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

N.B.J. Koning[1,*], M.K. Van Ittersum[2], G.A. Becx[3], M.A.J.S. Van Boekel[4], W.A. Brandenburg[5], J.A. Van Den Broek[3], J. Goudriaan[2], G. Van Hofwegen[3], R.A. Jongeneel[1], J.B. Schiere[3] and M. Smies[6]

[1] Agricultural Economics and Rural Policy Group, Wageningen University, P.O. Box 8130, NL-6700 EW Wageningen, The Netherlands
[2] Plant Production Systems Group, Wageningen University, Wageningen, The Netherlands
[3] Wageningen International, Wageningen University and Research Centre, Wageningen, The Netherlands
[4] Product Design and Quality Management Group, Wageningen University, Wageningen, The Netherlands
[5] Plant Research International, Wageningen University and Research Centre, Wageningen, The Netherlands
[6] Shell Exploration & Production B.V., Rijswijk, The Netherlands
[*] Corresponding author (e-mail: niek.koning@wur.nl)

Received 21 December 2007; accepted 21 April 2008

Abstract

During the 20th century hunger has become a problem of poverty amidst plenty rather than absolute food scarcity. The question is whether this will remain so or whether the hunger of the poor will once more be exacerbated by rising food prices. In this paper we discuss biophysical conditions, social forces and non-linear interactions that may critically influence the global availability of food in the long term. Until 2050, the global demand for primary phytomass for food will more than double, while competing claims to natural resources for other purposes (including biobased non-foods) will increase. A sober assessment of the earth's biophysical potential for biomass production, which recognizes competing claims and unavoidable losses, suggests that this is in itself still large enough for accommodating this rising demand. However, the exploitation of this biophysical potential proceeds through technical paradigms that set a relative maximum to food production. In addition, socio-economic mechanisms make the food economy run up against a ceiling even before this maximum is reached. As a consequence, current developments may well entail a new trend change in international markets. These developments include the depletion of land and water reserves, the stagnation of the potential yields of major crops, the rise in energy prices, and the way in which systemic socio-economic factors lead to a strong underutilization of production possibilities in the developing world. Given these conditions, the avoidance of steep rises in food prices may depend on the timely relaxation of socio-economic constraints in developing countries and on timely breakthroughs in sustainable yield increases, biorefinement and non-farm production systems. Myopic expectations make it doubtful

whether spontaneous market forces will provide the necessary incentives for this, which may be reason for societal actors to consider the need for more active policies.

Additional keywords: biofuels, biorefinement, competing claims, food markets, food prices, food security, potential production

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 (1817) 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

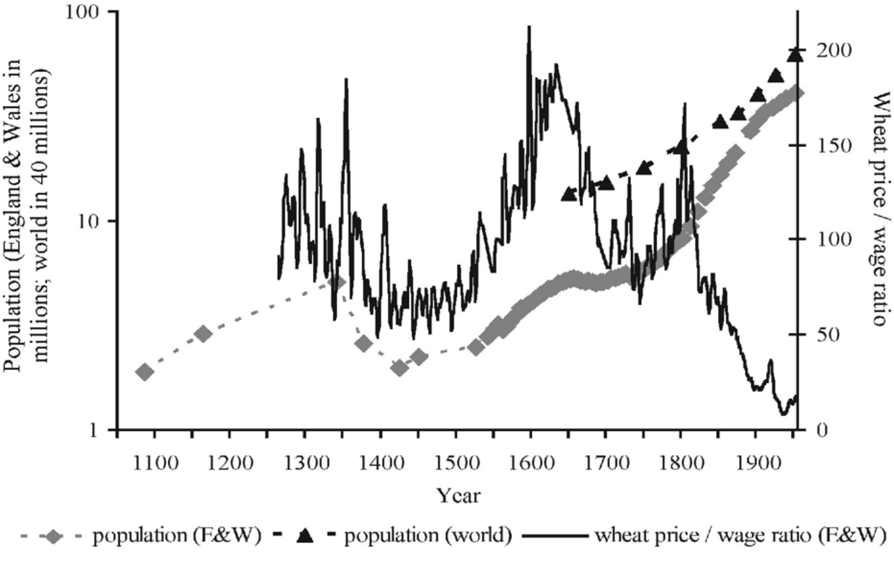


Figure 1. Population of England & Wales, world population, and average wheat price / wage ratio in England & Wales, 1086–1954. Ratio presented as 5-year moving average, 1300 = 100. Sources: Population England & Wales 1086–1540, Hatcher (1977) and estimates by various authors mentioned in Coleman & Salt (1992); 1541–1800, Wrigley *et al.* (1997); 1801–1954, Anon. (1993). World population: McEvedy & Jones (1978). Wheat prices 1264–1315, Rogers (1866); 1316–1770, Beveridge (1929); 1771–1954, average gazette prices in Mitchell (1990). Wages, Phelps Brown & Hopkins (1956).

of land reserves in temperate zones outside Europe, artificial fertilizers accelerated the increase in yields, and electricity, internal combustion and artificial fibres reduced the claim to 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.

