

Long-term global availability of food: continued abundance or new scarcity?¹

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Niek Koning, Martin van Ittersum, Gertjan Beex, Tiny van Boekel, Willem Brandenburg, Joep van den Broek, Jan Goudriaan, Guido van Hofwegen, Roel Jongeneel, Hans Schiere, Maarten Smies

“Over a thousand years ago the Chinese had a system which they called the "ever-normal granary." ...[W]hen the crops went beyond a certain size and prices below a certain point, the government was empowered to buy grain and put it into the government-owned warehouses. Here it stayed until a year came when the crop went below a certain point... [If] we had a really intelligent comprehension of agricultural statesmanship, we would work out in this country a combination of the Chinese idea of an ever normal granary with a common sense handling of our surplus.” (Henry Wallace in Wallace’s Farmer, October 8, 1926)

“As part of the effort to win the peace, I am hoping that ... the "ever normal granary principle" can be established for a number of commodities on a world-wide scale. ...[T]he fourth point ... in the Atlantic Charter mentioned the enjoying by all the states, great or small, victor or vanquished, of access on equal terms to the raw materials of the world. To give this lofty ideal a more definite substance should be one of our chief objectives...” (Henry Wallace as vice president of the US, Atlantic Monthly, January 1942)

Abstract

Between now and mid-century, the global demand for phytomass for food will more than double. At the same time, competing claims on natural resources for urbanization and new non-foods will strongly increase. We combine insights from the natural and the social sciences to discuss the feasibility of a sufficient increase in world food production in this situation. A sober assessment of the technical potential for increasing production still shows that this is still sufficient for feeding the world population by 2050. However, its realization requires biorefinement, yield increasing ecological modernization, improved exploitation of marine resources, and the combination of biodiversity conservation with food production. Timely investment in these conditions cannot be left to spontaneous market forces but requires active government policies that go beyond traditional government tasks like infrastructural investment. Moreover, multilaterally coordinated policies are needed to overcome obstacles to production growth in developing countries and moderate the increase in demand for feed and new non-foods like biofuels.

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Executive summary

In the 20th century, global food scarcity gave way to abundant supply in international markets. The fact that 800 million people are still undernourished is the result of poverty rather than lack of supply. However, will this remain so in the 21st century? Serious studies steer clear of eco-pessimist or cornucopian preconceptions, but they are wrestling with the complexity of the issue. In this essay, we discuss biophysical and social forces as well as non-linear interactions that critically influence the supply side of the world food situation in the long term.

Between now and mid-century, the global demand for phytomass for food may more than double. The world population may grow from 6.5 billion to 9 billion people. Moreover, rising incomes in successful developing countries will induce a twofold increase in the global consumption of animal foods which involve high phytomass inputs. The preference for these foods, though influenced by culture, is rooted in the biological evolution of humans. Traditionally, many animals were fed with wastes or grazed on lands with few alternative uses, but the growth in global livestock is intensifying the competition between feed and vegetable foods.

To meet the rising demand for food, the world will still be largely dependent on agriculture. The output of this is constrained by the metabolic efficiencies of plants and the availability of suitable lands and water. A Wageningen study in the 1990s estimated the global potential for agricultural phytomass production at 72 GT of grain equivalents. In practice, however, yields beyond 80 percent of the theoretical limit that is set by the metabolic efficiencies of crops are difficult to achieve. Moreover, human settlement and biodiversity conservation will claim part of the land, as will non-foods like biofuel and biochemicals, the demand for which is boosted by rising energy prices. As a lower bound we assume that these functions will take up one-fifth of the potential agricultural land, while as an upper bound they might claim all land that is not currently used for food production. These factors reduce the potential production of phytomass for food to 32 to 47 GT of grain equivalents. Assuming an unavoidable consumer waste of 20 percent, this would suffice to provide an affluent diet to 16 to 24 billion people, or 1.8 to 2.7 times the expected world population by 2050. However, producing this amount may rapidly deplete the world's reserves of mineral phosphate. As long as a solution for this is not in sight, the realistic potential is considerably smaller.

Realizing the potential for farm-based food production is bound to certain fundamentals. Raising the output per area requires increases in human-controlled energy flows. This involves diminishing returns, at a rate that can be moderated by more complex forms of management. At low levels of energy input, simple production systems have better input-output ratios because they need less energy for maintenance. Conversely, systems that are efficient at higher levels of energy input tend to be more complex. In spite of synergic relations between many inputs, however, diminishing returns can ultimately not be avoided.

The global potential is a technical possibility space. Its exploitation depends on decisions of numerous individual and collective actors. The production functions that inform their decisions are cascades of energy input / phytomass output functions up to the prevailing levels of complexity that producers have mastered. The exact point on these sets that producers select is influenced by risks and scarcity relations, which in turn depend on the availability and distribution of assets. As a consequence, they will normally produce less than the maximum that is technically achievable by them. When faced with high risks or unfavourable price ratios, they may deliberately opt for technologies at lower complexity levels because these are efficient at lower input levels. This may entail endogenous effects (for example, low investment in human capital or in supply and marketing chains) that make local production functions lag behind those in more favoured areas.

As a consequence, a larger food economy may run up against a ceiling before the technical possibilities at the frontier have been exhausted. Adequate policies can push the ceiling upward, but overcoming it eventually requires a leap to a new techno-economic paradigm that allows the exploitation of production possibilities at a new complexity level. This is the substance of an 'agricultural revolution'.

In pre-industrial times, agricultural revolutions were facilitated because population growth raised agricultural prices. This made food expensive for the poor, but it also stimulated investment in larger farms. Together with linkage effects on non-farm activity, this created employment and increased the supply of food so that the population growth could be accommodated. Apart from external disturbances, Malthusian crises only followed when the farm economy once again approached a ceiling, which was able to happen because technical and cultural learning was slow in pre-industrial settings.

In the course of the 19th century, a number of circumstances and new developments caused the relation between population and prices at the global level to be broken. While the world population continued to grow, international agricultural markets witnessed a series of price falls. Where wages were sticky or rising, the effect was that large farms declined. In this situation, government support became essential for a new type of agricultural revolution which was based on smaller-scaled farms. Where this support materialized – first in the West, then in parts of Asia – a 'green revolution' boosted the supply of food. It reproduced stimulated the global abundance and ended hunger-through-scarcity. Where it occurred, the green revolution became an engine of industrialization that decreased hunger-through-poverty, although some population sections lost out.

In regions whose previous history did not induce supportive farm policies, the global regime change in agricultural markets had less favourable results. In Latin America, European colonization had led to 'disarticulated' economies where large growers faced poor workers whose incomes were too low to sustain much domestic demand for bulk products. When international agricultural prices declined, the growers stuck to open trade regimes to safeguard their exports and used their dominance to shift the burden to the rural poor. In the end, they evicted large numbers of workers to pave the way for an extensive modernization that involved low yields per hectare.

In Sub-Saharan Africa, the colonial scramble coincided with the onset of the international price decline. It thwarted the emergence of larger farms and reproduced undifferentiated peasant societies. After Independence, the clientelist politics that characterize such societies encouraged public sector growth rather than the switch to supportive farm policies that was being seen in many Asian countries. When population pressure increased, high risks and unfavourable price ratios precipitated a vicious spiral of soil degradation and poverty.

Latin America and Sub-Saharan Africa account for more than one half of the world's unused potential for food production. The encompassing dynamics that cause an underutilization of these regions' production capacities pose a serious threat to the global availability of food in the future. There is no shortage of appropriate technologies that could help poor farmers in developing countries to increase their production. They include simple techniques for sustainable land management, water harvesting and light irrigation; integrated pest management; and simple storage and processing measures to decrease post-harvest losses. However, as long as the above dynamics remain in place, the adoption of such techniques remains much too slow.

Meanwhile, it may be questioned whether the downward trend in international agricultural prices that contributed to these dynamics will continue. In several developed countries and Asian developing countries, the low-hanging fruit that could be harvested by tapping large reserves of land and water and by using first-generation scientific breeding techniques is gradually being depleted. Further growth of global phytomass production will depend on an increased application of external nutrients, which requires large inputs of energy. This is especially true for nitrogen fertilizer, which currently accounts for half of the energy input in agriculture. With an unchanged global crop response to nitrogen fertilizer, a doubling of phytomass for food would raise the ratio of fertilizer input and crop output by at

least one-third. Considerable increases in fertilizer use efficiency or the energy efficiency of the fertilizer industry will be needed to compensate for this effect. More generally, in large parts of the world, significant improvements will be needed to avoid further increases in the already high energy intensity of agriculture. It will make food production costs sensitive to energy prices, which are likely to rise between now and mid-century. Together with other factors (rising irrigation costs, growing water scarcity in major basins, etc.) this could cause a moderation, a halting or even a reversal of the long-term price decline that started in the late 19th century. Whether recent price rises already reflect a trend change or a more short-term fluctuation (like that in the 1970s) is difficult to say.

While a moderate rise in international agricultural prices might improve global food security by encouraging socially inclusive agricultural growth in regions whose capacities are now underutilized, steep rises in food prices will have a negative impact because they threaten the access to food of the poor. Such price rises could especially occur if a change in the secular trend were to coincide with a temporary undershooting of the normal level of investment in agricultural production capacities. This might happen if myopic expectations were to induce producers and policy makers to respond to short-run abundance and low prices by cutting down on long-term investment and on various kinds of support given to agriculture. Theoretical models and historical data indicate that international agricultural markets show 'cobweb cycles' that involve periodic overshooting and undershooting of normal investment levels. The global decline in agricultural research investment over the last decades suggests that we are currently in a phase of undershooting.

The effect of this on future food prices could be aggravated if the global food economy were to approach a new ceiling. In spite of the enhanced learning capacities of modern society, this could occur if world system dynamics were to hamper the utilization of production capacities in major regions while crop yields in other regions approached the hard-to-surpass limit of 80 percent of potential yield. In that case, rather than the boundaries of a specific agro-production system, those of agriculture as a meta-paradigm would become the constraining factor. The fact that the yield potential of major crops has hardly increased in recent decades suggests that such a situation could indeed occur. If so, significant production increases in the agricultural frontier areas would require either a much further reduction of yield gaps than has thus far been achieved, or a stretching of the basic constraints that define the potential yield, or a strong improvement in conversion efficiencies, or the development of new techniques for the large-scale production of phytomass on other bases than farming. Technically speaking, none of these avenues is closed, but the problems involved are considerable:

- A further reduction of yield gaps requires much more effective stress control and reduction of post-harvest losses. At present, even in Europe, biotic stresses alone cause a quarter of crops to be lost. The ways in which production growth is pursued themselves increase the risk of pests and diseases, as they involve regional specialization, monocropping, reduction in varieties and increased transport. A further reduction of pre-harvest losses requires solutions for problems like pest adaptation. So far, however, even genetically modified Bt-varieties are threatened by Bt-resistant pests.
- To raise potential yields one could try to improve the metabolic efficiencies of crops, even though these are the results of eons of biological evolution. One could try, for example, to introduce improved forms of Rubisco from algae into C3 plants or to transform C3 plants into C4 plants in order to raise their light-use efficiency. Alternatively, one could try to reduce the time during which sunlight remains unutilized, for example by breeding perennial cereals. Such feats seem difficult to achieve, however, and the yield effects remain to be seen.
- Raising conversion efficiency by further improving the feed ratios in developed countries will become more difficult. Past improvements were coupled to a shift from fat to lean meat, which has now largely been completed. Moreover, the human taste for meat is not easily tricked by vegetable substitutes. Attempts to make substitutes from grains or pulses have failed by lack of consumer acceptance. Fungal protein might prove more promising.

More generally, conversion efficiencies could be raised by biorefinement. For example, enough protein could be extracted from cassava residues to replace one fifth of world soy protein.

- *To increase phytomass production on a non-farm basis, one could think of new marine production systems like seaweed plantations or the cultivation of certain algae or bacteria. However, it seems improbable that such systems would allow large-scale food production before mid-century. This holds even more for futuristic techniques like bio-nanotechnology.*

Although some of these options may be feasible, considerable investment in research and human capital will be needed before they can significantly relax the constraints on global food supply. This may aggravate the effect that an undershooting of normal investment levels could have on future food prices.

The above considerations have important consequences for the kind of policies that would guarantee the global availability of food in the long term. In a world whose inherent dynamics cause underutilization of production capacities in major regions, where existing production paradigms in other regions are gradually being exhausted, and where myopic expectations affect the exploration of new technical options, liberalization may not suffice for a balanced development of global production capacities. In fact, abandoning price stabilization may increase the risk of steep price rises; the wholesale dismantling of state enterprises and reduction of import protection in developing countries may exacerbate the underutilization of capacities in these countries; and cuts on public research may cause a neglect of innovations that help resource-poor farmers to increase their production. To ensure a balanced evolution of the global food supply, a much more coordinated approach seems to be needed.

- *To stimulate food production capacities in developing countries, public investment in infrastructures and agricultural research for development should be strongly increased. Governments should play an active role to overcome obstacles for effective supply and marketing chains. To stimulate land productivity, the rights of poor tillers should be strengthened. Developing countries should retain policy space to support their farmers through import tariffs if needed. Infrastructural projects and institutional meal programmes should compensate the effects on poor consumers. Co-financing by international donors for these purposes should be strongly increased.*
- *To enhance the capabilities for food production worldwide, research should be aimed at biorefinement and at farm techniques that reduce emissions while raising yields rather than only minimizing yield losses. Price policies should provide sufficient incentives for such an ecological modernization. Supply management should prevent increased capabilities from causing oversupply and dumping in the short term.*
- *To prevent steep rises in food prices, the demand for feed should be moderated. This can be done by discouraging the consumption of animal foods that involve especially unfavourable feed ratios (for example feedlot beef) and by developing vegetable meat substitutes that are acceptable to consumers. Caution is needed in stimulating the use of phytomass for new non-foods. To prevent the demand for these from outcompeting the poor's demand for food, one could consider a tax on biofuel and biochemicals that is levied when the prices of food staples exceed a certain ceiling.*

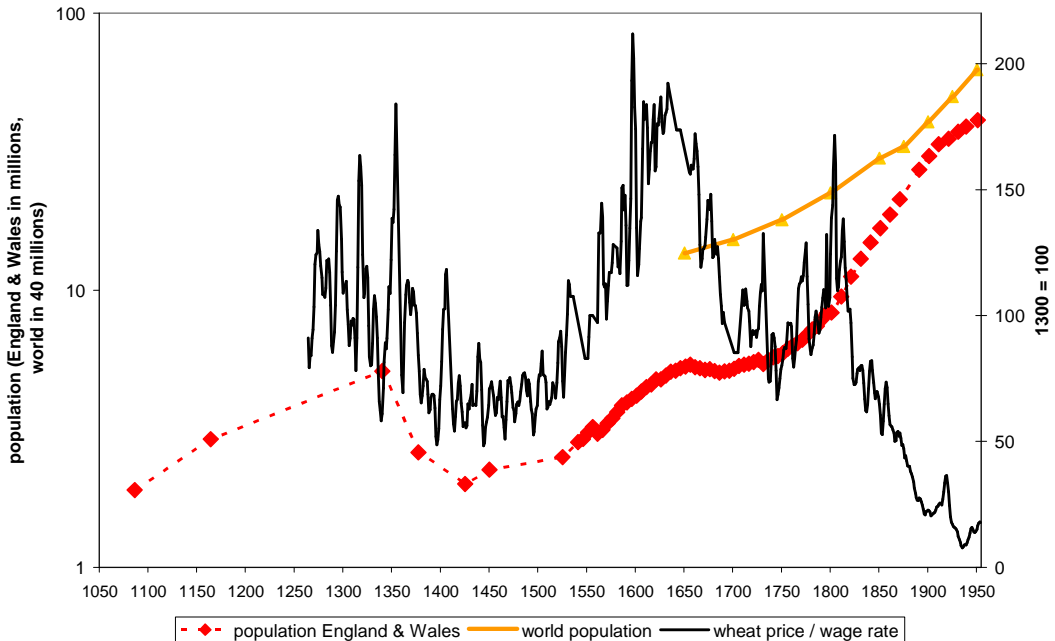
1. Hunger, poverty, and the supply of food

For most of the history of mankind, food supply was a precarious commodity. Even though Malthusian crises alternated with periods when agricultural intensification accommodated population growth, scarcity was never far off. Like the English economist David Ricardo explained in the early 19th century, additional mouths could only be filled by reclaiming less

fertile lands or by using more labour-demanding soil management techniques. As Figure 1 illustrates for his own country, until the mid-19th century population growth was always accompanied by expensive bread.

In the late 19th century, a number of developments broke these constraints. Modern transport reduced the freight rates of bulk foods and enabled the tapping of land reserves that became available in temperate zones outside Europe; industrial fertilizer accelerated the increase in yields; and electricity, internal combustion and artificial fibres reduced the claim on farm production capacity for biomaterials and bioenergy. These breakthroughs, in which the use of non-renewable energy sources played a key role, caused the supply in international food markets to outstrip the effective demand. From the late 19th century, real grain prices declined although the growth in world population accelerated (Figure 1). They continued to fall in the 20th century when high-yielding varieties and a fivefold increase in irrigation brought about new production surges, first in temperate countries, and later in parts of Asia.

Figure 1: Population and ratio between wheat price and wage rate in England & Wales, and world population, 1086-1954 (wheat price / wage ratio as 5-year moving average, 1300 = 100)



Sources: Population England & Wales: 1086-1540, Hatcher (1977) and estimates by various authors mentioned in Coleman & Salt (1992: table 1.1); 1541-1800, Wrigley et al. (1997); 1801-1954, HMSO (1993). World population: McEvedy & Jones (1978) Wheat prices: 1264-1315, Rogers (1866); 1316-1770, Beveridge (1929); 1771-1954, average gazette prices in Mitchell (1990: 756-757). Wages: building wage rates in Phelps Brown & Hopkins (1956).

The resulting abundance is a relative one. Eight hundred million people still suffer from undernourishment and many more from protein or micronutrient malnutrition. However, this is no longer due to skyrocketing food prices, as was the case during earlier Malthusian crises. Hunger has become a problem of poverty amidst plenty. Agricultural growth, if socially inclusive, can help to reduce this. In East Asia, the Green Revolution has become an engine of industrialization, providing employment to millions of people. Even if the transition involves hardship for some, the numbers of undernourished have been strongly reduced. Conversely, South Asia is lagging behind, while much of Africa is suffering from a rural crisis that is

dragging the rest of society with it (Table 1). The Millennium Development Goal of a further halving of undernourishment by 2015 will not be achieved (FAO 2003).

Table 1: Number of undernourished people in the developed regions, 1990-2002 (million people)

	1990-1992	2000-2002
Northern Africa	5	6
Sub-Saharan Africa	170	204
Latin America and the Caribbean	60	53
Eastern Asia	199	152
Southern Asia	302	317
South-Eastern Asia	78	66
Western Asia	9	17
Total developing regions	824	815

Source: United Nations (2005a)

Meanwhile, the excess of global food supply over effective demand is limited. Low price elasticities give small surpluses a strong downward effect on food prices, but by the same token small deficits may cause prices to skyrocket. From the late 1960s, a spate of neo-Malthusian publications has stirred anxieties about a new impending scarcity (for example Ehrlich 1968; Meadows *et al.* 1972). Some authors warned that increase in demand for livestock products in China could triple international grain prices, wreaking havoc in food-importing poor countries (Brown 1995). Established institutions contradicted these gloomy predictions (FAO 2003; Mitchell *et al.* 1997; Penning de Vries *et al.* 1995). Nevertheless, some warned that a decrease in the support of farm progress could cause serious problems (Rosegrant *et al.* 2001). Recent rises in world market prices have caused new concerns. Some new projections predict a reversal in the long-term decline in cereal prices (Rosegrant *et al.* 2006) – a possibility that some of us anticipated some years ago (Koning *et al.* 2002).

