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ABSTRACT

This working paper examines the question whether food is a limiting factor for population growth. It argues that we must distinguish five levels of food production capacity: (1) the bio-physical maximum carrying capacity of the earth, which is roughly equivalent to its "Net Primary Production" (NPP). This purely hypothetical production potential, however, must be decreased due to various constraints and restrictions. Thus, we must study the world's food production capacity as determined by (2) technical and logistic restrictions limitations, (3) environmental constraints and feedback mechanisms, (4) economic limitations, and (5) socio-cultural conditions. The key for balancing people and food is the speed with which constraints can be pushed back or modified that hinder people to utilize the full potential of the earth's food resources in a sustainable way. Technology could easily increase the earth's carrying capacity for sustaining a 12 to 14 billion world population if it is applied with ecological care and in the framework of an economically sound and socially-just development policy. The carrying capacity of the earth is not a natural constant--it is a dynamic equilibrium, essentially determined by human action.

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HOW MANY PEOPLE CAN BE FED ON EARTH?

Gerhard K. Heilig

1. INTRODUCTION

This working paper examines the question whether food is a limiting factor for population growth. Many distinguished writers have studied the problem. Since the time when Malthus started the debate some 200 years ago[1] thousands of books, research papers, and study reports have been published on the subject.[2/3/4/5/6] Despite these intense efforts, we are still far from consensus. A screening of available literature on estimating the earth's population carrying capacity reveals surprising diversity of results. In 1945 F.A. Pearson and F.A. Harper calculated that between 902 million and 2.8 billion people could be supported by the earth's agriculture.[7] Some 20 years later C. Clark estimated the sustainable population maximum of the earth to range between 40 and 147 billion (!).[8] However, in the late 1960s P. Buringh and others considered the world food production potential as equivalent to just 5.3 billion people.[9] In the late 1970s and early 1980s a large FAO study concluded that on Third World soils alone, between 3.9 and 32.4 billion people could be fed, depending on the level of agricultural inputs.[10] Only a decade ago Simon's *Ultimate Resource* became a popular book.[11] It resolutely denied any limits to (population) growth; people were considered the "ultimate resource". Today the

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[1] He was not the first scholar dealing with the problem, but probably the most influential. See: Malthus, R. (1967): *Essay on the Principle of Population.* 7th ed. London (Dent) (Original: 1798); Ricardo, D. (1964): *The Principles of Political Economy and Taxation.* London (Dent)

[2] Boserup, E. (1981): *Population and Technological Change.* Chicago (University of Chicago Press)

[3] Boserup, E. (1965): *The Conditions of Agricultural Growth.* Chicago (Aldine)

[4] Clark, C. (1967): *Population Growth and Land Use.* London (The Macmillan Press), Chapter IV: Population and Food.

[5] Clark, C. and Haswell, M. (1964): *The Economics of Subsistence Agriculture.* London (Macmillan)

[6] Livi Bacci, M. (1991): *Population and Nutrition. Essay on the Demographic History of Europe.* Cambridge (Cambridge University Press)

[7] Pearson, F.A. and Harper, F.A. (1945): *The World's Hunger.* New York (Cornell University Press)

[8] Clark, C. (1967): *op. cit.*

[9] Buringh, P., Van Heemst, H.D.J., and Staring, G.J. (1975): *Computation of the Absolute Maximum Food Production of the World.* Wageningen (Center for World Food Market Research)

[10] Higgins, G.M., Kassam, A.H., Naiken, L., Fischer, G., and Shah, M.M. (1983): *Potential Population Supporting Capacities of Lands in the Developing World.* Technical Report FPA/INT/513 of Project Land Resources for Population of the Future. Rome (FAO)

[11] Simon, J. (1981): *The Ultimate Resource.* Princeton (Princeton University Press)

Meadows' *Beyond the Limits* is a bestseller.[12] They argue that we have already passed the limits of sustainability and are on the way to ecological disaster. In their 1992 report the World Resource Institute published a wealth of data and analyses which imply that we are already approaching ecological limits in many sectors of our economies, including agriculture.[13] Most recently Paul and Anne Ehrlich, together with Gretchen Daily, analyzed the subject. According to their estimate it is "doubtful...whether food security could be achieved indefinitely for a global population of 10 or 12 billion people." They thought it "rather likely that a sustainable population, one comfortable below the earth's nutritional capacity, will number far fewer than today's 5.5 billion people...".[14] There are many other studies,[15] but probably the highest estimate of the globe's population carrying capacity was published by C. Marchetti, who, in 1978, argued that a world population of 1000 billion people would not be impossible.[16]

Obviously, these numbers are not much of a help to the student of future population trends. One reason for the large discrepancies are methodological divergences of the various approaches. Some authors deal with global averages of carrying capacity, while others study small agroecological areas and only later aggregate the results. Some authors base their estimates on the most advanced agricultural technology or assume future innovation; others define the carrying capacity in terms of current, in some regions rather low levels of agricultural output. Biologists usually explain carrying capacity as the balance between natural resources and the number of people--social scientists consider human resources the critical factor and accentuate social limits to growth. More systematically we can identify four reasons for the conceptual confusion: there is (1) dissent about the reference area, (2) disagreement about the means of sustenance, (3) controversy on the mode of reaction to limitations; and (4) confusion about the time frame. We will later discuss some of these problems in detail. For the moment we can only conclude that there are more dimensions to the problem than one would expect at first sight. It seems to be necessary to combine the various aspects of the earth's carrying capacity into a consistent theoretical framework. This is what we will do next.

2. DIMENSIONS OF THE EARTH'S CARRYING CAPACITY

To see the major dimensions of the problem, imagine a pipe through which the earth's food resources have to pass before they can be used for feeding people (see Figure 1). The diameter of the pipe, however, is not constant. While it is quite large at the "input" side, it is significantly smaller at the "output" end. The pipe's stepwise-decreasing diameter symbolized different kinds

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[12] Meadows, D.H., Meadows, D.L., and Randers, J. (1992): *Beyond the Limits: Global Collapse or a Sustainable Future.* London (Earthscan Publications Limited)

[13] The World Resources Institute/The United Nations Environment Programme/The United Nations Development Programme (1992): *World Resources, 1992-93.* New York, Oxford (Oxford University Press)

[14] Ehrlich, P., Ehrlich, A., and Daily, G.C. (1993): Food security, population, and environment. *Population and Development Review* 19(1):1-32

[15] The World Hunger Programme at Brown University estimated that present agricultural production could sustain either 5.5 billion vegetarians or 3.7 billion people who eat 25% of their calories from animal products. In the late 1980s Paul and Anne Ehrlich published an estimate of 5 billion for the world's maximum population carrying capacity. See also: Cohen, J.E. (1992): How many people can earth hold? *Discover* (November), pp. 114-119

[16] Marchetti, C. (1978): *On Ten-to-the-power-twelve: A Check on Earth Carrying Capacity for Man.* Research Report, RR-78-7. Laxenburg, Austria (International Institute for Applied Systems Analysis)

of restrictions to the earth's carrying capacity: technological, ecological, economic, and socio-cultural.

(1) The hypothetical maximum carrying capacity: At the input side of our "conceptual pipe" we have the theoretical maximum of the earth's food production capacity. This purely hypothetical measure is roughly equivalent to what biologists have termed the "net primary production" (NPP) of the earth. The measure is based on the assumption that the ultimate limitation of food production is given by the energy conversion ratio of photosynthesis. This is the basic biochemical process by which green plants transform solar radiation into biomass. Since we (roughly) know the total solar radiation input of the earth, we can calculate the globe's maximum biomass production, which quantifies the initial product of all animal and human food chains.

The NPP is only restricted by physical constants, such as the total solar radiation energy input of the earth[17] and by natural laws that govern the biochemical processes of plant growth. In its most extreme version the measure not only ignores economic, social, cultural, or political restrictions of food production, but also technical constraints and ecological feedback mechanisms. It assumes homogeneous implementation of most advanced agricultural technologies throughout the world. Authors who have adopted this rather narrow definition of carrying capacity have estimated that the maximum world population that can be sustained indefinitely into the future would be in the range of 16 to 147 billion people--depending on the specific method applied.[18] C. Marchetti's monstrous estimate of several thousand billion is based on a similar approach.[19]

(2) Technical and logistic restrictions and chances: The previous definition of carrying capacity assumes homogeneous distribution and instantaneous implementation of (advanced) food production technology. But this is impossible in reality. Even existing agricultural technologies would need years before they could be used throughout the world. They have to be adapted to local conditions, integrated with existing food distribution channels, and often require previous implementation of service and support schemes. The production and distribution of regionally adapted high-yield seeds, for instance, can take years or decades. Also the breeding cycles in husbandry have to be taken into account.

In addition to the usual delays in technology transfer, we have to realize that advanced agricultural methods are primarily available for good quality soils in temperate climates and for (sub)tropical irrigation cultures (such as Asian paddy rice crops). In the arid and semi-arid zones of Africa, however, we still have traditional pastoral systems which survived quite well as long as animal and human population density was low. But since the population has doubled or tripled the socioecological system is out of balance. The situation obviously requires new technology to increase productivity of food production. However, we cannot be sure that high-tech alternatives of animal husbandry which could potentially boost productivity by orders of magnitude, are adaptable to the hot and dry climate. Current experiments are not too promising. It is not

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[17] Usually the total solar radiation input of earth is seen as a (near-) constant. However, at soil level, it can certainly vary considerably with specific atmospheric conditions, such as water vapor and dust concentration in the higher atmosphere, as well as cloud cover conditions in the lower atmosphere.

[18] Clark estimated that the earth could support between 47 people at American-type diet and 147 billion at a cereal subsistence diet. See: Clark, C. (1967): *op. cit.*

[19] Marchetti, C. (1978): *op. cit.*

impossible that there simply is no high-tech alternative to traditional cattle ranging and primitive agriculture in certain parts of the world. We are just beginning to apply scientific methods to the management of arid or tropical soils, and it will probably take years or decades before we have drought-resistant high-yield crops and livestocks.

This indicates that the global carrying capacity is certainly diminished by agrotechnical and logistic restrictions and delays. Some studies have tried to take this into account by defining different input levels for various agroclimatic regions. The FAO/UNDP/IIASA study, for instance, assumed three levels of agricultural input which largely correspond to levels of technology.[20]

(3) **Ecological constraints and feedback mechanisms:** Since agriculture and livestock production--as everything else--are embedded in a natural environment, we also have to take into account ecological constraints and feedback mechanisms, such as acidification, soil loss, groundwater pollution, or desertification. These consequences of intense agriculture and animal production can gradually diminish returns. Some ecologists have argued that over-utilization of arable land (and forest areas) in Europe and Northern America has already degraded the soils to such an extent that artificial fertilization and soil management techniques cannot repair the damage.

However, there is more to the ecological perspective than the necessary integration of environmentally-sound production systems into natural environments. For instance, we need to reserve space for the (still remaining) fauna and flora, if we want to avoid additional termination of whole strains of evolution. Keeping biodiversity at a high level is not (only) a matter of aesthetics and respect--a large pool of plant and animal genes could be a primary resource for future biosciences. We must also reserve natural space for human recreation. The 10 billion world population of the 21st century, cramped into multi-million urban agglomerates, will certainly need some of the potential crop area for leisure activities, such as playing golf or riding a horse. And finally, a significant proportion of our environment cannot be utilized for agriculture or cattle ranging because it has vital functions in stabilizing the climate. Cutting down tropical rain forests for agricultural expansion would probably backfire. It would trigger or speed up climate change which could worsen agricultural conditions elsewhere and diminish overall food production. These examples show that the ecologically sustainable population maximum is certainly below the theoretical or technologically feasible.