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 it helps to improve the incomes of broad sections of the population, 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 (Bruinsma, 2003).

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 (as is also illustrated by the recent price rises in world food markets). From the late 1960s, a spate of neo-Malthusian publications has stirred anxieties about a new impending scarcity (e.g., Ehrlich, 1968; Meadows *et al.*, 1972). Some authors warned that an 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 (Penning De Vries *et al.*, 1995; Mitchell *et al.*, 1997;

Table 1. Number of undernourished people (x 10^6) in the developing regions, 1990–1992 and 2000–2002.

Region	1990–1992	2000–2002
Northern Africa	5	6
Sub-Saharan Africa	179	204
Latin America and Caribbean	60	53
Eastern Asia	199	152
Southern Asia	302	317
South-East Asia	78	66
Western Asia	9	17
Total	824	815

Source: Anon., 2007a.

Bruinsma, 2003). Nevertheless, some warned that a decrease in the support of farm progress could cause serious problems (Rosegrant *et al.*, 2001). Some new projections predict a reversal in the long-term decline in cereal prices (Anon., 2007c) – 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; Anon., 2007c). Both groups experienced their own difficulties. Whereas the former had to establish what the limits really are, the latter wrestled with non-linearities that complicated any attempt at long-term prediction. In the following 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, focusing on basic issues rather than precise quantitative prediction. In the next chapter we present basic concepts that pertain to the biophysical side, the social side and the dynamics of food production. In the four chapters thereafter we explore the forces and interactions that influence the global demand and supply of food between now and mid-century. In the final chapter we draw some policy conclusions on how to ensure a balanced evolution of food supply.

Basic concepts

Over 95 percent of the world's food supply derives 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 increases in agricultural biomass.

Under the farm paradigm (a techno-economic paradigm, see definition on p. 238), solar energy is utilized for the production of phytomass through cultivation (or controlled grazing) of plants on 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, atmospheric CO_2, the metabolic efficiencies of plants, and the available fresh water and nutrients. The part that is usable depends on the possibilities for converting phytomass into consumable products through physico-chemical methods (for example milling, cooking) or biological processes (fermentation, livestock). Additionally, raising production per unit area 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.

The farm paradigm is a meta-paradigm encompassing 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 co-operation, which together form an agro-production (input supply, primary farming, conversion and distribution) system. In the following we consider the biophysical and social sides and the dynamics of such systems.

The biophysical side

The agro-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 (for instance, manual, mechanical or chemical weeding). However, the agronomic conditions that they realize (field preparation, water and nutrient supply, pest and disease control, etc.) are also characterized by synergetic relations (Van Keulen, 1982; De Wit, 1992). For example, nutrient use efficiency is higher for well-watered and healthy crops. More generally, the various inputs need to be supplied in proper ratios to maximize input use efficiency. For simplicity, therefore, we see intensification within a given production system as the increased application of a balanced input package. As long as intensification allows binding more solar energy into harvestable phytomass, it entails constant returns (De Wit, 1979; 1992), but beyond a certain level the returns diminish.

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; Ruthenberg, 1980; Mazoyer & Roudart, 2006). The corresponding input–output function is a cascade of the functions of these systems (Figure 2B). Different systems use different inputs and input packages, but to make them comparable, the inputs can be lumped together by using energy as a common

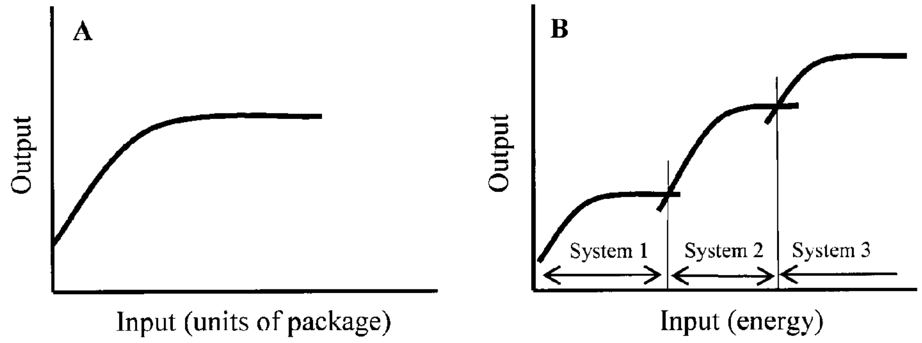


Figure 2. Change in per area phytomass output in response to increased input of non-land resources, within one production system (A), and across production systems (B).

Table 2. Co-evolution of population, natural resources, techniques and institutions in Europe.

Time scale	Inhabitants per 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 land rights; 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	Inorganic fertilizer & imported fodder.	

Source: freely after Mazoyer & Roudart (2006).

