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Potential and attainable food production and food security in different regions

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SUMMARY

Growing prosperity in the South is accompanied by human diets that will claim more natural resources per capita. This reality, combined with growing populations, may raise the global demand for food crops two- to four-fold within two generations. Considering the large volume of natural resources and potential crop yields, it seems that this demand can be met smoothly. However, this is a fallacy for the following reasons. (i) Geographic regions differ widely in their potential food security: policy choices for agricultural use of natural resources are limited in Asia. For example, to ensure national self sufficiency and food security, most of the suitable land (China) and nearly all of the surface water (India) are needed. Degradation restricts options further. (ii) The attainable level of agricultural production depends also on socio-economic conditions. Extensive poverty keeps the attainable food production too low to achieve food security, even when the yield gap is wide, as in Africa. (iii) Bio-energy, non-food crops and nature 'compete' with food crops for natural resources.

Global and regional food security are attainable, but only with major efforts. Strategies to achieve alternative aims will be discussed.

1. INTRODUCTION

The UN projects population growth into the next century, and expects the global population to stabilize around 2040 (United Nations 1992). The world will then carry 1.5–2.2 times more human beings than in 1990, many of whom will require 2–3 times more primary biomass to produce their food. Can the Earth provide enough food by socially acceptable and economically rewarding ways of farming without sacrificing its natural resources? This is a very pertinent question, since the World Watch Institute warned that limits on growth might be in view (Brown & Kane 1994), the authoritative study by the International Food Policy Research Institute (IFPRI) on hunger and poverty in 2020, which indicates that the number of undernourished persons could well be stagnant at 800 million (IFPRI 1995), and the World Food Summit's calls for extra efforts to reduce the number to 400 million (FAO 1996). Since regions vary considerably with respect to their natural and economic resources and the size of their populations, their prospects for securing an abundant and reliable food supply are equally variable.

One answer to this question can be given by exploring whether the globe as a whole, and each region separately, has ample land and water resources to provide food for all persons if these resources are used at maximum efficiency. However, not only are future food supply and future demand for food difficult to quantify, they depend also on the attitude of future societies towards agriculture and the environment.

In considering the potential supply of food, one must consider that farmers do not only aim at maximum production, but also at diversification and stability, and for the best return on financial investment in external inputs (fertilizer, seed, water, etc.). The attainable level of production is therefore lower than the potential one. Production of food with animal protein has a special place: it requires extra plant biomass, part of which consists of grain that could have been used for human food (already 40% of all grain is currently fed to animals!). Non-food crops, such as energy crops, trade crops, and nature often compete with food crops for limiting natural resources, particularly water and land.

Here we address regional potential food security, quantify and discuss 'yield gaps' at a regional level, and discuss competition between food crops, industrial crops and energy crops. A full technical report on methods and basic data has been published (Luyten 1995). Highlights were presented in the wider context of use of natural resources for industry, transportation, and recreation (WRR 1994). In other articles, we described the model (Penning de Vries *et al.* 1995*a*), explored implications for soil science (Penning de Vries *et al.* 1996) and zoomed in on China (Luyten *et al.* 1997). Other issues discussed relate to contributions of biotechnology, to yield stagnation, and attention was given to prior studies, partial validation, errors of approximation, and sensitivity analysis.

2. OUTLINE OF THE APPROACH

(*a*) *Potential food security*

To quantify potential future food security, we computed the amount of plant biomass required to feed the future population in each of 15 regions (groups of countries), and compared the results with the amount of food that could be produced from an agrotechnical point of view in a sustainable manner in these regions. Our 15 regions are those distinguished in the UN population study (United Nations 1992); we added the very small region of the Caribbean to Central America, and grouped the four European regions into one. For the purpose of this study, the Peoples' Republic of China is similar to the region Eastern Asia: it has 85% of its population and covers 94% of its territory. These regions differ significantly in many respects (table 1). Potential global and regional food securities for the year 2040 were computed by dividing the potential food supply of a region by its potential food demand (WRR 1994; Penning de Vries *et al*. 1995*a*). This calculation for regions assumes absence of global-scale trade in food and feed.

Potential supply of and demand for food do not depend only on population size and natural resources. The intensity with which societies will exploit natural resources is uncertain, and depends on political convictions and perceptions of environmental risks. Four basic scenarios were therefore defined, representing contrasting attitudes towards natural resources, the environment, and the risks associated with them. The attitudes are characterized as 'utilizing', 'saving', 'managing' and 'preserving' (table 2 and Appendix 1).

For the food consumption side of food security, we translated these broad attitudes into a fully adequate vegetarian diet for the 'preserving' and 'saving' attitudes, and into an affluent diet for the 'utilizing' and 'managing' attitudes. For food production technologies, the attitudes translate into yield oriented production systems for the utilizing and saving attitudes, and in an environment oriented for the managing and preserving attitudes. It is important to recognize that the difference in food consumption per person between these scenarios is four-fold, and in production three-fold per unit of land. Here we discuss potential food security in the four scenarios. To avoid an excess of numbers, we use only the medium population growth scenario.

Table 2. *Four attitudes and their translation into different production systems (yield oriented agriculture or environment oriented agriculture) and consumption levels (vegetarian and affluent diets); source: Netherlands Scientific Council for Government Policy 1994*

	consumption	
production	affluent diet	vegetarian diet
yield oriented	utilizing	saving
environment oriented	managing	preserving

Demand for food is the product of population size and per capita consumption. In 2040, the global population may amount to 9.4 billion (UN medium growth scenario; table 3; cf. Fischer & Heilig, this volume). The amount of plant biomass needed annually to produce food for an average person ranges from 490 kg grain, equivalent to that of a largely vegetarian diet, to 1535 kg for an affluent diet (table 4). This very important relation to diets often remains unrecognized (e.g. Dyson 1996).