The discussion produced model studies on the availability of food in the long term. Some, like the Wageningen Limits-of-Food-Production study, explored the technical limits of global food production (Luyten 1995; Penning de Vries *et al.* 1995). Other ones, like IFPRI's IMPACT model, tried to predict the evolution of the global food economy (Rosegrant *et al.* 2001; 2006). Both experienced their own difficulties. While the former had to establish what the limits really are, the latter wrestled with non-linearities that complicated any attempt at long-term prediction. Below we explore some of these complications. We try to identify biophysical and social forces and non-linear interactions that critically influence the global availability of food in the long term, focussing on basic issues rather than precise quantitative prediction. In Section 2 we present basic concepts that pertain to the biophysical side, the social side and the dynamics of food production. In Sections 3 to 6 we explore the forces and interactions that influence the global demand and supply of food between now and mid-century. In Section 7, we draw some policy conclusions on how to ensure a balanced evolution of food supply.

2. Basic concepts

Over 95 percent of the world's food supply comes from biomass produced under the farm paradigm that Neolithic farmers initiated 10,000 years ago. Only a small part (mainly wild fish) comes from foraging, while a tiny part (mainly hydroponic vegetables) conforms to

really industrial food production. The former can hardly increase – many natural fish stocks are already over-exploited – but the latter might gradually expand. Yet for the coming decades, increases in food supply will overwhelmingly depend on agricultural biomass.

Under the farm paradigm (a techno-economic paradigm, see definition in 2.2), usable phytomass is produced through the cultivation or controlled grazing of plants on the thin layer of biologically and physically transformed erosion material that we call soil. At the most basic level, the global output of phytomass is constrained by the landmass that is suitable for cropping or grazing, the length of growing seasons, the metabolic efficiencies of plants, and the available freshwater, nutrients and atmospheric CO₂. The part that is usable depends on the possibilities for converting phytomass in consumable products through abiotic methods (for example milling, cooking) or biotic processes (fermentation, livestock). Additionally, raising production per area unit requires the conservation of soil and water; the replenishing of soil nutrients; improved supply of nutrients and water; better control of pests and diseases; and varieties with more favourable input/output ratios and improved stress resistance. In the last instance, the scope for extending the global potential for phytomass production may be constrained by the gene pool of the earth and the fossil inputs that can be extracted from the earth's crust.

The farm paradigm is a meta-paradigm that encompasses more concrete sub-paradigms that range from slash-and-burn systems to modern high-tech agriculture and agro-industrial chains. Each sub-paradigm implies specific land use patterns, varieties, tools, and forms of human cooperation, which together form an agro-production (input supply, primary farming, conversion and distribution) system. Below we consider the biophysical and social sides and the dynamics of such systems.

2.1 The biophysical side

The potential production landscape

Figure 2a shows the general form of the input-output relationship in an agro-production system. A rightward movement along the X-axis represents an increasing input of non-land resources on a given land area, or what we call 'agricultural intensification'. Some inputs are substitutable for each other. However, the agronomic conditions that they realize (field preparation, water and nutrient supply, pest and disease control, etc.) are characterized by synergetic relations (de Wit 1992; van Keulen 1982). For simplicity, therefore, we see intensification within a given production system as the increased application of a balanced input package. As long as it allows binding more solar energy into phytomass this entails constant returns (de Wit 1979), but beyond a certain level the returns diminish (see Figure 2a).

When marginal returns become low or negative, an agro-production system needs to be replaced with one that makes a more productive use of higher inputs. In the long run, agricultural intensification is an evolution through successive production systems (Boserup 1965; Grigg 1980; Mazoyer & Roudart 2006; Ruthenberg 1980). The corresponding input-output function is a cascade of the functions of these systems (see Figure 2b). Different systems use different inputs and input packages, but these can be lumped together by using energy as a common denominator. By way of illustration, Table 2 lists the succession of agro-production systems that was typically for the agricultural history of Europe. Figure 3 shows the impact on wheat yields.

In this long-term perspective, the output of usable phytomass in an area becomes a function of two general variables:

- *Energy input.* Increases in phytomass are based on the reduction of fallow or increases in phytomass yields. Both require larger human-controlled energy flows, in the form of (human, animal or machine) labour or external inputs like fertilizer, in addition to natural flows like solar radiation or precipitation (Leach 1976; Smil 1991).
- *Complexity of human control.* Reduction of fallow and increases in yields involve a loss of natural biodiversity on agricultural land, while the human control (i.e. production

system) that manages the agro-ecosystems becomes increasingly tight and complex (Schutkowski 2006). The discussion on the precise definition of ‘complexity’ continues (for example Adami 2002; Stoop et al. 2003), but it is commonly associated with the length of the simplest model that predicts a system’s behaviour (‘Kolmogorov complexity’). It is a discrete variable because the transition to new production systems involves new inputs and relations between inputs.

Figure 2: Change in per area phytomass output as response to increased input of non-land resources, within one production system (a), and across production systems (b)

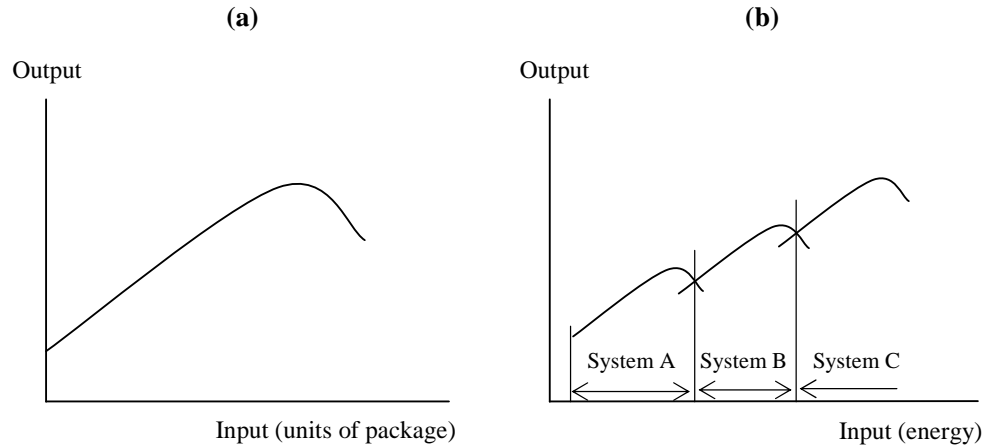


Table 2: Co-evolution of population, natural resources, techniques and institutions (Europe)

Timescale	Inhabitants km ⁻²	Mode of land management	Techniques	Social structures
-2000	1-20	Long fallow	Slash-and-burn, digging stick, hoe	Small scattered villages, little stratification, clientelist socio-political relations, stateless societies, collective non-tradable rights in land, individual rights in people
0	20-40	Fertility concentration on light soils	Separation of pasture and arable land, night kraaling, ox-drawn hook plough	↓
1000	40-60	Fertility concentration on heavy soils	Mouldboard plough, new harnesses, horse traction	
1750	60-200	Zero fallow	New rotations with fodder crops	Centralized states, strong stratification, class-based interest articulation, individual tradable rights in land & other non-human inputs
2000	200-1000	Nutrient import	Artificial fertilizer & imported fodder	

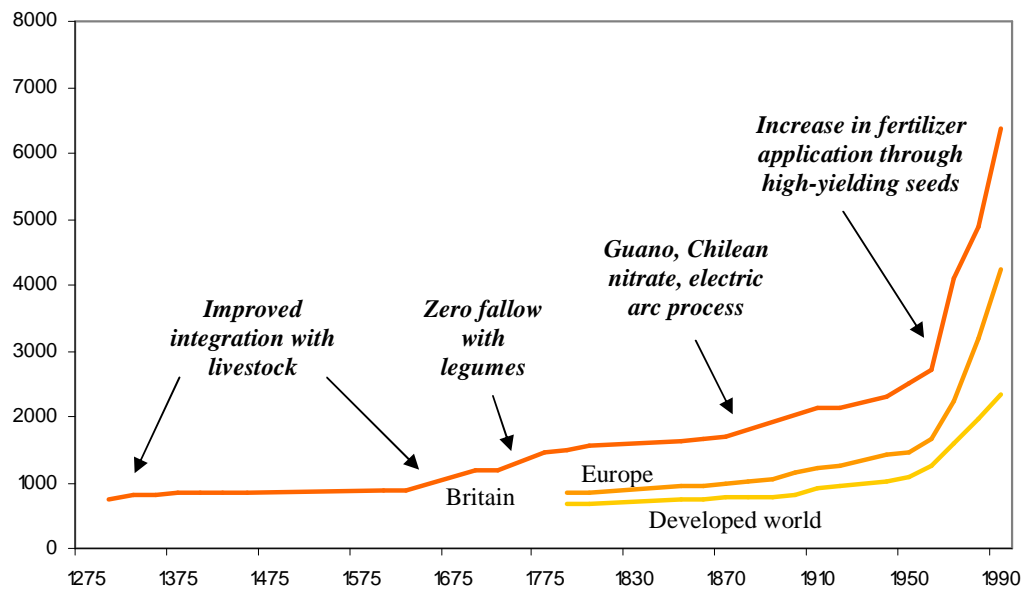
Source: Freely after Mazoyer & Roudart (2006)

Increases in energy input and complexity are generally interlinked. At lower input levels, less complex control systems tend to be more efficient because their maintenance requires less energy. Conversely, sustaining higher fluxes, often of higher quality (lower-entropy) energy, is more complicated. Moreover, systems (plants, animals, agro-production systems) that make a more efficient use of such fluxes tend to be more complex. In their turn, such complex systems are less ‘likely’ (in the sense of Boltzmann’s thermodynamic theory) and therefore

need higher fluxes of negentropy (negative entropy, i.e. high quality energy) for maintenance.²

Accordingly, short or zero fallow systems tend to be more complex than long fallow systems. They require a permanent separation of pasture and arable land, careful management of nutrient streams from the former to the latter, and careful weed control for which ploughing with animal traction becomes more efficient than hand hoeing (Mazoyer & Roudart 2006; Pingali et al. 1987). High-external-input systems are even more complex. Modern agro-production systems are composite structures where many functions have been split off from farms to input producers, traders, processors, researchers, and extension agents. As a consequence, modern farms may be simpler than traditional farms, but the agro-production systems of which they are part are much more convoluted.

Figure 3: Wheat yields (kilos per hectare) in Britain¹, Europe² and the developed world³, 1275-1990



¹ Until 1800 England, from 1800 UK. ² Excluding Russia. ³ Excluding Japan and South Africa.

Sources: Bairoch (1999); Clark (1991).

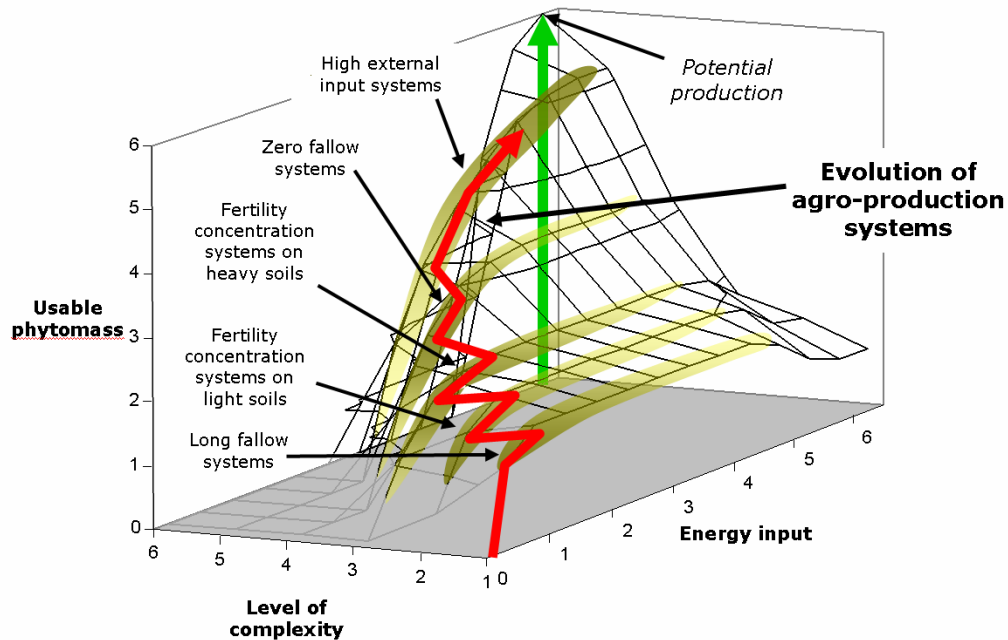
The fact that intensive systems are more complicated is no rule without exceptions. Sometimes less intensive systems are quite complex in order to make the most out of a difficult natural environment. Moreover, unfavourable socio-economic conditions may induce farmers to stick to an older production system in spite of a growing population pressure (see 2.2). This system may then become ever more involved to allow poverty sharing and coping with an increasingly precarious situation. Such 'involution' (cf. Geertz 1963) explains for example the considerable complexity of many current African systems (de Steenhuijsen Piters 1995; InterAcademy Council 2004; Seur 1992).

However, such a situation is ultimately not sustainable. Sooner or later, involutory complexity has to give way to a new step in productive complexity if a society is to survive (see 2.3). In the long term, therefore, the relation between energy and complexity holds. Plotting energy input along the X axis, complexity levels along the Y axis, and phytomass output along the Z axis, the natural resource base of an area can be seen as supporting a

² These insights are based on discussions between one of the authors (Hans Schiere) with physical chemist Hans Lyklema. See also Schiere (1995) for examples from animal science.

potential production landscape (Figure 4). The ribs of the landscape are ranges rather than single curves, because one complexity level can contain several production systems whose relations between energy input and phytomass output vary (see Section 2.2). The long-term growth in phytomass output can be seen as the climbing of a potential production hill by increasing the energy input while shifting to new levels of complexity from time to time to postpone diminishing returns (cf. Robinson & Schutjer 1984; Wood 1998). The price for this growth in production was still an increase in the energy input per unit of output, partly because diminishing returns could not be entirely avoided, and partly because animals or machines were substituted for human labour (Leach 1976; Smil 1991). It is true that rising oil prices have increased the energy efficiency of modern systems since the 1970s (Cleveland 1995; Meul et al. 2007; Uhlin 1999), but these systems are nevertheless much more energy-demanding than traditional ones.

Figure 4: Schematic representation of the relationships between energy input, levels of complexity (agro-production systems), and phytomass output in an area



Conversion

Most phytomass is processed, stored, and/or transported before being consumed by humans. Moreover, part is fed to livestock, poultry or cultivated fish to produce animal products. Some conversions do not affect the supply of food. Whether people eat porridge or fine pastry makes little difference for wider grain markets. Other conversions increase the supply of usable phytomass. Soaking, cooking, fermenting or baking may allow the use of otherwise inedible plants or plant parts. Livestock may allow crop residues or roughage from marginal lands to be transformed into edible zoomass. Better means of storing reduces post-harvest losses. And conservation enhances the usability of biomass by allowing more flexibility with respect to the consumption. Such conversions are elements of the potential production landscape. At higher complexity levels, more sophisticated techniques become possible through which more phytomass is used and upgraded.

On the other hand, there are conversions that raise the demand for phytomass without causing a corresponding increase in the supply. This is especially true when livestock is being

fed with biomass (phytomass or zoomass like fish meal) that could be consumed by humans or that competes for natural resources with food staples. When this helps to provide local populations with an adequate diet (for example, feeding maize to raise pork consumption in pellagra-stricken areas) the supply effect could still be seen as positive. Beyond this, such activities do not belong to the potential production landscape because the supply of usable phytomass is not increased by them. We will go into this in more detail when we discuss the demand.

Limits of the farm paradigm

Humans have climbed the potential production hill by controlling ever more aspects of the agro-production process. They have relaxed water and nutrient limitations; bred varieties that store more phytomass in usable organs; reduced pre-harvest and post-harvest losses; and improved supply-increasing conversion techniques. However, none of these improvements has increased the basic metabolic efficiencies of plants. In this respect, modern varieties do not differ significantly from the cultivars of Neolithic farmers (Loomis & Amthor 1999). This is important because the light-use efficiency of plants (and their water-use efficiency where water is limiting at basin level) determines the yield that can potentially be attained in an area (Figure 4).³ Ten thousand years of agro-industrial progress have allowed humans to realize an increasing share of this potential. However, stretching the potential itself is a different matter because the metabolic efficiencies of plants is the result of eons of biological evolution. Admittedly, in a country like the Netherlands, grain yields now exceed what was seen as the potential yield in the 1960s (de Wit 1965). However, this is due to an increase in the harvest index (which has now reached a maximum), not an increase in potential phytomass output.

It may be asked whether, even in a purely technical sense, the limit that is set by plant metabolic efficiency could be fully realized in practice. As this limit is approached, additional gains require ever more fine-tuning in the management of soil, crops, water, nutrients and pests (Bindraban 1997; Cassman, 1999). Some deterioration of soil and water quality is hard to avoid (Cassman et al. 2003). And the evolution of pest resistance against control methods makes full pest control virtually impossible. Even in Europe a quarter of crop production is still lost due to pests and diseases (Oerke et al. 1995). The causes are partly economic, but the evolution of pest resistance against control methods also plays a role. Indeed, even genetically modified Bt-varieties are already being threatened by Bt-resistant pests. The development of pest resistance could be countered by for example maintaining refuge areas for non-resistant pests, but this implies that the yield gap cannot fully be closed (Laxminarayan & Simpson 2002).⁴

On the other hand, there might be some scope for outperforming nature by improving the light-use and water-use efficiencies of plants that define the limit. In this way, additional room for increasing the global output of agricultural phytomass could be created. Beyond this, increases in production would require a shift to some other meta-paradigm for biomass production than farming. It seems improbable that this would have significant effects on the global supply of food before mid-century .

2.2 The social side

The ‘potential production landscape’ refers to a biophysical reality. However, the food economy is a *socio*-biophysical system – an ecosystem managed by humans. While ecosystems of lower animals are driven by blind causality, humans are capable of learning and cultural transmission – which enables them to achieve new complexity levels

³ Strictly speaking, water-use efficiency is not seen as a determinant of potential yield because water supply is seen as a limiting factor that can be made less constraining by e.g. irrigation (van Ittersum & Rabbinge 1997). If water is limiting at the basin level, however, water-use efficiency also becomes a determinant of the maximum output.

⁴ Additionally, the strategy seems to be less than fully effective (Chilcutt & Tabashnik 2004).

(Schutkowski 2006). It should be noted that the potential production landscape is not directly known to humans. They only have a cognitive representation, or *map* of it. This is always imperfect; the fringes remain terra incognita; and the maps of different actors – for example scientists and farmers – can vary (see examples in Fairhead & Leach 1996 or Richards 1997).