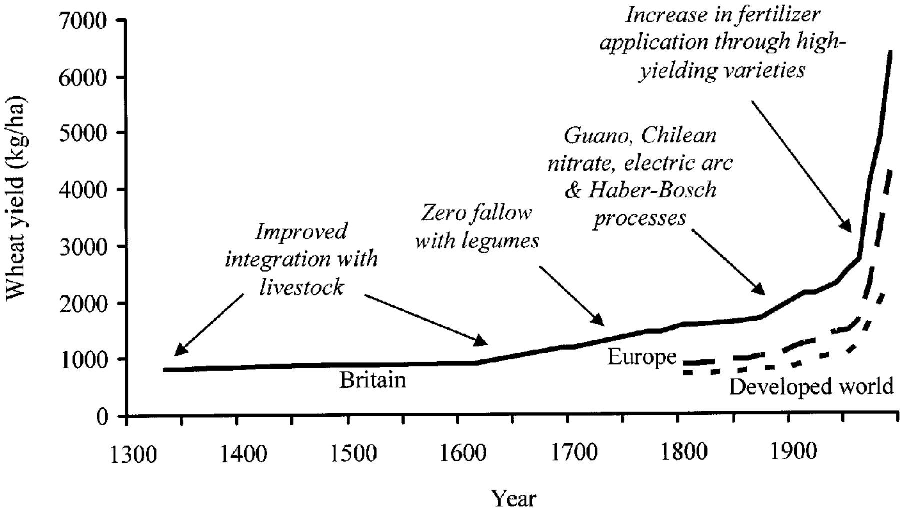


Figure 3. Wheat yield in Britain (until 1800 England; since 1800 UK), Europe (excluding Russia) and the developed world (excluding Japan and South Africa) 1300–1990. Sources: Clark (1991) and Bairoch (1999).

denominator. By way of illustration, Table 2 lists the succession of agro-production systems that was typical 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* and *complexity of human control*.

- *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 such as 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 (e.g., Adami, 2002; Stoop *et al.*, 2004), 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.

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 low entropy energy for maintenance (see e.g., Schiere, 1995 for examples from animal science).

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 (Pingali *et al.*, 1987; Mazoyer & Roudart, 2006). 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 form part are much more convoluted.

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 below). This system may then become ever more involved to allow poverty sharing and coping with an increasingly precarious situation. Such 'involution' (Geertz, 1963) is an explanatory factor in for example the considerable complexity of many current African systems (Seur, 1992; De Steenhuijsen Piters, 1995; Anon., 2004a).

However, sooner or later, involutionary complexity has to give way to a new step

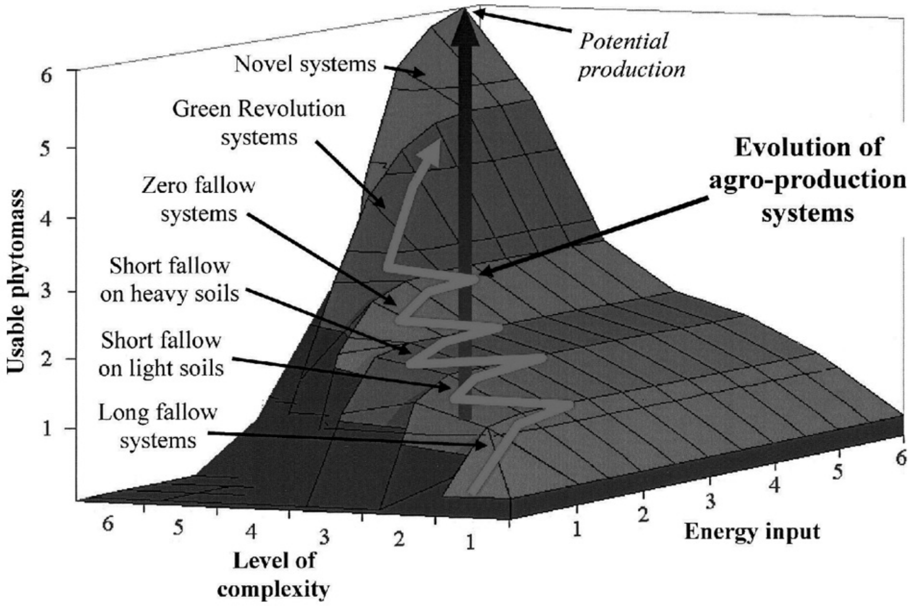


Figure 4. Schematic representation of the relationships between energy input, level of complexity (agro-production system), and usable phytomass output in an area. The green ranges are production possibilities, the red line is the evolution of agro-production systems, the green arrow indicates potential production.

in productive complexity if a society is to survive (see p. 241 ff.). 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 an *agro-production landscape* (Figure 4). The ribs of the landscape are zones rather than single curves, because one complexity level can contain several production systems whose relations between energy input and phytomass output vary (see below). The long-term growth in phytomass output can be seen as the climbing of a production possibility hill by increasing the energy input while shifting to new levels of complexity from time to time to postpone diminishing returns (see also Robinson & Schutjer, 1984; Wood, 1998). Over a short time horizon, this may allow increases in phytomass output per unit of energy input. For example, the energy efficiency of modern Green Revolution systems may be larger than that of systems that use less external inputs and traditional varieties (see also De Wit, 1992), and present livestock systems in Western Europe are far more energy efficient than those of 20 years ago (Meul *et al.*, 2007). Over a longer time horizon, however, the price for the growth in phytomass production has been an increase in the energy required per unit of output, partly by the decrease in the share of plant nutrients provided by natural processes, and partly because animals or machines were substituted for human labour (Leach, 1976; Smil, 1991).