(4) **Economic barriers:** Nothing in the world is free. Agricultural modernization and expansion is costly. One needs investment capital, functioning price mechanisms, adequate incentives for farmers, and a whole set of other economic conditions and mechanisms to boost food production for a multi-billion world population. Current estimates of a global carrying capacity usually ignore these economic dimensions. However, in real life we find numerous economic difficulties and limitations which further restrict global carrying capacity. Some studies have developed complex models that take into account prices and (international) trade, but their methodology and assumptions are debatable.[21]

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[20] FAO/UNDP/IIASA (1982): *Potential Population Supporting Capacities of Lands in the Developing World.* Technical Report of the Project, FPA/INT/513

[21] Parikh, K.S., Fischer, G., Frohberg, K., and Gulbrandsen, O. (1988): *Towards Free Trade in Agriculture.* Dordrecht (Nijhoff)

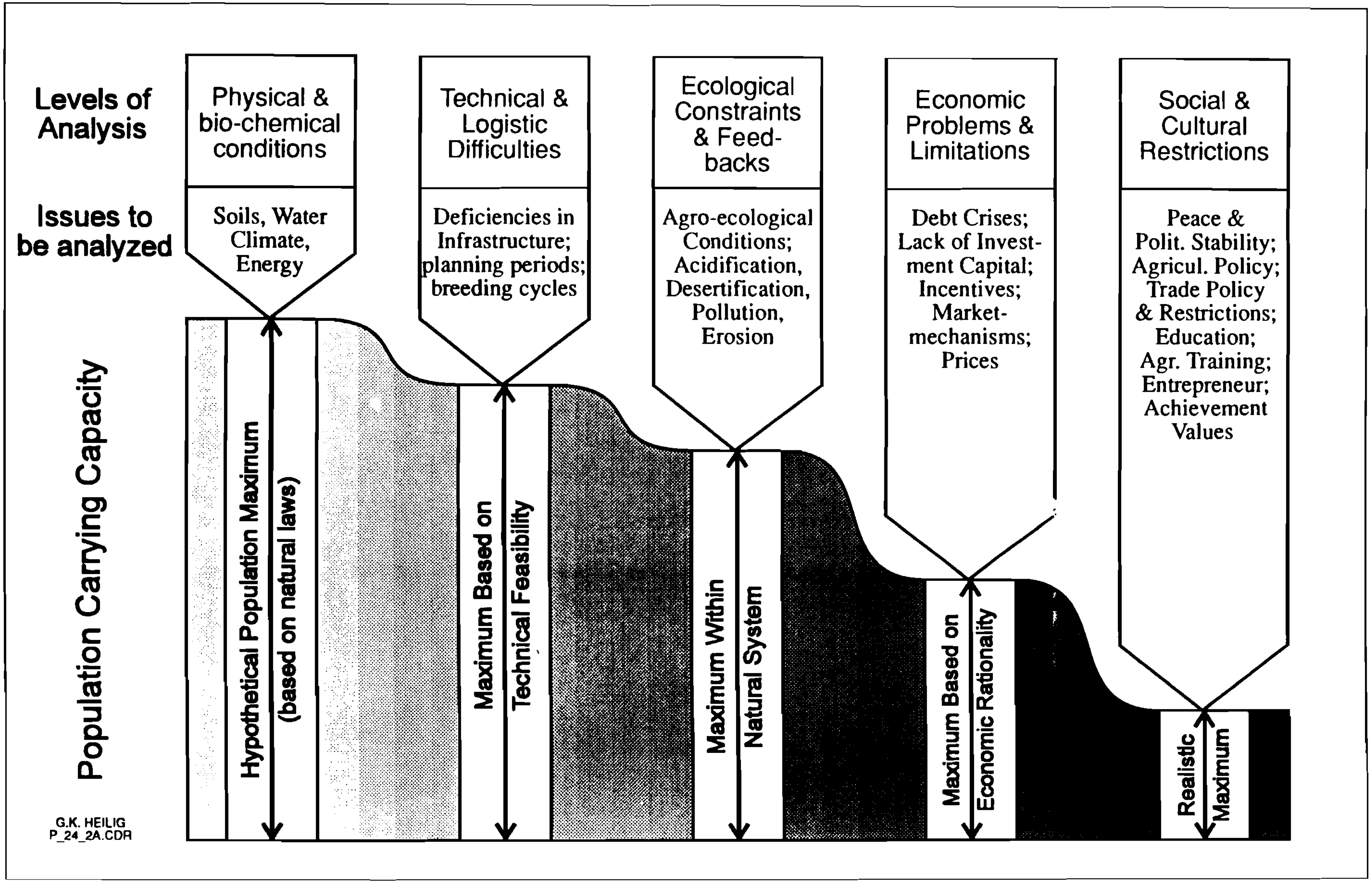

Figure 1. Five dimensions of the global population carrying capacity.

It is an illusion to believe that economic development is predictable for more than a few years. The fundamental changes in global economic patterns, from the rise of the "Asian Tigers" (Taiwan, South Korea, Singapore, Thailand, Malaysia) and the economic boom in China to the total breakdown of Soviet and East European economies, should have taught us a lesson. The economic framework of agriculture is man-made and can be changed to the better or the worse.

The earth's carrying capacity in the 21st century will be a matter of economic decisions at least to the same extent as it will be a matter of sufficient natural resources. Three aspects are most important: (a) the conditions of international agricultural trade, (b) the dissemination of agricultural technology and (c) the implementation of functioning incentive structures. We can boost or doom worldwide agricultural productivity, depending on what we will do with trade restrictions and food subsidies. We can speed up or slow down agricultural modernization, depending on what we do with the results of agricultural research and development; and we can block farmers' initiative or encourage their entrepreneurial spirit, depending on how we arrange property rights, taxation, price mechanisms, access to modern agricultural inputs, and education. The earth's carrying capacity not only depends on natural conditions and technology, it is also a function of specific economic arrangements.

(5) Social, cultural and political conditions: Some people believe that we just have to provide land, tractors, high-yield seeds, fertilizers and pesticides, agricultural training and free markets to make a person a highly efficient farmer. This technocratic approach, however, ignores the social nature of man. We must realize that probably the most serious restrictions for maximal utilization of the earth's population carrying capacity have nothing to do with natural resources or technology, but stem from social, political and cultural conditions.

Social and cultural constraints which prevent optimal land utilization can be found not only among traditional food collectors, hunters and cattle rangers of Africa and Asia. In many societies we have political and social conditions which hinder the farmers to fully exploit the carrying capacity of their land. In some cases these restrictions are voluntary and based on ecological considerations. For instance, a growing number of European farmers and agricultural politicians have realized that maximizing food production by means of agrochemistry and mechanization cannot be the ultimate goal of agriculture. They begin to exclude land from cultivation in order to make it available for natural reservations or recreational purposes. However, this noble self-restriction of agriculture (which is facilitated by substantial government subsidies) is rather atypical. Usually, there are other, more nasty socio-cultural and political constraints. Many farmers throughout the world are working their fields in the midst of (civil) wars; suffer from lack of technology and modern inputs; or are restricted by ridiculously low producer prices or market regulations. They are forced into collectivization by fanatical bureaucrats; and their children are deprived of adequate education and training. These kinds of socio-cultural and political constraints probably restrict the carrying capacity of the earth much more than anything else.

To the knowledge of the author there is no estimate of carrying capacity which takes into account all five kinds of restrictions. Usually, the concept is defined in terms of natural resources available for food production on a given level of agricultural technology. This reflects widespread ignorance of the actual factors that limit food, which are economic, social, cultural, and political. In the next section we will examine the multiple dimensions of the earth's carrying capacity in greater detail.

3. NATURAL RESOURCES

According to our "tube concept" of carrying capacity, natural conditions (such as the globe's solar radiation input) and basic biochemical processes (such as photosynthesis) ultimately determine the earth's food production potential. If we could transform the total solar energy input of the earth into biomass--and if we could eat this biomass--we could probably feed one thousand billion people. But this is just a theoretical exercise (which will be discussed later). For all practical purposes we have to consider real agroclimatic conditions. There are four natural resources and conditions that might directly limit the globe's carrying capacity: land, water, climate, and fossil energy.

3.1. Land

Since the beginning of the debate on the globe's carrying capacity, it was usually the factor "land" which was considered a limitation for the increase of food production. The world's land area is, undoubtedly, limited and only a small proportion is suitable for agriculture. Many physical and chemical constraints restrict the arable area--some land is too steep or too shallow, other areas have drainage or tillage problems. There are serious constraints of soil fertility, such as low nutrient retention capacity, aluminum toxicity, phosphorus fixation hazards, low potassium reserves or excess of salts or sodium. Both in its 1990-91 and 1992-93 reports on "World Resources" the World Resources Institute (WRI) published detailed estimates of these physical and chemical soil constraints by climatic class for major regions and on a country-by-country basis.[22] The estimates are based on a complex methodology, which combines

- the "Fertility Capability Classification System" (FCC) developed by the North Carolina State University,[23]
- agroclimatic data from FAO's "Agro-Ecological Zones Project,"[24] and
- the "FAO/UNESCO Soil Map of the World."

The estimates--as published by the World Resources Institute in its 1992-93 report--are shocking: The most seriously handicapped region is Southeast Asia: more than 93 percent of the soils have physical or chemical constraints. The situation is not much better in Southwest Asia: only 12 percent of the soils are free of inherent fertility constraints. In South America 80 percent and in Africa 82 percent of the soils have constraints. Only Central America is a little better: "only" 73 percent of the soils are hampered by physical or chemical restrictions.[25] On a country-by-country basis the estimates are even more dramatic: For India, WRI reports just 33.2

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[22] In the following discussion we only use the most recent estimates from the 1992-93 report.

[23] Sanches, P.A., Couto, W., and Buol, S.W. (1982): The fertility capability soil classification system. Interpretation, applicability and modification. *Geoderma* 27:283-309

[24] *Report on the Agro-Ecological Zones Project,* Vol. 1: Methodology and Results for Africa. World Soil Resources Report 48/1, Rome (FAO), 1978; Vol. 2: Results for Southwest Asia. World Soil Resources Report 48/2, Rome (FAO), 1978; Vol. 3: Methodology and Results for South and Central America. World Soil Resources Report 48/3, Rome (FAO), 1981; Vol. 4: Results for Southeast Asia. World Soil Resources Report 48/4, Rome (FAO) 1980

[25] These are data from the 1992-93 report of the WRI. The estimates of soil constraints in the 1990-91 Report were even higher for most countries. See: The World Resources Institute/The United Nations Environment Programme/The United Nations Development Programme (1990): *World Resources, 1990-91.* New York, Oxford (Oxford University Press), pp. 286-287

million hectares of unconstrained soils; this would be equivalent to 0.04 hectares (or 400 square meters) (!) per person. Bangladesh's unconstrained soil resources would be even less: only 0.02 hectares per person. Pakistan, the Philippines, and Indonesia would have 0.4 to 0.6 hectares per person of soil without inherent physical or chemical constraints (see Table 1).

What do these statistics indicate? The WRI thinks that "the extent of land with soil constraints is an important indicator of agricultural costs, the *potential and success of future expansion* [italics by the author], and the comparative advantage of a nation's agricultural production."[26] And later the WRI explains that "in the past 10 years, the FCC system has proven a meaningful tool for describing fertility limitations on crop yields."[27] In other words, do the estimates indicate that we are already short of fertile soils for future expansion of food production?

Not at all! First, one has to read the tiny footnotes attached to the WRI tables. Here we can find a few hints that explain what is actually meant by the various soil constraints. It turns out that most of the so-called "constraints" are just *specific natural conditions* that can be more or less easily overcome by modern agricultural technology. Consider the case of soils with "low potassium reserves" which constrain crops because of potassium deficiency. There is a simple solution: throw potassium fertilizer on it! Another example of soil constraints are "steep slopes" or "drainage problems". Would one think that many of these soils can be found in the extremely productive paddy rice and wheat areas of Asia, where agriculture is sometimes practiced for more than 8000 years (as in China)? "Aluminum toxicity" is also one of these so-called constraints that turns out to be less dramatic than its name: it limits the growth of common crops, "unless lime is applied"[28]--a practice that should not be completely impossible.

There are, of course, serious soil constraints that cannot be overcome by technology, but the WRI data do not distinguish between these and simple problems of soil management. For thousands of years farmers have coped with soils that were not perfect. They built terraces, added (natural) fertilizers, irrigated or drained the soil. But this did not hinder them to supply some of the most prominent empires of history, such as the Dynasties of China or the Kingdoms of ancient Egypt.

