system | | | LEI system | | |
|---|---|---|---|---|---|---|---|
| | | veg.diet low.pop. | mod.diet med.pop. | affl.diet high.pop. | veg.diet low.pop. | mod.diet med.pop. | affl.diet high.pop. |
| 1 | South America | 89.2 | 41.7 | 20.0 | 30.1 | 14.1 | 6.8 |
| 2 | Central America | 15.6 | 7.2 | 3.5 | 6.8 | 3.1 | 1.5 |
| 3 | Northern America | 49.3 | 22.3 | 10.5 | 25.0 | 11.3 | 5.3 |
| 4 | Northern Africa | 13.7 | 6.0 | 2.8 | 8.1 | 3.5 | 1.7 |
| 5 | Western Africa | 16.0 | 6.4 | 2.9 | 6.8 | 2.7 | 1.2 |
| 6 | Central Africa | 83.2 | 35.6 | 17.1 | 29.6 | 12.7 | 6.1 |
| 7 | Eastern Africa | 22.0 | 9.4 | 4.3 | 7.4 | 3.2 | 1.5 |
| 8 | Southern Africa | 31.0 | 14.8 | 6.9 | 14.6 | 7.0 | 3.3 |
| 9 | Oceania | 270.7 | 126.9 | 60.6 | 146.5 | 68.7 | 32.8 |
| 10 | Southeast Asia | 11.8 | 5.1 | 2.4 | 3.8 | 1.7 | 0.8 |
| 11 | Easthern Asia | 5.7 | 2.6 | 1.3 | 3.2 | 1.5 | 0.7 |
| 12 | Southern Asia | 3.7 | 1.6 | 0.8 | 2.0 | 0.9 | 0.4 |
| 13 | Western Asia | 10.5 | 4.4 | 2.0 | 5.6 | 2.3 | 1.1 |
| 14 | (former) USSR | 29.5 | 14.0 | 7.0 | 16.0 | 7.6 | 3.8 |
| 15 | Europe | 13.5 | 6.4 | 3.2 | 6.5 | 3.1 | 1.6 |
| | World | 19.7 | 8.8 | 4.2 | 8.4 | 3.7 | 1.8 |

that maximum land productivity should be achieved and some environmental damage is acceptable is likely to concur with the view that 'better diets are deserved', that economic development in less-endowed countries should originate completely from local production, which grows slowly, so that poverty and high population growth rates pertain. In other words, the HEI production system is more likely to be combined with the medium-high food demand scenario. By the same reasoning, a view leading to LEI-agriculture might concur with vegetarian-moderate diets, faster economic development of poor countries due to better terms of trade, and therefore lower population growth rates. LEI-agriculture could then be compared to the low-medium demand scenario.

It is interesting to observe that, by coincidence, the potential supply/demand ratios for the globe and by region are about equal for these HEI and LEI-scenarios. Three groups of regions can be distinguished: those in the danger zone (ratios close to 2 or less), those with a capacity to produce more than 10 x the potential demand, and those in between. For much of Asia:

*Table 8b.*

| # | Region | HEI system | | | LEI system | | |
|---|---|---|---|---|---|---|---|
| | | veg.diet low.pop. | mod.diet med.pop. | affl.diet high.pop. | veg.diet low.pop. | mod.diet med.pop. | affl.diet high.pop. |
| 1 | South America | | | | | | |
| 2 | Central America | | | | | | 1.5 |
| 3 | Northern America | | | | | | |
| 4 | Northern Africa | | | | | | 1.7 |
| 5 | Western Africa | | | | | | 1.2 |
| 6 | Central Africa | | | | | | |
| 7 | Eastern Africa | | | | | | 1.5 |
| 8 | Southern Africa | | | | | | |
| 9 | Oceania | | | | | | |
| 10 | Southeast Asia | | | | | 1.7 | 0.8 |
| 11 | Easthern Asia | | | 1.3 | | 1.5 | 0.7 |
| 12 | Southern Asia | | 1.6 | 0.8 | 2.0 | 0.9 | 0.4 |
| 13 | Western Asia | | | 2.0 | | | 1.1 |
| 14 | (former) USSR | | | | | | |
| 15 | Europe | | | | | | 1.6 |
| | World | 19.7 | 8.8 | 4.2 | 8.4 | 3.7 | 1.8 |

the supply/demand ratio is always in danger zone. The situation is even worse than the ratio reflects since the 'option' of a fully vegetarian diet might not exist (rangelands contribute to food production as much or more than arable cropping). The Americas, Central Africa and Oceania are consistently in the second group, implying that there is ample scope for alternative land use (e.g. for rain forests). While for the regions in the middle group ample food can be produced, parts of the regions may be much more limited in their options of land use.