Two agricultural production systems are defined that differ in their impact on the environment. In the first type (yield oriented agriculture: YOA), a global and market oriented view of production leads farmers to aim for maximum productivity; society accepts the limited amounts of environmental damage that result from unavoidable losses of chemical inputs because this loss is minimal per unit of product. Nutrients are returned from the consumers to the farmers. Crop yields with full irrigation are high (typically 10 t ha^{-1}; this corresponds with the definition of 'potential yield'

Table 1. *Key characteristics of the 15 regions (after Penning de Vries et al. 1995)*

region	total land area [M km^2]	average land suitability [frac.]	number of crops per year [∝]	available irrigation water [km^3 yr^{-1}]	population in 1990 [million]	GNP per capita 1990 [k US$]
South America	16.8	0.82	2.3	3150	297	1.6
Central America	2.3	0.69	2.4	410	151	1.5
North America	15.9	0.56	1.3	730	276	18.3
North Africa	7.9	0.70	2.2	150	141	1.1
West Africa	5.9	0.74	2.9	550	194	0.5
Central Africa	6.3	0.86	2.2	1380	70	0.4
East Africa	5.9	0.80	1.9	1250	197	0.2
South Africa	2.6	0.74	1.5	270	41	1.5
Oceania	7.9	0.77	2.4	390	27	8.7
South-east Asia	3.5	0.58	2.7	290	445	0.6
East Asia	11.0	0.52	1.4	430	1336	2.6
South Asia	6.5	0.60	2.4	620	1201	0.3
West Asia	4.1	0.66	2.4	170	132	2.4
(former) USSR	20.9	0.38	1.1	480	289	8.7
Europe	4.6	0.72	1.5	160	98	11.1
World	122.0	0.64	2.0	10430	5293	3.6

Table 3. *Three scenarios for 50 years of population growth (United Nations 1992; numbers in millions); in this paper, only the middle scenario is used*

			2040		
	region	1990 actual	low growth	medium growth	high growth
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	Eastern Asia	1336	1503	1770	2098
12	Southern Asia	1201	1965	2408	2889
13	Western Asia	132	249	324	399
14	(former) USSR	287	323	369	419
15	Europe	498	437	498	563
	World	5293	7730	9404	11291

(Penning de Vries & Rabbinge 1995; cf. Evans, this volume), and proportional to rainfall on rainfed land ('water-limited potential yield'). In environment oriented agriculture (EOA), production systems are more oriented towards local markets, and are designed to minimize loss of inputs per unit area and impact on the environment. This is realized by replacement of all nitrogen (N) in chemical fertilizer by biological N fixation (phosporous (P) and potassium (K) fertilizer cannot be replaced biologically, and remain needed as inputs), elimination of biocides, minimal use of energy for transport, and hence 'local' consumption of the products and recirculation of nutrients. In this scenario, crop yields per unit of land are only one-third of the YOA yields. In YOA and EAO alike, farmers are assumed to cultivate according to the 'best technical means', i.e. the best agricultural technology that is now available for that agroclimatic zone.

We computed maximum global food production (figure 1) with the simple model SIMFOOD, taking into account four natural resources: crops, land, water and climate (Luyten 1995). Total production by region results from aggregation of yields from small units (soil–climate combinations). Crop production per unit area was quantified with a crop submodel. We used data from 15 500 land units, over 700 weather stations, and about 100 large river basins. The quantity of water available for irrigation was set equal to all surface water minus the estimated future demand for urban and industrial use (computation for each major river basin separately). Water is supposed to be used at maximum efficiency at the plant, crop and irrigation system levels. Crop duration depends on temperature only; it is a short season in the northern temperate zones, and a sequence of up to three crops annually is possible in the humid tropics. In YOA, crop production is limited by radiation and temperature, and by precipitation on rainfed areas. In EOA, N-supply is the yield-limiting factor, so that a small submodel for N–soil dynamics is incorporated in SIMFOOD. Unavoidable crop losses were set at 10% of yield (YOA) to 20% (EOA). The values presented below correspond therefore with the maximum attainable yield levels.

To compare food consumption and production, both are expressed in grain equivalents (GEs). 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 was grown (wheat) plus the amount of grain that need not be produced because of grass supplied by land that is unsuitable for arable farming. 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).

Abiotic ways of producing food have not yet emerged. Seafood is unlikely to become more important in absolute quantities, as its catch is already close to its global ceiling (WRI 1994). It is therefore proper to concentrate food production by primary production. Aquaculture of fish and shrimps provides an opportunity to produce animal protein that is still insufficiently exploited (ICLARM 1992), but a major increase in its contribution is possible. Although these animals also require feed as an input, they can convert efficiently low quality biomass, crop residues, and waste into valuable food products.

(*b*) *Actual food production*

To compute the yield gap, it is necessary to extract data on the actual production levels from published sources. Country data on actual production volume and area harvested are obtained from the FAO (1995); 1983–1992 country data are extrapolated to 1995 to fill in missing data and smooth out variations. Production data by crop are first converted to GEs by computing how much energy these crops contribute to food, relative to wheat, then summed by country, and finally