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[26] *Ibid.*, p. 289

[27] *Ibid.*

[28] The World Resources Institute/The United Nations Environment Programme/The United Nations Development Programme (1992): *op. cit.*, p. 284

Table 1. Cropland in percent of land without soil constraints: 25 highest and lowest.

Country	Population in 1000 1989	Land Area in 1000 Ha 1989	Cropland in 1000 Ha 1989	Land Without Soil Constraints in 1000 Ha 1989	Cropland in % of Land Without Soil Constraints 1989
Lesotho	1724	3035	320	1	32000.0
Malaysia	8451	32855	4880	196	2489.8
Lao PDR	4024	23080	901	37	2435.1
Thailand	54857	51089	22126	983	2250.9
Burundi	5315	2565	1336	66	2024.2
Mauritius	1069	185	106	7	1514.3
Rwanda	6994	2467	1153	91	1267.0
Sierra Leone	4049	7162	1801	187	963.1
Syrian Arab Rep	12085	18406	5503	643	855.8
Viet Nam	65276	32549	6600	989	667.3
Uganda	18118	19955	6705	1210	554.1
Bangladesh	112548	13017	9292	1719	540.5
Benin	4493	11062	1860	360	516.7
Lebanon	2694	1023	301	59	510.2
India	835610	297319	168990	33232	508.5
Cote d'Ivoire	11552	31800	3660	730	501.4
Brazil	147283	845651	78650	17081	460.5
Togo	3424	5439	1444	319	452.7
Cambodia	8044	17652	3056	695	439.7
Nigeria	105015	91077	31335	7797	401.9
Pakistan	118476	77088	20730	5250	394.9
Cuba	10500	10982	3329	888	374.9
Cameroon	11453	46540	7008	1949	359.6
Ethiopia	47942	110100	13930	30079	46.3
Mexico	86672	190869	24710	55930	44.2
Kenya	23187	56969	2428	7342	33.1
Argentina	31914	273669	35750	111781	32.0
Botswana	1256	56673	1380	4792	28.8
Sudan	24487	237600	12510	50390	24.8
Peru	21105	128000	3730	15264	24.4
Somalia	7257	62734	1039	4519	23.0
Bolivia	7115	108439	3460	15415	22.4
Uruguay	3077	17481	1304	6100	21.4
Kuwait	1971	1782	4	31	12.9
Egypt	51186	99545	2585	24633	10.5
Chad	5539	125920	3205	34160	9.4
Niger	7492	126670	3605	41388	8.7
Namibia	1725	82329	662	9308	7.1
Mali	8938	122019	2093	40865	5.1
Libya	4382	175954	2150	54004	4.0
Saudi Arabia	13585	214969	1185	30579	3.9
Yemen, PDR	2416	33297	119	3870	3.1
Oman	1446	21246	48	3897	1.2
United Arab Emirates	1538	8360	39	3707	1.1
Albania	3186	2740	707	96958	0.7
Mauritania	1970	102522	199	58867	0.3

There is a second reason why the WRI data on soil constraints are worthless as indicators of the earth's carrying capacity: they do not match with current trends in food production. Or to be more precise: in some cases the indicators are just absurd when compared with agricultural performance--for instance, India. According to the WRI the continent-size nation has only 33.2 million hectares of internally unconstrained soils; but FAO reports that India's farmers are cultivating some 169 million hectares of cropland, which is five times the area of "unconstrained soils".[29] In other words, according to WRI most of India's farmers are producing on more or less marginal land, which should limit crop yields. But just the opposite happened during the past 30 years. Between 1961 and 1989 India's farmers increased cereal production by a spectacular 129 percent (from 87,376 to 199,816 thousand tons). They also increased cereal yields from 947 to 1921 kg per hectare area harvested. In Thailand just 983 thousand hectare are free of soil constraints, according to WRI data. It seems strange that the country's farmers actually cultivated 22.1 million hectares of cropland--nearly 23 times the area of the unconstrained soils. Only the rice area harvested was 10 times (!) the size of the unconstrained soils area. Thailand's farmers also managed to increase cereal production by 131 percent between 1961 and 1989. Most absurd are the estimates of soil constraints for Malaysia: According to WRI data only 0.6 percent (or 196 thousand hectares) of the country's land area is covered by unconstrained soils. Obviously this did not much affect the country's farmers, who cultivated 4.9 million (!) hectares of cropland in 1989--25 times the area of unconstrained soils. It also did not affect their productivity, since they managed to increase cereal production by 62 percent between 1961 and 1989. These are only a few examples. We can find a large number of countries where the farmers expanded cultivation far into the area of constrained soils, while at the same time substantially increased crop yields.

And there is a third reason why WRI's soil data have limited relevance in our context: a high percentage of unconstrained soils in a country does not correlate with good agricultural performance. Consider the following example: according to the WRI, Chad has one of the largest areas of excellent soils--34.2 million hectares have no inherent physical or chemical constraints, an opulent 6.2 hectare per person. Is it not strange that the farmers use less than 10 percent of this area for cultivation and that famines are notorious in a place with one of the largest per capita resources of first-rate soils? This is not just an isolated case: According to WRI data, nearly all typical famine countries of Africa (Ethiopia, Sudan, Somalia, Mali) have huge areas of top-rated soils which are many times the size of their actual cropland.

Given these examples it is obvious that other factors than soil quality were responsible for agricultural performance during the past three decades. There is simply no correlation between food production and soil constraints as being reported by the WRI. Why should we expect that this will be different in the future?

On the other hand we have a large number of agricultural techniques available that could either help to expand the arable land and increase yields on marginal soils or improve the overall efficiency of crop production:

(1) We could expand the area of multiple harvests. In many places farmers could use their land several times during a growing season instead of only once or twice. Modern seeds, advanced agricultural technology, artificial fertilizers and other agricultural inputs have made these techniques of multi-cropping possible. It is a myth that we are already overutilizing the world's arable land. This is only true in some European and Asian regions. In large parts of Latin America and Africa we find excellent soils which are still cultivated

[29] Cropland = arable land plus land under permanent crops

with most primitive agricultural technology. Crop yields are often 60 to 90 percent below the average European level. Better inputs and modern agricultural methods could substantially expand the area of multiple harvests.

(2) We could cultivate marginal land. The farmers can expand the production areas to regions that were previously unsuitable for agriculture. There is still plenty of dry land that could be irrigated, swamps that could be drained, steep hills which could be terraced. We can cover land with glasshouses in cold regions or use forests for multi-layer cultivation. It is also possible to convert shallow seas into agricultural land. The Netherlands have demonstrated that even in adverse climate one can produce more than enough (tropical) fruits and vegetables on artificially climatized and drained land. In most countries it was not necessary to increase arable land during the past decades, but some agricultures have demonstrated that spectacular growth rates are still possible. Libya, for instance, has converted desert into circles of irrigated cropland; between 1961 and 1989 its area of irrigated agriculture nearly doubled (from 121,000 to 242,000 ha).[30] Burundi, which is already densely populated, managed to increase its arable land from 765,000 to 1,120,000 ha and the area of irrigated agriculture from 3,000 to 72,000 ha, respectively. Tanzania nearly doubled its arable land and increased the irrigated agriculture more than seven times. There are still spectacular land reserves in parts of Africa and Latin America.

(3) We can expand food production areas to the water bodies of our globe--lakes, rivers and seas.[31] While there is certainly a danger of exploiting the natural fish population of the sea, we have just started to explore the potential of fish farming. There is already some fish farming at the northern coast of England, in Norwegian fjords and Chinese paddy rice fields. A significant proportion of Europe's salmon supply is produced in fish farms near the Shetland Islands. But these are still small production sites compared with the huge coastal zones of our continents. It was argued that large-scale fish-farming schemes might disturb the natural balance of the maritime ecosystem, which, in turn, could limit its production potential.[32] While there is certainly a risk of local sea pollution through intense fish production it is rather unlikely that this might affect the whole ecosystem.

The early writers thought that a given plot of land can only feed a fixed number of people. Later, scientists realized that it is not only the size and natural quality of the land, but mainly the level of agricultural technology which determines the land's food production capacity. This basic understanding is still rare among today's environmental doomsayers, such as the World Resources Institute. They continue to focus their attention to the physical conditions of soils, collecting ever more detailed inventories of soil characteristics. But they are obviously blind to the fact that it is less and less these characteristics which are relevant. The size and quality of soils are just two variables in a multi-term equation of agricultural productivity which is mainly determined by technological, economic, social-cultural and political factors.

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[30] Allan, J.A. (1976): The Kufrah agricultural schemes. *The Geographical Journal* 142(1):48-56

[31] Sindermann, C.J. (1982): Aquatic animal protein food resources--actual and potential. Pages 239-255 in R.G. Woods, ed. *Future Dimensions of World Food and Population.* 2nd Printing. A Winrock International Study. Boulder, Colorado (Westview Press)

[32] Uthoff, D. (1978): Edogene und exogene Hemmnisse in der Nutzung des Ernährungspotentials der Meere. 41. Deutscher Geographentag, Mainz 1977. Tagungsberichte und Wissenschaftliche Abhandlungen. Wiesbaden, pp. 347-361; UNO/FAO (1976): *Report of the FAO Technical Conference on Aquaculture.* Kyoto 1976. FAO Fishery Report, No. 188. Rome (FAO)

3.2. Water

Some experts have argued that it is not land, but water which is the critical resource for the global carrying capacity.[33] Other scientists consider this a false alarm. We should not confuse--so they argue--man-induced regional water shortages with (climate-related) resource scarcity.[34] The discussion is hot, but frequently lacks solid ground, since basic data are often simply not available. For reasons of space, only some of the arguments will be discussed here.

Globally around 70% of all water withdrawal is used in agriculture. This explains why the water situation is, in fact, important to the earth's food production capacity. And there are also good reasons for raising alarm: Available statistics confirm that in some river basins freshwater is being extracted for human use (including agriculture) at rates approaching those at which the supply is renewed. Especially Egypt is on the brink of a water crisis. The country's renewable freshwater resources include some 58.3 km^3, of which 56.5 km^3 are from the Nile's annual flow and 1.8 km^3 from other internal renewable resources. 97 percent of these resources (or 56.4 km^3) are already withdrawn. Egypt's agriculture needs most: 49.6 km^3. Only 2.8 km^3 are used in the industry, and the withdrawal for domestic purposes is about 3.9 km^3.

Libya's agriculture might be also limited by extreme water shortage. According to recent estimates the country has a renewable freshwater resource of some 0.7 km^3 per year, mostly from underground aquifers. Libya's annual withdrawal, however, is estimated at about 2.83 km^3 which is four times the rate of natural replacement. 75 percent of this unsustainable withdrawal is used in agriculture. The country's spectacular increase of grain production is obviously borrowed from future generations.

Another interesting case is Saudi Arabia. Since 1961 the desert country has increased its wheat production by a spectacular 4706 percent, from merely 85,000 to 4,000,000 metric tons. Today, the country's farmers are not only able to provide more than 35 percent of the domestic food supply, which is a spectacular achievement in itself--they actually produce more grain than the country would need. In 1991 Saudi Arabia's net export of wheat was 1,805,000 metric tons--as compared to a net import of 67,600 metric tons in 1974. Ecologists have argued that the bumper harvests were mainly achieved by exploiting fossil--that is non-renewable--water resources below the desert. They estimated that in 1988 the country withdrew some 20.5 km^3 of water, 90 percent from non-renewable fossil groundwater aquifers. They also estimated that Saudi Arabia's agriculture needed 90 percent of the water--with 35 percent of the agricultural water consumption being used in wheat production. According to the Middle East Economic Digest (which cites a confidential U.S. government agency report), at the current rate of depletion Saudi Arabia's fossil groundwater would be exhausted by 2007.[35] Many writers have argued that Africa is a parched continent.[36] The most pessimistic position is probably held by Falkenmark, who argues that "water scarcity now threatens two-thirds of the African population.[37] She thinks that

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[33] Rivière, J.W.M. (1989): Threats to the world's water. *Scientific American, Special Issue: Managing Planet Earth* 261(3):48-55

[34] Bandyopadhyay, J. (1989): Riskful confusion of drought and man-induced water scarcity. *Ambio* 18(5):284-292

[35] "Hopes dry up for food security." *Middle East Economic Digest* 33(40):15, 1989

[36] Pearce, F. (1991): Africa at a watershed. *New Scientist,* March 23, pp. 34-40

[37] *Ibid.*, p. 35

already by the year 2000, Tunesia, Kenya, Malawi, Burundi and Rwanda will suffer a permanent water crisis.