With respect to the current world food situation, it is recognised that if all food were equally distributed, no one would go hungry (Smits 1986). In fact, as many as one billion persons are hungry because of unequal income distribution that keeps food inaccessible to the poor.

A supply/demand ratio of 1.0 reflects situations where food security is met if food is distributed very efficiently. Particularly for the LEI scenario, where massive food transports are not in line with the environment friendly attitude, a somewhat higher ratio is required to achieve full food security for all households. Economic studies are to refine issue. Supply/demand ratios of 2.0 and more indicate that food could be produced on a smaller areas than all

*Table 8c.*

| # | Region | HEI system<br>Affluent diet<br>High population | LEI system<br>Moderate diet<br>Med. population |
|---|---|---|---|
| 1 | South America | 20.0 | 14.1 |
| 2 | Central America | 3.5 | 3.1 |
| 3 | Northern America | 10.5 | 11.3 |
| 4 | Northern Africa | 2.8 | 3.5 |
| 5 | Western Africa | 2.9 | 2.7 |
| 6 | Central Africa | 17.1 | 12.7 |
| 7 | Eastern Africa | 4.3 | 3.2 |
| 8 | Southern Africa | 6.9 | 7.0 |
| 9 | Oceania | 60.6 | 68.7 |
| 10 | Southeast Asia | 2.4 | 1.7 |
| 11 | Easthern Asia | 1.3 | 1.5 |
| 12 | Southern Asia | 0.8 | 0.9 |
| 13 | Western Asia | 2.0 | 2.3 |
| 14 | (former) USSR | 7.0 | 7.6 |
| 15 | Europe | 3.2 | 3.1 |
| | World | 4.2 | 3.7 |

suitable soils, with less intensive production techniques, with less productive crops or varieties, or that land is available to grow bio-energy crops or bulk export crops.

## Discussion

### *Issues related to food demand*

The range in increase in the demand for food till 2040 is about 6-fold. Although not in all regions the full range has to be considered (growth in some regions is slow and consumption is already high, other regions may choose vegetarian diets), probably 2.5–3.5 times more food will be needed at the global level. More than half of this increase could result from more 'expensive' diets. It is desirable, therefore, that food technologies are developed to produce 'expensive' food (in terms of GE) considerably more efficiently (cf. table 3).

Simulated yields per unit area in the under HEI system (table 6) correspond reasonably well to experimental yields in optimal conditions, as mentioned already by Buringh *et al.* (1975), and has been confirmed in related studies for many agro-ecological zones (Penning de Vries *et al.* 1989). A spot-check in West Africa (Kayes, Mali) showed SIMFOOD-yields of 22 t $ha^{-1}$ (3 crops irrigated rice), and 7 t $ha^{-1}$ for a rainfed crop; these values compare favourably with observations (Penning de Vries and Djitèye 1982).

In real production systems, many crop species are grown in addition to cereals: (sweet) potato, cassava, soybean, vegetable crops, fruits, etc. Yet, 75% of the worlds arable crop yield (by weight of dry product) originates from cereal crops, 7% from tuber and root crops, 8% from pulses, vegetables, and fruits, and 4% from oil crops (FAO 1993). Light, water and nutrient use efficiency of non-cereal crops are roughly similar to those of cereals, and differences in HI are compensated by differences in energy content. Hence, grain production is a fair approximation of potential food production. We did not evaluate the benefit of biotechnological breakthroughs. These may lead to better local adaptations, quality and crop protection, but we do not expect breakthroughs in higher efficiency in use of light or water as nature has been selective in these respects for aeons.

Top yields at experimental farms have not really increased for decades, and there is some concern that top yields are unsustainable (Yoshida *et al.* 1972; Pinstrup-Andersen 1994; IRRI 1990). It is crucial that top yields do not decline. Fortunately, recent indications are that inability to reproduce previous record yields was only a temporary setback, caused by the fact that soil and crop environment changed much more than was anticipated (Kropff *et al.* 1993). Global average hectare yields of cereal crops have not increased over the past years (Pinstrup-Andersen 1994; Brown and Kane 1994). The main reason for stagnating production is falling food prices, but since this is unrelated to yield potentials, it does not affect results of our study.