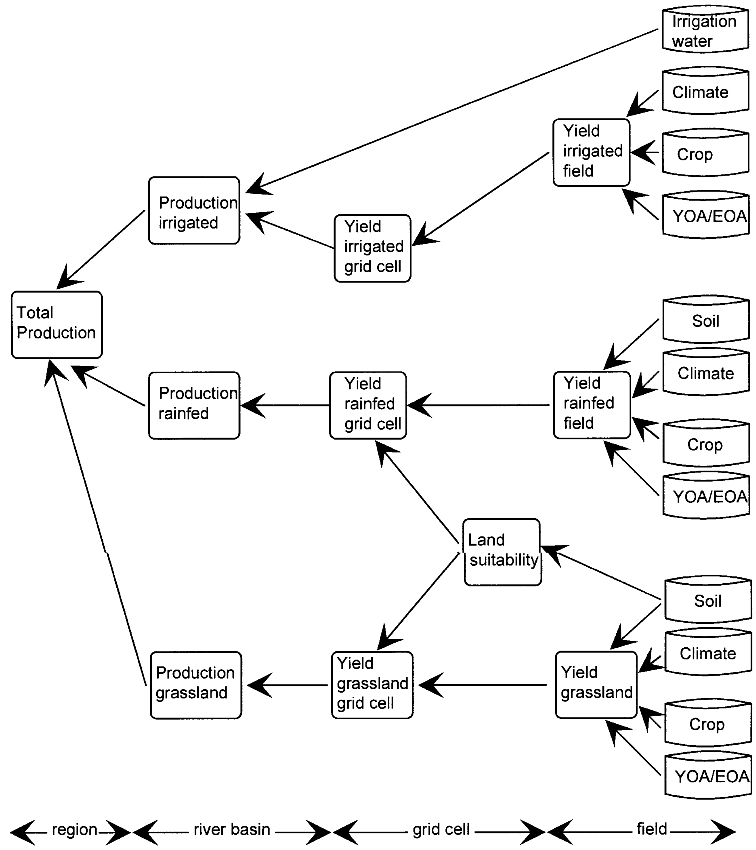

Figure 1. Steps and aggregation level to compute food production by region. Source: Penning de Vries *et al.* 1995.

Table 4. *Cost (in grain equivalents) and composition of a largely vegetarian diet, an affluent diet, and an intermediate diet; the part of the cost required for feed is given in parentheses*

diet	grain equivalent ($kg\ cap^{-1}\ yr^{-1}$)	energy ($kJ\ d^{-1}$)	animal protein ($g\ d^{-1}$)	plant protein ($g\ d^{-1}$)
vegetarian	490 (100)	10.0	8.6	66.7
moderate	860 (530)	10.0	31.2	50.0
affluent	1535 (1120)	11.5	63.2	28.9

aggregated by region. The average yield of each region is obtained by dividing the total production volume by the total area harvested. The amount of GEs per kilogram of storage organ is given in table 5. (It is computed as: (energy content) × (fraction dry matter) × (fraction food) / (16.3 × 0.85). The index gives the value relative to wheat; food energy content is obtained by: fraction (carbohydrate + protein) × 17.6 $kJ\ g^{-1}$ + fraction lipids × 38.6 $kJ\ g^{-1}$).

The area harvested for food crops is generally significantly less than the FAO's 'arable land': the latter includes non-food crops, temporary fallow (plus 'set aside') and short-term grassland (FAO 1993: definitions). Only in Eastern Asia is the area larger, because many fields are already cropped 2–3 times a year (Smil 1993). By comparing the harvested areas of the individual crops in the largest countries in each region with the total arable area, we found that up to 60% of the arable land was not used for food crops, and adjusted the cropped area by region correspondingly. The area of permanent grassland is specified in FAO production yearbooks but not its production, so we had to ignore their contribution to food production. Fortunately, this omission is insignificant for Asia, where the most crucial issues with respect to food security are located.

3. THE POTENTIAL REGIONAL AND GLOBAL FOOD SITUATION

(*a*) *Potential food security*

A summary of simulated potential production is given in table 6. The results are self-explanatory. Production on rangelands is included, implying that grasslands provide meat and milk, and boost the total food supply significantly. The global sums in table 6 have only a reference value as different regions can simultaneously practice YOA or EOA. The simulation indicated that the potential arable land area (i.e. all land which, in principle, is suited for modern mechanized farming) is a little less than one-third of the total land area; another one-third is suitable for grass production only (Penning de Vries *et al.* 1996). Due to the high efficiency of water use in irrigation

Table 5. *Of the major food crops, the harvested organs and their composition* (*Penning de Vries et al. 1983*), *and the productivity index* (*relative to wheat*) *; multiplying FAO-reported yields with the productivity index provides production in GE*

storage organ	composition food component: energy ($MJ\ kg^{-1}$)	protein ($g\ kg^{-1}$)	dry matter ($kg\ kg^{-1}$)	fraction food component	productivity index	note
wheat grain	16.3	120	0.87	0.85	1.00	reference crop
paddy rice	15.5	80	0.88	0.60	0.68	high residue fraction
course grains	15.4	90	0.90	0.65	0.75	sorghum and millets
potato	15.3	90	0.24	1.00	0.30	high harvest index
sweet potato	16.4	50	0.30	1.00	0.41	high harvest index
cassava	16.2	30	0.38	1.00	0.51	
sunflower, palm and other oilcrops	21.0	110	0.80	0.60	0.84	high oil content
soybean	18.6	370	0.93	0.70	1.00	high oil and protein
pulses	15.4	250	0.89	0.80	0.91	high harvest index
groundnut	22.2	270	0.95	0.75	1.31	several featues high
sugarcane	17.6	0	1.00	1.00	1.46	only sugar
apple, other fruits	16.0	80	0.18	1.00	0.24	low dry matter content
tomatoes, other vegetables	14.0	170	0.06	1.00	0.07	low dry matter content

Table 6. *Maximum annual food production* (in GE, 10^9 kg) *in YOA and EOA*

(The total production (column 2) is the sum of irrigated crops (column 3), rainfed crops (column 4) and rangelands (column 5) (after Luyten 1995).)

		YOA				EOA			
#	region	total production	irrigated grain	rainfed grain	rainfed grass	total production	irrigated grain	rainfed grain	rainfed grass
1	South America	20373	11837	1636	6901	6877	3804	0	3073
2	Central America	1853	949	0	905	811	284	0	527
3	North America	6418	2396	1217	2805	3252	1519	0	1733
4	Northern Africa	1798	648	365	786	1066	290	150	626
5	Western Africa	3546	1449	1012	1085	1503	788	192	522
6	Central Africa	7505	4691	161	2653	2672	1467	0	1205
7	Eastern Africa	5594	3169	603	1822	1892	1057	0	835
8	Southern Africa	1304	654	205	445	616	326	0	290
9	Oceania	4137	1020	1131	1986	2238	821	275	1142
10	Southeast Asia	3670	1394	0	2276	1185	368	0	817
11	Eastern Asia	4056	1949	0	2108	2261	740	0	1521
12	Southern Asia	3442	1594	581	1268	1836	931	53	851
13	Western Asia	1245	772	33	440	658	305	1	352
14	(former) USSR	4524	1645	902	1977	2459	1113	0	1346
15	Europe	2792	1011	55	1727	1348	375	0	973
	World	72256	35175	7899	29182	30673	14188	671	15814

systems ('best technical means'!), and assumed use of all available irrigation water, as much as two-thirds of the arable land is irrigated in the YOA scenario, and almost all in the EOA scenario (crops require less water per unit area). The distribution of irrigable land is highly irregular: Asia already has much irrigable land, and there is much potential for irrigation in South America, Central and Eastern Africa, North America and the former USSR.