When humans explore a new range of the landscape, they have a crude image of it. This is gradually improved through experience and research. In addition to knowledge, realizing novel options requires new forms of co-operation. These may be hindered by short-term self-interest even when all actors were to benefit (Hardin 1968; Olson 1965). Overcoming such ‘tragedies of the commons’ necessitates new institutional solutions and mindsets (Ostrom 1990). The concept of techno-economic paradigms, on which our notion of farming ‘paradigms’ is based, refers to patterns in cognitive *and* cultural learning (Freeman 1991; Freeman & Perez 1988). Accordingly, agro-production systems co-evolve with social relations (Johnson & Earle 2000; see also Table 2).

Suppose that the producers in an area have largely exploited the possibilities of an agricultural sub-paradigm – say the zero fallow systems of 19th century Europe. They have introduced new rotations, carried out enclosures and so on and so forth, to the point that little progress is possible without external nutrient inputs. In Figure 4, their production function – their set of known techniques – is then the cascade of ribs up to the 4th complexity level. Which point of the set the producers will choose depends on risks and social scarcity relations. The latter result from the size and the composition of the population, needs and resources, and from the distribution of entitlements (cf. Sen 1981). Scarcity relations fix prices or shadow prices to productive assets and needs. At the demand side, these influence the translation of physical needs into effective demand. It makes it possible that the physical needs of a poor underclass contribute little to effective demand so that farmers are faced with glutted markets while their output fails to end hunger.

At the supply side, the relative scarcity of productive resources influences the techniques that producers will choose at each complexity level. When land is scarce compared to labour, they may use labour-intensive techniques to gain large harvests from small plots. In the opposite case, they may use more extensive technologies that give lower yields but more output per worker (see Hayami & Ruttan 1985 for the historical pathways followed by Japan and the USA). This is why the ribs of the landscape are sets of technologies whose energy requirements for a certain phytomass output vary.

The most important factor concerning the subject of the present essay is the influence of social scarcity relations on the output levels that producers will choose. Let Figure 5 – a front view of Figure 4 – be the *map* that producers have of the potential production landscape. Suppose that historical experience has taught them one technology per complexity level, so that the ribs narrow down to curves. On these curves, which together form their production function, producers will choose a point where their profit is maximized. For simplicity, let us see energy as a single input and phytomass as a single output, between which a given price ratio exists. The profit function can then be written as

$$W = p_p P - p_e E$$

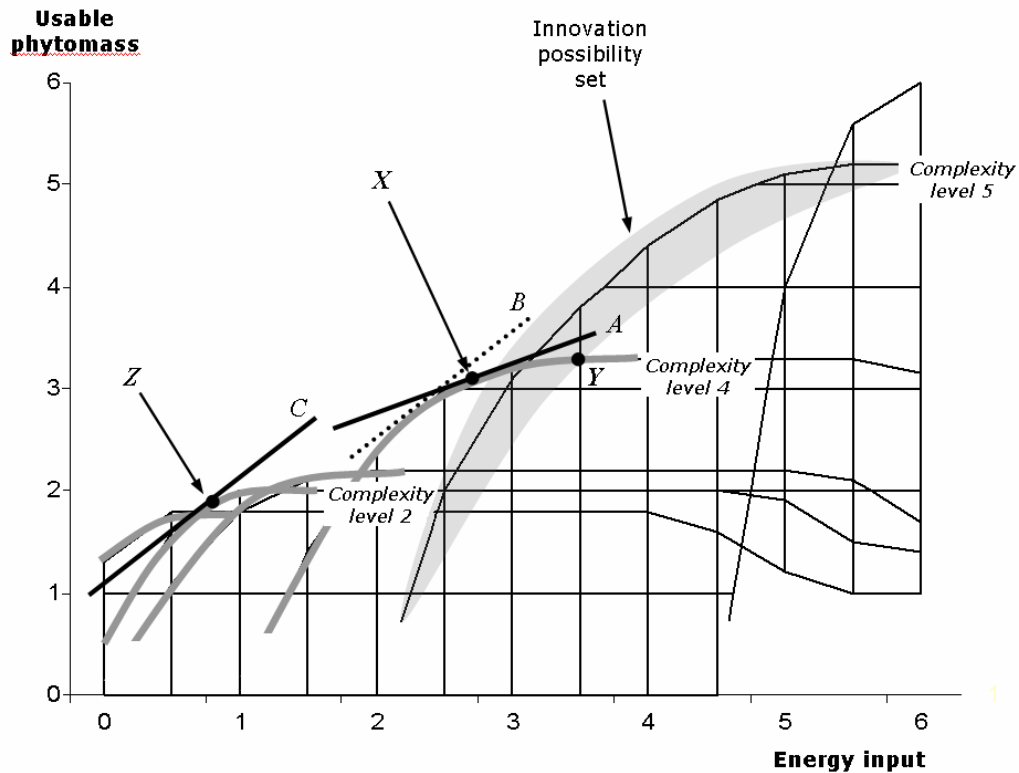
where W is the profit, p_p the price of phytomass, P the phytomass output, p_e the energy price and E the energy input. This equation can be re-written as

$$P = W/p_p + (p_e/p_p)E$$

which is a line with the price ratio of phytomass and energy as its slope. The intercept with the vertical axis is W/p_p . It follows that profit (W) is maximized when farmers produce at the point on their production function through which the line with slope p_e/p_p and the highest intercept with the vertical axis can be drawn. If the input-output price ratio equals the slope of line A, farmers will produce at point X. They will not produce the technical maximum (Y), because this gives them a lower benefit.

In this case, farmers are still producing at complexity level 4 (zero fallow systems). Price relations may also induce them to stick to less advanced systems. Suppose that in an adjacent area, farmers are faced with higher transport costs that reduce the price of phytomass while raising that of energy inputs, so that their profit lines are steeper than *A*. Let the slope of their profit lines be that of *B*. However, *B* has a lower intercept with the vertical axis than the parallel line *C*. It means that maximum profit is now achieved at point *Z*, which belongs to a technology of complexity level 2 (short fallow systems). Farmers will not shift to zero fallow systems, even if these are known to them (also cf. Boserup 1965; Grigg 1980; Pingali et al. 1987).

Figure 5: Subjective physical production functions derived from Figure 4



That producers in core and peripheral areas make different choices was already explained by the German economist von Thünen in the 19th century. A more recent insight is that such choices may retroact on production functions. For example, they restrict the marketed volumes in remote areas. This may make it too risky for individual actors to invest in supply and marketing chains that more advanced farming systems require, even if the actors collectively were to benefit (Dorward et al. 2007). Also, a less advanced agriculture can make it less rewarding for people to acquire higher skills, which may lead to a self-reinforcing constraint on human capital (cf. Azariadis & Drazen 1990). There are several such poverty traps in peripheral areas, and endogenous growth enhancers in core areas (cf. Lucas 1988; Romer 1987). The effect is a spatial divergence of production functions. In Figure 5, where the frontier function goes up to complexity level 4, the production function in less favoured areas may be limited to the curves up to level 2 or 3.

The upshot is that a larger food economy runs up against a ceiling long before the technically attainable maximum under its (frontier) sub-paradigm is reached. The location of this ceiling can be influenced by policy measures, but not endlessly – also because socio-political obstacles to this may themselves be endogenous (see Section 6.1). While social

scientists should understand that the adaptability of production functions does not make the underlying biophysical landscape perfectly malleable,⁵ technical scientists should understand that the same holds for economic relations. Nevertheless, a socio-technical ceiling should not be taken for an absolute carrying capacity. From time to time, humans succeed in lifting a historical ceiling. In Figure 5, this means a shift to an *innovation possibility set* of production systems that can be reached by a quantum leap along the complexity axis. Because complexity is closely connected to learning (cf. Bialek et al. 2001), one can also see the innovation possibility set as the set of new production possibilities that can be attained through a certain investment in searching and experimentation (cf. Ruttan 2001). The size of this investment varies with the capacity for (cognitive and cultural) learning, which evolves with the evolution of human societies.

2.3 Changing dynamics

Now that we have discussed the social conditions that steer humans in their climbing of the potential production hill, let us look at the climbing itself. We begin with the dynamics of pre-industrial food economies, and then consider the regime switch that occurred in the 19th century.

Pre-industrial dynamics

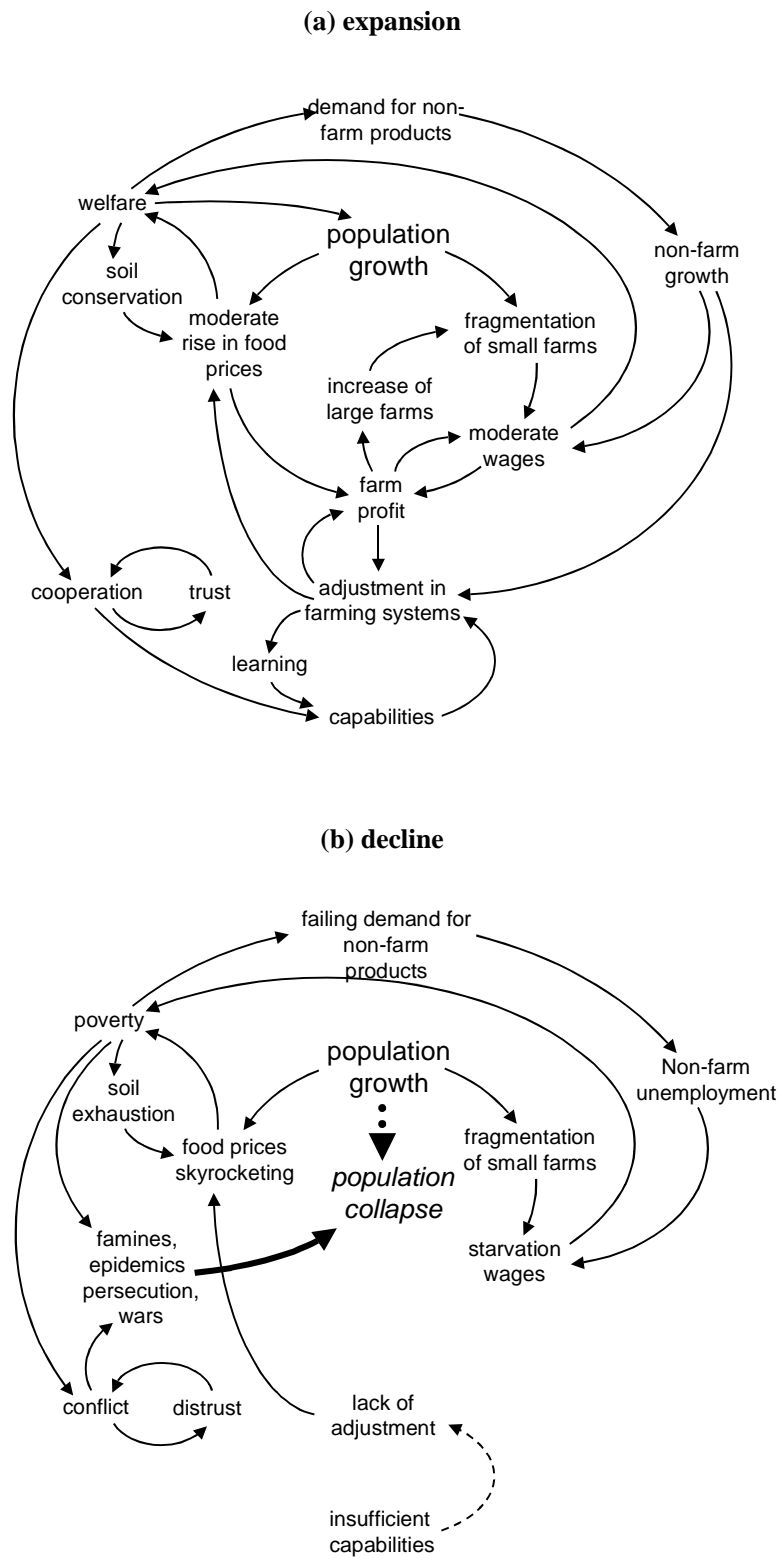
Pre-industrial food economies were marked by chronic fluctuations. Short-term price fluctuations were connected to cobweb cycles or environmental variation (Bauernfeind & Woitek 1996). Long-term fluctuations were related to ages of demographic growth and ages of stagnation or decline (Abel 1978; Slicher van Bath 1963; for prehistorical societies Zimmermann 1996). Although environmental variation played a role, the causes were at least partly endogenous. Ages of expansion were connected to the exploitation of a new sub-paradigm. Central to this was Ricardo's law of population and prices. A dearth of fertilizer complicated increases in yields, and high transport costs restricted food imports (Bairoch 1976; Shiell 1991). As a consequence, population upswings raised the prices of agricultural products. This made food expensive for the poor, but as Malthus already observed,⁶ it also lowered real wages and prompted investment and innovation in larger farms, and thereby fuelled the phases of sustainable intensification that historians call 'agricultural revolutions' (cf. Boserup 1987). During these phases, increases in food supply acted as a moderating feedback effect on rising food prices (see Figure 6a). More mouths could be fed; rural markets for commerce and industry expanded; and no severe distress precluded co-operation and the maintaining of soil fertility.

In this exploitation phase (cf. Holling & Gunderson) of an agricultural sub-paradigm, the food economy was more or less robust. Harvest failures caused suffering but no collapse, and increased market exchange facilitated the diffusion of innovations. However, risk aversion and slow communication made collective learning a sluggish process (Boserup

⁵ See references in Van den Belt (1995) to social scientists who embrace this idea. For all practical purposes, the unknown aspects of the biophysical landscape can be assumed to conform to basic thermodynamic laws (cf. Martinez-Alier 1987; Georgescu-Roegen 1971).

⁶ "The food therefore which before supported seven millions must now be divided among seven and a half or eight millions. The poor consequently must live much worse, and many of them be reduced to severe distress. The number of labourers also being above the proportion of the work in the market, the price of labour must tend toward a decrease, while the price of provisions would at the same time tend to rise. The labourer therefore must work harder to earn the same as he did before. (...) the cheapness of labour, the plenty of labourers, and the necessity of an increased industry amongst them, encourage cultivators to employ more labour upon their land, to turn up fresh soil, and to manure and improve more completely what is already in tillage, till ultimately the means of subsistence become in the same proportion to the population as at the period from which we set out." (Malthus 1798: 29-31).

Figure 6: Dynamics of demo-economic expansion and decline in the pre-industrial era



1981). New breakthroughs often did not arrive in time to prevent the food economy from approaching a ceiling. When this happened, the relations depicted in Figure 6a weakened. The supply response to price rises diminished. Further increases in output required ever more efforts, and the food security of large segments of the population was threatened. For some time, a precarious stability could be maintained by elaborate safety nets, intricate social hierarchies, small technical improvements and cultivation practices that exploited every niche of the accessible production landscape (Geertz 1963; also cf. Holling & Gunderson 2002, Tainter et al. 2003). However, regulation and fine-tuning likewise involved diminishing returns (cf. Tainter 1990), and in the end, strong increases in scarcity could not be avoided. Then the system fell into the dynamic that is sketched in Figure 6b. Food prices skyrocketed squeezing the demand for non-farm products. Artisans lost their livelihoods, swelling the ranks of the rural poor. And small farmers over-exploited their plots in an effort to minimize their dependence on food markets (cf. Meuvret 1946). Harvest failures or other shocks could push society into a spiral of soil degradation, food insecurity and disruption, which finally ended in demographic crisis.^{7,8} Once this occurred, the pressure between population and food supply was released. Wages rose and farm prices fell, causing a decline in large farms and halting or reversing the process of intensification. It initiated a low tide in economic development, which lasted until a new population upswing prompted a new cycle.

From scarcity to abundance

In the course of the 19th century, a number of developments broke this Malthusian cycle (Bairoch 1976; Pomeranz 2000). One was the transport revolution. From the 15th century, a global transport system had emerged for trade in luxury products, but freight rates long remained prohibitive for long-distance trade in bulk foods. When a new European population boom ran up against a ceiling around 1700, there were no massive food imports to prevent a Malthusian crisis. In the course of the 19th century, however, freight rates decreased sharply, which made the production for export of bulk foods in peripheral areas a profitable option. At the same time, history had opened a window of opportunity for a strong expansion of such production in the Americas, where Eurasian diseases had wiped out indigenous populations (also cf. Mann 2005). Together with comparable developments in Oceania and South Africa, it allowed an explosion of the global area of commercial farming.

Meanwhile, the Transport Revolution allowed European farmers to import natural fertilizers (guano and Chilean nitrate) from other regions. This was followed by the invention of the electric arc process and then the Haber-Bosch process that made cheap synthetic fertilizers available (Smil 2001). At the same time, the exploitation of fossil fuels for heat and the coming of the chemical and petro-chemical industries, electricity, and internal combustion saved vast stretches of land for food production that otherwise would have had to produce materials and energy sources.

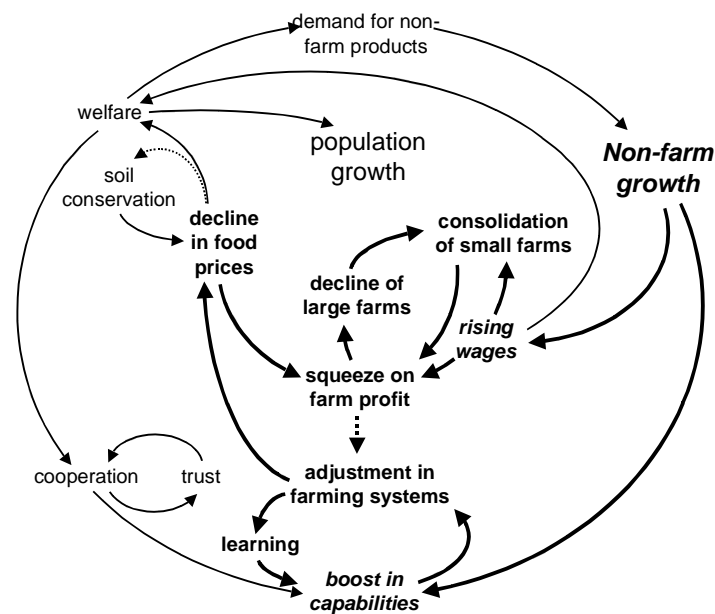
Together, these forces raised the ceiling on global food production more rapidly than the demand. The Ricardian constraint that tied population growth to expensive food was finally broken (Schultz 1945). Although the increase in world population accelerated, international agricultural prices went through a series of price falls. As before, farm profits were squeezed and large farms declined – especially where industrial competition prevented a downward adjustment in wages (Koning 1994). But this time there was no slow-down in agricultural growth. Government support, co-operatives and chain integration bolstered knowledge infrastructures, moderated the diseconomies of small farms, and ensured that

⁷ Soil degradation and social disruption occurred because poverty affected the time preference of people. This made them select exhaustive farming techniques and non-cooperative (social capital eroding) strategies that gave higher immediate returns but hurt them in the longer term (also see Section 6.1).