Conversion

Most phytomass is processed, stored, and/or transported before being consumed by humans. Moreover, part is fed to livestock 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 reduce post-harvest losses. And conservation enhances the usability of biomass by allowing more flexibility with respect to the consumption. Such supply-increasing conversions are elements of the agro-production landscape. At higher complexity levels more sophisticated supply-increasing conversion 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 agro-production landscape because the supply of usable phytomass is not increased by them. We shall go into this in more detail when we discuss demand.

Limits of the farm paradigm

Humans have climbed the agro-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. So they have enhanced the capacity of agro-production systems to intercept solar energy and transform it into consumable products, increasing the globe's carrying capacity for farm-based consumption. However, none of these improvements has increased the basic metabolic efficiencies of plants. The efficiencies of photosynthesis and respiration seem to have been little altered by domestication and breeding, for in this respect modern varieties do not differ significantly from the varieties 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).[1] 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. 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 thanks to improvements in plant and crop architecture, not to an increase in potential phytomass output. For the major cereals the room for such improvements, which allowed increases in the harvest index, now seems to have been depleted.

It may be wondered 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 to 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 to 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 maintaining refuge areas for non-resistant pests, but this implies that, in those areas, the yield gap cannot be closed (Laxminarayan & Simpson, 2002). Moreover, the strategy seems to be less than fully effective (Chilcutt & Tabashnik, 2004).

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

The social side

The 'agro-production landscape' refers to a biophysical reality. However, the food economy is a *socio*-biophysical system – an ecosystem managed by humans. Whereas ecosystems of lower animals are driven by blind causality, humans are capable of learning and cultural transmission, enabling them to achieve new complexity levels (Schutkowski, 2006). It should be noted that the agro-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 if all actors were to benefit (Olson, 1965; Hardin, 1968). 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 & Perez, 1988; Freeman, 1991). Accordingly, agro-production systems co-evolve with social relations (Johnson & Earle, 2000; see also Table 2).

Suppose producers in an area have largely exploited the possibilities of an agricultural sub-paradigm – say the high-external-input systems of the Green Revolution. They have introduced fertilizer, high-yielding varieties and so on and so forth, to the point that little progress is possible without new technologies like precision farming and novel forms of pest management. In Figure 4, their production function – their set of known techniques – is then the cascade of ribs up to the 5th 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 (see also Sen, 1981). Scarcity relations fix prices or shadow prices to productive assets and needs. At the demand side, these relations 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. This is why, rather than single response curves, the ribs of the landscape are sets of technologies with varying energy requirements for a certain phytomass output. If land is scarce compared with labour, producers may use labour-intensive techniques to obtain 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). Similarly, if energy becomes scarce one may see the development of more energy efficient techniques. Thus rising oil prices have increased the energy efficiency of modern high input systems since the 1970s (Cleveland, 1995; Uhlin, 1999; Meul *et al.*, 2007), although it does not alter the fact that modern systems are much more energy demanding than traditional ones.

Let Figure 5 – a front view of Figure 4 – be the *map* that producers have of the agro-production landscape. Suppose historical experience has taught them one technology per complexity level, so that the zones narrow down to curves that together form their production function. Rational choice theory – which we use for convenience abstracting from problems of imperfect information and bounded rationality – states that producers will choose a point on this function where their profit is maximized. For simplicity, let us see energy as a single input and phytomass as a single output, between which there is a given price ratio. The profit function can then be written as:

$$W = p_\mathrm{p}P - p_\mathrm{e}E$$

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:

$$P = W/p_\mathrm{p} + (p_\mathrm{e}/p_\mathrm{p})E$$

which is a straight 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 a line can be drawn with slope $p_\mathrm{e}/p_\mathrm{p}$ and the highest intercept with the vertical axis. If the input–output price ratio equals the slope of line A, farmers will produce at point X. They will not produce the potential production, because this requires technologies that farmers and researchers have not yet mastered. They will not even produce at the technical maximum of their existing production function, because this gives them a lower benefit.

In this case, farmers are producing at complexity level 5 (Green Revolution techniques). Price relations may also induce them to stick to less advanced systems. Suppose that in a more remote area, less favourable conditions shift the input–output relations of Green Revolution techniques to the dotted curve in Figure 5. If farmers would be faced with the same price relation as in the core areas, they would produce at point Y. However, higher transport and transaction costs reduce the price of phytomass while raising that of energy inputs, so that farmers are faced with steeper profit lines 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 *B'*. It means that maximum profit is now achieved at point *Y'*, which belongs to a technology of complexity level 4 (low external input techniques with zero fallow). Farmers will not shift to Green Revolution systems, even if these are known to them (see also Boserup, 1965; Grigg, 1980; Pingali *et al.*, 1987).