Excluding large-scale movement of food between regions, the ratio of potential supply over demand is a measure of potential relative food security at the regional level. The ratios that follow from the previous sets of supply and demand data are shown in table 7, and some broad conclusion are summarized in Appendix 2. A distinction is made between the ratio based on arable land only (data between parentheses) and those where grassland contributes as well, because with current technologies grasslands can only be used for grazing cattle, and this may not be a realistic option in Asian regions. The scenarios differ more than ten-fold for each region, and range across regions from below 1.0 (shortfalls) to over 100. Generalizations are not possible as each region has its own balance of resources and food demand. Interestingly, the saving and managing scenarios give similar results, even though agriculture and societies would be quite different. Figure 2*a–f* presents the potential level of food security for the four scenarios and for selected regions. In Asia, not all attitudes to food and production can be pursued because of too little arable land (East Asia) or irrigation water (South Asia).

Table 7. *Ratios of potential food supply over food demand, by region for each scenario*

(To compute potential food demand, the medium population size was selected. The ratio when grasslands do not contribute to food production is given inside parentheses.)

#	region	saving	utilizing	preserving	managing
1	South America	77 (51)	24 (16)	26 (14)	8 (4.4)
2	Central America	13 (7)	4.1 (2.1)	6 (2.0)	1.8 (0.6)
3	North America	41 (23)	13 (7)	21 (10)	6 (3.0)
4	Northern Africa	11 (6)	3.5 (1.9)	7 (2.7)	2.1 (0.8)
5	Western Africa	12 (8)	3.6 (2.5)	5 (3.3)	1.5 (1.0)
6	Central Africa	66 (42)	20 (13)	23 (13)	7 (4.0)
7	Eastern Africa	17 (12)	5 (3.6)	6 (3.3)	1.9 (1.0)
8	Southern Africa	28 (18)	9 (5.6)	13 (7)	4.1 (2.1)
9	Oceania	234 (120)	74 (38)	127 (61)	40 (19)
10	Southeast Asia	9 (3.6)	2.9 (1.1)	3.0 (0.9)	1.0 (0.3)
11	Eastern Asia	4.8 (2.3)	1.5 (0.7)	2.7 (0.9)	0.8 (0.3)
12	Southern Asia	3.0 (1.9)	1.0 (0.6)	1.6 (0.9)	0.5 (0.3)
13	Western Asia	8 (5.2)	2.5 (1.6)	4.3 (2.0)	1.4 (0.6)
14	(former) USSR	26 (15)	8 (4.5)	14 (6)	4.3 (2.0)
15	Europe	12 (4.5)	3.6 (1.4)	6 (1.6)	1.8 (0.5)
	World	16 (10)	5 (3.0)	7 (3.3)	2.2 (1.0)

Table 8. *Actual average crop production and production area (arable plus permanent crops), excluding feed*

	production area				average yield	
region	actual food crops (Mha)	actual arable total (Mha)	potential Luyten (Mha)	actual yield (t ha^{-1})	potential YOA (t ha^{-1} yr^{-1}	potential EOA (t ha^{-1} yr^{-1})
S. America	72	109	851	2.3	15	4.5
C. America	25	38	55	2.1	17	5.1
N. America	115	186	480	2.5	7	3.2
N. Africa	23	41	137	1.8	7	3.0
W. Africa	29	55	213	2.3	11	4.0
C. Africa	12	25	318	2.6	15	4.6
E. Africa	21	43	254	2.3	12	4.1
S. Africa	6	15	89	2.6	8	3.7
Oceania	22	53	283	1.5	6	3.7
S. E. Asia	46	91	77	4.1	18	4.7
E. Asia	130	104	236	5.7	9	3.2
s. Asia	189	236	197	1.8	11	5.2
W. Asia	27	45	60	2.3	11	5.1
former USSR	126	227	432	1.9	6	2.6
Europe	130	130	120	3.6	10	3.3
World	973	1397	3802	2.9	10	3.9

Even though a supply–demand ratio of over 1.0 indicates that all demand can potentially be met, it can only be so if all food is distributed perfectly among all households. As this condition is almost impossible to meet, we distinguished three groups of regions: those in a danger zone (ratios close to 2 or less), those with a capacity to produce more than ten times the potential demand, and those in between. For much of Asia the supply–demand ratio is in a critical zone; particularly for the saving and preserving scenarios, and when the potential contribution of rangelands (beef, milk) remains unutilized. 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 rainforests). High supply–demand ratios indicate that food could be produced on a smaller area, with less intensive production techniques, with less productive crops or varieties, or that crop land remains available for bio-energy crops or export crops. While for entire regions in the middle group ample food can be produced, individual countries may have problems; this level of detail is not pursued in this paper.

Particularly for EOA scenarios, 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. The paradoxical situation may arise that EOA requires more transportation of food and inputs than YOA.

(*b*) *Yield oriented agriculture*

A substantial proportion of the non-irrigated land receives sufficient rain to produce a decent rainfed crop. Yet, globally, the potential irrigated production exceeds rainfed production five-fold. Grasslands can contribute a very significant quantity (table 6).