Simulated yields for the LEI-production system are more difficult to compare with observed values, as experimental data for this type of agriculture are scarce. Indirect evidence confirms the values that we computed: average wheat yields in the Netherlands around 1900, when little fertiliser was used and cereals were grown in rotation with legumes, were about 2 t $ha^{-1}$ (Spiertz *et al.* 1992); in Thailand, with a low rate of fertiliser application (FAO 1993), average rice yields in rice-legume cropping systems are about 1.8 t $ha^{-1}$, which for 2–3 crops leads to production level as shown (table 6). Yet, our yield estimates are probably on the conservative side, since in the cases quoted the soil P-level was probably sub optimal for N-fixation. Predicted crop yields depend heavily on the assumed N-fixing capacity of leguminous crops, which is subject to discussion (Caporali and Onnis 1992). It has been suggested that biotechnology might increase this significantly (e.g. by giving cereals the capacity to fix N). An increase in N-use efficiency is not expected as selection pressure for this feature has been high for ages. Doubling N-input would hardly increases production on irrigated land (6%) since the irrigated area decreases (more productive crops need more water), but the rainfed area grows and productivity of plots would go up, so that in total production could be up by 59%.

Our computations are based on the concept that all farming systems are in an equilibrium situation in 2040, and that a maximum of nutrients harvested and removed from the field are recycled. But to achieve this stable situation, build-up of crop nutrients in the soil is required, among others of inorganic P. Saturating the soil with P has already occurred in some countries (e.g. The Netherlands, Wijnands 1992), but massive amounts are still needed in areas where little fertiliser has been applied or mining is even still ongoing (Smaling 1993). Leguminous crops in particular require high levels of soil P to achieve maximum rates of N fixation. In a rough approximation, we estimate that in the order of 1 t $ha^{-1}$ of P is required to permit optimal production and growth. Such a value, multiplied with the area of potential agricultural land, leads to the potential need for 8 billion ton of P. The identified commercially exploitable P-reserves are estimated at 4–10 billion ton, most of which as rock phosphate in Africa (Tisdale *et al.* 1985). Apart from the question whether production of fertiliser P would release a harmful quantity of fluorine or bring about cadmium pollution (De Wit, personal communication), all known stocks would become exhausted. When the 'stable' situation is reached, agriculture continues to require small amounts of P to compensate for incomplete recycling. Hence, there is a distinct possibility that there is insufficient P in the world to feed the 2040 population when only LEI-production methods are practiced.

Errors of approximation are made because of the rather large area of our smallest soil units ($10^4$ $km^2$) and fresh water resources (river basins). The study would be more informative when performed for countries, and for regions with natural rather than administrative boundaries. A finer level of detail was not attempted by lack of basic data, the eventual size of the study, and because we aimed at a global overview. However, we do intend to zoom in on specific areas and issues (e.g. Luyten *et al.* 1995).

Suitability classification of soils has a major effect on the results of this study, while water holding capacity and soil depth are very important in rainfed conditions. Our knowledge of soils shows important weaknesses with respect to the extent of global cover, extrapolation of point observations to grid cells, definition of 'suitability', definition of soil characteristics compatible with crop models, and handling of preferential flow (Penning de Vries *et al.* 1995). We computed the relative suitability of land for modern agriculture (per grid cell) as the multiple of relative values for slope, soil 'phase' and texture. This is only correct when these features are distributed independently;

otherwise this study underestimates suitable land area and potential food production.

Our model does not take into account any heterogeneity in soils and feedbacks at the watershed level. These phenomena will probably affect yield negatively.

It may be argued that some soils that are not suitable for HEI-production may be used for LEI-systems, where mechanisation is not crucial. When we eliminated the reducing effect of slope on agriculture, about the irrigated area increased by 14% and rainfed production even more (34%), leading to an overall global increase of 16%. The largest relative benefit is in the Asian regions. This shows the importance of good hill-side agriculture in LEI-production systems.

Our procedure assumed maximum efficiency of external inputs, including fertiliser and water. This implies that humid areas are irrigated first (with only just enough water), and drier areas only when irrigation water is left. We have not yet compared the resulting distribution of irrigated land with the actual distribution.