There is also much concern about the arid regions of the North China plain. According to recent calculations by the World Resources Institute, the 200 million local population is already exploiting freshwater resources to a large extent. The institute concludes that "if present trends continue, the region will have 6 percent less water than needed by the end of the century."[38]

These few examples certainly seem to confirm the conclusion that water is a critical factor for limiting global carrying capacity. But there is also empirical evidence which does not fit into the pessimistic outlook.

Let us first check some global statistics. According to the most recent estimate, the earth's total annual freshwater resource is some 40,673 km^3. The annual agricultural withdrawal is about 2,236 km^3, which is less than 6 percent of the globe's renewable water. Worldwide industrial and domestic water consumption together accounted for another 995 km^3 (or just 2.5 percent of the total water resource).[39] It is hard to imagine that we are approaching global limits of freshwater withdrawal when more than 92 percent of the known reserves are still untouched.

If there is no scarcity on the global level, the uneven regional distribution of the resource might be the problem. Africa is frequently considered an example of agricultural stagnation triggered, or at least intensified, by water scarcity.[40] But available statistics do not confirm this theory. Africa has 4,184 km^3 of annual internal renewable water resources, which was nearly 6500 m^3 per person per year in 1990. This is almost five times the per capita freshwater availability of West Germany, which was only 1300 m^3. Moreover, Africa's freshwater is not only located in the tropical areas, as one might suspect--there are large reserves all over the continent. Famine ridden Somalia has more than twice (!) the per capita internal[41] freshwater resource of the Netherlands (1520 versus 680 m^3). The "arid" Chad has internal freshwater sources of 6760 m^3 per person--more than three times the per capita water resource of the rainy United Kingdom (which is only 2110 m^3). And in Angola there are 15,770 m^3 of freshwater for each person--nearly 28 times more than, for instance, in Hungary, which has just 570 m^3 available. There is also more than enough freshwater in South America: The total resource is estimated at 10,377 km^3 which is equivalent to the combined renewable water resources of Europe, the whole (former) Soviet Union, and Africa. On average, each inhabitant of South America has potential access to 34,960 m^3 of freshwater, which is 7.5 times more than in Europe. All large South American nations have abundant per capita freshwater resources--ranging from 18,860 m^3 in Uruguay to 43,370 m^3 in Venezuela (which is many times the typical ratio for Europe, Asia or the USA). Only Peru is

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[38] The World Resources Institute/The United Nations Environment Programme/The United Nations Development Programme (1992): *op. cit.*, p. 163

[39] The World Resources Institute/The United Nations Environment Programme/The United Nations Development Programme (1992): *op. cit.*, p. 328

[40] Falkenmark, M. (1991): Water, energy, and development. Rapid population growth and water scarcity--the predicament of tomorrow's Africa. In K. Davis and M.S. Bernstam, eds. *Resources, Environment, and Population: Present Knowledge, Future Options.* New York (Oxford University Press) (*Population and Development Review*, A Supplement to Volume 16, 1990)

[41] River flows from other countries are an unreliable source of water supply, since they can be influenced by the neighboring country. Therefore we compare only "annual internal renewable water resources", such as underground aquifers.

somewhat "shorter" in freshwater: 1,790 m^3 per person are available--a still abundant amount, however, if compared to the 850 m^3 of Belgium's internal renewable water resource. The situation in North and Central America is mixed--very large resources in Canada, more limited resources on the Caribbean Islands. However, there is no indication that freshwater resources are running out in the region. Mexico, for instance, has larger internal freshwater resources than Italy: 4,030 versus 3,130 m^3 per person per year. The freshwater resources of Asian countries are also very different: On a national level China has enough water: 2,470 m^3 per person per year.[42] India, Pakistan, and Thailand have a little less (2,170, 2,430 and 1,970 m^3 per person per year), but are far from critical. There is abundant freshwater in Indonesia (14,020 m^3), Bangladesh (11,740 m^3), and Malaysia (2,630 m^3).

An interesting indicator of water stress is the proportion of annual withdrawals from available resources (see Table 2). In 51 countries the annual withdrawals are just 1 (or less than 1) percent of the renewable freshwater resources, including populous nations such as Indonesia, Brazil, or Nigeria. China uses 16 percent of its annual freshwater resource, India 18 percent, Kenya just 7 percent. In all of Africa, including the drought-affected Sahel, only three countries extract more than 50 percent of their annual freshwater resource, namely Egypt (90%), Libya (404%) and Tunesia (53%). Most African countries are extracting less than 3 percent of their resources. In South America the highest extraction is reported from Peru: a mere 15 percent. All other South American nations have not even touched their renewable water reserves--they use typically less than 2 percent. Even in Asia, where the situation is a little tighter, extraction rates typically range between 1 and 30 percent. Only Afghanistan, Israel, and Cyprus have extraction rates of more than 50 percent. For these countries the situation is certainly serious. Jordan, Algeria and Tunesia are also critical. The real "dramatic" cases, however, are only a small number of states of the Arabian Peninsula: Qatar, Saudi Arabia, United Arab Emirates, and Yemen. They are all withdrawing water at much higher rates than those at which their resource is renewed.

It is also important to understand that human water use is essentially a recycling process: frequently water is just moved through biological and technical systems for cleaning or as some kind of biological catalyst. Much of the freshwater withdrawal (especially in agriculture) is not consumed, but directly returned to a river or underground aquifer. From there it can be used several times before it finally reaches the sea. We usually do not consume water in the same way as we exploit fossil fuels or scarce minerals. These natural resources have a much lower recycling rate than water--they are actually destroyed or at least removed from natural cycles for a very long time through human consumption. Consumptive use of water, such as the evaporation from industrial cooling towers and irrigation systems, makes up only a small proportion of water withdrawal. The real water problem is not scarcity, but the pollution we add to the returning flows.

On the basis of these considerations we cannot see water scarcity as a limitation for the globe's carrying capacity. No doubt, there are nations with rather limited resources. We also have local or regional shortages that will require expensive water infrastructures. But really dramatic shortages can only be found in a small number of desert states of North Africa and Western Asia. Most of these countries are enormously wealthy oil exporters and could artificially "produce" water for their high-tech agriculture--in fact this is what they are doing with the highest density of desalination plants in the world. But is this natural water scarcity of some oil billionaires really worth the concern?

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[42] The situation within this continent-like country is, however, different. There is water scarcity in the northeastern agricultural areas.

Table 2. Selected countries: Freshwater resources and withdrawals.

	Annual River In-flow (in cubic km)	Annual Internal Renewable Water Resources			Annual Withdrawals Per Capita (in cubic m)	Annual Withdrawals in % of Total Water Resources/1	Agricultural Withdrawal (in % of Total Withdrawal)
		Total (in cubic km)	Per Capita (in cubic m)	Per 10000 Ha of Cropland /2			
Egypt	56.50	1.80	0.03	0.01	1202	97%	88%
Sudan	100.00	30.00	1.19	0.02	1089	14%	99%
Kenya	x	14.80	0.59	0.06	48	7%	62%
Australia	0.00	343.00	20.48	0.07	1306	5%	33%
Ethiopia	x	110.00	2.35	0.08	48	2%	86%
Nigeria	47.00	261.00	2.31	0.08	44	1%	54%
Uganda	x	66.00	3.58	0.10	20	0%	60%
Germany (West)	82.00	79.00	1.30	0.11	668	26%	20%
Netherlands	80.00	10.00	0.68	0.11	1023	16%	34%
Somalia	0.00	11.50	1.52	0.11	167	7%	97%
Chad	x	38.40	6.76	0.12	35	0%	82%
U.S.A.	x	2478.00	9.94	0.13	2162	19%	42%
Mexico	x	357.40	4.03	0.14	901	15%	86%
Tanzania	x	76.00	2.78	0.14	36	1%	74%
Mozambique	x	58.00	3.70	0.19	53	1%	66%
China	0.00	2800.00	2.47	0.29	462	16%	87%
Angola	x	158.00	15.77	0.44	43	0%	76%
Brazil	1760.00	5190.00	34.52	0.66	212	1%	40%
Colombia	x	1070.00	33.63	1.99	179	0%	43%

Source: WRI/UNEP/UNDP (1992): World Resources, 1992-93. New York, Oxford (Oxford University Press), p. 328-329, 274-275

/1 Total water resources include both internal renewable resources and river flows from other countries.

/2 Cropland includes arable land and land under permanent crops

x = unknown/no data available

In principle, water scarcity is not a limiting factor for the further increase of food production. It might be difficult and costly to pump freshwater to agricultural areas (such as from the northern United States to southern California); it might be necessary to settle conflicts over limited water resources between neighboring countries (such as Israel and Lebanon); some islands (such as Malta) and some densely populated agricultural regions (such as northern China) might require the implementation of advanced water conservation and recycling schemes. But all this is not impossible and it is not being done for the first time in history. We tend to forget that highly sophisticated irrigation systems were built in the Middle East some four to five thousand years ago, and that during the Roman Empire the capital city could flourish only because it was supplied with water through aqueducts across hundreds of miles.[43]

One reason for concern, however, is the pollution we add to the returning water flows. Both industries and private households have already caused serious local or regional water contamination. Unfortunately, high-tech agriculture itself is a major polluter of groundwater and river flows.[44] In some intensively-cultivated agricultural areas of Europe, the excessive use of fertilizers has raised the nitrate concentration in groundwater to dangerously high levels. We also can observe pesticide contamination of freshwater resources in some areas of North America and Europe.[45/46] An increase of food production could easily lead to further deterioration of water resources.

On the other hand this trend is not inevitable. All experts agree that there is still a huge potential for improving the efficiency of fertilizer use, irrigation, water treatment and recycling.[47] Much has already been done to clean lakes and rivers in Europe. Twenty-five years ago the lakes in southern Germany frequently had to be closed to swimmers because of pollution with coli bacteria. Today one could drink the water while swimming in these lakes. European farmers have also realized the danger of over-fertilization. Contrary to popular belief they use less nitrogen fertilizers per ha of arable land than they used 15 years ago. We also observe rapid development of technologies that could help in cases of real water shortages. Prices for the desalination of water are declining rapidly as larger plants with better technology are set up.[48]

3.3. Climate

The globe's food production potential certainly depends on the climate. The annual fluxes of precipitation and evapotranspiration which determine the potential water supply available for human exploitation (so-called run-off) vary greatly by region. They are much higher at the

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[43] Meybeck, M., Chapman, D., and Helmer, R. (1990): *Global Environment Monitoring System: Global Freshwater Quality. A First Assessment.* WHO/UNEP. Cambridge, Mass. (Blackwell Reference)

[44] Biswas, A.K. (1993): Water for agricultural development: Opportunities and constraints. *Water Resources Development* 9(1):3-12

[45] Hallberg, G.R. (1989): Pesticides pollution of groundwater in the humid United States. *Agriculture, Ecosystems and Environment* 26:299-367

[46] Leistra, M. and Boesten, J. (1989): Pesticides contamination of groundwater in Western Europe. *Agriculture, Ecosystems and Environment* 26:369-389

[47] Biswas, A.K. and Arar, A. (1988): *Treatment and Reuse of Wastewater.* London (Butterworths)

[48] Wangnick, K. (1990): IDA Worldwide Desalting Plants Inventory. Report No. 11, prepared for the International Desalination Association (Wangnick Consulting), Gnarrenburg, Germany

equator than in the arid or semi-arid regions around the latitudes of 40° north or 30° south.[49] The vast deserts and arid lands of Asia and Africa that have emerged as a result of these climate conditions are certainly among the most hostile environments for agriculture on earth. The lowest precipitation and evapotranspiration--and consequently the lowest potential water supply for human exploitation--can be found at the poles.