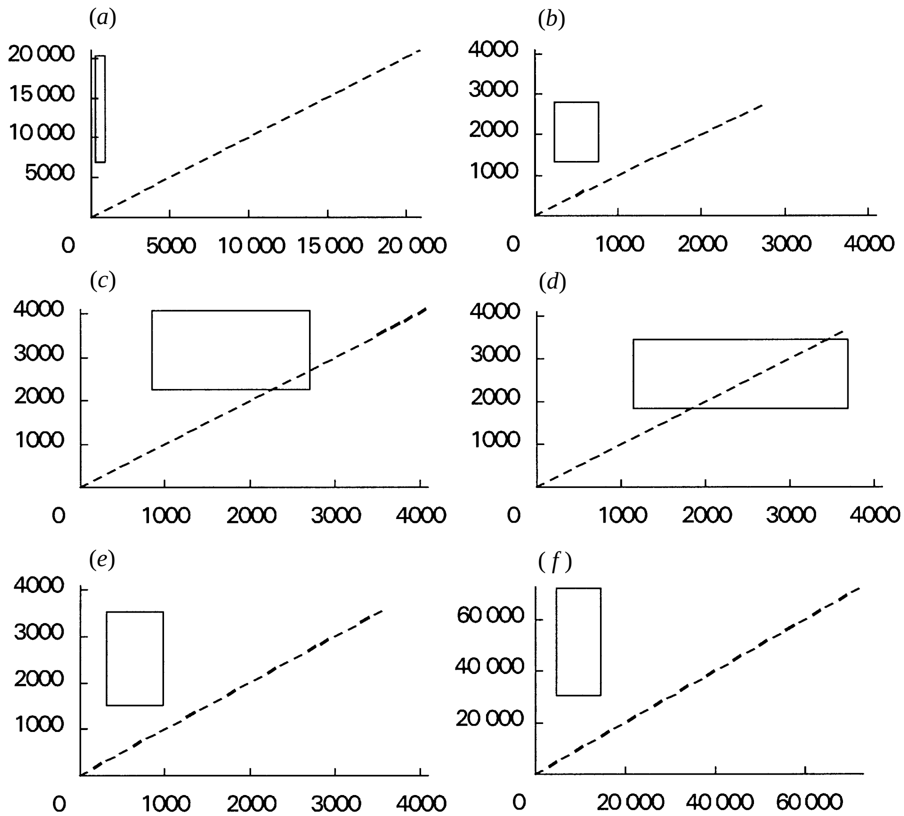

Figure 2. (*a–f*) *Potential demand for food (horizontal axis) versus potential supply (vertical axis) for five regions: Europe, Southern Asia, Eastern Asia, Western Africa and South America, and the world total (unit:* 10^9 *kg GE). The corners of the rectangles represent the situations of the four basic attitudes (table 2). Values above the 1 : 1 line represent potential food security at the national level.*

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, realization of this potential would involve cultivation of areas, which are currently occupied by rainforest. A second substantial area for irrigated cropping is Central Africa, while East Africa comes third. Clearly there is enormous potential in areas with few people (table 1). In Oceania there is so much rangeland that the maximum rainfed production equals that of irrigated production.

Under YOA, all regions can produce enough food, even for an affluent diet, except for East, South and West Asia. Also South-East Asia and West and North Africa come close to the lower limit (table 7). The three regions with the least leeway will carry almost half of the global population. Europe, the former USSR, the Americas 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. (Results of an earlier study for Europe also showed that much land is not needed for agriculture in the future (WRR 1992)). More details are given in tables 6 and 7.

(*c*) *Environment oriented agriculture*

Yields (in hectares) in EOA are one-third of those in YOA, but this is partially offset by a larger irrigated area: maximum global food production is about 40% of YOA (table 6). In most regions, all arable land can be irrigated (lower yields demand less water, so a larger area can be served). Feed production from rangelands is always substantial. Again, differences among regions are very large.

With EOA, only South Asia cannot produce all food it will need in the managing and preserving scenarios (table 7). In this crowded region, there is no way out via less expensive diets, particularly when the contribution to food from grassland cannot be used. In the preserving scenario, Europe could grow all the food it needs using 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. Practicing EOA, Asia and to a lesser extent Europe, cannot produce the food to provide an affluent diet to its population, unless production of animal protein becomes much more efficient or massive food imports occur. North Africa's production largely originates from rainfed crops and grassland, which are also significant in South and West Asia.

4. ACTUAL PRODUCTION AND PRODUCTION GAP

(*a*) *Actual production*

The data on the average actual production and the cultivated area for the 15 regions are presented in table 8. The actual area from which food is harvested is generally significantly smaller than the reported area of arable land (see also § 2 (*b*)). Globally, about half of the arable crop land is actually cropped in a particular year! Also, the differences between the areas currently identified as arable land and those that appear potentially suitable for arable farming on the basis of soil, water and climate characteristics, are considerable; these point at virgin areas with suitable soils into which agriculture eventually could expand. In the American and African regions and in Oceania, a significant quantity of land is not cropped; in Asia and Europe the margins are thin. Information on land degradation and its consequences for food supply is not included, as the available data were not compatible with our model, and the translation of the level of degradation into consequences for food production is not yet evident. A reduction of the significant uncertainty concerning the land area deserves a high priority in follow-up studies.

Table 8 presents the average actual yields, next to their potential levels. The difference is the yield gap. The global average yield is now already almost 3 t GE ha^{-1} yr^{-1}, while its maximum value is about 10 t ha^{-1} yr^{-1} for YOA and 4 t ha^{-1} yr^{-1} for EOA. It is interesting to note that the average regional yield now exceeds 1.7 t ha^{-1} everywhere (with exception of the dry region of Oceania). Some broad comments about the yield gap are summarized in Appendix 3.

The actual production volume (actual yield × actual area; table 8) divided by the current population (table 3) gives the per capita consumption of GE, the values of which are in line with the dietary requirements (table 4).

(*b*) *Yield gaps*

The yield gap is the difference between the potential yield and the average yield a farmer currently achieves. The concept of 'yield gap' is normally applied to field crops. 'Potential yield' is achieved at experimental farms when scientists use the best known techniques, apply sufficient inputs to stimulate crop growth to the maximum, and eliminate all pre- and post-harvest losses. This potential yield level is also the one simulated for the wheat, rice and grass crops by SIMFOOD, already adjusted downwards by 10% (YOA) and 20% (EOA) to account for difficult-to-avoid imperfections in management and economic optima in nutrient application rather than agroecological optima. Below, we review briefly that value.