Current total irrigated area in Asia amounts to 1.6 M km$^2$ (FAO 1993), while 0.7 M km$^2$ is potentially irrigable (Crosson and Anderson 1992); these are below our estimate for Asia (4.5 M km$^2$ for HEI, 5.5 M km$^2$ for LEI), mainly because we assume use of all available water and a higher water use efficiency. Our estimates of the maximum irrigable area in South America (7–8 M km$^2$) and Africa (6–8 M km$^2$), however, exceeds current irrigated areas (FAO 1993) 5–10 fold. This is presumably due to the fact that we neither address the economics of new realising irrigation systems nor the rate with which this can be implemented. Fifty years at a growth rate of 2–3% year$^{-1}$ (World Resources Institute 1990; Delft Hydraulics 1992) would only triple or quadruple irrigated land. This indicates that our estimates of potential food production cannot be realised without special and major efforts, but at the same time that there are probably still very important possibilities to expand irrigation and boost food production. Autonomous growth is definitely not sufficient.

We assume that all farmers use the currently known 'best technical means' of production and resource use. Although this may sound 'conservative' as better techniques will emerge, it already implies that an enormous amount of adaptive research is needed to adapt known technologies to local conditions.

In the HEI-scenario, transport of inputs (fertiliser, seed) and outputs (food, manure) comprises only a small fraction of the fossil energy input, most being required for production of N, P and K fertiliser, mechanical operations and processing. In the LEI-scenario, even less use of fossil energy is implied, as more localised production requires less transportation (but long distance transport of P-fertiliser is often unavoidable). Animal products and the feed required to produce them are generally transported over longer distances than vegetarian products. But as fossil energy is not part of this study, we did not explore further the implications.

## Conclusions

This explorative study indicates that natural resources are available in the world to increase food production very significantly. The 15 regions are very different in their potential demands by 2040 and in their potential production capacities.

When HEI-agriculture is practised, all regions can produce food required even for an affluent diet, except for East, South and West Asia, and also Southeast Asia and West and North Africa come close to the lower limit. A diet much less expensive (in terms of basic food products) provides the only option for escape, though the contributions of pastures to food supply will be needed. The three regions with the least leeway will carry almost half of the global population. On the other hand, Europe, the former USSR, the American regions and Central Africa are well off. Depending on the level of consumption chosen, Europe can grow its food on 0.3–0.6 of the suitable area, North America on 0.2 of the land, and South America and Oceania on an even smaller fraction.

When LEI-agriculture is practised, only South Asia will have food shortage. In this crowded region, there is no way out via less expensive diets or lower population growth (both already at a minimum). Moreover, our model computes that grass is harvested and converted into food, which is not in agreement with the assumption of the vegetarian diet, making shortage worse. If the LEI system goes with the low food demand scenario, then Europe could again grow all its food at less than half of its suitable soils. Only the former USSR, North and South America, Central Africa and Oceania can consider to offer its population an affluent diet. A major challenge to Asian science is to develop management techniques that allow expansion of the area of soil suitable for efficient farming, e.g. on hill sides. It should be explored whether global P-reserves would be sufficient for large scale LEI-farming.

Though people in many countries nudge already towards the middle of the range of diets (including East Asia), this study provides the warning that it might be impossible to follow this course till the end, and that some countries cannot afford its people the choice between a vegetarian or moderate diet and the affluent one. To permit more individuals a full choice of diets, food technology should help by increasing drastically the efficiency of producing socially acceptable diets at low biomass cost. Currently, three times as much biomass is required to produce an affluent diet as for a vegetarian diet. This ratio is too high. Aqua culture of fish and shrimps provides an opportunity to produce animal protein that is insufficiently exploited (ICLARM 1992). These animals can be grown from plant biomass, crop residues and waste.

This technology provides therefore an option to valorise food materials, and hence to contribute to raise the efficiency of making animal products (cf. tables 3 and 4). Seafood is unlikely to become more important, in absolute quantities, as its catch is already close to its global ceiling (World Resources Institute 1994). Abiotic ways of producing food have not yet emerged.

It should be explored whether global P-reserves are sufficient for the high productive HEI and LEI-systems considered. If not, than production levels remain significantly below the values currently considered.

## Acronyms

| | |
|---|---|
| GE | Grain Equivalent |
| HEI | High External Input farming |
| HI | Harvest Index |
| LEI | Low External Input farming |
| LEISA | Low External Input Sustainable Agriculture |

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