The spatial pattern of the global water cycle not only influences the water supply for rainfed agriculture; it also determines variations in the flux of solar radiation energy, which is the fuel of photosynthesis, the basic process of plant growth. In the arid or semi-arid mid-latitudes of low precipitation, cloud cover is rare or absent so that less solar radiation is absorbed or reflected. Consequently, insolation in these regions is some 20 percent higher than at the equator where one would expect the highest solar energy flux.[50] Since there is also a low level of actual evaporation in these arid zones, the solar energy input mainly heats up the ground and the air which further increases the region's water deficit and worsens environmental conditions for agriculture.

It is not only the (absolute) shortage of water and the high temperatures in arid and semi-arid regions that make agriculture difficult or impossible. There is also the interannual variation in precipitation, which is typically three or four times greater than in temperate regions. This high climatic variability explains why the desert can move back and forth in an unpredictable temporal pattern. During the early 1970s we experienced a global redistribution of rainfall which led to the 1970-72 Sahel drought and contributed to widespread famines in the Sahel and Ethiopia. The bio-climatic zones of the Sahel moved south and expanded the area of high desertification risk.

During the 1970s and 1980s many scientists considered desertification--triggered by climate variation--one of the major causes of declining food production potential in large parts of Africa and Asia. But there is no general consensus. Others reported evidence for a major anthropogenic component in the desertification process.[51] We also have to take into account that the transformation of arid and semi-arid lands to desert during the Sahel drought was (at least partially) compensated by higher precipitation north of the Sahara.[52] There is still a debate whether the total desert area really expanded or just shifted southward into densely-populated and more intensely-cultivated areas, causing serious famines. There is also evidence that the climatic risk of desertification in the arid and semi-arid regions of Africa is amplified by unsustainable practices of agriculture, deforestation and cattle ranging in this region. According to some, human mismanagement of land resources is the major factor causing desertification of Africa's Sahel region.[53] And finally, climate data show that the drought was not restricted to the famine areas of the Sahel. Much higher precipitation anomalies were observed during the same

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[49] Baumgartner, A. and Reichel, E. (1975): *The World Water Balance.* Amsterdam (Elsevier Scientific Publishers)

[50] Stanhill, G. (1983): The distribution of global solar radiation over the land surfaces on earth. *Solar Energy* 31:95-104

[51] Garcia, R. (1981): *Drought and Man: The 1972 Case History. Volume 1: Nature Pleads Not Guilty.* New York (Pergamon Press)

[52] Stanhill, G. (1989): World water problems: Desertification. Pages 251-278 in S.F. Singer, ed. *Global Climate Change. Human and Natural Influences.* New York (Paragon House)

[53] *Ibid.*

period in Asia and south of the equator. The absence of serious famines in these regions indicates that factors other than climate must have caused the great African famines.[54]

While climate conditions are certainly major factors restricting the area of profitable agriculture, this does not mean that we are totally dependent. We can grow tropical fruits in cold climates or wheat in the desert. We can heat or cool, irrigate or drain cultures. This is a matter of technology, food prices and investment capital. Of course, farmers are still very much dependent on natural conditions, such as soils or climates, but they have also made great steps forward to reducing their impact. As will be discussed later, technology is the driving force of this trend.

3.4. Fossil Energy Input

Most experts agree that we could boost food production in many developing regions, if we would modernize agriculture. Crop yields in Africa and Latin America are frequently 70 to 80 percent below the European average. Modern agricultural inputs, such as nitrogenous fertilizers, irrigation, pesticides, and agricultural machinery could easily double or triple the output. With modern technology we could also reduce after-harvest losses, which are substantial in many developing countries.[55] This modernization, however, is linked to one basic factor: commercial energy. Therefore, some scientists have argued that (fossil) energy is the limiting factor for the global carrying capacity.[56]

However, available statistics and research on energy consumption in agriculture give no indication that fossil energy will be a limiting factor for agricultural modernization. Contrary to widespread belief, modern agriculture does not consume large amounts of commercial energy. On average, just 3 percent of worldwide fossil energy consumption is used in agriculture--and less than 1 percent (!) is needed for the production of (nitrogenous) fertilizers.[57] Most likely more fossil energy is needed to fly the doomsday advocates of the global food problem to their many international conferences than it would cost to produce adequate amounts of crop nutrients, pesticides and fungicides for the stagnating agricultures in Africa and Latin America.

Some critics have rejected agricultural modernization as an option for increasing global food production on the basis of its supposedly high consumption of fossil energy. They obviously misunderstood energy statistics which indicate that some 70 to 80 percent of all commercial energy is used in the food sector. While these numbers might certainly be correct, they only indicate the overall fossil energy consumption in human food chains. Most of this energy, however, is not spent in agriculture, but used for packaging, cleaning, transport, conservation, bottling, canning, refrigeration and preparation of food. As the author has demonstrated

[54] Lamb, H.H. (1982): *Climate, History and the Modern World.* London (Methuen)

[55] In some developing countries (such as India) it was estimated that up to 60 percent of the harvest is lost to mice, rats, and fungi before reaching the consumer.

[56] In 1974 *The Futurist* wrote that Lester Brown "refuses to own an automobile and uses public transportation, so that more energy can go into food production". Cited from: Smil, V. (1987): *Energy, Food, Environment. Realities, Myths, Options.* Oxford (Clarendon Press), p. 100

[57] *Ibid.*

elsewhere[58] we spend enormous amounts of fossil energy for post-harvest processing of food and for running a most energy-consuming international food distribution network. We have accepted that, for instance, French or Austrian (mineral) water is bottled and shipped to the United States of America or Australia--completely unaware that a huge amount of fossil energy is needed to produce the bottles and ship the water halfway around the globe. Most of the energy consumption in the food sector has nothing to do with agriculture, but with lifestyles, trade regulations, state subsidies, or marketing strategies. If we would discontinue only the most irrational practices in the food processing and distribution sector, we could save much more fossil energy than is needed for the modernization of agricultures in developing countries.

3.5. Conclusion: Are the Natural Resources Limited?

If we take into account the creative potential of man, there is no foreseeable limitation to the basic natural resources of food production, which are space, water, climate conditions, solar energy, and man-made inputs. All these resources are either unlimited for all practical purposes, or can be expanded, better utilized, or redesigned to a very large extent. This might be the reason why several experts have denied any upper limit for population growth. The notion of "physical limits to growth" is a faulty concept--it makes it easy for agricultural technocrats to deny any basic problems in boosting the world food supply. We have to find better arguments to convince people that global food production may be limited.

4. TECHNICAL LIMITATIONS AND CHANCES

Technology is certainly one of the most important determinants of the earth's carrying capacity. If the human race would have failed to invent agriculture some 10 thousand years ago, only a few million people could have survived on this planet as hunters and gatherers. Cut-and-burn agriculture, the next step in the evolution of human sustenance, lifted the carrying capacity to at least twice or three times the level of primitive food collectors.[59] The invention of soil cultivation and animal husbandry in stable settlements, which was the first agricultural revolution, set the ground for the big empires at the Nile, Euphrates, Tigris and along the great Asian rivers. Since World War II, the second, chemotechnological, revolution of agriculture has established a new level of sustenance. We are certainly capable of producing enough food for 5 to 6 billion people--in fact we are facing severe problems of over-production. Now the important question is whether technologies will be available that could further lift the earth's carrying capacity? And what are the restrictions and risks for their implementation?

4.1. Chances

Despite nearly hysterical criticism by some scholars, only the application of modern technology to agriculture will provide the necessary tools for increasing the earth's carrying capacity. Of course, we are not talking about a simple-minded, high-input agriculture which--for the sake of short-term increase of yields--would degrade soils, pollute groundwater or harm the environment in some other way. We are talking about the numerous technical options that could improve yields, while at the same time reducing the environmental impact of agriculture. In general these

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[58] Heilig, G. (1993): Food, lifestyles, and energy. Pages 60-86 in D.G. van der Heij, ed. *Food and Nutrition Policy.* Proceedings of the Second European Conference on Food and Nutrition Policy, The Hague, Netherlands, 21-24 April 1992. Wageningen, the Netherlands (Pydoc)

[59] See: Pimentel, D. (1984): Energy flow in the food system. In D. Pimentel and C.W. Hall, eds. *Food and Energy Resources.* Orlando (Academic Press), p. 4

technical options would be targeted to improve energy and water efficiency, re-fertilize exhausted soils, or minimize pesticide application. They would optimize crop rotation, adapt cultivation methods to local soil conditions, or prevent adverse effects of large-scale irrigation.

4.1.1. Irrigation

One possibility for increasing the earth's food production capacity is the expansion of irrigation. However, since two-thirds of the global freshwater withdrawal is already used in agriculture, it would be essential to implement only those technologies that improve irrigation efficiency, reduce water loss, and prevent environmental damage in irrigation schemes. Fortunately, there are techniques available that could achieve these objectives. We cannot go into detail but will just list a few options that are considered rather promising by agricultural experts.[60]

(a) An obvious technical option is the *conservation* of existing water resources (rather than the exploitation of new ones). In most irrigation schemes efficiency is incredible low--usually less than 25 percent of the applied water is consumed by the plants. In the United States it was possible to double water use efficiency by relatively simple means, such as laser land leveling and automatic pulsed water application.

(b) *Run-off control,* cleaning, and recycling of agricultural wastewater could also contribute to the conservation of existing water resources.

(c) A modification of *cropping practices* could save water or increase yields with available resources. For instance, farmers could switch to crops that can be grown during seasons of lower climatic water demand, which are the cooler and more humid seasons of the year. This simple measure could increase yields per unit of water by up to 50 percent. By carefully timing the planting dates, substantial yield increases are possible.

(d) Insufficient leaching[61] is one of the most serious dangers in irrigation agriculture. To avoid problems farmers tend to apply much more water to their irrigated fields than would be necessary. This frequently results in serious soil damage and has already destroyed large irrigation areas. Agricultural science and technology could *prevent* this *irrigation mismanagement.* There are methods for precise calculation and application of the water amount needed for leaching requirements, which take into account soil salinity and evaporation.

(e) Desertification and soil loss is frequently triggered by the removal of significant areas of vegetation cover, through overgrazing, cattle trampling, or deforestation. *Intelligent land-use practices* which avoid phases of total vegetation removal could substantially increase the local water availability. *Afforestation* on water catchment areas would also help to conserve the water resources.

(f) Modern technology could reduce water *evaporation losses.* The three major sources for evaporation of water in agriculture are: water storage and conveyances, irrigation systems, and plant evapotranspiration. All three can be reduced by technical means. There are several methods for reducing plant transpiration[62] but the gains are probably not too big

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[60] Most examples are from: Stanhill, G. (1989): *op. cit.*

[61] In irrigation systems a certain proportion of the water applied is not intended for the plants, but for washing out ("leaching") soluble salts which are concentrated in the topsoil by evapotranspiration. Especially in arid and semi-arid areas this practice is absolutely essential. Otherwise soil salinity would build up to toxic levels. Frequently farmers apply too much water for leaching, which is not only a waste of the resource, but also results in serious soil damage.

[62] Stanhill, G. (1986): Water use efficiency. *Advances with Agromanagement* 39:53-85

and negative side-effects are likely. Much, however, could be done to reduce evaporation in irrigation such as better timing of water application, trickle irrigation, etc. The evaporation from lakes and conveyances could be reduced by removing water plants and by building deep, instead of shallow, reservoirs. It was estimated that Lake Nasser, dammed by the Aswan high dam, is losing more water by evaporation than it makes available for irrigation.[63]

(g) *Water harvesting* is also a very attractive technical option to increase local water resources for agriculture. There are several possibilities: One can use special kinds of fences at high altitude to "milk" water out of clouds, as is being done in some places of the Andes mountains. A very cost-efficient method is cloud seeding. Certain chemicals are used to increase the number of condensation nuclei in the atmosphere which can trigger precipitation.

(h) And finally we can exploit previously neglected sources of water, such as the large bodies of brackish water. There are also great rivers that are practically unused for irrigation, such as the Shari and Logone rivers in Chad.[64] Their combined water flow is comparable to Egypt's withdrawal from the Nile. Well-designed irrigation schemes could make the desert bloom.

As we have demonstrated above, many arid and semi-arid countries in Africa have vast resources of fertile soils. If these countries would be able to apply proper irrigation technology to these lands (such as Israel did under similar climatic conditions) they could increase food production by orders of magnitude.