Its value ranges from as little as 3 t ha^{-1} (East Asia) to over 10 t ha^{-1} (South America and Africa, where several irrigated crops per year can be grown.). The relatively modest potential yields and yield gaps in North Africa and Oceania are due to drought; those in North America and the former USSR are due to a relatively cool, short growing season. Nonetheless, there is ample room for yield improvement. The value of the yield gap does not correlate with the amount of unused arable land.

(*c*) *Causes of the yield gap*

A large yield gap implies that farmers did not adopt fully the existing technologies because they were not packaged appropriately, or that economic conditions made them unattractive. A small yield gap (e.g. 2 t $ha^{-1}crop^{-1}$) indicates that the available technologies are almost fully used. The yield gap results from strategic choices farmers make, from tactical choices, and from day-to-day events.

Since we apply the concept of 'yield gap' also to these regions, the relative frequency of cultivation of crops with a 'low' yield contributes to the yield gap (e.g. vegetables are a high value and low GE crop: table 5). This feature comprises the first category of causes of the yield gap. At the root of the differences between crops are differences in harvest index, biochemical composition in the harvested organ, storage organ water content, and crop duration. Of the total yield (dry weight) of the world's arable crops, 75% originates from cereal crops, 7% from tuber and root crops, 8% from pulses, vegetables, and fruits, and 4% from oil crops. We computed that, as a consequence, 16% less energy is currently produced by food crops of choice than would be produced by standard crop, and even 25% less protein. This implies that even if there were no yield gap at the level of individual crops, the regional yield gap (world average) amounts to 16%. This could be called the 'crop diversification yield gap'. With the coefficients for individual crop species and the proportion of these crops in different continents, we estimate that in Africa on average 54–78% of the potential yield (energy and protein, respectively) is achieved while not growing (a crop like) wheat, 77–92% in Asia (with 75–89% for China), and 84%–84% for Europe. Over recent decades, the global average of the diversification yield gap decreased a little due to the increasing emphasis on cereal crops relative to other crops (figure 3; L. Evans, personal communication). We expect this trend to reverse slowly as rising incomes demand a wider variety of crops on the market.

Extremely hot and cold weather, flushes of air pollution, sudden new diseases, and other hazards that occur only once every few years, reduce the average yields. Although these factors are not considered in simulating the potential yields, they do contribute to the yield gap as it is defined here. The extremes in the yield gap can be minimized by choosing the best crop varieties for each environment (see Sivakumar, this volume), but cannot be eliminated in open field agriculture. The large-scale production of rice in Japan, with a significant yield gap due to extreme weather conditions, shows that farmers sometimes deviate considerably from optimal agroecological zoning, for good economic reasons: a first exploration of the yield gap due to environmental extremes indicates a value of almost zero up to 25% of the potential yield (R. van Haren, AB-DLO, Wageningen, personal communication).

Decisions about how to manage the crop, i.e. planting at certain dates, fertilizer application, and the timing of weeding and crop protection measures, do influence to what extent the potential of a variety will be realized. These decisions are aimed at maximum income and or food for the household, stability, and maintenance of natural resources. When social factors (labour availability), or the economic environment

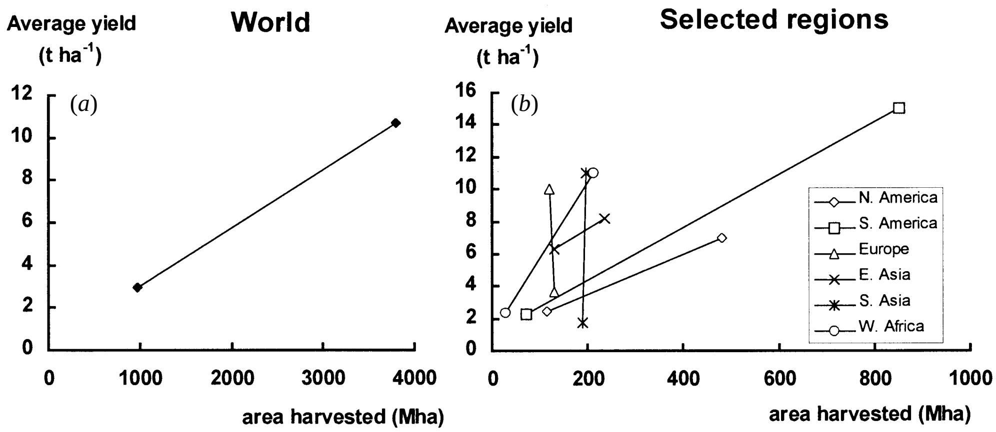

Figure 3. (*a–b*) Average yield (t ha^{-1}) and area harvested (Mha) for the world and selected regions. The lower point of each line refers to the current situation, the upper point to the potential (YOA).

(prices) or the physical environment (degraded soils, water), are not conducive to high inputs and careful management, crop yields fall well below the potential. The degree to which these factors cause a certain yield gap therefore depends strongly on socio-economic conditions and rural infrastructure. Farm household models (Dent 1995; Van Rheenen 1995; Van Keulen & Kuyvenhoven 1997) can be used to explore how these conditions translate into farmers' choices of farm management and investment. As the economic environment of 2040 is even less predictable than the agrotechnological environment, no effort is undertaken to quantify the 'economic yield gap'. However, there is no prior reason why farmers, if supported by a market, ample knowledge, techniques and relevant data, would not be able to close the yield gap almost completely. The values of yield reduction of 10% (YOA) and 20% (EOA) used in SIMFOOD, can be regarded as reflecting the economic yield gap.

In conclusion, we can argue for lower levels of the potential production, as simulated by SIMFOOD, by 10% to 20% for both YOA and EOA, in order to account for the effects of crop diversification and extreme weather. The data on potential food supply (table 6) and food security (table 7) are then to be reduced proportionally.