⁸ Malthusian ‘corrections’ could be aggravated by causes like hierarchical mentalities that were fostered by involution and hampered adjustment (De Vries et al. 2002), or the multi-equilibrium nature of agro-ecosystems. This latter can be caused by conservation investment (Antle et al. 2006), but the effect may be strengthened when the ecosystem has a physical multi-equilibrium nature (see 4.2).

frugal smallholder families kept margins for investment. Rather than leaving a sector with low earnings, small farmers seized upon the technical and market opportunities to defend their incomes – which led to them being trapped in a treadmill of production growth, low prices and new innovations (Cochrane 1959; see diagram in Figure 7). As a consequence, the external inputs revolution that had started with Victorian “high farming” in the mid-19th century (Moore 1965) was able to continue on a new, family farm basis. Existing crop varieties responded only modestly to additional nutrients, but cheap fertilizer boosted the profitability of breeding varieties that transformed more nutrients into harvestable product. After the 1950s, yields steeply increased (see Figure 3), and at the global level no diminishing returns to increases in fertilizer have since appeared (Figure 8).

Figure 7: Dynamics of agricultural development from the late 19th century (to be compared with Figure 6)

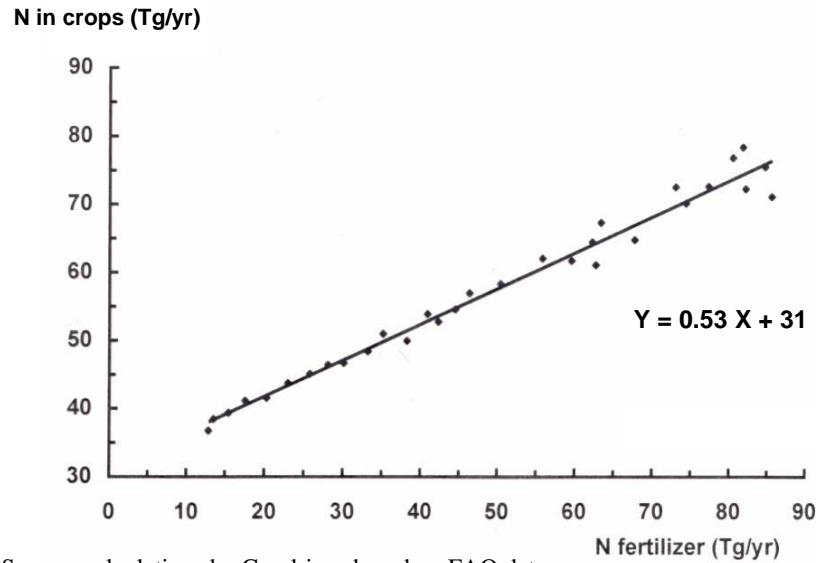


Nevertheless, there is no guarantee that the abundance in international food markets will last. In the coming decades, the demand for phytomass for foods and non-foods will strongly increase. At the same time, land and water will become scarcer and rising energy prices will affect the costs of further intensification. Indeed, this might lead to a new trend change in agricultural markets. Moreover, the world farm economy might approach a new and harder ceiling when the limits of the agricultural meta-paradigm were to come in sight. Long before the technical maximum were to be attained, this could raise the demands on global capacities for fine-tuning and organization to maintain stability in food markets. Besides, it would necessitate great efforts for achieving the timely exploration of novel paradigms for biomass production. Whether a balanced evolution of the global availability of food would be ensured in such a situation is not clear a priori. In the last instance, this will depend on human ingenuity and mindsets.

The following sections explore the forces and interactions that influence the global supply of food between now and mid-century. Section 3 deals with the demand for food. In Section 4 we consider the natural resource base that supports the potential production landscape, as well as the changes in, and competing claims, on these resources. Section 5 surveys technical possibilities to expand food production within or outside this landscape.

Section 6 discusses the social dynamics that influence what use humans will make of these possibilities.

Figure 8: Global response of N in crops to N-fertilizer, 1960-1995



Source: calculations by Goudriaan based on FAO data

3. Demand for food

Between now and mid-century, the global demand for food is expected to more than double. The main drivers are further growth in world population and increase in the consumption of animal foods. Besides, there are secondary influences like an increase in pets and increased wasting of food by affluent consumers.

3.1 Population growth

After a century of unprecedented population growth, the world is now inhabited by some 6.5 billion people. A decelerating growth is expected until the mid-21st century, after which the world population might stabilize at around 9 billion (IIASA 2004; United Nations 2005b). Almost 99 percent of this population growth will occur in developing countries (Table 3). Although models of long-term food security mostly treat population growth as an exogenous variable, it really has an endogenous aspect. Poor and food-insecure people value having many children as a source of labour and as a kind of old-age insurance (Dasgupta 1995). As a consequence, the highest population growth occurs in areas where poverty is widespread and economic growth is sluggish. Continued poverty might slow down the decline in fertility in poor countries causing increases in world population beyond what is currently being expected (Table 3).

Table 3: Total fertility rate (children per woman) and evolution of population in more developed, less developed, and least developed countries under different assumptions on decline in fertility

	Total fertility rate 2000-2005	Population (millions) (percentage of world population)		
		2000	2050 (UN medium variant)	2050 if poverty further retards decline in fertility ¹
More developed regions	1.56	1 193 (19.6)	1 236 (13.6)	1 236 (11.0)
Less developed regions²	2.58	4 219 (69.3)	6 104 (67.3)	7 213 (64.4)
Least developed countries	5.02	674 (11.1)	1 735 (19.1)	2 744 (24.5)
World	2.65	6 086 (100)	9 076 (100)	11 193 (100)

¹ Assumptions: population growth in more developed countries like in the UN medium variant, in less developed countries like in the UN high variant, in least developed countries like in the UN constant-fertility variant
² Excluding least developed countries

Source: United Nations (2005b)

3.2 Livestock revolution

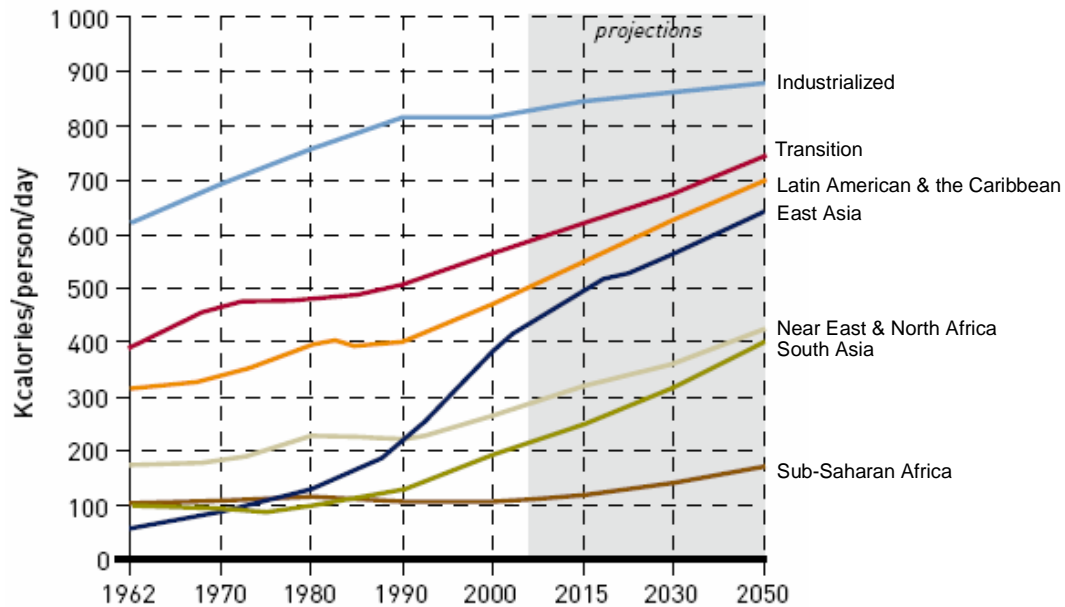
While population growth increases the number of people to be fed, it is also important what these people will eat. The rapid population growth in poor areas may entail little more than a proportional increase in biomass consumption for food. In more successful developing countries, however, rising incomes and changes in the way of living will induce a shift in dietary patterns. In particular, people will increase their consumption of livestock products (Figure 9). While world population will increase by half, the consumption of animal foods may double between 2000 and 2050 (Steinfeld et al. 2006).⁹ This strongly affects the total demand for biomass for food through the required feed inputs (Delgado 2003; Delgado et al. 1999; Keyzer et al. 2005; Smil 2002). An affluent western diet, in which animal foods make up a significant share, involves a three times larger input of grain equivalents than the adequate vegetarian diet that is still normal in many developing countries (Penning de Vries et. al. 1995). This has limited effects when animals are fed with wastes or grazed on lands with few alternative uses, but as the global livestock increases, more animals are fed with products that compete for land and water with food crops or are fed with fish that could be used for human consumption.¹⁰ This is not just true for monogastric animals; increasingly, beef cattle are also fed on grains. This involves unfavourable conversion efficiencies, for while ruminants are supreme converters of fibrous plants that are unsuited for human

⁹ Projections of the increase in the global consumption of animal foods are troubled by poor statistics on meat consumption and livestock in China (see e.g. Fuller et al. 2000; Ma et al. 2004). This may also affect the expectation of a strongly decreasing growth of meat consumption in East Asia in Rosegrant et al. (2006). Nevertheless, the projections in this publication do not contradict the general impression that the global consumption of animal products may double.

¹⁰ At present, over half of the fish captured is already fed to livestock (Steinfeld et al. 2006).

consumption, they are poor converters of starchy and protein crops. On the world level, the claim on cultivable land per kilo of beef already exceeds that per kilo of pigmeat or chicken (Wirsenius 2003; also Bouwman et al. 2005).

Figure 9: Past and projected per capita consumption of livestock-based foods, 1962-2050



Source: Steinfeld et al. 2006.

Meat consumption is influenced by food cultures. The consumption of livestock products in Brazil is twice that in Thailand, although these countries have comparable income levels and urbanization rates (Steinfeld et al. 2006). Nevertheless, the growth in consumption of animal foods is not easily checked by cultural norms.¹¹ Buddhist countries like Taiwan and South Korea saw considerable increases in per capita meat consumption when their incomes rose in recent decades.

Apparently, the high income elasticity of the demand for animal foods is rooted in a more deep-seated predisposition. The origins of this may well lie in biological evolution. Some initial condition that selected for an increase in the brain size of early hominids must have pushed humans into a self-reinforcing cycle of dependence on animal foods to sustain this large brain and further increases in brain size to acquire and handle these foods (Aiello & Wheeler 1995; Foley 2001; Vasey & Walker 2001). This feedback cycle has generated selective pressures that led to a genetically based taste for meat (Logue 1998; Rozin 2003; Ulijaszek 2002). Indeed, the diets of pre-agricultural human populations contained high proportions of animal foods. Agricultural populations shifted to more vegetarian diets only out of necessity. When incomes rise, humans veer back to a higher consumption of animal foods and even tend to raise this consumption beyond what is wholesome, given their reduced physical activity (Popkins *et al.* 2001; Smil 2002). The increase in per capita meat

¹¹ Restrictive norms that renounce all meat-eating seem to become less forceful when incomes rise. Moreover, most food taboos restrict the consumption of a few animals only. These taboos originated in practical limitations. For instance, many pastoral peoples who despised the lifestyle of sedentary farmers developed a taboo for eating pigs, which could not be herded over long distances and were therefore sedentary farmers' animals (Harris 1985; den Hartog 2003). Because such taboos do not forbid the eating of other animals, they have only a limited effect on total meat consumption.

consumption in western industrialized countries has now levelled off, but at levels that are too high from a public health perspective.

Many affluent consumers express concerns on meat and meat products even though they eat plenty of animal foods (Fiddes 1991; Holm & Møhl 2000; Richardson et al. 1993; Willets 1997). Explicit reasons given for such concerns relate to health concerns, modern production methods, and the killing of animals. Underneath this may be a more general undercurrent, for consumers who do not present a coherent criticism of modern meat production exhibit similar negative attitudes (Holm & Møhl 2000). Indeed, the deep-rooted human craving for meat seems to be coupled to an equally deep-rooted moral uneasiness about meat-eating.¹² Nevertheless, up to now these concerns have not moderated the growth in per capita meat consumption strongly (ibid.; Beardsworth & Bryman 1999; Eastwood 1993). One might think that food scandals, epidemics of livestock diseases and zoonoses, and closed 'agro-production parks' to control these risks may change this situation in the future, but until now slumps in demand caused by, for example, BSE have still been followed by recovery.

What is changing in modern lifestyles, however, is the kind of meat that is consumed and the way it is prepared. There is a shift from red to white meat, meat is becoming one ingredient rather than the centrepiece of the meal, and there is a shift towards minced meat – a convenience product in which the animal origin is veiled (de Boer et al. 2006; Holm & Møhl 2000). In the longer term, these changes might widen the room for vegetable substitutes and livestock species with better feed conversion ratios. The conversion efficiency of beef cattle is about one-tenth of that of pigs or poultry (Wirsenius 2003). A shift to pork and chicken would moderate the pressure of demand if it were to reduce the number of beef cattle fed from land that is suited for arable farming (ibid.; Smil 2002). Cultured herbivorous fish like carp would be a better option still. The same holds for other aquatic animals and mini-fauna (Meerman & Van Huis, 2002; Nakagaki & DeFoliart, 1991), but consumers tend to move away from such foods as their incomes rise.

Vegetable meat substitutes could strongly moderate the demand for biomass for food, but the humans' natural taste for meat is not easily deceived. Up to now, attempts to make successful meat substitutes from grains or pulses have failed (Aiking et al. 2006). The substitutes that have been produced are not fibrous and juicy enough to be appreciated by consumers. Fungal protein might prove more promising, however (de Boer et al. 2006).

3.3 Other factors

In addition to raising the consumption of animal foods, rising incomes have other effects that increase the demand for biomass for food. Affluent consumers tend to keep more pets. A country like the Netherlands would need 10 percent of its agricultural area if it were to produce the feed for its pets from its own land (van der Zijpp 2001). The Netherlands is a densely populated country (though one with high yields), but other industrialized countries may also need a few percent of their agricultural land for pet foods.

Furthermore, affluent consumers tend to waste a larger share of their food (Rathje & Murphy 1992; Smil 2000). In the Netherlands, 10 to 15 percent of the food that consumers purchase is wasted without being prepared, and even more after preparation (LNV Consumentenplatform 2006). Younger consumers tend to waste more than older ones, and waste increases with the consumption of convenience foods. Communication campaigns have

¹² In traditional religions, evil forces are often seen as having an insatiable lust for meat (e.g. Geschiere 1995), and the ascetic vegetarianism of e.g. orthodox Buddhists or orthodox-Christian monks betrays a similar disposition. To explain it, Stanford (1999) surmises that meat was a political commodity in societies of hominid hunters, where males used it for networking and getting access to females. One might add that the emotional chargedness of meat may have been reinforced in agrarian societies where eating meat became a prerogative of the rich and powerful.

little effect on this behaviour. Apparently, some extent of food wasting is an aspect of affluent life styles that is hard to avoid.

4. Natural resource base for food production and competing claims

4.1 Total resources and current use

The increased food demand must almost entirely be met with the natural resource base that mankind has for farm production. Particularly important are the solar radiation, nutrient resources, suitable lands, freshwater, and the gene pool that are available for biomass production. The incoming solar energy on the land surface that is suitable for agriculture is several thousand times more than the energetic content of the current food production – an ample supply, even though plants can transform at most 3 percent of this into food.

Atmospheric nitrogen for producing nitrogen fertilizer is likewise abundantly available, although much energy is required for ammonia synthesis. Phosphorus is much more limiting. Total reserves are around 2.5 billion tonnes, and potential reserves around 7 billion tonnes of P (Smil 1999; Steen 1998). In the long term, mineral phosphate may become scarce and its supply increasingly dependent on one country: Morocco (IFA/UNEP 1998). We will look at this issue in more detail in Section 5.1.

Land and freshwater are also limiting. Globally 7.6 Gha are suitable for agriculture, of which 3.5 Gha for cropping and 4.1 Gha for grazing.¹³ About 1.6 Gha and 2.8 Gha is already used for these purposes, respectively.¹⁴ These figures suggest the existence of a significant land balance, but most of the spare land is less fertile and easily degradable and much is under forest. The vast reserves of fertile land of the early 20th century no longer exist. Only a few countries in South America (Argentina, Brazil, Bolivia and Colombia) and in Africa (Angola, Democratic Republic of Congo and Sudan) retain significant reserves of good land (Fischer et al. 2001).

About 48,000 km³ of freshwater yearly can be renewed by natural recycling through the atmosphere and the earth. Only 6 percent of this is currently withdrawn for the irrigation of about 0.25 Gha of cropland.¹⁵ More relevant, however, is the situation per basin. In the Nile basin, the Indus basin and the river basins of North-East China, withdrawal for irrigation significantly exceeds 50 percent of the renewable water. In the Ganges basin it is only modestly below it. In these areas, where the food supply to hundreds of millions of people depends on irrigated systems, the room for further increases in water withdrawal is small or absent. At present, some 1600 million people are living in river basins where there is barely enough to keep rivers flowing and lakes filled or that are rapidly approaching this state (Molden 2007). Parts of the US – another important granary of the world – are likewise faced with increasing water scarcity (Rosegrant et al. 2002; also Seckler et al. 1999).

In addition to the current amounts of natural resources, ecological changes that affect the productive potential of these resources and non-food claims on these resources are important. The following subsections deal with these issues.

¹³ Penning de Vries et al. (1995) assumes that 7,8 Gha is suitable for farming, of which 3,8 Gha for cropland and 4 Gha for grazing. However, Young (1999) argues that mapping problems have caused a 10 to 15 percent overestimation of cultivable land in the developing world. The developing world contains 84 percent of all suitable lands, and we assume that half of the land that should be deducted from the cultivable area can also not be used for grazing.

¹⁴ The standard estimate of cropland is 1.5 Gha, but Young (1999) thinks that the developing world has 10 to 20 percent more cropland than assumed in this estimate.

¹⁵ Part of this water is returned to the source and reused downstream, so that the final water consumption for irrigation is about 1400 km³.

4.2 Ecological changes

The most salient ecological change in today's discussions is climate change. During the 20th century, the average surface temperature of the earth has increased by 0.6 to 0.8 percent. Predictions that it may rise by another 3 to 6 percent during the 21st century are based on models that assume greenhouse gas emissions to be the main driver of global warming (IPCC 2007). This assumption is a credible one, but alternative explanations (referring for example to solar activity) have not been ruled out (Crok & Jaarsma 2007; de Jager 2005; McKittrick et al. 2007; Soon 2007).¹⁶ If the latter are true, global warming might be a temporary phenomenon.

Continuing anthropogenic global warming would have mixed impacts on food production. On the positive side, it would enhance photosynthesis, increase precipitation and water use efficiency, and shift agricultural frontiers towards the North and South poles. On the negative side, it would increase the occurrence of extreme weather events, accelerate the spread of pests and diseases, make some areas too hot for staple crops, and raise sea levels causing flooding and salinisation. Various studies suggest that the aggregate effect of global warming and increased CO₂ on global food production might be small, but the geographic distribution of these effects would be uneven (for example Rosenzweig & Hillel 1998; Stern 2006). While the positive effects may dominate in the temperate zones, in tropical and subtropical zones the negative effects may be more significant.

Production methods that reduce biodiversity and genetic variability can make crops more vulnerable to pests and diseases. The increased mobility of people, products and seeds accelerates the spreading of pathogens (Anderson et al. 2004). The concentration of livestock systems increases the risks of livestock diseases and zoonoses. We will return to this topic in Section 6.3 where we discuss the influence of economic developments on the vulnerability of the global food economy.