4.1.2. Breeding, Bio-engineering

Apart from irrigation there are many technological options to boost rainfed agriculture. We have just started to explore the potential of bio-engineering for increasing crop yields[65] and livestock efficiency.[66] In a few years or decades the "creation" of new plants by techniques of bio-engineering could replace traditional breeding techniques. This would speed up the process of adapting animal and plant species to marginal environments such as arid regions or wetlands. The new techniques could also lead to high-yield food and feed crops which bind nitrogen from the air and thus require less input of fertilizers. There is also speculation about bio-engineering plants and animals which have a "natural" resistance against many kinds of diseases which would reduce the consumption of pesticides and animal medicines. Most experts agree that all this could possibly boost food production by orders of magnitude.[67]

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[63] Stanhill, G. (1989): *op. cit.,* p. 268

[64] Melamed, A. (1989): Commentary on Gerald Stanhill's paper. Pages 279-281 in S.F. Singer, ed. *Global Climate Change. Human and Natural Influences.* New York (Paragon House)

[65] Gasser, C.S. and Fraley, R.T. (1989): Genetically engineering plants for crop improvement. *Science* 244 (16 June 1989):1293-1299

[66] Pursel, V.G., Pinkert, C.A., Miller, K.F., Bolt, D.J., Campbell, R.G., Palmiter, R.D., Brinster, R.L., and Jammer, R.E. (1989): Genetic engineering of livestock. *Science* 244 (16 June 1989):1281-1288

[67] Holló, J. (1986): Foreseeable developments in food production and processing. In: United Nations, Economic Commission for Europe: Biotechnology and Economic Development. Papers from the Economic Commission for Europe Symposium on the Importance of Biotechnology for Future Economic Development, June 1985, Szeged, Hungary. Published as *Economic Bulletin for Europe* 38(1). Oxford (Pergamon Press)

Photosynthesis is the complex and still poorly understood biochemical process by which plants build up biomass. It is fueled by solar radiation energy, and needs, among other things, atmospheric carbon, plant nutrients, and water as inputs. Until today not much could be done to increase the overall efficiency of the process--if we forget about artificially CO_2-enriched atmospheres in glasshouses. However, there is a chance that recent advances in biochemistry and plant genetics can somewhat improve the net-efficiency of photosynthesis by reducing the respiratory losses of CO_2.[68] The gains will probably not be spectacular in food grain, but it is possible that animal food with very high photosynthetic efficiency can be bio-engineered.

4.1.3. Food Processing

Much can also be done to optimize post-harvest crop processing, drying, transport and storage. In some parts of the Third World (such as India) enormous amounts of food and feed crops are lost to mice, rats, and fungi. Improper storage and transport frequently causes after-harvest losses of up to 40-50 percent. Much can also be done to improve the processing, transport and preparation of food. Most people are not aware that some 90 percent of fossil energy use in a food chain is linked to non-agricultural activities--only 5 to 10 percent is consumed on the farm. Also, if we would reduce meat consumption in Europe and Northern America by a few percent we could save enormous amounts of grain. And finally, we could boost the productivity of agriculture by optimizing system integration of farms, such as linking energy generation (biogas) and livestock production.

4.1.4. Synthetic Food Production

Finally, there is the option of synthetic food production. Those who shiver from abhorrence about this possibility should think twice. We are already using considerable amounts of artificial ingredients in our food. The yeast in our beer and bread is industrially produced in bio-converters; citric acid and hundreds of food preservatives are manufactured by the biochemical industry.[69] The taste of fruit yoghurt is usually a synthetically re-designed and enforced "natural" flavor. The colors of meat sausages or fruit juices often come straight from the chemical laboratory. In a not-too-distant future it is possible that we will produce "synthetic" meat or vegetable protein in cell cultures. If this perspective affects your appetite it is just because you are not familiar with what we currently do in slaughter houses or chicken farms all over the world. Actually, it might be more humane to feed a 10 or 12 billion world population on bio-engineered protein than to breed and kill millions of animals or convert the last natural ecosystems into paddy rice fields.

A big step toward synthetic food production was recently made in Japan, when 12 "lettuce factories" started business. They look like high-tech electronic laboratories: the "lettuce farmers" wear white gloves and breathing masks. The production sites are so-called "clean rooms"--hermetically isolated and sterilized chambers which prevent the introduction of fungi, insects and crop diseases. There is no soil, rainfall or sun. The lettuce is grown on a synthetic fiber, the roots are automatically sprayed with fertilizer-enriched water, radiation energy (for photosynthesis) is applied by special electric lights. Lettuce output is ten times that of natural cultivation and highly profitable. The taste of this "high-tech" lettuce cannot be distinguished from the naturally grown plant. Rash critics might jump to the conclusion that this high-tech production is rather

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[68] Smil, V. (1987): *op. cit.*, p. 165-166

[69] The richest Austrian (Mr. Kahane) made his fortune by producing citric acid for the European food industry.

energy-inefficient as compared to conventional cultivation. But this is most likely not the case. While more fossil energy is used to control the production environment (heating, lighting, irrigation), much less is needed for production of pesticides, fungicides, weed killers, and insecticides, because of the sterile growing conditions. Moreover, high-tech cultivation needs much less space and can be located close to the consumers, such as in the middle of a city. Thus, enormous amounts of fossil energy for transportation, conservation and storage can be saved. (Usually, the fossil energy consumption needed for the production of lettuce and other vegetables is a small fraction of the energy that is spent in packaging, transportation, and storage of the product.) In some Japanese supermarkets lettuce is already produced directly on the spot and "harvested" by the sales personnel according to demand. It is very likely that the urban agglomerates of the 21st century will be supplied locally with vegetables and fruits. This is not science fiction. A large proportion of the tomatoes, cucumbers, zucchini, and eggplant we eat in Europe are already produced in a similar way in the high-tech greenhouses of the Netherlands.

4.2. Limitations

After reading the previous paragraph one might have the impression that the author considers technology the "golden key" to opening the earth's unlimited resources of food. But this is not the case. Agroscience and agrotechnology, of course, have limitations and dangers.

First, there are unintended side-effects of agricultural technology. Especially the input-oriented, large-scale technology of the 1970s and early 1980s has caused many problems, such as soil degradation, over-fertilization, salination or water logging in irrigated soils, groundwater pollution and toxification of agricultural workers by pesticides, etc. These problems are usually caused by lack of know-how, poor management techniques, faulty maintenance of irrigation systems and agricultural machinery, or simply by corruption and ignorance.

Second, we have consequences of agricultural modernization and expansion that were well predicted but seem to be inevitable. When farmers transform natural ecosystems into cropland or meadows, they inevitably disturb their biological balance. A new, artificial balance has to be reestablished. This requires careful planning and proper long-term management of soils, water sources, and infrastructure. One of the greatest threats to natural ecosystems--such as the tropical rainforests--is the "unconfined cut-down, plant and move" exploitation by poorly trained, inexperienced farmers (or ignorant and cynical agro-businesses).

Third, there is the problem of education and socio-cultural adaptation. It is obvious that not every culture and ethnic group is flexible enough to learn new ways of food production. Chinese farmers, for instance, quickly adapted to using modern technology when the government abandoned many restrictions of the communist economy during the 1970s. Within a few years China experienced one of the most spectacular increases in nitrogenous fertilizer consumption and tractor use--and a tripling of cereal production. Compare this to Nigeria, the oil-wealthy African nation! The country has all the resources (including capital, land, water, and fossil energy for fertilizers) to make it the breadbasket of Africa. But the agriculture has stagnated for the last three decades.

And finally, there are enormous costs for implementing a more efficient agricultural technology. We are not only talking about the farmers who need investment capital. There is also the need for upgrading the general infrastructure. Agricultural modernization requires a steady supply of inputs (fertilizers, water for irrigation, crop sanitation products) for which working transportation and distribution systems have to be implemented. There are also significant social costs. Agricultural modernization inevitably increases the pressures on the rural labor force. Both farmers and landless agricultural workers have to adapt to new methods and conditions. They must accept retraining and technical education, and there are always groups of the population that lack the necessary flexibility for change. It is also very likely that agricultural modernization will produce rural unemployment, even if labor-intensive production methods are applied.

5. ECOLOGICAL LIMITS

Ecological constraints and feedback mechanisms are frequently considered limiting factors of growing food production.[70] Currently scientists discuss four types of problems: (1) The expansion of agricultural areas and the increase in the catch of fish could destroy large ecological systems. This would lead to a reduction of biodiversity in the fauna and flora and diminish the global gene pool. (2) The increase of agricultural inputs, such as fertilizers, pesticides, fungicides, weed killers, and other chemicals could pollute groundwater bodies, lakes and seas. It could change the chemistry of the soils and speed up soil erosion. (3) Genetically modified plants (and animals) could be a danger to the natural environment. And finally (4) a significant increase in food production could even change the global climate; emissions of greenhouse gases, such as methane, could dramatically increase due to the expansion of livestock and paddy rice production. What evidence do we have that these ecological consequences are in fact unavoidable?

5.1. Shrinking of Natural Ecological Systems

There is little doubt that feeding an ever-growing number of people will further diminish the living space of other species. For many kinds of wild animals we will leave only small niches of natural ecosystems. This competitive race between man and other living creatures (including plants) can probably not be avoided. It seems to be an evolutionary constant. The best we can hope for is that we will be able to preserve key natural habitats in order to stop further extinction of species. The only realistic protection of the planet's natural "gene pools" and "green lungs", such as the Amazonas, is a combination of strictly-managed natural parks and careful economic utilization with a minimum of environmental damage. If we want to reserve the tropical rainforests exclusively for butterfly catchers, anthropologists and botanists in the face of millions of landless hungry farmers, we will have to answer some tough questions on our moral standards.

Food production, however, is not the only activity that tends to diminish natural ecosystems. The spread of human settlements, infrastructures and industries must be added to a possible expansion of agricultural land. Undoubtedly, the human race is changing the surface of the earth with unprecedented speed.

5.2. Soil Degradation (Acidification, Soil Loss) and Water Pollution

There are many agricultural practices which can have a destructive impact on the environment. Excessive use of fertilizers can contaminate the groundwater; crop monocultures and unsuitable tillage practices can aggravate soil erosion; the use of pesticides poses health risks on farm workers and the runoff can pollute the groundwater. There are concerns that "artificial" pest and weed control can trigger the emergence of resistant animal and plant species, which in turn would require the further increase of pesticides. In some parts of Europe we have industrial-size livestock production systems which produce enormous amounts of manure. If the manure is not properly processed and just spread in large quantities on crop fields and meadows it can run off

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[70] Chen, R.S. (1990): Global agriculture, environment, and hunger. Past, present, and the future. *Environmental Impact Assessment Review* 10:335-358

into rivers and lakes, seep into the groundwater or increase the already existing nitrogen overload of the soil. In Africa's pastoral societies overgrazing and trampling by cattle is an enormous problem.

These environmental risks of agriculture are well known and certainly diminish the actual carrying capacity of many regions. One of the most recent studies conducted by the International Soil Reference and Information Center in Wageningen has estimated that agricultural activities have caused moderate to extreme soil degradation of 1.2 billion hectares worldwide--which is about the combined size of China and India.[71] This does not mean that the soils are completely lost for agriculture, but that their natural fertility is more or less diminished. The impact of agriculture on the water is also well documented: Some 25 percent of the population in the European Community are already drinking water with a nitrate level greater than the recommended maximum of 25 milligrams per liter.[72] Pesticides can be found in the groundwater of 34 states of the United States of America.

These are serious problems of intensive crop and livestock production, but there is no reason why we should not be able to solve them. With modern technology, agricultural know-how and better agricultural policy, it would be possible to expand food production, while at the same time reducing its environmental impact. A good example is Europe's agriculture. Contrary to widespread belief the farmers did not just proceed with their practices of over-fertilization and mindless use of pesticides (which they in fact had adopted during most of the 1970s and 1980s). If the FAO statistics are correct the consumption of nitrogenous fertilizers significantly declined during the past six or seven years in most European agricultures, while the production increased. In all of Europe the consumption of nitrogenous fertilizers fell from some 15.1 in 1983/84 to about 13.6 million tons in 1990/91--a decline of more than 10 percent.[73] In West Germany the farmers consumed 1.52 million tons in 1985; four years later consumption was down to 1.48 million tons.[74] The fertilizer input in kg per hectare of cropland fell from 464 to 404 between 1977/79 and 1987/89.[75] Modern methods of crop management try to optimize--rather than maximize--the input of crop nutrients and pesticides. We also have to take into account that in large parts of the Third World, especially in Africa, fertilizer consumption is a small fraction of what is typical in Europe or some Asian countries. Even if these farmers would double or triple fertilizer consumption they would be far away from the levels that are typical for high input agricultures.