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 (see also Azariadis & Drazen, 1990). There are several such poverty traps in peripheral areas, and endogenous growth enhancers in core areas (see also Romer, 1986; Lucas, 1988). The effect is a spatial divergence of production functions, like the one between the functions of favoured and less favoured areas in Figure 5.

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 p. 263 ff.). While social scientists should understand that the adaptability of production functions does not make the underlying biophysical landscape perfectly malleable (see also Van Den Belt, 1995),[2] 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 (see also 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.

Changing dynamics

Having discussed the social conditions that steer humans in their climbing of the potential production hill, let us have a look at the climbing itself. We begin with the

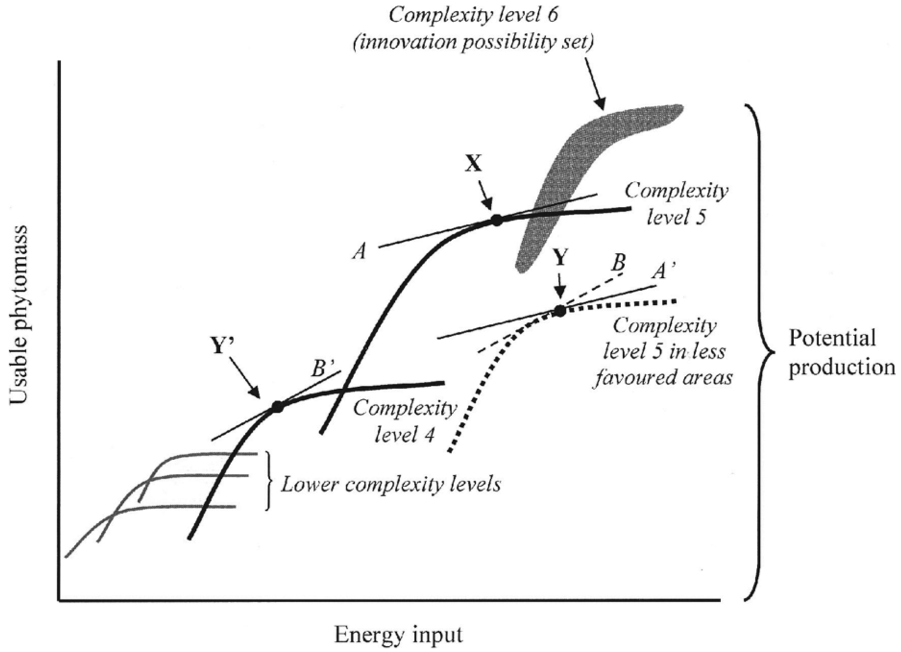


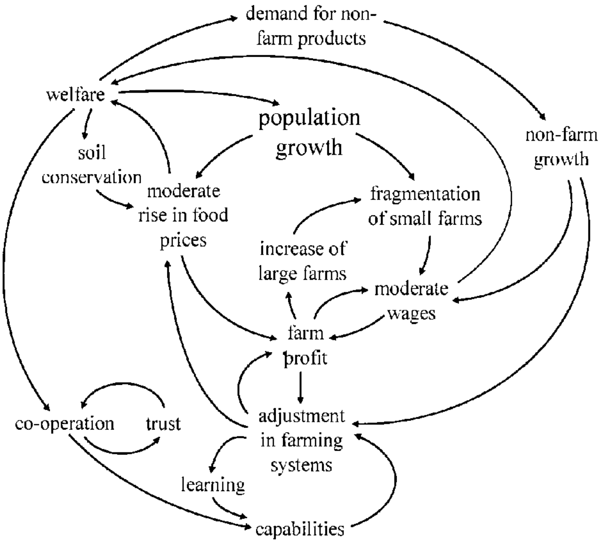
Figure 5. Subjective physical production functions derived from Figure 4. *A*, *A'*, *B* and *B'* are lines with input–output price relations as slopes. Producers in favoured areas produce at point X, producers in less favoured areas at point Y'.

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 variation in weather or endogenous cobweb cycles (Bauernfeind & Woitek, 1996). Long-term fluctuations were related to ages of demographic growth and ages of stagnation or decline (Slicher Van Bath, 1963; Abel, 1978; 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. The prevailing dearth of fertilizer complicated increases in yields, and high transport costs restricted food imports (Bairoch, 1976; Shiel, 1991). As a consequence, population upswings raised the prices of agricultural products. This made food expensive for the poor, but as Malthus already observed, it also lowered real wages and prompted investment and innovation in larger farms, thereby fuelling the phases of sustainable intensification that historians call 'agricultural revolutions' (Malthus, 1798: 29–31; see also Boserup, 1987). During these phases, increases in food