Another problem is soil degradation. Really irreversible loss of productive soils is limited, probably to 0.1 to 0.2 percent of all suitable land per year (Scherr & Yadav 2001), but productivity losses through less serious forms of degradation are much more widespread. According to the indicative GLASOD study (Oldeman et al. 1990), 38 percent of the world's 1500 million hectares of cropland had undergone human-induced degradation between 1945 and 1990. Various sources suggest that soil degradation caused 10 to 15 percent of global crop production to be lost in this period (Crosson 1994; Scherr & Yadav 2001).

Until now, the impact of soil degradation on global food production has been amply compensated by innovations that increased land productivity. However, soil degradation may increase fertilizer costs and jeopardize further productivity increases in the future. Again, the geographic distribution of the effects is uneven. Especially Africa, Central America and some parts of Asia have many poor soils that are easily degraded. In the temperate zones, most soils are less vulnerable to degradation.¹⁷

Other forms of natural resource degradation are also important. Natural fish stocks in many seas and inland waters have been over-exploited. Genetic erosion threatens the gene pools on which the breeding of new crop varieties is based. Groundwater- and soil pollution is a serious problem in areas with intensified agriculture, and ozone pollution is reducing crop yields in large areas (Giles 2005; Kempenaar et al. 1999). Aquifer depletion is threatening the productivity of several irrigated systems. In parts of North China, groundwater levels are falling by one meter per year, and in some places in India, two to three meters per year (Rosegrant et al. 2002). In the United States, one fifth of the irrigated area is supplied by groundwater pumped in excess of recharge (Postel 1992).

At larger geographic scales, changes in natural resources are mostly gradual, but not always. Many natural resources are non-linear dynamic systems with multiple attractors that may appear, disappear, split or merge through gradual parameter changes. This may lead to

¹⁶ See also Svensmark et al. (2006) for evidence supporting the possibility that global warming is largely due to solar forcing.

¹⁷ A major exception is Australia, where salinisation is a major problem.

sudden changes when certain threshold values are exceeded (Cohen & Stewart 1994; Scheffer & Carpenter 2003). For example, if soil degradation exceeds certain thresholds, effects like leaching of nutrients and poor rooting of plants can reduce the nutrient recovery rates of crops, hampering the regeneration of fertility and organic matter (Breman 1997; Van de Koppel et al. 1997). Such biophysical characteristics add to economic factors by which agricultural ecosystems can be locked into low productivity equilibrium (cf. Section 2.3).

From a geological point of view, the global warming that has occurred in the 20th century is a gradual change. Nevertheless, one cannot be sure that it will remain so. World climate is a complex dynamic system that is susceptible to relatively abrupt changes. For example, some scientists speculate that non-linear behaviour in the Northern thermohaline seawater flow might cause sudden cooling in Northern Europe if the melting of continental ice sheets were to exceed a certain threshold (NCDC).

Ecosystem-climate interactions could also lead to sudden changes. For example, by reducing the resilience of the eastern half of the Amazon forest, global warming and deforestation could cause a massive forest die-off that would change the regional climate and turn the area into savannah. In its turn, such a drastic change in one of the world's major biome-climate systems might have climatic effects over a large part of the globe.¹⁸

4.3 Non-food claims

Non-farm claims to land and water

Claims to land and water for non-food purposes will also increase. It is often assumed that human settlement (buildings, roads, parks, etc.) requires 30 ha per 1000 people (for example FAO 2003), but according to Young (1999) 50-65 ha will become a more realistic figure. We therefore suppose that something like 50 ha per 1000 people may be required for this by 2050. If half of this land were to be potentially suitable for agriculture (cf. Döös 1994), this means that 0.23 Gha of potential farm land would be used for this purpose. Human settlement would then claim 3 percent of all potential farm land.¹⁹

The claim for water for non-agricultural purposes will likewise increase. Rosegrant et al. (2002) expect that the non-farm consumption of freshwater will grow by 60 percent between 1995 and 2025, and that its share in the total human water consumption will rise from 18 to 25 percent. In many areas, the supply of renewable water is large enough to accommodate this increase while still allowing a considerable increase in water consumption for irrigation. However, many densely populated river basins where water stress is already high are also faced with a rapid rise in domestic and industrial water consumption (also cf. Molden 2007; Rijsberman 2006; Vorosmarty et al. 2000). This is a serious impediment for increasing the production of food in these areas. Especially the demand for clean drinking water for the cities often gains priority over the demand for water for agricultural purposes. The efficiency of urban water use could be strongly increased, but this requires considerable investment in pipes, the reducing of leakages and pollution, and the recycling of wastewater (Sherk et al. 2002).

The effect of environmental claims is ambivalent. On the one hand, there is some room for synergy between environmental policy and food production. One could think for example about agricultural practices that raise crop production while at the same time increasing groundwater recharge and enabling a more stable river base flow (Kauffman et al. 2005). In this way, non-agricultural claims on water could also more easily be accommodated. Similarly, increasing the amount of organic matter in land under food crops could both raise crop yields and reduce CO₂ concentration in the atmosphere.²⁰ However, this

¹⁸ Pavel Kabat and Carlos Nobre, presentations Wageningen November 3-4, 2005

¹⁹ Potential production is determined by the availability of water as well as land, so that 3 percent of potential production corresponds to more than just 3 percent of the land.

²⁰ The generation of biochar (charcoal from biomass) in combination with biofuel from organic materials like organic waste, residues or energy crops could be a promising technique to sequester CO₂

requires farming systems that in many places are not cost-effective and will therefore need special economic incentives. The price for carbon sequestration that follows from the current Kyoto agreement is a far cry from what will be needed to realize this option.

On the other hand, biodiversity conservation will mostly compete with agricultural production. Of the 4.0 Gha that is under forest in the world, one-tenth has currently been designated for conservation purposes (FAO 2006). This area may significantly increase in the coming decades. How much will be potential farm land is hard to say. Besides, some agriculturally suitable non-forest land may also be reserved for nature conservation.²¹

Like the livestock revolution, claims for nature conservation involve an aspect of competition between rich and poor. The demand of western citizens for wildlife parks or forestry projects in developing countries may compete with livelihoods for the local poor. The effect on global food supply will be limited as long as the land that is concerned has low suitability for agriculture. However, this would change if more fertile land were to be used for nature and landscape conservation in developing countries or in developed countries themselves. For the moment, we assume that at least 10 percent of the global potential agricultural land may be claimed for these purposes by 2050. Depending on the evolution of conservation policies, however, it may also be considerably more.

Non-food claims to farm capacity

In addition to non-farm claims to land and water, non-food claims to farm production capacity may also increase. The production of cheap pumpable oil has peaked and oil prices will probably remain above 40 USD per barrel (Campbell 1997; Hallock et al. 2004; Shell 2001; US Department of Energy 2006).²² It may induce a reversion of the substitution of fossil fuels for farm-based materials and energy sources that started in the 19th century.

The last few years have seen surges in the production of biofuel. Brazil now uses half of its sugarcane and the United States one-fourth of its maize for fuel ethanol (Buntrock 2007; Cassman & Liska 2007; World Bank 2007). Indonesia and Malaysia want to use half of their current production of palm oil (of which they are the world's largest producers) for bio-diesel. The current biofuel boom is driven by a spike in oil prices and political decisions. With the feedstock prices of the early 2000s, Brazil could competitively produce fuel ethanol at crude oil prices above 29 USD per barrel. However, the US and the EU could only do so at oil prices above 45 USD (OECD 2006), and the recent increase in cereal prices has pushed this threshold upward. Both blocs are supporting biofuels through subsidies, tax reductions or minimum consumption requirements. These policies are based on the greenhouse hypothesis and the wish to reduce energy dependence on Russia and the Middle East. Such objectives are sensitive to changes in scientific insights and world politics. Additionally, a fall in oil prices might end the biofuel boom like it did in the 1990s.

In spite of the current biofuel boom, the substitution of biomass for fossil fuel will probably be a gradual process. Considerable stocks of coal and unconventional oil, progress in extraction techniques, renewable energy sources like wind energy (and a possible come-back of nuclear power), and efficiency increases in energy use will moderate the rise in fossil fuel prices (Odell 2004; Smil 2003). New techniques including nanotechnology might even allow a further substitution of synthetic products for farm-produced materials like cotton or natural rubber (ETC group 2004).

Nevertheless, in the longer term, the substitution of biomass for fossil hydrocarbons is almost sure to continue. In addition to the rising prices of the latter, new techniques will make this substitution more profitable. Techniques for making ethanol out of (ligno-)cellulosic materials (AgriHolland 2006; Demirbaş 2005) will allow using whole plants rather than seeds

from the atmosphere. Once applied to agricultural land, biochar sustainably increases soil carbon, water and nutrient retention capacities (Marris, 2006).

²¹ It is believed that total protected areas currently take up 0.2 Gha of potential arable land in developing countries (Young 1999).

²² The expectation in IMF (2005) that crude oil prices will stabilize around 34 USD per barrel after 2007 seems too optimistic.

or tubers and thereby make fuel ethanol competitive at lower oil prices (OECD 2006).²³ Moreover, there are more promising non-food applications of biomass than fuel, heat or electricity. Especially functionalized chemicals – which contain elements like nitrogen or oxygen – can be made with less energy from biomass components that already contain these elements rather than from fossil fuel in which they are lacking. Rising oil prices will stimulate the research for suitable biorefinery techniques, and once these exist, the production of biochemicals may become quite profitable. It has been estimated that dedicated crops could give a turnover of €1940 per ton if a 20 percent fraction could be used for functionalized chemicals and the rest for bioenergy (Sanders et al. 2007).

The potential impact of bio-chemicals and -energy on food markets should not be underestimated (see also Cassman & Liska 2007). It has been suggested that biomass for non-foods will price itself out of the market before having large effects on food markets (Schmidhuber 2006), but by reducing conversion costs, new techniques will push the price at which this occurs upward. Bio-energy requires large inputs of land and water. With current conversion techniques, the US would need 30 percent and the EU-15 72 percent of their cropland to replace a mere 10 percent of their fossil fuel consumption (OECD 2006). New techniques will improve these ratios but also raise the demand. An assessment of the claim that bio-based non-foods will make to farm resources requires an economic model that endogenizes the demand for these products. Unfortunately, no such study seems to have been made up to now (see also Meeusen & van Tongeren 2006; OECD 2006).

Some authors have suggested that bio-energy could be produced from residues, dung and waste only (for example Fischer & Schrattholzer 2001), or from feedstock that is grown without irrigation on land that is not very suitable for food crops (for example Woods 2006). Several studies have explored the global room for bio-energy while assuming crop yields up to some agronomic potential as well as and some socially desirable allocation of natural resources over food and energy crops (for example Hoogwijk et al. 2005; Smeets et al. 2005; Wolf et al. 2003).²⁴ On this basis, optimistic assessments are given that range from 162 EJ to 1440 EJ – 0.2 to 1.75 times the global energy consumption expected in 2050.²⁵ However, these studies ignore economic constraints and agronomic limitations on energy balances that will lead to much lower yields. They also forget that in a market economy, non-food crops cannot simply be stopped from competing with food crops for good land and irrigation water,²⁶ as cotton also illustrates. Furthermore, firms will often prefer dedicated crops over residues and wastes because of the high costs of collecting and separation involved in the latter. These materials also contain many elements that could be used for food or feed. It is only if these are extracted that their use for non-foods will really stop to compete with food production (Rabbinge 2005).

The truth is that, until novel techniques for cheap energy production like nuclear fusion or photosynthetic fuel cells are operational (Pandit et al. 2006; Smil 2003), which is

²³ Additionally, feedstocks like wood or switchgrass are traditionally grown on marginal land and promote soil regeneration and fixing carbon in soils (McLaughlin 2002; Watson et al. 2000), and the net energy balance and CO₂ reduction effects of second generation biofuels will be better than those of existing biofuels, which are at most slightly positive (Farrell et al. 2006; Berndes et al. 2001; Greene 2004; Shapouri et al. 2002; US Department of Energy 2003). These characteristics will encourage policy measures to stimulate the use of advanced biofuels if the greenhouse hypothesis holds.

²⁴ The assessment by the European Environment Agency (2006) of the room for bionenergy production in the EU is more cautious. This study starts from an economic model projection of the area that would be used for food production in the absence of competition from bioenergy crops, and requires that the EU food self-sufficiency ratio does not decrease and that environmental standards are respected.

²⁵ Bio-energy production under the low scenario of Wolf et al. (2003) is 162 EJ, under the highest scenario of Smeets et al. (2005) 1440 EJ (including bio-energy from residues and surplus forest growth). The medium projection of global primary energy consumption in 2050 of the World Energy Council is 836 EJ (World Energy Council 2005).

²⁶ See Azar & Larson (2000) for a concrete example. Additionally, much of the land that is unsuitable for food production is also unable to produce biomass for non-foods in an ecologically or economically viable way (Hoogwijk et al. 2005).

not expected before mid-century, the claim on farm production capacity for new non-foods may grow considerably (cf. also Berndes 2002; McCarl et al. 2001; De Wit 2004). For a rough guesstimate, one could use the middle-of-the road scenario of the World Energy Council (2005) in which bio-energy would provide around 84 EJ by 2050. With 15 GJ per ton, 5600 Mt of biomass would be needed to produce this. This should be supplemented with the needs for functionalized chemicals. With 3 percent growth per year, the global output of these would increase from the current 250 Mt to 1000 Mt by 2050. Some 1000 Mt of biomass would be needed for this, which would bring the phytomass demand for energy and chemicals to 6600 Mt. If we assume that 14 tons of dry matter per hectare would be an attainable global average, 0.48 Gha would be required for this.²⁷ Adding 0.05 Gha for other non-food crops would bring the total claim for non-foods to 0.53 Gha, or 7 percent of the global potential agricultural land. Together with the assumptions on the claims for human settlement (3 percent) and biodiversity conservation (at least 10 percent) that we have made above, this would bring the total claim for non-farm and non-food purposes to minimally 20 percent of the global area that is potentially suitable for farming.

The bottom line is this: the demand for phytomass for food will more than double, but land, water and phosphorus are becoming scarcer while competing claims will reduce the global potential for producing this phytomass by at least one-fifth – and possibly significantly more. These are robust tendencies, which can be channelled and mitigated, but hardly be stopped. They involve a competition between the demand of the poor for bulk foods and that of the affluent for animal foods, bio-based non-foods and green services. Only a sufficient increase in food production can prevent these developments from causing strong rises in food prices. The next section discusses the technical options that are available for this.

5. Technical possibilities for raising food production

At present, the global output of agricultural phytomass amounts to 7 MT of grain equivalents (see scenario 1 in Table 4). The Limits-of-Food-Production study (Luyten 1995; Penning de Vries *et al.* 1995) that was carried out in Wageningen in the 1990s assessed the room for expanding this output within the potential production landscape of farming. To that end it estimated the maximum yield that could be attained with existing crop varieties, under given soil and climatic conditions and with the available water supply at basin level, provided that all land (including grazings) were to be optimally fertilized and losses in the food production chain were to be limited to 10 percent. It was concluded that world agriculture could produce 72 MT grain equivalents of food.²⁸ This would suffice to provide an affluent diet of 4.2 kg grain equivalents per day to 47 billion people – or 5.2 times the medium UN population estimate for 2050 (see scenario 2 in Table 4).²⁹

Before discussing the implications, some qualification of this outcome seems to be justified:

- As has been indicated in Section 3.3 above, affluent consumers have a habit that is hard to eliminate of wasting food because it is inherent in affluent lifestyles. We therefore assume

²⁷ Greene (2004) thinks that extracting protein from feedstock, using grain stover, and producing additional biofuels at a higher cost would allow reductions in the area needs for biomass in developed countries. However, this may be cancelled out by lower feedstock production efficiencies in developing countries

²⁸ The Limits-of-Food Production study assumes that suitable land globally amounts to 7.8 Gha. In Section 4.1 we corrected this to 7.6 Gha. The effect on the global potential is negligible, also because this reduction involves no corresponding reduction in the availability of water for irrigation.

²⁹ This ratio masks strong differences between regions. In South America the room for increasing production is still ample, while in South and East Asia it is quite small. Under a low external input scenario, without biocides or chemical nitrogen fertilizer, only 20 billion people could be provided with an affluent diet, and significant shortages would appear in some regions.

an unavoidable consumer waste of 20 percent, which raises the requirement for an affluent diet to 5.25 kg grain equivalents per person per day.

Table 4: Maximum food production and population that could receive an affluent diet under different scenarios

	1.	2.	3.	4.	5.	6.	7.
	Current situation	Original high-external-inputs scenario	Adjusted high-external-inputs scenario	As 2, with current yield gap and no increase in irrigation	As 2, with 40% yield gap and increase in irrigation limited to 50%	As 2, with increase in irrigation limited to 50%	As 2, with 25% yield gap in core regions but larger yield gaps in other regions, ¹ and increase in irrigation limited to 50%
Rainfed cropland (Gha)	1.2	1.4	0.2 to 0.6	1.2 to 2.5	1.2 to 2.5	1.2 to 2.5	1.2 to 2.5
Irrigated cropland (Gha)	0.2	2.5	1.3 to 2.2	0.2 to 0.2	0.3 to 0.3	0.3 to 0.3	0.3 to 0.3
Grassland (Gha)	2.8	4.0	2.8 to 3.3	2.8 to 3.3	2.8 to 3.3	2.8 to 3.3	2.8 to 3.3
Food production (GT grain equivalents)	7	72	32 to 47	7 to 16	20 to 28	27 to 37	14 to 19
Assumed input for affluent diet (kg grain equivalents person ⁻¹ day ⁻¹)	?	4.20	5.25	5.25	5.25	5.25	5.25
Population that can receive an affluent diet (10 ⁹)	?	47	16 to 24	4 to 8	10 to 14	14 to 19	8 to 10
Idem as proportion of medium UN estimate for world population in 2050	?	5.2	1.8 to 2.7	0.4 to 0.9	1.2 to 1.6	1.5 to 2.1	0.8 to 1.1

¹ 25% yield gap in North America, West & Central Europe, Oceania, and East, Southeast & South Asia; 40% yield gap in former USSR; 60% yield gap in Latin America; 80% yield gap in Sub-Saharan Africa.

Source: Luijten (1995) and own calculations based on data in this publication

- The production potential of 72 GT of grain equivalents presupposes that all suitable land (including forests if the land is suitable for agriculture) is used for food production. In reality, one has to reckon with claims for non-food purposes. Based on the considerations in Section 4 above, we assume that by mid-century, at least 20 percent of the potential agricultural land will be claimed by human settlements, biodiversity conservation and non-food crops.³⁰ We take 43 percent as a maximum bound for these claims, which would mean that the global agricultural area would be restricted to its current size.
- The production potential is derived from the light- and water-use efficiencies of plants. As has been indicated in Section 2.1, however, agronomic complications make yields beyond 80 percent of the potential yield difficult to achieve. Indeed, a further reduction of the yield gap might prove more difficult than stretching the potential itself. External causes like air pollution (especially ozone pollution) also reduces crop yields in large areas (Section 4.2). Additionally, environmental considerations set limits to farm production growth, because this entails nitrate and phosphate emissions that may degrade aquatic ecosystems and thereby impair the use of water for drinking and other purposes

³⁰ Ecological changes can also affect the potential for food production, but we assume their aggregate effect to be neutral. Soil degradation might well cause losses in the order of 10 percent of the potential yield, but this can largely be compensated by increased nutrient application.