(*d*) *Closing yield gaps*

De Wit (1979) observed that once a national average yield level of 1.7 t ha^{-1} is surpassed, the economic balance for farmers often shifts to inputs, farm improvements and management, such that an increase of 80 kg ha^{-1} crop^{-1} is achieved and sustained for one or more decades. He found this was the case for many crop species, and in temperate and tropical zones (in Indonesia with two rice crops per year, the annual figures exceeded 160 kg ha^{-1} for decades). Figure 4 confirms this observation with a few sets of recent data and, more importantly, shows that such growth rates can be maintained even when the yield gap is small and does not hint at diminishing returns. It suggests that when societies succeed in providing the proper conditions, farmers improve their crops and management rapidly, and continue to do so even when yield levels come close to the ceiling. Indeed, at such a rate, the yield gap of 2–3 t ha^{-1} in East Asia will be closed in one generation.

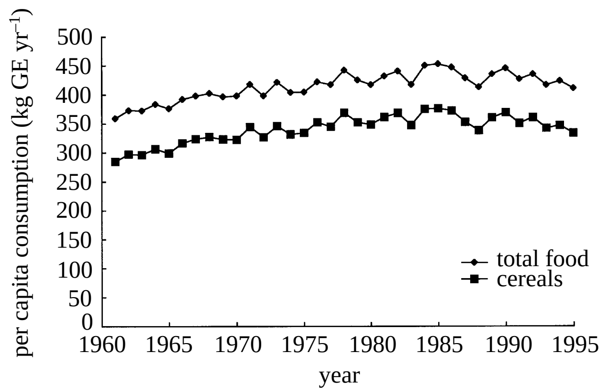

Figure 4. Global average of per capita cereal consumption and total food consumption (GE).

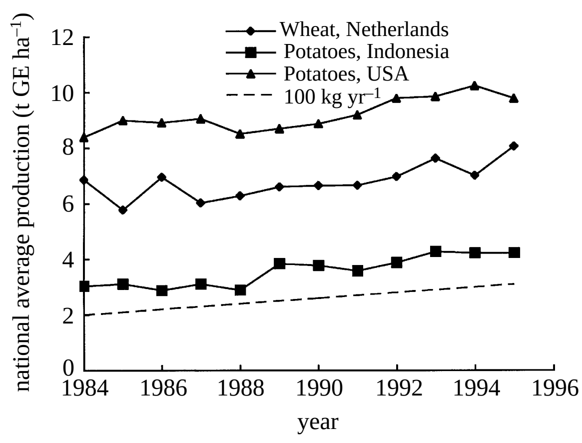

Figure 5. Yield levels (GE) of selected crops in the last decade.

The actual yield in E. Asia exceeds already the EOA yield, so that large scale EAO cannot be considered as a serious option. Rangelands and extensively used grasslands are currently mainly exploited through cattle. The yield gap on grasslands is very large indeed, as potential yields are often considerable and application of fertilizer is still unused. But for vegetarian societies, grasslands are not an extra source of food. China's meat consumption is rising fast (Simpson *et al.* 1995), particularly in the form of pigs, poultry and fish. To make use of the large potential of the rangelands, much more could be invested to harvest this natural resource, through cattle, sheep, fish, insects or industrially. This is a particularly important issue for China.

(*e*) *Widening yield gaps*

Asia needs crops and crop management that leads to significantly higher potential yields, and wider yield gaps. IRRI (1988) concluded that when rice farmers close the gap in the near future, new technology will be required, and it adopted as its key objective the development of a new rice variety with a yield ceiling of 15 t ha−1 in the tropics, raising the potential yield and the yield gap by 5 t ha^{-1}. Khush (1996) indicates that the new rice cultivar will probably soon increase the potential production by 2 t ha^{-1}, while another 20–25% is expected from employing indica-japonic hybrids. The International Rice Research Institute (IRRI) expects to be already halfway with this breeding objective (Fischer, IRRI, personal communication), and it may take another 5–10 years to complete the task and release the varieties. It would be most welcome if future biotechnological techniques allow increases in the yield gap to occur at a faster rate.

The amount of land used for food in any production scenario under YOA is less than half that under EOA. The large difference in use of land, water and fertilizer to produce an affluent diet with respect to a vegetarian diet with current 'best technical means' provides a strong drive towards more efficient production of animal protein. This can be achieved by (i) improving feeding methods of animals; (ii) raising animals that convert biomass more efficiently into food (e.g. fish, poultry and even pigs); (iii) by leaving cattle only on land that cannot be cropped; and (iv) by producing food items that are appreciated as meat or animal protein but made directly from plant material (as is done on a limited scale with soya). If we succeed in harvesting vegetation from rangelands and processing it directly into 'animal protein', then we will have achieved a major new supply of food.

Fruit trees, which are in the same high value/low energy category as vegetables, could possibly be grown on soils that are too steep for mechanized cropping, leaving arable land for the more productive food crops.

(*f*) *Arable, but uncropped land*

Of the arable land reported in FAO yearbooks, a significant fraction (20–60%) is not used for cropping, but for temporary grassland, fallow, set aside, or non-food crops such as cotton; maize is still counted as a food crop, though a significant portion of the yield is already fed to cattle. Also, land under rural infrastructure may be in this category. In China, for instance, agricultural land declines annually by about 0.5% due to the expansion of cities and industries. It is expected that non-food crops will become more important: they serve increasingly to produce a wide range of biodegradable products used, for example, for packaging, construction material, and car components. Special non-food crops could fetch high prices, such as pharmaceutical products, flavourings, flagrant or specific products from plant bioprocessors. While non-food crops can be quite beneficial for the farmer, they also capture some of the natural resources, and are therefore competitive.

(*g*) *Energy and other non-food crops*

Consumption of non-metabolic energy varies from less than 20 GJ $caput^{-1}$ yr^{-1} (traditional living in sub-Saharan Africa; equal to 0.4 tonnes of oil equivalents (TOE), mainly used in cooking) to 225 GJ and more in OECD countries (or five TOE for heating, transport, and manufacturing; Hassing 1996). Rapid growth in energy consumption is expected in many developing countries, not in the least in China (WRR 1994; Smil 1995). To provide the energy and avoid emissions of the greenhouse gas CO_2, the large-scale introduction of energy crops has been proposed. Energy crops (annual, perennial or tree crops), produced in sustainable plantation systems, yield in Europe 6–40 t ha^{-1} yr^{-1} of biomass (YOA), and provide a net energy budget of 70–210 GJ ha^{-1} yr^{-1} (CLM 1996). In the humid tropics, the figure may be twice as high; without fertilizer (under EAO) about one-third as high. This implies that if all energy for human use was provided by well-managed energy crops, every individual would need 0.2–2 ha. The land requirement for green energy would be an order of magnitude larger than that for food! If all the land in Europe that may become available in the next decades is planted with energy crops (19 Mha), then its contribution to Europe's energy consumption will still be only 8% (CLM 1996). While we cannot explore here the possible developments of energy crops in different parts of the world, the important point is that the strong demand for energy may cause a significant competition for land and water between energy crops to food crops.