5.3. Risks of Genetic Engineering and Advanced Breeding Practices

Previously we have mentioned that genetic engineering could be a great opportunity for increasing food production, especially if we could breed drought and pest resistant crops; but it

[71] Oldemann, L.R., Hakkeling, R.T.A., and Sombroek, W.G. (1990): World Map of the Status of Human Induced Soil Degradation. An Exploratory Note. Wageningen (International Soil Reference and Information Center)

[72] Gardner, B. (1990): European Agriculture's Environmental Problems. Paper presented at the First Annual Conference of the Hudson Institute, Indianapolis, Indiana, p. 5

[73] FAO (1992): *Fertilizer Yearbook.* Rome (FAO), p. 56

[74] FAO, AGROSTAT

[75] The World Resources Institute/The United Nations Environment Programme/The United Nations Development Programme (1992): *op. cit.*, p. 275

could be also a danger. There was much concern that genetically-manipulated plants and animals could "escape" control and drive out other natural species from their habitat. There were also several other unintended side effects under discussion. However, recently governments in Europe and Northern America have loosened restrictions for field experiments with genetically-modified plants. They obviously consider the risks rather low as compared with possible benefits.

5.4. Climate Change

In theory, there are two links between climate change and global food production. First, the expansion and intensification of agriculture, which is necessary for sustaining the growing world population, could be a driving force for global warming. Emissions of methane (CH_4), which is the third most important greenhouse gas, could increase when livestock and paddy rice areas are expanded. (Livestock and paddy rice areas are important sources of anthropogenic methane emission to the atmosphere.[76]) And agricultural mechanization could boost CO_2 emissions. The second link between climate change and agriculture works the other way round: there is concern that global warming could reduce (or increase) agricultural output. One of the most detailed approaches to the problem was IIASA's "integrated climate impact assessment" which--for the first time--not only analyzed first-order consequences of global warming to agriculture, but also second-order impacts.[77] This is not the place to comment or analyze this major scientific study, but it might be interesting to note that Parry and Carter are very cautious about the predictive validity of their research. In a "Summary of Results" they write:

> The estimates reported in this volume are *not predictions* of future effects [italics by Parry/Carter]. Present-day uncertainties and inaccuracies in simulating the behavior of the world's climate and in evaluating the agricultural implications of climatic change do not permit realistic predictions to be made. Furthermore, we cannot forecast what technological, economic and social developments in agriculture will occur over the next half century. The estimates should therefore be considered as measures of the *present-day sensitivity* [italics by Parry/Carter] of agriculture to climate change.[78]

No doubt, there are links between climate and agriculture, but it is also obvious that these links are not just simple one-way causations. They work through a complex system of intermediate variables, which can modify their strengths and turn them around from positive to negative (and vice versa). The most important intermediate variables are the availability of advanced technology, the existing economic arrangements, the political situation, and the level of education and training among the farmers. If farmers have no access to advanced technology, are hampered by poor education and training, or are restricted by stupid economic arrangements, a worsening of climate conditions (such as the increase of drought or unstable precipitation) can seriously diminish agricultural output. However, the climate change could also have the opposite effect: it could trigger the development of advanced agricultural methods, which in the end are even

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[76] Heilig, G. (1993): The greenhouse gas methane: Sources, sinks and possible interventions. Forthcoming in *Population and Environment*

[77] Parry, M.L., Carter, T.R., and Konijn, N.T. (Eds.) (1988): *The Impact of Climate Variations on Agriculture.* Vols. 1 and 2. Dordrecht (Kluwer)

[78] Parry, M. and Carter, T. (1988): The assessment of effects of climatic variations on agriculture: Aims, methods and summary of results. Page 69 in M.L. Parry, T.R. Carter, and N.T. Konijn, eds. *The Impact of Climate Variations on Agriculture.* Vol. 1. Dordrecht (Kluwer)

more productive. Israeli and Finnish farmers, for instance, have demonstrated that high productive agriculture is possible under very harsh--and rather diverse--agroclimatic conditions.

Our knowledge is too limited to decide whether the projected climate change would reduce global carrying capacity. However, we believe that a possible (but by no means certain) global warming would be a gradual process, which would give us enough time to adapt the socioeconomic framework of agriculture and implement new technologies in order to counterbalance its negative effects.

6. SOCIAL, ECONOMIC AND POLITICAL DIMENSIONS OF CARRYING CAPACITY

For decades the scientific discussion on the food-population nexus has avoided a key issue. While scientists spent their time elaborating hypotheses with rather weak empirical evidence (such as the "law of diminishing returns") or engaged themselves in intellectual self-gratification by building all kinds of complex models of global carrying capacity, they mostly ignored the political, social and economic dimension of food production. The news media, however, reported the facts on a day-by-day basis: In most cases it was colossal policy failure which has caused widespread undernutrition and famine during the past four decades. Agricultural stagnation and food deficits were usually unrelated to a shortage of soil, water, rainfall, fossil energy or investment capital. They were also unrelated to high population growth. Typically, food crises could be found where social, cultural and economic conditions have prevented agricultural modernization, as in large parts of Africa, Asia and Latin America.

There are so many socio-cultural constraints to agricultural modernization that we could dedicate the whole paper to this problem. Due to limitation of space we just mention some of the most important factors:

(a) **Policy failure:** The most serious famines in recent times had nothing to do with population pressure, crop failure or natural disasters. They were either (1) directly and intentionally triggered by scrupulous regimes as a means for executing their political strategies (as the Khmer Rouge did in Cambodia[79/80]), (2) accepted as necessary side-effects of coercive development measures (as in China's Great Leap Forward during the Mao Tse Tung era[81]) or (3) simply emerged from cynical ignorance, because the regimes were more interested in other political and military issues (as in most civil wars of Africa from Ethiopia to Somalia).[82]

(b) **False economic policy and corruption:** The stagnation of agricultural production in some parts of the Third World--especially in Africa south of the Sahara and in parts of Latin America--was closely related to the notorious inefficiency, massive corruption, unbelievable

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[79] Becker, E. (1986): *When the War Was Over. The Voices of Cambodia's Revolution and Its People.* New York (Simon and Schuster)

[80] Barnett, A., Kiernan, B., and Boua, C. (1980): The bureaucracy of death--documents from inside Pol Pot's torture machine. *New Statesman*, May 2, London

[81] Bernstein, T.P. (1984): Stalinism, famine, and the Chinese peasants. Grain procurements during the Great Leap Forward. *Theory and Society* 13:339-377

[82] Griffith, I. (1988): Famine and war in Africa. *Geography* 73(1):59-61

incompetence, and ideological blindness of political leaders and their administration. Many of these incompetent regimes in Africa simply transplanted the Soviet model of a centrally planned command economy to their pre-industrial society. They eliminated traditional market mechanisms by fixing food prices on very low levels to appease urban masses.[83] They collectivized most of the fertile land (as in Ethiopia) and forced the farmers to sell their production to state-owned trade agencies for prices that were close to production costs (as in Tanzania). The ideologically legitimized lack of incentives demotivated the farmers and prevented agricultural modernization.[84] In Latin America military regimes stabilized feudalistic rural societies and prevented agricultural modernization. Very often these disasters of agricultural policy were joined by a general failure of development policy. The political and administrative elites in many developing countries of Africa and Latin America did little to modernize infrastructure, neglected technical education and training, and blocked industrial modernization. Huge amounts of development aid were wasted on expensive but useless prestige projects or simply vanished to the (Swiss) bank accounts of the small ruling class. Even "rich" countries, such as exporters of oil and other natural resources (Nigeria), neglected the agricultural sector.

(c) **Social inequality:** There is still chronic undernutrition and hunger among certain groups of the population in food surplus countries such as India or Indonesia. However, this kind of food problem can also be found in highly developed, affluent societies such as the United States of America. It is a problem of distribution and has nothing to do with the availability of food. Lack of entitlements to acquire adequate food in the lowest classes of society are the cause of the problem. The class and cast structure of some societies also prevents adequate distribution of agricultural land.

(d) **Development of human resources (health, education):** Much land in the Third World cannot be cultivated in the most efficient way because the farmers are suffering from chronic diseases (malaria, river blindness) or are hampered by lack of education and agricultural know-how. Several studies, for instance, have shown the impact of malaria among rural populations on food production.[85] A dramatic situation is evolving in parts of Africa and Asia (Thailand) because of AIDS. The spread of this disease among rural populations in Eastern Africa has already made a measurable impact on food production.[86]

(e) **Traditions:** There are many traditions that help people to improve their sustenance. Especially agricultural societies have developed numerous rules, habits, taboos and traditions to prevent food crises, maintain soil fertility, or improve the environment for the next generation. Consider the traditional rules of crop-rotation or the tradition to plant a tree on certain occasions. Unfortunately there are also cultural values that prevent agricultural modernization and a full utilization of resources. For instance, in most of

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[83] Bale, M.D. (1981): Price distortions in agriculture and their effects. An international comparison. *American Journal of Agricultural Economics* 63(1):8-22

[84] Bates, R.H. (1981): *Markets and States in Tropical Africa--The Political Basis of Agricultural Politics.* Berkeley (University of California Press)

[85] Bradley, D.J. (1991): Malaria. Pages 190-202 in R. Feachem and D. Jamison, eds. *Disease and Mortality in Sub-Saharan Africa.* New York (World Bank, Oxford University Press)

[86] Norse, D. (1991): Socioeconomic Impact of AIDS on Food Production in East Africa. Paper prepared for the VII International Conference on AIDS, Florence, Italy, 16-21 June 1991

Africa agriculture is considered low-prestige women's work. It is part of their household duties--in addition to cooking and caring for the children. Whenever a man can afford to avoid working in a field, he will do so. This traditional disregard of food production, deeply embedded in African men, can be also found in development plans and investment decisions of African governments.

7. DISCUSSION

We have demonstrated that culture and food are closely related. A society can only develop sciences, technology and arts when it has a highly productive system of food supply. As long as everyone is busy collecting or hunting food, no real development as we know it is possible. We can study this link between development and food in early agricultural societies which emerged in the alluvial lowlands and river floodplains of Africa and Asia. These ancient people developed complex social and economic systems, which included bureaucratic hierarchies and specialized professions. The social differentiation was necessary to solve typical problems of agriculture, such as water management or storage administration. The societies also institutionalized mechanisms of conflict resolution--for instance, to settle conflicts of water distribution and land ownership--and they developed cognitive systems which helped them to understand and predict the natural cycles of floods and rainfalls. They also managed to establish a stable (if not always peaceful) relationship with their neighbors. This social and cultural framework was essential for making their agriculture prosper and, in turn, the highly productive agriculture propelled the social and cultural development. In his many books on Indonesia, Clifford Geertz has studied these dialectics of development in an agricultural society.[87]

In today's traditional societies of hunters, food collectors or cattle rangers the carrying capacity of land is not only low, as compared to an agricultural society, because these societies lack certain technical means (such as ploughs) and economic structures (such as markets). They also lack specific cultural values and social institutions. One of the most serious restrictions which hinder the full exploitation of Africa's carrying capacity is embedded into the cultures and societies of some of its people. When East African governments tried to turn nomadic cattle rangers (such as the Massai in Kenya) into settled farmers they were bound to fail. The world's view of this nomadic tribe just did not fit into an agricultural society. This is the tragedy of the few remaining endogenous people of Africa, Asia and Latin America. Their existence depends on a fixed balance of people and land. They are in a process of losing this balance because of two trends: population growth and/or shrinking of their land.