(for example Carpenter et al. 1998). Even though increased nutrient applications do not necessarily involve higher nutrient loss rates,³¹ emissions cannot be avoided.³² For these reasons, we see a 20 percent yield gap as unavoidable.

The upshot of these corrections is shown in scenario 3 in Table 4. The minimum and maximum numbers in this scenario are related to the lower and upper bounds that we assume for the non-farm claims to natural resources. The global potential for biomass for food is reduced to 32 to 47 GT of grain equivalents. This would suffice to provide 16 to 24 billion people with an affluent diet, or 1.8 to 2.7 times the medium UN population estimate for 2050. The technical implications of realizing this potential are discussed below.

5.1 Realizing the potential

Growing along production functions and shifting of production functions

A first increase in the production of phytomass for food above the current output might be achieved by expanding agriculture to all suitable land that is available while maintaining average yield at its current level. This could be seen as a growth along the production functions that currently exist in different areas. Yet it would be more than a simple horizontal growth with unaltered input-output relations. It would require an increase in the input of fertilizer per hectare, because much of the spare land is less fertile and more easily degradable. Assuming that this scenario involves no expansion of the current irrigated area, global production would rise to between 7 GT and 16 GT, depending on the claims to natural resources for non-food purposes. This would only allow an affluent diet for a population of 0.4 to 0.9 times that expected in 2050 (scenario 4 in Table 4).

A further increase in production can be achieved by extending already known techniques to areas where they are still under-utilized. In many places, straightforward fertility and water-saving measures would allow considerable increases in yields. Simple techniques for water harvesting and light irrigation would enable significant production growth in rainfed agriculture (Molden 2007). In many irrigated systems that are faced with water shortages, water-use efficiency could easily be doubled (Tuong et al. 2005). Furthermore, integrated pest management would reduce pre-harvest losses; simple storage and processing measures would decrease post-harvest losses; and improved livestock systems could moderate the large gaps between feed ratios in developing and developed countries (Wirsenius 2003).³³ Such improvements can be seen as a shift of local production functions in the direction of the frontier function that exists in more favoured areas. Unlike a growth along existing functions, they require major improvements in education and research systems in less favoured areas.

How much global food production could increase in this way is difficult to assess. However, we assume that in addition to an expansion of food production to all available land, it would involve a 50 percent expansion of the current irrigated area and a generalisation of the yield gap of 40 percent that now prevails in the developed world. Global production could then attain 20 GT to 28 GT of grain equivalents. This would still only allow an affluent diet for a population of 1.2 to 1.6 times the medium UN estimate for 2050 (scenario 5 in Table 4).

³¹ De Wit (1992). See also Figure 8 which shows that the global relationship between N-fertilizer and N in crops did not decrease in recent decades in spite of a huge increase in fertilizer use. (Under less favourable conditions, increases in yields beyond relatively low levels may involve decreasing resource use efficiency. See e.g. Nijland & Schouls 1997 for the effect of uncontrolled heterogeneity in time and space.)

³² The Dutch Institute for Public Health and the Environment showed that end-of-pipe technologies may be more effective than solutions through agricultural measures in some cases (RIVM 2004).

³³ It should be noted that present low feed ratios in developing countries are not always inefficient. They are partly related to the consumption of fatty meat, which is rational where the supply of food energy is minimal. Additionally, they are often coupled to the use of lower quality feed which may be efficient in prevailing conditions in these countries.

A further rise to a range of 27 GT to 37 GT of grain equivalents would require more stress-resistant varieties and other solutions for reducing biotic and abiotic stresses and post-harvest losses (scenario 6). The final step to an output between 32 GT and 46 GT of grain equivalents would in addition require an eightfold increase in the irrigated area to 2.0 Gha. The innovations needed for these steps would mean a shift in the frontier function to an innovation possibility set that corresponds to the outer limit of what is possible given the existing metabolic efficiencies of crops (cf. Figures 4-5). This can only be achieved through massive agro-industrial R&D, skills improvement and co-operation, not just in less favoured areas but at the global level.

How much energy would it cost?

The energy requirements of agricultural growth can be moderated by raising the water and nutrient use efficiencies of farming (Smil 2000). Techniques like drip irrigation and monitoring the moisture status of soils can make irrigation much more precise. Additionally, significant savings are possible by adapting crop choice to regional water availabilities and using trade to bridge differences in supply and demand. Nutrient use efficiency can be improved by proper tillage, better recycling of residues, and fine-tuning of fertilizer application in both time and place. GPS-led precision farming (Gandah et al. 2000; Robert 2002) is just one possibility for this. Furthermore, the biofixation of nitrogen could be increased through leguminosae or techniques like inoculation with nitrogen-fixing growth-promoting rhizobacteria (Bashan et al. 2004; Dobbelaere et al. 2003; Giller & Merckx 2003).³⁴

Nevertheless, raising global production to 47 GT of grain equivalents would involve large increases in energy inputs. Much of it would be needed for nitrogen fertilizer. Even if fertilizer recovery rates could be raised to 80 percent, a yearly application of about 1 GT of N would be needed – about 12 times the current use.³⁵ The most efficient ammonia factories currently use 34.5 GJ per ton of N. The stoichiometric limit of the Haber-Bosch process is 25.4 GJ per ton of N, and no other processes for producing N-fertilizer are in sight (Smil 2001). Assuming that the energy requirement could be reduced to 30 GJ per ton of N (also cf. Jenssen & Kongshaug 2003), and that all nitrogen could be applied in the form of ammonia, a total energy input of 30 EJ would be needed – about 5 times the current amount. This is a sharp increase, but not an impossible one in a physical sense. Assuming that world energy were to evolve in line with the middle-of-the-road scenario of the World Energy Council (2005), it would mean an increase in the energy for N fertilizer from 1 to 4 percent of the global energy consumption.

The energy requirements for irrigation would also be considerable. The eightfold increase in irrigated area that would be needed presupposes a drastic change in the allocation of water. Rather than dryer land, where irrigation investment is most profitable, more humid land where irrigation gives the highest additional crop per drop should be irrigated first (Penning de Vries et al. 1995). This requires building large storage capacities and transporting water over large heights and long distances to deliver small volumes of water per hectare that give moderate increases in yields (also cf. Rosegrant et al. 2002; Seckler et al. 1999). Nevertheless, there is no reason why this would be physically impossible. The global energy input for irrigation is about 0.3 EJ (Smil 1991). Even if an eightfold expansion in irrigated area were to involve a twentyfold increase in energy demand to 6 EJ, this would still be less than one percent of the expected global energy consumption at mid-century.

The greatest challenge would be the elimination of phosphate limitations. To begin with, about 6.5 GT of P would be needed to build up the phosphate status of phosphate-poor

³⁴ Other solutions like the breeding of N-fixing cereals or raising the nutrient efficiency of plants are more remote possibilities. For instance, increasing the nutrient efficiency in rice would require the simultaneous introduction of three new enzymes into rice plants (Britto & Kronzucker 2004).

³⁵ It is assumed that crops contain 2 percent of nitrogen and that 0.15 GT of N comes from other sources.

soils.³⁶ This would practically deplete the world's potential phosphate reserves (see Section 4.1; also cf. Penning de Vries et al. 1995 and Steen 1998). After this, a yearly application would still be required to make up for the phosphorus that is removed by the harvested crop. Assuming that the phosphorus recovery rates of crops could be raised to 100 percent, around 0.23 GT of P – about 13 times the current global consumption – would be needed for this.³⁷ Some three-quarters of this might be met by recycling through livestock or recovery from waste streams (cf. Steen 1998), where possible in combination with energy generation (Lundin et al. 2004). The rest could only be covered by exploiting unconventional reserves or by using chemical or biological methods to win phosphorus from seawater. This will involve huge energy costs, but we are not aware of any attempt at a quantitative assessment.

5.2 Can the potential be stretched?

The potential of 32 GT to 47 GT of grain equivalents is circumscribed by the availability of freshwater and suitable land, the existing pool of germplasm, and the existing light- and water-use efficiencies of plants. These are relatively hard constraints, but unlike what is sometimes suggested (for example Jordan 2002), it does not mean that they could not be stretched (cf. Section 2.1).

Land availability has been discussed in Section 4 and we think Table 4 presents extremes as to the availability of this resource. To increase irrigation water, one could think of the purification of sea or wastewater through capacitive deionisation or nanotechnology (Wetsus; Royal Society & Royal Academy of Engineering 2004). This option seems feasible only in exceptional circumstances, and its influence on the global potential for food production seems negligible for the foreseeable future.

A much more effective strategy would be to increase the potential yield of crops. However, this is a difficult task. The effects of scientific breeding for enhanced plant metabolism are declining (Duvick & Cassman 1999). Although the actual yield increases in major crops show no tendency to diminish (Haffner 2003), the yield potential of rice and maize has barely improved during the past few decades (Duvick & Cassman 1999; Peng & Khush 2003; Tilman et al. 2002).

From a genetic point of view, improving harvest indices no longer seems a promising route to substantially increase yield potentials (Reynolds et al. 2005; Shearman et al. 2005). Several authors argue that yield potentials of cereals such as rice are now source-driven rather than sink-driven. In other words, yields cannot be further increased by changing plant architecture to re-allocate biomass within the crops. Nevertheless, in crops with an indeterminate architecture or where less breeding has been done, the scope for raising the harvest index may still be considerable (see for example Berry & Spink 2006 for rapeseed).

Within the current gene pool, light- and water-use efficiencies can still be improved through integrated crop and livestock management. For example, light-use efficiency could be increased by reducing the time during which sunlight remains unutilized. Adapted crop rotations and intercropping could be ways to achieve this (Horwith 1985). In theory, perennial cereals could have a similar effect (Cox et al. 2006). However, it remains to be proven whether these approaches would entail significant effects on yield potentials.

In the major cereals, boosting yield potentials requires enhanced photosynthesis to increase light-use efficiencies. The most prominent route proposed for rice, for example, is to change rice from a C3 crop into a C4 crop.³⁸ Comparing the productivities of maize and rice crops with similar growing seasons and grown under similar conditions, Sheehy et al. (2007) expect that C4 rice would allow increases in rice yields of up to 50 percent (see also Long et

³⁶ Penning de Vries et al. (1995) estimate that 1 ton of P per hectare would be needed for this purpose. Multiplying this by 6.5 Gha of available land gives 6.5 GT of P.

³⁷ It is assumed that grains contain 0.5 percent P.

³⁸ Other routes include e.g. the introduction of improved forms of Rubisco from algae into C3 plants (Long et al. 2006).

al. 2006). Additionally, C4 rice would enable strong improvement in water- and nitrogen-use efficiencies. However, whether it will be possible to breed C4 rice is still highly speculative. Moreover, turning C3 crops into C4 crops will be effective only in relatively warm climates. For temperate regions, breeding for C4 is not a viable route.

Yin and Struik (2007) assess some of the pathways for introducing C4 biochemistry and physiology into C3 plants. Some perspectives seem promising at a certain experimental level (short time span and particular leaf area index), but when processes are scaled up to a full growing season or full crops, negative feedbacks may largely cancel out any positive effects that arise at the micro level. More generally, these authors suggest that crop systems biology is needed to take advantage of modern functional genomics (and traditional sciences like crop physiology and biochemistry) for understanding and manipulating crop phenotypes that are relevant for farm production.

Another option for stretching the limits of farm-based food production would be to increase the efficiency of the conversion of phytomass into food. Because an increasing share of the phytomass produced is transformed into animal products, the global room for food production is sensitive to changes in feed ratios. There is still room for improving feed ratios in developed countries (for example Nevens et al. 2006), but less than a few decades ago (see for example projections in Bouwman et al. 2005). Past improvements were coupled to a shift from fat to lean meat, which has now largely been completed.³⁹

Better prospects for converting biomass into more food are offered by biorefinement. Enough protein could be extracted from a crop residue such as cassava to replace one fifth of the world's soy protein. Protein could also be extracted from N-rich fodder like alfalfa or grass from fertilized meadows. The residue could still be used as roughage.⁴⁰ Additionally, protein could be gained as a by-product from the production of biofuel from cellulosic feedstock (Greene 2004; Ragauskas et al., 2006).

5.3 Beyond the farm paradigm

Although one can anticipate some possibilities for expanding our map of the potential production landscape, what lies behind the limits is in fact *terra incognita*. Moreover, even our knowledge of the landscape within the limits may change as new options for increasing input-use efficiency are discovered that were hidden by the specific pathway that human knowledge had taken rather than by the physical complexity involved by these options themselves. Our map of the potential production landscape can change, slowly and sometimes suddenly, as a consequence of new breakthroughs in human knowledge. In this sense, every notion of a potential or carrying capacity has a historical-social dimension (Benton 1992; Van den Belt 1995; WRR 1995). This is even true for our concept of the physical potential production landscape itself, which is bound to a meta-paradigm of cultivating or controlled grazing of plants on soil. Indeed, one could also consider increasing food production on bases other than farming. This could be done by learning from converging developments in agricultural and industrial processes.

A logical first step would be the application of farming principles to the marine environment (mariculture). The global wild fish stock is on the verge of being over-exploited,⁴¹ but one could argue that this is comparable to the over-exploitation that threatened Mesolithic hunter-gatherers 10,000 years ago. Wild capture is mere fish foraging. Likewise, current seaweed harvesting is predominantly plant gathering. A marine variety of the Neolithic Revolution (not to be confused with aquaculture based on farm biomass) would allow strong increases in the production of seaweeds or marine animals. It would require a solution for the problem of how to control nutrient flows in open water systems. Here we may

³⁹ A notable exception is marbled beef in the US.

⁴⁰ In some parts of Europe, protein from N-rich grass could already compete with imported soy protein.

⁴¹ Over 90 million tonnes of fish are being captured annually, while the estimated quantities that are sustainably available for human consumption vary between 74 million tonnes and 114 million tonnes.

learn from precision farming techniques that deal with the parallel problem of controlling water and nutrient flows in the field. For example, hollow cords for fixing seaweeds and on-the-spot drip fertilization could be used to cultivate seaweed plants that could be combined with offshore windmill parks and with fish and shellfish culture. Based on a first rough assessment, Reith et al. (2005) think that such a system could profitably be used to produce chemicals for the food industry and other industries.

In the saline fringes between sea and land, maricultural and agricultural approaches could be combined to make the best use of natural resources. Such mixed systems might also be used for remedying P shortages after mineral phosphate reserves have been depleted. Phosphorus that is lost on the land ends up in the sea, largely in estuaries where mixed sea-land production systems can be developed.

An exciting possibility that may be elaborated in maricultural systems is to create a bypass for the limit on biomass production that is set by photoreception efficiency. Agricultural crops are restricted to photosynthesis that is only triggered by the red spectrum of solar light. However, seaweeds and marine microalgae also have other photoreceptor systems that use the green light spectrum. By combining organisms with different systems, both the red and the green spectrum might be used, so that the same sunlight is utilized twice. A first experiment in Wageningen suggests that this could increase the potential for biomass production significantly.

The same principle might also be applied in industrial-biological production systems that exploit the nutritious value and the high input-use efficiency of certain algae, photobacteria or chemo-autotrophic organisms (Spolaore et al. 2006). The biomass produced by such systems could for example be used as feed or to produce zooplankton that is fed to fish. This could reduce the need for fishmeal for cultivated fish, which currently claims one-third of the global fish capture (Hentzepeter 2005). Such industrial-biological production systems would require solutions for the problem of harvesting and controlling the dynamics of microbial growth in watery environments. New and efficient harvesting principles should be explored, such as the milking of microalgae, which is already successfully being applied for harvesting carotenoids in continuous microalgae cultures (Hejazi & Wijffels 2004). It may be noted that various kinds of micro-organisms are already being cultured in the food industry. For example, yeasts are used in various processes and adapted to production aims and cultivation conditions by breeding. Experiences with such techniques may yield valuable insights for designing new processes based on, for example, microalgae.

Some microalgae can switch between heterotrophic growth and autotrophic growth (mixotrophy). This opens the possibility of cultivation systems where biomass is first generated heterotrophically after which secondary metabolites are produced autotrophically. Similar switching mechanisms are known for chemotrophic organisms. The exploration of such mechanisms may indicate new opportunities for developing industrial-biological production systems.

It should be noted, though, that all biological food production systems, including industrial-biological systems, are subject to the second law of thermodynamics. Living systems can only exist by avoiding thermodynamic equilibrium which would mean death; rather they search for a steady-state situation with a constant influx of energy and mass and an output of mass and entropy. This is realized by metabolic processes that continuously use energy and produce entropy that is dissipated to the environment. There is now evidence that the metabolic efficiency of living systems is linked to the way in which entropy is produced (e.g., Lems et al. 2003). More insight in this relationship would allow us better to assess the room for increasing food production through industrial-biological systems.

Some scientists are speculating on bypassing biological organisms altogether, using bionanotechnology for assembling foods directly from anorganic inputs (Moraru *et al.* 2003 and other references in ETC Group 2004). Such techniques could be based on the photochemical pathways used by algae and plants, as well as on the chemical pathways that are used by chemo-autotrophs. Nevertheless, others think that for a long time to come synthetic techniques for food production will remain science fiction (Royal Society and Royal Academy of Engineering 2004).

6. Economic forces

The above can be summarised as follows. In several developed countries and Asian developing countries, the low-hanging fruit that could be harvested by tapping large reserves of land and water and by using cheap fertilizer and first-generation scientific breeding is gradually being depleted. Nevertheless, the room for raising food production is far from exhausted. Provided the phosphate problem can be solved, it may be sufficient to provide an affluent diet to well over twice the world population expected by mid-century. Improvements in conversion efficiency may raise this ratio, as may new non-farm systems for food production.

This margin might seem reassuring, but it still refers to a qualified *technical* potential. To which extent it will be realized depends on economic forces, to which we now turn our attention. We first consider obstacles that are holding back food production in developing countries. Then we discuss whether the world food economy is approaching a new ceiling, and whether we might see a new trend change in food prices. Finally, we examine possible causes of disturbances in international food markets.