A. Expansion



B. Decline

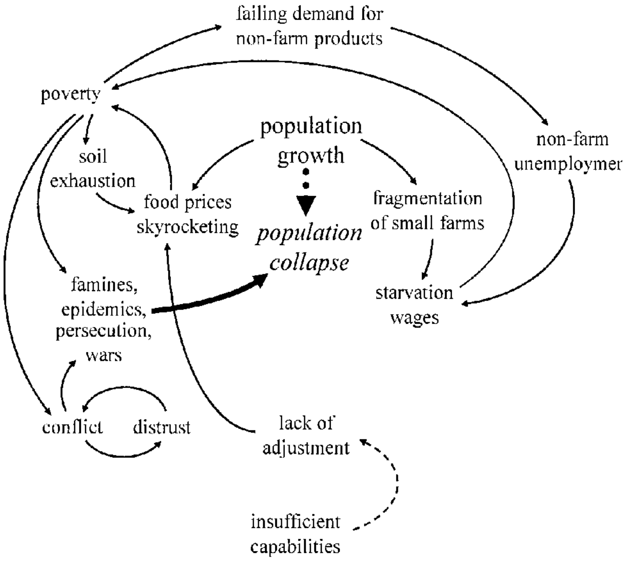


Figure 6. Dynamics of demo-economic expansion and decline in the pre-industrial era.

supply acted as a moderating feedback effect on rising food prices (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, 2002) of an agricultural sub-paradigm, the food economy was more or less robust. Harvest failures caused suffering but no collapse, and the increased market exchange facilitated the diffusion of innovations. However, risk aversion and slow communication made collective learning a sluggish process (Boserup, 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; see also 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.[3] 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 (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 artificial fertilizers available (Smil, 2001). At the same time, the exploitation of fossil fuels and the rise 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 the number of large farms declined – especially where industrial competition prevented a downward adjustment in wages (Koning, 1994). But this time there was no slowdown in agricultural growth. Government support, co-operatives and chain integration bolstered knowledge infrastructures, moderated the diseconomies of small farms, and ensured that 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 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 could use high quantities of nutrients

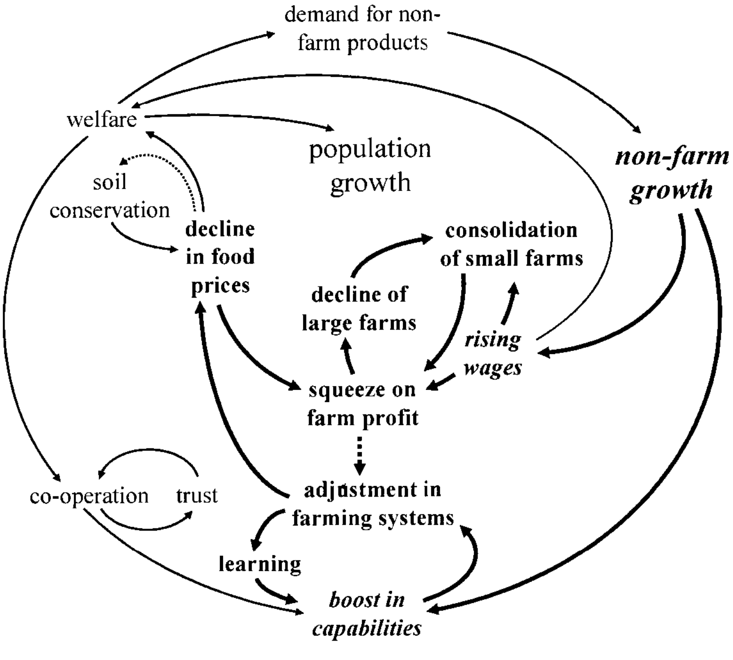


Figure 7. Dynamics of agricultural development since the late 19th century. Compare with Figure 6.

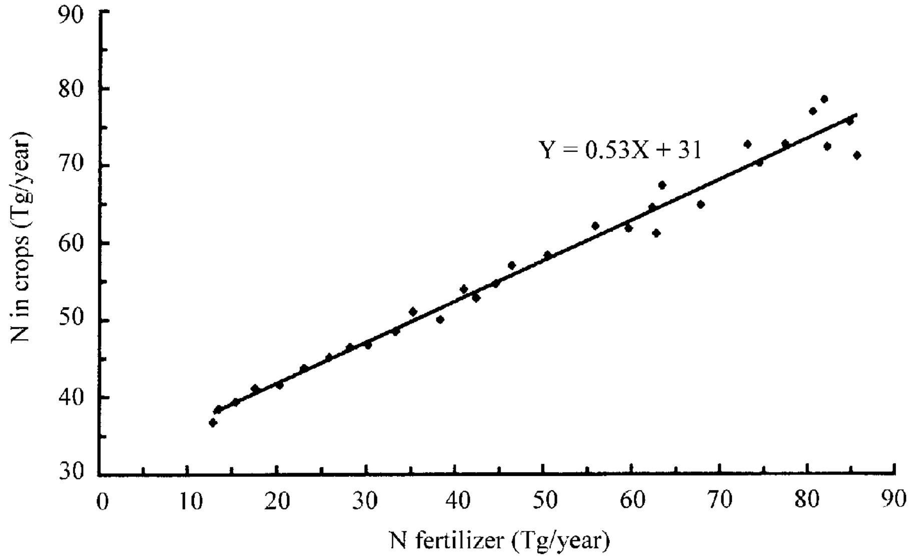


Figure 8. Global response of N in crops to N fertilizer, 1960–1995. Source: calculations by J. Goudriaan, based on FAO data.

efficiently. After the 1950s, yields steeply increased (Figure 3), and at the global level no diminishing returns to increases in fertilizer have since appeared (Figure 8).