While the balance of people and food in traditional societies is getting more and more fragile, the phenomenon does--of course--not indicate that they are already approaching the (absolute) maximum carrying capacity of their land. They have just failed to adapt their culture and mode of production to new conditions of population density and/or land availability. In the end, other people with better technology and a more flexible social and economic organization will drive them out of their environment. One might not like this brutal fight for dominance, but it is precisely what is happening to the Indians of the Amazon or to some nomadic tribes in Africa.

This fight for dominance with the help of (better) technology and more flexible socioeconomic arrangements goes on not only between endogenous tribes and majority populations, but also between whole nations and continents. The political, social and economic disaster in some developing countries of Africa and Latin America is so obvious because it is in such sharp

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[87] Geertz, Clifford (1963): *Agricultural Involution: The Process of Ecological Change in Indonesia.* Berkeley (University of California Press)

contrast to the roaring success of some developing nations in Asia. Consider the case of China: When China's leaders finally abandoned collectivization, when they diminished central planning of agriculture and introduced market mechanisms, the food sector began to boom--since the early 1960s cereal production more than tripled and meat production increased tenfold. In India and Indonesia cereal production more than doubled. India, which was notorious for its succession of severe famines, achieved self-sufficiency of food during the last decades. Thailand, Malaysia and China combined the rapid growth of domestic food production with enormous growth rates in other sectors of the economy. Currently China is worrying about its 12 percent annual growth rate of the GDP (they are afraid of an "overheating economy").

From a system-analytic point of view most studies on carrying capacity are surprisingly unrealistic in their economic and social assumptions. They usually define carrying capacity in terms of direct agricultural self-supply as a population supporting capacity of land, given a certain level of agricultural technology. This concept might be sufficient to describe traditional rural societies which lack strong division of labor, international trade, political organization, science and industry. But this concept is inadequate for today's functionally differentiated societies and economies. Here the division of labor expands from the household to the national economy and the international market. During the last decades Arab nomads in the deserts of Saudi Arabia could feed their families quite well from the scarce land by selling the oil resources underneath on the world market, for instance, to French farmers who in turn produced a significant proportion of their meat supply.

Today, the supply of food, which once was a simple process of collecting, hunting or self-sufficient local agriculture, has evolved into a complex international network of production activities, industrial processes, market and price mechanisms, trade arrangements, food policies and distribution channels. At each stage of this widely expanded food chain we might find conditions that could limit the food supply of a population. It might be a shortage of fertile soils or water, adverse climate conditions, or a lack of fossil energy for fertilizer production. But the limitation might also arise from widespread analphabetism and a lack of agricultural know-how in a population; it could be caused by the persistence of inefficient market structures and production regulations; or it might be the consequence of international trade restrictions.

The carrying capacity of the earth not only depends on its natural resources or the level of technology, but essentially on the quality of our worldwide economic, social and political arrangements. Land, water, climate and energy are just four parameters in the much more complex set of equations for the earth's carrying capacity. These equations must describe the world as a system of interdependencies--a system of exchange mechanisms (food trade) and complementary production activities, which can counterbalance regional variations in the density of natural and human resources. Today, carrying capacity cannot be defined on a purely local or regional level. It cannot be calculated from the availability of natural resources. We know that the natural supporting potential of land can only be realized if there are educated and trained people who can live in peace, who have access to (world) markets, who can use modern agricultural and industrial techniques and inputs, and who are not punished and demotivated by a centrally-planned command economy.

8. CONCLUSION

How many people can be fed on earth if we take into account technical, ecological, political, and social constraints? Most experts would probably agree that we could sustainably supply the current 5.5 billion world population. At the moment European governments are pressing their farmers to reduce food production; grain is cheap on international markets, and Asian countries are harvesting bumper crops year after year. The scandal of famines in Africa is not a result of agriculture approaching carrying capacity--it is mostly a consequence of massive policy failures, corruption, ethnic conflicts, ignorance, and incompetence of ruling elites. There are different and more complex reasons for widespread undernutrition in some parts of Asia, but they have nothing to do with natural limitations. Certain groups of the population lack the means to acquire food, which would be available in principle. Here we obviously have the socioeconomic and cultural problems of uneven distribution of entitlements. Latin America has vast resources of land, freshwater, and--at least in some cases--oil-money. The real problem is the feudalistic distribution of land which prevents a more efficient agriculture.

But could we also feed 10 or 15 billion people? Most likely, if we can prevent (civil) wars with soldiers plundering harvests or devastating crop fields with land mines; if we can stop collectivization and central planning in agriculture; if we can agree on free (international) trade for agricultural products; if we redistribute agricultural land to those who actually use it for production; if we provide credits, training, and high yield seeds to poor farmers; if we can adapt the modern high-yield agriculture to the agroclimatic and socio-cultural conditions of arid regions, and if we use it carefully to avoid environmental destruction; if we implement optimal water management and conservation practices. If we do all this during the next few decades, we would certainly be able to feed a doubled or tripled world population.

But there are many "ifs" in our conclusion. Almost certainly, business as usual will not provide the conditions which are necessary for feeding the world population of the 21st century. We need fundamental political, social, and economic changes, especially in Africa, Latin America and parts of Asia. Only a democratization in these regions will open the gates for the development of human resources, for better education and training, for private economic initiatives and functioning markets.

There are positive and negative signs that this change will be possible: The governments of China, India and some other Asian countries have removed economic controls which chained down agricultural productivity; they have provided a relatively stable political environment and they have actively supported agricultural modernization (the "Green Revolution"). Consequently, they doubled or tripled domestic food production within two or three decades. Many African governments, on the other hand, neglected the agricultural sector. They introduced rigid methods of central planning, suppressed free markets, and collectivized or coercively resettled the farmers. They did not stop the devastation of agricultural areas due to civil wars, and they mostly failed in introducing modern techniques of crop production and livestock management. It is no surprise that per capita food production stagnated or declined in most parts of Africa during the last three decades.

Let us do a simple exercise: How many people can be fed in Sudan? The FAO estimated that on a low input level the country's arable land could sustain nearly 60 million people--3.7 times the actual population of 1975 (which was 16 million); a high-input agriculture could even supply 1.036 billion (!) Sudanese, which would be twice the actual population of Africa. All we hear from Sudan, however, is the persistent resurgence of famines and the slow degeneration of the agricultural system. Theoretically, Sudan could be the corn-belt of Africa--in practical terms it is one of the continent's famine areas. On the other hand the FAO estimated that Algeria's agroclimatic conditions could support only 7 million people at low inputs and 24.6 million at medium inputs. Currently Algeria has a population of 25 million and not much is heard about food shortages in this country. Given the substantial restraints and difficulties that can slow down or even prevent the--theoretically almost unlimited--increase of global food production, we have to cut down our expectations. It is unlikely that the world food problem will be solved within the next decades, despite the fact that it would be possible in theory. There are serious social, economic, and political limits to growth.

We should return to the initial concept that visualizes the problem of carrying capacity in a pipe with declining diameter. Using this image, we can conclude that the key for balancing people and food is the speed with which the social, economic, cultural and political constraints are pushed back that hinder people to utilize the full potential of the earth's food resources in a sustainable way. If we can open the pipe quickly enough, if we can stop some of our collective stupidities, we could produce more than enough food for the people of the 21st century. The carrying capacity of the earth is not a natural constant--it is a dynamic equilibrium, essentially determined by human action.

APPENDIX TABLES

Table 1. Potential population supporting capacity in 1975 by input level. Source: FAO/UNDP/IIASA (1982): *op cit.*

	Actual Population 1975	Potential Population, 1975		
		Low Input	Medium Input	High Input
Africa	380.2	1,121.9	4,391.0	12,872.5
Southwest Asia	136.3	107.3	173.0	267.7
Central America	106.6	175.5	451.5	1,226.6
South America	215.8	1,313.7	5,187.0	12,349.3
Southeast Asia	1,117.7	1,247.5	3,376.7	5,690.6
Total	1,956.6	3,965.9	13,579.2	32,406.7

Table 2. Potential population supporting capacity in 2000 by input level. Source: FAO/UNDP/IIASA (1982): *op cit.*

	Actual Population 2000	Potential Population, 2000		
		Low Input	Medium Input	High Input
Africa	780.1	1,253.7	4,488.6	12,868.1
Southwest Asia	264.8	180.1	239.6	324.8
Central America	215.2	292.3	556.7	1,293.4
South America	392.6	1,417.6	5,288.3	12,375.3
Southeast Asia	1,937.7	2,463.6	4,358.3	6,333.7
Total	3,590.4	5,607.3	14,931.5	33,195.3

Table 3. Selected countries with massive surplus of land resources in 1975 by input level. Source: FAO/UNDP/IIASA (1982): *op cit.*

	Actual Population 1975	Potential Population, 1975 (Carrying Capacity of Land)		
		Low Input	Medium Input	High Input
Angola	6.2	53.2	279.2	931.3
Argentina	25.4	151.8	437.9	924.1
Bolivia	4.9	77.9	309.0	726.6
Cameroon	7.5	76.8	209.2	612.9
Central African Rep.	2.0	44.8	211.8	597.7
Congo	1.4	40.4	162.4	405.4
Gabon	0.5	41.8	126.8	280.5
Paraguay	2.6	34.4	128.4	309.7
Sudan	16.0	59.4	238.7	1,036.4
Zaire	24.5	291.9	1,281.0	2,887.7

Table 4. Selected countries with massive surplus of land resources in 2000 by input level. Source: FAO/UNDP/IIASA (1982): *op cit.*

	Actual Population 2000	Potential Population, 2000 (Carrying Capacity of Land)		
		Low Input	Medium Input	High Input
Angola	11.8	53.1	276.7	929.3
Argentina	32.9	169.2	450.9	937.8
Bolivia	9.3	80.0	310.6	727.2
Cameroon	13.0	76.5	208.2	608.6
Central African Rep.	3.6	44.8	212.1	596.9
Congo	2.5	40.6	162.3	404.8
Guyana	1.3	27.9	107.0	257.5
Malaysia	20.2	91.8	260.0	237.4
Zaire	46.2	290.6	1,282.2	2,874.2
Zambia	10.4	48.7	214.7	762.9

Table 5. Selected critical countries with massive land resource deficits in 1975 by input level.*
Source: FAO/UNDP/IIASA (1982): *op cit.*

	Actual Population 1975	Potential Population, 1975 (Carrying Capacity of Land)		
		Low Input	Medium Input	High Input
Bangladesh	76.6	35.4	100.6	160.8
Egypt	36.9	61.6	61.6	61.6
Iran	32.7	28.4	38.2	54.1
Yemen, AR	5.3	2.5	3.7	7.7
Pakistan	70.3	80.1	87.2	95.9
Afghanistan	19.3	12.0	15.0	20.5
Israel	3.5	1.3	2.1	3.1
Saudi Arabia	7.2	1.5	1.9	4.7
Jordan	2.7	0.6	1.1	1.4
Lebanon	2.8	0.7	1.2	1.4

* We did not include small Gulf states with less than 1 million population (United Arab Emirates, Bahrain, Kuwait, Qatar, and Oman) and small islands (Cape Verde, Antigua, Barbados, Mauritius, Neth. Antilles, Singapore). All of these also have very critical land resource deficits.

Table 6. Selected critical countries with massive land resource deficits in 2000 by input level.*
Source: FAO/UNDP/IIASA (1982): *op cit.*

	Actual Population 2000	Potential Population, 2000 (Carrying Capacity of Land)		
		Low Input	Medium Input	High Input
Jordan	5.9	0.9	1.3	1.6
Lebanon	4.9	1.1	1.5	1.6
Saudi Arabia	15.3	2.7	3.0	5.8
Israel	5.6	1.8	2.3	2.8
Afghanistan	36.7	15.9	18.8	24.3
Rwanda	9.0	0.7	3.4	7.7
Yemen, AR	10.0	3.4	4.7	9.0
Iran	65.4	41.3	51.0	66.8
Bangladesh	153.3	120.7	149.5	185.2
Iraq	24.3	9.2	18.5	29.8

* We did not include the smaller Gulf states (United Arab Emirates, Bahrain, Kuwait, Qatar, and Oman) and small islands (Cape Verde, Antigua, Barbados, Mauritius, Neth. Antilles, Singapore). All of these also have very critical land resource deficits.