6.1 Obstacles to food production growth in developing countries

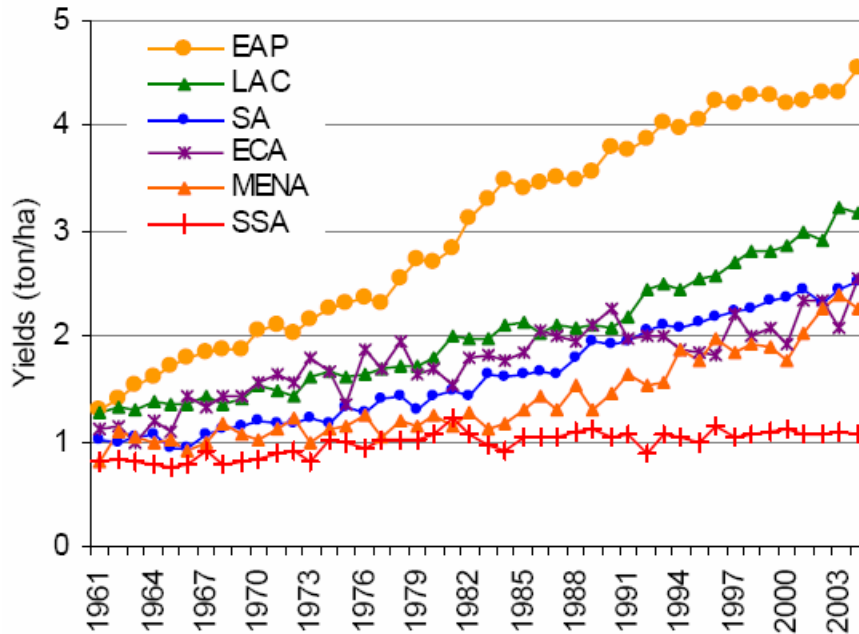
Of the global potential for phytomass production revealed by the Limits-of-Food-Production study, less than one-fifth is found in North America, Oceania and West and Central Europe. More than half is in Latin America and Sub-Saharan Africa, which also have the largest margin for raising production. It suggests that the expansion of food production should for a large part be realized in the developing world. However, the agricultural growth performance of different developing regions shows differs widely. In East Asia, grain yields have much increased since the 1960s, but in South Asia and Latin America they have increased more slowly, while in Sub-Saharan Africa they have stagnated (Figure 10).

What explains this divergence? In Section 2.3, we highlighted the population-price nexus as a mechanism in pre-industrial agricultural revolutions. Population growth raised agricultural prices, which acted as a catalyst for investment and innovation in larger farms. However, the global regime change in agricultural markets has broken this traditional relation. Population in the developing world soured in the 20th century, but the abundant global supply caused agricultural prices to fluctuate downwards. Where governments emulated the West through supportive and redistributive policies, a green revolution based on smallholder farms was still possible (Dawe 2001; Dorward et al. 2004; Francks et al 1999; Kajisa & Akiyama 2005; Timmer 2002). Such policies were introduced by ‘developmental states’ (cf. Öniş 1991; Wade 2003; Wong 2004) that were stimulated by a well-developed rural middle class, a relatively autonomous political class, and class-based interest articulation – conditions that stemmed from a long history of agricultural intensification and state formation. Parts of Asia had such a history, but other regions had not. They responded differently to the decline in international prices.

In Latin America, European markets for tropical crops induced the rise of plantations that used coercive labour systems to prevent workers from setting themselves up as independent peasants. It created a social divide between planter elites and rightless workers, whose low living standards hampered the development of consumer goods industries and reinforced the export dependence of the plantations. When international agricultural prices declined, this ‘disarticulated’ structure (de Janvry 1981) made the agrarian elites stick to open trade policies to secure their exports and use their socio-political dominance to shift the burden to the rural poor. In the end, they evicted many workers to pave the way for cost-

cutting mechanization. It allowed a development of a kind, but the ensuing growth was limited by low land productivity, social tensions raising transaction costs, and poverty-restricting domestic markets (cf. Johnston & Kilby 1975, World Bank 2005).⁴² After the 1970s, liberal-economic policies paved the way for new export-led growth based on large farms. In some cases, it generated new forms of intensive production (see for example Anríquez & López 2007 for horticulture in Chile), but elsewhere, land productivity and labour demand remained low.⁴³

Figure 10: Cereal yields in various regions, 1961-2004



SSA—Sub-Saharan Africa, SA—South Asia, EAP—East Asia and Pacific, MENA—Middle East and North Africa, ECA—Eastern Europe and Central Asia, LAC—Latin America and Caribbean

Source: World Bank (2007; based on FAOSTAT)

In Sub-Saharan Africa, the colonial scramble coincided with the onset of the downward trend in international agricultural prices. It limited the evolution of larger indigenous or European-owned farms and reinforced the smallholder nature of the economy, but colonial governments hardly supported smallholder farmers (Bundy 1972; Huijzendveld 1997; Munro 1976). For some time, land abundance provided a safety valve for population growth, but as this was gradually closed farmers were pushed into a spiral of poverty and soil degradation (Koning & Smaling 2005). Unlike colonial Asia, where similar developments were seen (Myrdal 1968), independence brought no change to supportive farm policies. African societies had personalist socio-political relations, and people tended to organize in factions rather than class-based movements (Bayart 1989; Goody 1976). This was normal for undifferentiated peasant societies with a recent history of long-fallow systems (cf. Table 2), but not conducive to Asian-type developmental states. Politicians were obliged to remunerate many clients with

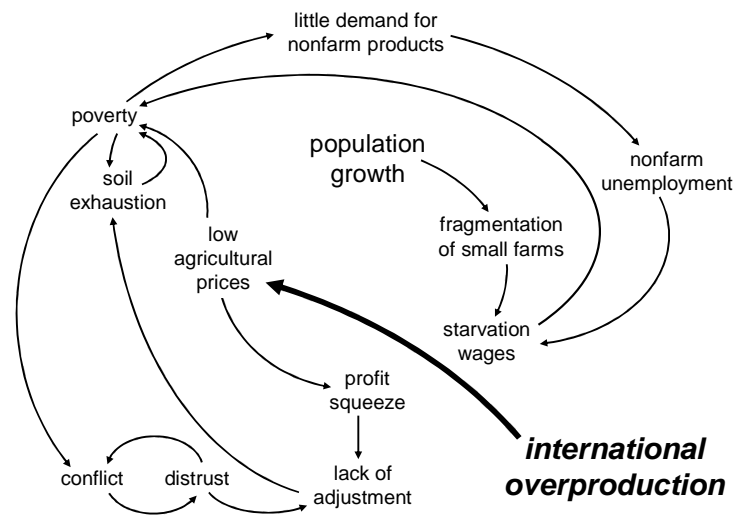
⁴² Similar conditions existed in South Africa, parts of South Asia, and for some time in the southern US.

⁴³ Additionally, the wild capitalism of the latifundios and the desperation of marginalized rural workers are driving a scramble for fragile natural resources, causing large-scale deforestation and soil depletion.

public sector jobs, and farmers were too weakly organized to prevent them having to foot the bill. In this situation, a new deterioration of the agricultural terms of trade strengthened the vicious socio-environmental spiral after the 1970s (Koning & Smaling 2005; see also Cleaver & Schreiber 1994; Savadogo 2007). People coped through redistributive social networks and risk-reducing diversification, making some experts hope that facilitating ‘sustainable livelihoods’ would allow an escape (for example Scoones 1998). As poverty continued, however, social capital eroded and social networks degenerated into rent-seeking cliques (see Ikelegbe 2001, Patterson 1998, or André & Platteau 1998 for examples).

In this situation, neither local nor national institutions could handle the increase in complexity that agricultural modernization involved. Experts debated on which approach could get agriculture moving – high or low external inputs, farmer field schools or training and visit – but the truth is that they all had disappointing results (for example de Jager et al. 2001). Several explanations have been proposed to explain these problems. Some point to poor soils, adverse climates or diversified food patterns that complicate a green revolution based on a few staples. Indeed, an agricultural revolution should be more diverse than in Asian circumstances (InterAcademy Council 2004). Nevertheless, these conditions hardly explain why areas with fertile volcanic soils and a predominance of maize are still stuck in stagnation. Other experts point to socio-political idiosyncrasies (for example Bates 1981; Djurfeldt et al. 2005), but do not explain why badly governed countries in Europe in the 18th century (like France under Louis XVI)⁴⁴ still saw farm progress while African countries do not.

Figure 11: Unsustainability spiral in poor areas



The real explanation is the way in which effectively post-Iron Age societies were plunged into global markets marked by chronic oversupply. Figure 11 illustrates the effects of this conjunction. As in pre-industrial situations (cf. Figure 6a), population growth entailed a fragmentation of small farms and low wages. However, with agricultural prices declining, it failed to stimulate larger farms and on-farm investment. As a consequence, an agricultural revolution was nipped in the bud. It precipitated a similar crisis to that which occurred in pre-industrial societies once an agricultural revolution had been exhausted. Rural poverty drove many people off the land but squeezed the demand for non-farm products so that this exodus

⁴⁴ Rather than being halted by bad governance, agricultural growth in France in the later 18th century helped paving the way for the changes of the French Revolution (Wertheim 1974).

only fuelled political markets based on the doling out of public sector jobs. Impoverishment made surviving today more urgent for people than caring for tomorrow, so that they opted for non-cooperative strategies that gave a high immediate pay-off but eroded the social capital. It started a vicious cycle of conflict and rising distrust, causing existing socio-political relations to degenerate. In this way, the governance problems that many see as a primary cause arose at least partly as an endogenous effect of the wider developments that led to stagnation. Unfortunately, the predicament was merely reinforced when international donors equated good governance with cutting down agricultural tariffs and wholesale dismantling of state services.

Disarticulation and the unsustainability spiral threaten both the availability and the access to food. While the former is undermined because the technical potential for food is under-utilized, the latter is affected by a vicious cycle of poverty and high population growth (cf. Cleaver & Schreiber 1994). If poverty suppresses the demand enough, the loss of production growth might not affect the price of food in the market, but the result is still undernourishment. A special risk arises when the unsustainability spiral raises the number of poor consumers in low-income countries where the stagnation of food production causes an increasing dependence on food imports. Today, 280 million people are surviving on less than one dollar a day in the world's least developed countries. If the incidence of extreme poverty in these countries were to remain unchanged, their number could rise to 770 million in 2050.⁴⁵ These countries are increasingly dependent on food imports and can hardly defend their poor if the import prices of food were to strongly increase in the future.

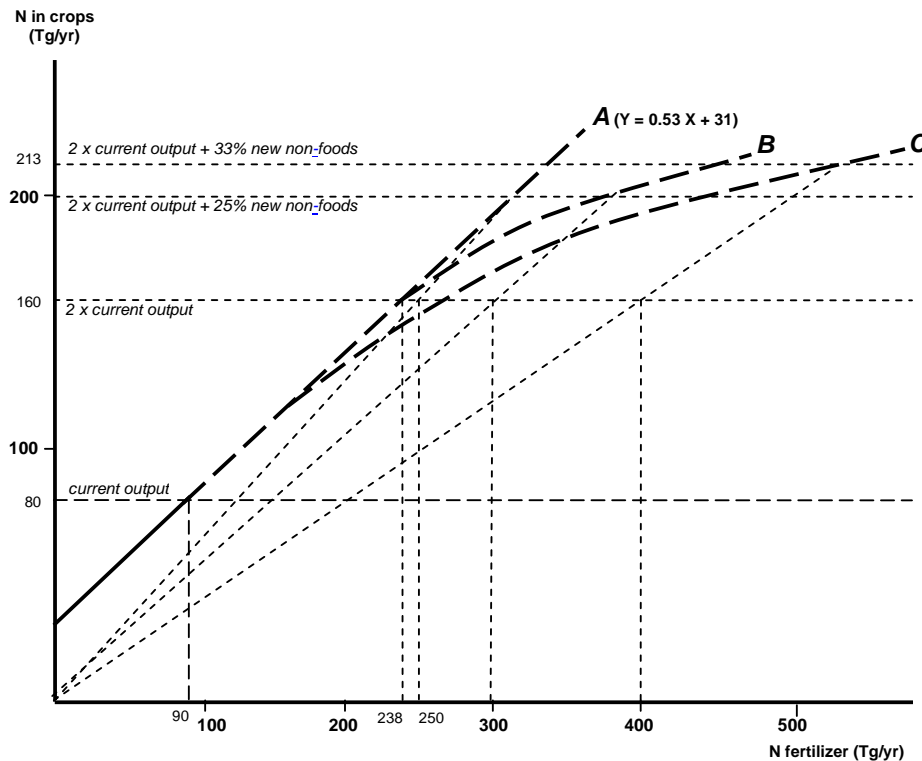
6.2 New ceiling? New trend change?

Even without disarticulation or unsustainability cycles, production functions in more peripheral areas will lag behind the frontier. As a consequence, the global food economy might approach a new relative ceiling before the technical room for expanding production is exhausted (cf. Section 2.3). In spite of the greatly enhanced learning capacities of modern society, this could happen when the increase in global demand caused crop yields in more favoured agricultural areas to approach the hard-to-surpass limit of 80 percent of potential yield. In that case, it would not be just the boundaries of a specific agro-production system (sub-paradigm) that would become constraining, but the harder boundaries of the agricultural meta-paradigm itself (see Section 2.1). In Section 5 we discussed possibilities for stretching the agronomic potential or for increasing food production on a non-farm basis. However, we have also seen that these are not the easiest ways to go.

To illustrate the possibility of a new ceiling, let us resume our thought experiments on the basis of the Limits-of-Food-Production study. Suppose that in those regions where the agricultural frontier areas are concentrated (North America, West and Central Europe, Oceania, and East, Southeast and South Asia), the yield gap were to be reduced to 25 percent, but that in the former USSR, Latin America, and Africa, it could only be reduced to 40 percent, 60 percent, and 80 percent, respectively. The effect would be that the more than doubling of the demand for food that is expected by mid-century will hardly be able to be met. If all suitable land that is not claimed for other purposes were to be used, and the irrigated area were to expand by 50 percent, world food production could then only increase from the current 7 GT to an output between 14 GT and 19 GT of grain equivalents (see scenario 7 in Figure 4.) This does not mean that world food is running up against absolute limits (a relative ceiling is not an absolute carrying capacity), but it suggests that a business-as-usual development might not suffice to prevent new scarcity in global food markets.

⁴⁵ Calculation based on poverty indicators in United Nations (2005a) and population projections in United Nations (2005b). The share of extreme poverty in all LDCs is assumed to equal that in those LDCs (22 out of 49) for which poverty indicators for the years between 1990 and 2005 were available.

Figure 12: Hypothetical representation of the amount of N-fertilizer required for a doubling of phytomass output for food



Apart from the question concerning whether the global food economy would approach a new ceiling, the question remains as to how much a doubling of the supply of agricultural phytomass for food will cost, and how this will affect food prices. This will in the first place be influenced by energy costs. Modern agricultural growth is especially energy-consuming. While the energy input-output ratio in industry has declined since the 19th century, that in agriculture has continued expanding (Smil 2003). In the US, energy costs are now 25 percent of crop production costs. In a country like Argentina, they are as much as 43 percent (OECD 2006). Although rising oil prices have induced improvements of energy efficiency since the 1970s (Cleveland 1995; Uhlin 1999), it is unlikely that the energy needs for farm production will strongly decrease in the future. This is illustrated in Figure 12, which is related to the historical data on crop response to N fertilizer in Figure 8. First suppose that the linear regression line A through these historical data would still adequately describe the fertilizer response at significantly higher levels of global production. In that case, a doubling of global phytomass output for food would raise the N-fertilizer required from the current 90 Tg to 238 Tg. The fertilizer-output ratio would increase by one-third, from 1.14 to 1.52 (N in fertilizer / N in crops). If global agriculture should also provide an amount of phytomass equal to 25 percent of that for food to meet the demand for new non-foods, the fertilizer-output ratio would increase to 1.59. This would bring the N-fertilizer required for food at 250 Tg – 5 percent more than when no additional phytomass for non-foods were to be produced.

However, all this presupposes that a 2.5 fold increase in global phytomass production were to involve constant returns – a very optimistic assumption that does not necessarily follow from Figure 8 which merely gives a statistical relation between historical data at the global level. Suppose that the global crop response to N-fertilizer were really to follow the curve B in the figure, which means that increases in global production above twice the current level would involve diminishing returns. The competition from non-foods would then raise the fertilizer input needed for food to 300 Tg – 26 percent more than the 238 Tg that would be

needed without new non-foods and with constant returns. The fertilizer-use efficiency should be raised considerably to compensate this effect and keep the increase in the fertilizer-output ratio to one-third. Even then, a 25 percent improvement in the energy efficiency of producing fertilizer (or an additional improvement in fertilizer-use efficiency) would be needed to prevent this increase from raising the share of energy for nitrogen fertilizer in the production costs of phytomass for food.

The fertilizer-output ratio would further increase if diminishing returns would set in earlier and/or the claim on phytomass for non-foods would be larger. Suppose that the fertilizer response were to follow the curve *C*, and that the amount of phytomass for new non-foods were to be one-third rather than one-quarter of that for food. The fertilizer input needed for food would then rise to 400 Tg, or 68 percent more than would be needed with constant returns and without new non-foods. In such a case, a rise in the share of nitrogen fertilizer in the production costs of phytomass for food would be virtually unavoidable.

Nitrogen fertilizer accounts for almost half of the energy that is used in agriculture (Smil 1991). Other factors, like the expansion of irrigated agriculture, the need to exploit less conventional phosphate reserves, and the further substitution of machines for human or animal power, will also result in keeping the share of energy in farm production costs at a high level. The overall effect will be to make food prices sensitive to energy prices, which are likely to increase. A recent model study suggests that crude oil prices of 60 USD per barrel rather than 35 USD would raise world crop prices by between 10 and 17 percent (OECD 2006). The above considerations suggest that such sensitivity is likely to persist in the future.

Irrigation costs might also affect the evolution of international agricultural prices. In several countries in South and East Asia, the real costs of new irrigation have doubled or tripled since 1980. In this situation, the eightfold increase in irrigated area that is assumed in the Limits-of-Food-Production study has little chance to be realized in practice. Most authors expect an increase of no more than 20 percent in the coming decades (Rosegrant et al. 2002; Serageldin 2001). A recent model study suggests that, in spite of improvements in water management efficiency, the shortfall between demand and supply of irrigation water will increase globally, and that absolute water limitations will appear in a growing number of basins (Rosegrant et al. 2002). The authors believe that this will contribute to a halting of the long-term decline of cereal prices and possibly pressure food prices upward.

A third factor that could influence the evolution of food prices would be a deterioration in the cost-benefit ratio of farm research. The high returns on agricultural research investment in the 20th century were largely based on the room for breeding plants that could transform more fertilizer into harvestable product. This room is now gradually being depleted. We have already indicated that raising potential yields or filling yield gaps beyond 80 percent is complex, and that yield potentials of major crops have hardly increased in recent decades (Section 5). This might raise the cost-benefit ratio of agricultural research, even though ICT and biotechnology are reducing the costs. Until now, no evidence for such an increase has been found (Alston et al. 2000). Nevertheless, if agricultural research were to become less rewarding, this would discourage research investment, thereby curbing the growth of productivity in farming.

The combined effect of the above developments might be a new global trend change in agricultural markets. The long-term decline in agricultural prices that started in the late 19th century might be moderated, halted, or even reversed. During the last few years, international agricultural prices have been rising, but whether this already reflects such a trend change is hard to say (also cf. World Bank 2007). Earlier price rises, for example in the 1970s, also induced expectations that agricultural prices would remain at a higher level, but they were refuted by new price declines in the 1980s and 1990s. The history of agricultural prices shows medium-term fluctuations around the secular price trend, and it is well possible that the current price rise will once more be followed by a decline. In fact, these medium-term fluctuations lead to a risk of underinvestment that could make the world ill-prepared for a new trend change. This is one possible cause of disturbances in world food markets, to which we now turn our attention.

6.3 Disturbances of international food markets

If the world food economy were to undergo a new trend change and/or approach a new ceiling, it could become more vulnerable to influences that might then disturb food markets. Below we discuss two such influences: pests and diseases, and myopic expectations.