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 four chapters explore the forces and interactions that influence the global supply of food between now and mid-century. First we shall deal with the demand for food. This is followed by a chapter in which we consider the natural resource base that supports the agro-production landscape, as well as the changes in and competing claims to these resources. Then the technical possibilities to expand food production within or outside this landscape will be surveyed, and finally we shall discuss the social dynamics that influence the use humans will make of these possibilities.

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 livestock-based foods. Besides, there are secondary influences like an increase in pets and increased wasting of food by affluent consumers.

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 mid-century, after which the world population might stabilize at around 9 billion (Anon., 2004b; 2007a). 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 actually 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. If poverty reduction would proceed more slowly than expected this might even slow down the decline in fertility in poor countries causing increases in world population beyond what is currently being projected (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 of decline in fertility.

Countries	Total fertility rate 2000–2005	Population ($\times 10^6$) (% *of world population*)		
		2000	2050 (UN medium variant)	2050 if poverty further retards decline in fertility [1]
More developed	1.56	1194 (19.5)	1245 (13.5)	1245 (11.0)
Less developed [2]	2.59	4250 (69.4)	6204 (67.5)	7304 (64.4)
Least developed	4.95	679 (11.1)	1742 (19.0)	2794 (24.6)
World	2.65	6124 (100)	9191 (100)	11343 (100)

[1] Assumptions: population growth in more developed countries as in the UN medium variant; in less developed countries as in the UN high variant; in least developed countries as in the UN constant-fertility variant.

[2] Excluding least developed countries.

Source: Anon., 2007a.

Livestock revolution

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. While world population will increase by half, the consumption of animal foods may double between 2000 and 2050 (Steinfeld *et al.*, 2006).[4] This strongly affects the total demand for biomass for food through the required feed inputs (Delgado *et al.*, 1999; Smil, 2002; Delgado, 2003; Keyzer *et al.*, 2005). An affluent western diet, in which livestock-based 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. As the global livestock increases, however, 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. (Over half of the fish captured is already fed to livestock or cultivated fish, (see Steinfeld *et al.*, 2006). 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 plant material that is unsuited for human consumption, they are poor converters of starchy and protein crops. At world level the claim on cultivable land per kilogram of beef already exceeds that per kilogram of pork or chicken (Wirsenius, 2003; Bouwman *et al.*, 2005).

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 livestock-based foods is not easily checked by cultural norms. Buddhist countries like Taiwan and South Korea saw considerable increases in per capita meat consumption when their incomes rose in recent decades. Restrictive norms that renounce all meat eating tend to become less forceful when incomes rise. Besides, most food taboos originated in practical limitations and restrict the consumption of a few animals only. For instance, many pastoral peoples have developed a taboo for eating pigs, which cannot be herded over long distances and are therefore animals of sedentary farmers whose lifestyle they despise (Harris, 1985; Den Hartog, 2003). Because such taboos do not forbid the eating of other animals, they hardly restrict total meat consumption.

Apparently, the high income elasticity of the demand for livestock-based 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 livestock-based 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 (see also Ulijaszek, 2002; Rozin, 2003). Indeed, the diets of pre-agricultural human populations contained high proportions of livestock-based foods. Agricultural populations shifted to more vegetarian diets only out of necessity. When incomes rise, humans veer back to a higher consumption of livestock-based foods and even tend to raise this consumption beyond what is wholesome, given their reduced physical activity (Popkin *et al.*, 2001; Smil, 2002). The increase in per capita meat 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 livestock-based foods (Fiddes, 1991; Richardson *et al.*, 1993; Willets, 1997; Holm & Møhl, 2000). 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 a widespread moral uneasiness about meat eating (Rozin, 2003). In animistic religions, evil forces are often seen as having an insatiable lust for meat (e.g., Geschiere, 1995), and the ascetic vegetarianism of orthodox Buddhists or Orthodox Christian monks betrays a similar disposition. Standford (1999) thinks that meat has become emotionally charged because it was a political commodity in societies of hominid hunters, where males used it for networking and getting access to females. The ensuing uneasiness may have been reinforced in agrarian societies because eating meat became a prerogative of the rich and powerful.