5. CONCLUSIONS

Natural resources are available in the world to increase food production very significantly in any of our four scenarios. The 15 regions are very different in their potential demands by 2040, in their potential production capacities, and therefore in their potential food securities. And even though the accuracy of these calculations is limited, the large differences between the four scenarios, and the comparisons among them, do provide a strong indication of where bottlenecks and the options for development will be.

Although people in many countries already nudge towards the middle of the range of diets, it is shown that it might be impossible to follow this course until the end. Some countries will not be able to afford their people the choice between a vegetarian or moderate diet and the affluent diet unless massive imports are realized. 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. Major challenges to Asian science include (i) developing varieties with higher top yields than currently exist; (ii) determining highly efficient means to produce animal protein; (iii) employing management techniques that allow expansion of the area of soil suitable for sustainable and efficient farming, e.g. on hill sides, particularly by tree and vegetable crops that otherwise replace more productive food crops; and (iv) using management techniques that allow use of rangelands for food production.

Mr P. W. J. Uithol and Ir. R. E. E. Jongschaap helped to compute crop conversion coefficients, to analyse FAO statistics and prepare figures.

APPENDIX 1. ATTITUDES TOWARDS FOOD AND NATURAL RESOURCES (AFTER WRR 1994)

1. Utilizing: ... a certain level of environmental risks can never be ruled out ... problems need to achieve a certain scale in order to unleash creative energy ... much can be achieved by technology ...

2. Saving: ... cutbacks in consumption are necessary for a fairer distribution of scarce resources both worldwide and between generations ... since ultimately everyone has the same right of access to sufficient resources ...

3. Managing: ... the environment is 'robust within limits' that need to be monitored closely ... dematerialize production, possibly followed by dematerialization of consumption...

4. Preserving: ... a willingness to change both consumer and producer behaviour ... minimize uptake of unrenewable resources ... people must submit to tight ecological constraints ...

APPENDIX 2. POTENTIAL FOOD SECURITY, SOME HIGHLIGHTS

1. A vegetarian diet requires much less natural resources than an affluent diet; yield oriented agriculture can be more productive per unit of natural resource than environment oriented agriculture.

2. In the saving and preserving scenarios, much of Asia is in a critical zone, particularly when the potential contribution of rangelands remains underutilized. Land is the key limiting factor in East Asia, water in South Asia.

3. The amount of natural resources in Africa is large compared to the needs for food production: widespread hunger results from political and economic factors and not from a lack of agrotechnical potential.

4. In the Americas, Central Africa and Oceania, there is ample scope in any scenario for alternative land use (e.g. for rainforests) and for non-food crops next to food crops.

APPENDIX 3. THE YIELD GAP

1. The current value is 3–11 t ha^{-1} yr^{-1}(in East Asia) in areas where several irrigated crops per year can be grown.

2. The regional yield gap results from crop diversification, extreme weather conditions, and levels of inputs and management that preclude reaching maximum yields.

3. Crop diversification lowers potential yield by 10–25%.

4. In Asia, yield gaps should be increased by varieties with higher potentials, and the efficiency of providing animal protein should be maximized.

5. Yield gaps increase when more non-food crops are grown on arable land, such as cotton and crops for degradable packaging material and energy.

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Discussion

H. Fell (*Horkstow*, *UK*). The world appears to face a stark choice, either to go down the route of extensive agriculture with no chemical inputs and to use nearly all land for food production, or to avoid agricultural use of environmentally sensitive areas and farm the best land intensively.

F. W. T. Penning de Vries. At the global level, this comment is in line with our paper, although it ignores the fact that consumers also play a role (the production of meat requires more natural resources than products from primary biomass). It also neglects the fact that the balance of potential food supply to demand in some nations is already such that the 'extensive agriculture' route is no longer a real alternative.

A. Wagner (*London*, *UK*). You mentioned sacrificing natural resources for food production, but people can also sacrifice some food production and retain more natural resources.

F. W. T. Penning de Vries. We agree, and think that an important problem is that many people are not aware of the extent to which they occupy a world of limited natural resources. Broad public awareness of the amount of land, water, and nutrients that are required to sustain an individual is a first step.

K. Syers (*University of Newcastle upon Tyne*, *UK*). The authors give values for a production system in which no inorganic fertilizers are applied. I do not believe that such a system is sustainable in the long-term.

F. W. T. Penning de Vries. In our production system 'environment oriented agriculture' (EOA), there is no chemical fertilizer but maintenance applications of K and P are required. To avoid exhaustion of minerals in the long run, P, K and micronutrients must be recycled completely from consumers to farms.

P. B. Tinker (*University of Oxford*, *UK*). Your paper suggests a six-fold increase in production between 1990 and 2050. Is this an overestimate given Dr Fischer's predictions that the increase in population will be slow after 2030 and much of the effect of increased wealth should also be evident by then?

F. W. T. Penning de Vries. We distinguish in our paper between food (what is eaten) and the primary biomass (food and fodder crops). Little increase in production will be required in the North, but several times more biomass is needed in countries where the population is rising rapidly and incomes are rising from 'poor' to 'middle class'. In the extreme scenario, six times more biomass is needed. There is not a single answer for the globe because there are different scenarios for population and income development that significantly affect the quantity of food and feed required. The effect of changing diets is generally underestimated: an affluent diet requires more than three times more primary biomass than a fully vegetarian diet that many of the poor currently have.