Pests and diseases

Filling the remaining room below a ceiling might involve overconnectedness and rigidities that increase the vulnerability of the world food economy (cf. Section 2.3). For example, continued application of existing paradigms, further increases in production and productivity, and increased transport could raise the risk of losses by pests and diseases (Fraser et al. 2005). In the short run, these developments have clear advantages. Scientific research provides higher-yielding varieties and crop protection. Production growth allows more mouths to be fed. Increased productivity brings welfare benefits. And trade can save inputs by shifting productions to suitable areas, fill local deficits, and cushion local harvest failure. The way in which grain imports helped the Soviet Union to cope with a massive grain deficit in 1972 or Bangladesh with the ‘flood of the century’ in 1998 (Dorosh 2001) speaks volumes.

However, these developments have a downside. A new expansion of rice production may aggravate water scarcity and reduce the protective effect of water culture on this crop (Mew et al. 2004; Savary et al. 2005). The concentration of livestock production – especially open and semi-open systems around growing mega-cities in Asia – increases the risk of livestock diseases and pandemic zoonoses (Jeggo & Eaton 2003).⁴⁶ More generally, increased transport and geographic concentration of production may facilitate the spread of pests and diseases (Anderson et al. 2004).

Reduced genetic variety and increased monocropping make crops more vulnerable (Anderson et al. 2004; Edwards 1996; Thrupp 2000). The spread of the first Green Revolution rice varieties in South East Asia opened the door to the Brown Plant Hopper plague that destroyed 55 percent of the Philippine crop in 1976. New varieties put an end to the disaster, but not the narrowing of the genetic base. In the 1990s, 95 percent of Philippine rice consisted of two varieties only (Anderson et al. 2004; FAO 1997). Rice is a poor man’s crop, where research is left to public institutions (Singh 1999).⁴⁷ In maize, wheat and soy, where seed markets are dominated by a few patent-protected companies, the genetic base has narrowed even more (Falcon & Fowler 2002; Pingali & Traxler 2002). In 1970, southern corn leaf blight and yellow corn leaf blight destroyed 17 percent of the US maize crop (Anderson et al. 2004). Eighty-five percent of the crop was of one variety that was susceptible to these diseases (FAO 1997). Resistant varieties and control measures have made large-scale crop failures less common since, but do not preclude new outbreaks in the future.

Pesticides protect crops, but also stimulate pest adaptation. Over the past three decades, the introduction of ever new pesticides has hardly reduced the global harvest losses that were caused by pests and diseases (Oerke & Dehnke 2004). In the longer term, the rat race between agricultural research and pest adaptation might prove unsustainable (Palumbi, 2001; Tilman, 1998). Expectations that the gene revolution would provide an escape route (for example Mew et al, 2004) have not yet been fulfilled. Integrated crop management may be a potentially superior technology, but its development is hampered because the head start that chemical control methods have had has entailed network and learning advantages that lock agriculture into this approach (Cowan & Gunby 1996).

⁴⁶ This risk could be reduced by rearing livestock in (sub)arctic areas or hermetically closed systems, but this will not readily occur.

⁴⁷ The corporations’ lack of interest in rice (Monsanto has already ended its rice research) is not only an advantage. Because yield gaps are smaller than in other grains, and yield potential has not increased since 1966 (Cassman et al. 2003), production increases require much research for stress control and increases in yield potential, and the lack of private investment does not help this.

If widespread crop failures were to occur, international prices would be sent skyrocketing. This would acutely endanger the food security of poor people. In particular, it would wreak havoc in food-importing low-income countries. Unlike more localized disasters, this could not be remedied by temporary import surges without sufficient stocks being maintained for this purpose.

Myopic expectations

If world food were to undergo a new trend change, productive investments should increase in time to prevent the transition from involving unnecessary scarcity. However, an adjustment in investment is complicated by imperfect foresight. The problem is aggravated if the food economy were also to approach a new ceiling, for then the adjustment would include timely research into new production paradigms. This involves considerable investment risk, certainly if the agronomic potential has to be stretched or new non-farm techniques for food production have to be developed (Sections 5.2-3). Technology history suggests that investors may not assume such risks until they feel an acute need to do so (Dosi 1982).

The interaction of myopic expectations and a new trend change may cause the global food economy to evolve less linearly than is assumed by most model studies.⁴⁸ In fact, different scenarios are conceivable:

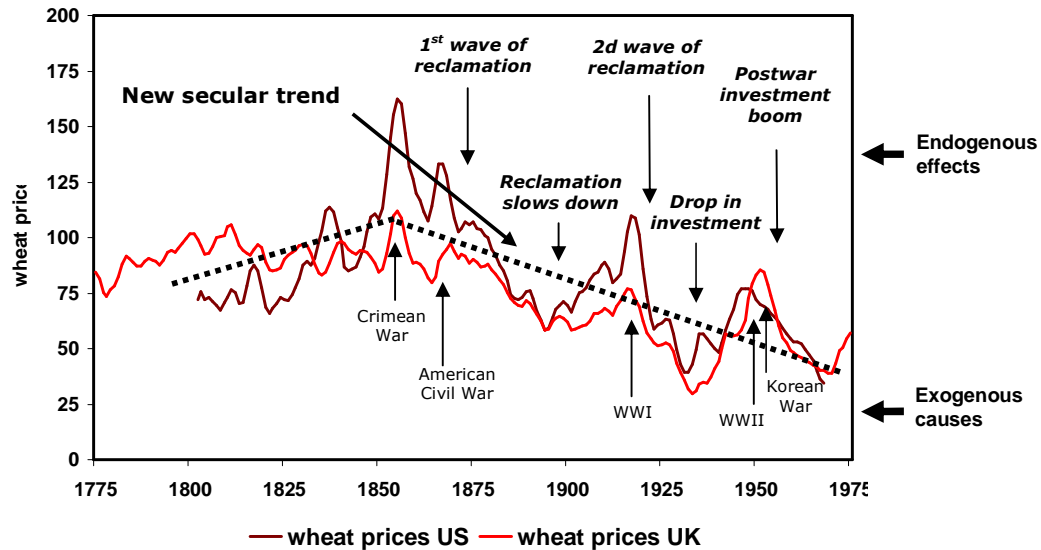
- A *continued abundance* scenario could materialize if the demand of affluent consumers for healthy and ethical foods were to stimulate investment in the opening of new reaches in the potential-production landscape (for example novel protein foods or ‘sea farming’) that allow significant increases in global food supply. In this way, a short-term development (rising incomes that increase the demand for certain types of luxury foods) would prompt a timely shift to a technological trajectory that allows continued abundance.
- A *soft landing* scenario could materialize if the rising demand for food and new non-foods were to cause a gradual price increase and this would stimulate sufficient investment in new possibilities for food production to avoid more extreme price rises. This would resemble the dynamics of agricultural revolutions in pre-industrial times, in which moderate price increases also played a role. The effect would be especially beneficial if a moderate increase in prices were to help reverse the unsustainability spiral in poor countries.
- An *unnecessary scarcity* scenario could materialize if a change in the secular trend were to coincide with a periodic undershooting of the investment level that conforms to the outgoing trend. This might happen if low current prices were to discourage investment and give citizens and decision-makers the impression that the global availability of food is no longer a problem.

Because cautiousness requires special attention to be paid to worst-case scenarios, we explore the last scenario in more detail. According to the cobweb theorem (Ezekiel 1938; Nerlove 1958), myopic expectations can induce cyclic over- and undershooting of long-term investment levels and thereby price fluctuations around the trend. Such fluctuations are a well-known phenomenon in, for example, markets for pigs (‘pig cycle’). The question is whether this mechanism could also cause fluctuations in agricultural world markets generally. Gérard et al. (2003) present a general equilibrium model of the world economy where prices are a lagged result of production decisions by actors who act on anticipated prices, which leads to fluctuations in agricultural prices with periods of 16 to 20 years. Similar fluctuations are found in the empirical world. Spectral analysis of historical wheat prices in England and the United States exhibits fluctuations of a comparable length to those in Gérard et al. (Díaz Jerónimo 2006). Comparison with key events (see Figure 13) suggests that some initial price

⁴⁸ The outcomes of models like IMPACT are heavily influenced by supposedly price-independent trends in cultivated area and food supply. In reality, myopic expectations may have a significant impact on the investment decisions on which these trends are based. See Gérard et al. (2002) for a global agricultural trade model where imperfect information leads to endogenous price fluctuations that influence investment decisions.

risers had exogenous causes (wars), but that they entailed endogenous, cobweb-type reverberations. For example, high prices during the American Civil War (exogenous cause) induced a wave of reclamation. This caused a slump in the late 19th century, which slowed down the global reclamation activity, raising prices above trend in the pre-WWI years (endogenous continuation). A similar sequence was seen in the inter-war period.

Figure 13: Fluctuations in real wheat prices in the US and England & Wales, 1800-1970 (5-year moving average, 1901-05 = 100)



Source: Calculations based on data in Mitchell (1975:191-5, 736; 1990: 737-41, 756-7; 1993:129-30; 696-8) and US Bureau of the Census (1976: 207-9)

In the 1950s, an investment boom caused by high prices during WWII and the Korean War caused a new fall in international prices. This time, protective policies prevented a drop in investment in developed countries.⁴⁹ However, the cobweb cycle reappeared in political markets. By the 1980s, the architects of post-WWII farm policies had been succeeded by a new generation of policy-makers who had not been formed by the 1930s depression, and these embarked on a project of farm policy ‘liberalization’.⁵⁰ Price supports were reduced and supply management measures relaxed or abandoned. Low prices discouraged the funding of research for sustainable increases in yields (Duvick & Cassman 1999; Rosegrant & Pingali 1999). Between 1976-81 and 1991-2000, the annual growth rate of global public agricultural research expenditures fell from 4.5 to 1.6 percent (Table 5). In developed countries, it became slightly negative, while an increasing share was devoted to environmental, food safety and quality issues. The slowdown in public funding was accompanied by a shift to private R&D. However, this was almost entirely restricted to high-income countries (Pardey et al. 2006), and in the 1990s, the growth of private R&D expenditures also declined (Table 5). Meanwhile, official development assistance for farm progress in developing countries declined from USD 6.2 billion to USD 2.3 billion between 1980 and 2002 (DFID 2004). Reinforcement of intellectual property rights complicated the development of a public pool of germplasm like that which facilitated the Green Revolution in the 1960s-70s (Falcon &

⁴⁹ The effect of dumping on investment in developing countries was partly redressed by donor support to the green revolution.

⁵⁰ Or pseudo-liberalization: the US and the EU introduced direct payments to farmers, which did not fully compensate the reduction in price support, but still distorted world markets by continuing dumping in disguised forms.

Fowler 2002; Pingali 2007; Safrin 2004). Private corporations prioritized things like herbicide resistance, which strengthen their position in farm inputs markets, rather than objectives like drought resistance that were vital for raising production in poor areas.

Table 5: Annual growth rates of investment in agricultural research (percentages)

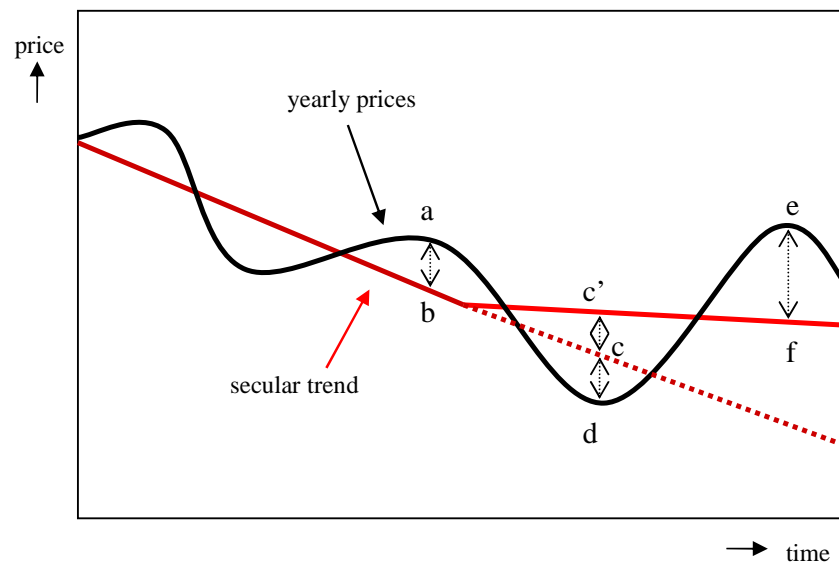
	1976-1981	1981-1986	1986-1991	1991-2000
Public research, world total	4.5	2.9	3.0	1.6
Public research, developed countries	2.5	1.9	2.2	-0.4
Private research, developed countries	--	--	3.9 ¹	2.2

¹ 1987-1991

Source: Pardey et al. (2006); Pardey & Beintema (2001); additional data provided by Nienke Beintema.

These data indeed suggest an undershooting of the investment level that conforms to the secular trend. This may in itself cause a price rise in a subsequent period. However, what will be the effect if this undershooting were to coincide with a change in the trend itself? This is illustrated in Figure 14. A cobweb cycle around the initial trend would cause prices to fall to point *d*, the same distance below the initial trend as the preceding boom was above it ($cd = ab$). However, in relation to the new trend, this is a larger price fall ($c'd > cd$), and the effect on investment causes a comparably large rise in prices above trend in the subsequent phase ($ef = c'd$). The result is a steep price rise that may last for several years before prices are brought down again as a result of the new investment induced by this price rise.⁵¹

Figure 14: Schematic representation of the effect of trend change on cobweb fluctuation



⁵¹ Because of path dependency in the long-term growth in food production, prices may still remain higher than they would otherwise have been (cf. Mundlak 2000).

7. Policy conclusions

In this section we draw some tentative policy conclusions from the above observations and discussions. Rather than to provide detailed policy recommendations, our aim is to emphasize that timely action is needed to ensure a sufficient global availability of food in the long term. Merely relying on spontaneous market forces for providing the incentives for this is insufficient.

Our analysis indicates that the technical potential for food production is sufficient to feed the world population that is expected by 2050. In this sense, ecopessimist predictions of impending, unavoidable scarcity are wrong. But it does not mean that cornucopians are right, for there is no guarantee that the potential will be realized, or can be realized at reasonable cost. Several conditions are complicating the increase in food production in particular in developing countries. One of them is low world market prices that discourage farmers from investing in sustainable intensification. This condition might change if a new trend change were to end the secular decline of prices in international agricultural markets. However, such a change would entail the opposite danger that myopic expectations would send food prices sky-high in the transitional period. This danger of overshooting the price trend arises especially if an adequate increase in food supply were to require researching new production paradigms with significant investment risk.⁵²

How to ensure a balanced development of global food supply? If we would live in a world of perfect information and with ample room for raising production under existing paradigms, we might assume the global food economy to be resilient. In such a world, an approach like the Millennium Ecosystem Assessment's 'global orchestration scenario' (Millennium Ecosystem Assessment 2005), where trade liberalization, privatization and corporate intellectual property rights are combined with public investment in infrastructures and human capital, might allow the optimal exploitation of the global potential. Indeed, when assessed through a general equilibrium model such as IFPRI's IMPACT model – which assumes a linear behaviour of the economy – this scenario performs quite well (Ringler 2006; Rosegrant 2006). In the real world, however, where food production is characterized by important non-linearities (threshold effects, non-rational formation of expectations etc.), such a scenario may prove less beneficial. Trade liberalization may strengthen import competition and reinforce endogenous price instability (Boussard 2006; Gérard et al. 2002) and thereby discourage investment in infrastructure and innovation (see discussion in Koning & Pinstrup-Andersen 2007). In addition, privatization of supply and marketing chains may raise thresholds for poor farmers in developing countries – an effect that may be enhanced rather than mitigated by certification and tracking-and-tracing to solve problems of food quality and food safety (Clay et al. 2005). Moreover, a shift from public to privately funded research is not conducive to innovations that help poor farmers to increase their production (Pingali 2007).⁵³

Rather than a neo-liberal approach, more active policies are needed to secure the global availability of food in the decades to come. A first priority is to increase food production capacities in developing countries. To this end, international support for agricultural research for development should be stepped up, targeting needs of poor farmers. National investment in hard and soft infrastructures for agriculture should be strongly increased and co-financed by international donors. Government initiative should overcome

⁵² In this case, the filling of the residual room for food production under older paradigms might also render the world food economy more vulnerable to pests and diseases.

⁵³ In addition to the failure of private companies to invest in breeding for drought resistance, Monsanto's decision to stop its research on rice is a telling example. Many rice systems operate at a high level of energy input. Yield gaps are smaller than in other grains, the yield potential has not increased since 1966, and water scarcity will make production increases even more strongly dependent on stress control. Therefore, hindrances for, or lack of investment in, research for this food staple on which half the world's population depends should be seen as a serious problem.

infant industry problems in supply and marketing chains, and countries should be allowed the policy space to protect their farmers through import tariffs when this is needed to get their agriculture moving. Infrastructural projects and institutional meal programmes should compensate the effects on poor consumers. Land reform and other measures to empower actual tillers should ensure that supportive farm policies stimulate increases in land productivity rather than a mere enlargement in farm size. Developed countries, which dominate world trade in agricultural products, should accept these policies and weigh the interests of developing countries against their own short-term commercial interests. Moreover, they should abstain from policies that destabilize world market by, for instance, the dumping of surpluses (whether through export subsidies or through direct payments).

A second priority is to enhance the capabilities for food production worldwide. As the global biosphere has to provide more phytomass for food and non-foods, the degrees of freedom that the world has in producing this phytomass will decrease. There will be less room for using traditional organic farming methods or for separating large areas from farm production. Where possible, biodiversity conservation will have to be combined with agricultural exploitation. Farm research will have to be aimed at techniques that reduce emissions while increasing yields rather than just minimizing yield losses. And new techniques for exploiting marine resources and for raising conversion efficiencies will have to be developed. Government policies should ensure that farmers and other private actors receive sufficient economic incentives to stimulate them to adopt the necessary innovations. This also requires adequate price policies. As the investments needed for this are dependent on adequate returns as well as sensitive to price risks, both the level and the stability of prices matter. As we have argued above, prices can be both too low and too high. In the former case, they hamper the built-up of sustainable production capacities, while in the latter case, they reduce the access to food of the poor. As long as international markets are still marked by abundant supply, price support to 'get prices right' should be coupled to supply management in order to ensure a restrained use of new production capabilities.⁵⁴ In addition, buffer stock policies should be used to 'get prices stable'. Both kinds of policies require sufficient international coordination.

A third priority is to mitigate the competition between animal foods for the affluent and staple foods for the poor. The consumption of animal foods that involve especially unfavourable feed ratios (for example feedlot beef) should be discouraged. Production systems for phytoplankton could be developed to moderate the demand for farm-produced feed and fishmeal. Determined efforts should be made to produce more attractive meat substitutes (possibly based on fungi) that are accepted by consumers.

Finally, caution is needed with respect to biofuels and other bio-based non-foods. Although a moderate increase in the demand for new non-foods might stimulate agricultural development in poor countries, large increases could send international food prices skyrocketing. The use of biomass for non-foods should be limited to efficient applications like functionalized chemicals (Sanders et al. 2007). Rather than policies that stimulate the production of biofuel, policies are needed that prevent such production from creating food scarcity. For example, one could think of a tax on new bio-based non-foods that is to be levied if world cereal prices were to exceed a ceiling.

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⁵⁴ There is nothing contradictory in this: a reliable car has a strong engine as well as a strong brake.

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