So the concerns of modern consumers may have deep roots. Nevertheless, up to now these concerns have not moderated the growth in per capita meat consumption strongly (Eastwood, 1993; Beardsworth & Bryman, 1999; Holm & Møhl, 2000). 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 (Holm & Møhl, 2000; De Boer *et al.*, 2006). In the longer term, these changes might widen the room for vegetable substitutes and livestock species with better feed conversion ratios. In energy terms, 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 (Smil 2002; Wirsenius, 2003). Cultured herbivorous fish like carp would be a better option still. The same holds for other aquatic animals and mini-fauna (Nakagaki & DeFoliart, 1991; Van Huis, 2003), 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 cereals 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).

Other factors

In addition to raising the consumption of livestock-based 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 (Anon., 2006a). Younger consumers tend to waste more than older ones, and waste increases with the consumption of convenience foods. Communication campaigns have little effect on this behaviour. Apparently, some extent of food wasting is an aspect of affluent life styles that is hard to avoid.

Natural resource base for food production and competing claims

Total resources and current use

We assume that the increased food demand must almost entirely be met by the natural resource base that mankind has for farm production. (Further down we shall discuss to what extent other means of producing food may become feasible but such production methods seem still very speculative.) Particularly important in the natural resource base for farming 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 thousands of times larger than the energetic content of the current stream of food production – an ample supply, even though plants can transform at most 3 percent of it into food.

Atmospheric nitrogen for producing N-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 tons, and potential reserves around 7 billion tons of P (Steen, 1998; Smil, 1999). In the long term, mineral phosphate may become scarce and its supply increasingly dependent on one country: Morocco (Anon., 1998a). Hereafter we shall look at this issue in more detail.

Also land and freshwater are limiting. Luyten (1995) and Penning De Vries *et al.* (1995) assume that globally 7.9 Gha are suitable for agriculture. However, Young (1999) argues that mapping problems have caused some overestimation in the developing world. We therefore estimate the global area of suitable land at 7.6 Gha, of which 3.5 Gha is suitable for cropping and 4.1 Gha for grazing.[5] About 1.6 Gha and 2.8 Gha respectively are already being used for these purposes.[6] 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 km^3 of freshwater can be renewed yearly 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.[7] 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 water to keep rivers flowing and lakes filled or that are rapidly approaching this state (Molden, 2007). Parts of the USA – another important granary of the world – are likewise faced with increasing water scarcity (Rosegrant *et al.*, 2002; see 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 to these resources are important. The following sections deal with these issues.

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 (Anon., 2007b). This assumption is a credible one, but alternative explanations (referring for example to solar activity) have not been ruled out (De Jager, 2005; Crok & Jaarsma, 2007; McKitrick *et al.*, 2007; Soon, 2007).[8] 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 salinization. Various studies suggest that the aggregate effect of global warming and increased CO_2 on global food production might be small, but the geographic distribution of these effects would be uneven (e.g., Rosenzweig & Hillel, 1998; Stern, 2006). Whereas 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 shall return to this topic below 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 soil 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, Australia and some parts of Asia have many poor soils that are easily degraded. In the temperate zones, most soils are less vulnerable to degradation.

Other forms of natural resource degradation are also important. Natural fish stocks in many seas and inland waters have been over-exploited (Anon., 2007e). The reduction in the number of species and varieties in modern agriculture may enhance their susceptibility to large-scale epidemics or diseases. In addition, there are concerns about the maintenance of sufficient gene pools on which the breeding of new animal and crop varieties is based. Groundwater and soil pollution is a problem in areas with intensified agriculture, and ozone pollution is reducing crop yields in large areas (Kempenaar *et al.*, 1999; Giles, 2005). Aquifer depletion is threatening the productivity of several irrigated systems (Postel, 1999; Anon., 2007e). In parts of northern China, groundwater levels are falling by one metre per year, and in some places in India, two to three metres per year (Rosegrant *et al.*, 2002).

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 sudden changes when certain threshold values are exceeded (Cohen & Stewart, 1994; Scheffer & Carpenter, 2003). For example, if soil degradation exceeds certain thresholds, effects such as 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.

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 (Anon., 2005a).

Also ecosystem–climate interactions could 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 (P. Kabat & C. Nobre, presentations 3–4 November 2005, Wageningen).

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) requires 30 ha per 1000 people (e.g., Bruinsma, 2003), but according to Young (1999) 50–65 ha will become a more realistic figure. We therefore surmise that by 2050 about 50 ha per 1000 people may be required for this. If half of this land were to be potentially suitable for agriculture (cf. Döös, 1994), this would mean that 0.23 Gha of potential farmland would be used for this purpose. Human settlement would then claim 3 percent of all potential farmland.

The claim to 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 (cf. Vörösmarty *et al.*, 2000; Rijsberman, 2006; Molden, 2007). 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 to water could also more easily be accommodated. Similarly, increasing the amount of soil organic matter of the land under food crops could both raise crop yields and reduce CO_2 concentration in the atmosphere. However, this 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 are under forest worldwide, one-tenth has currently been designated for conservation purposes (Anon., 2006b). This area may significantly increase in the coming decades. How much will be potential farmland is hard to say. Besides, some agriculturally suitable non-forest land may also be reserved for nature conservation. It is suggested that total protected areas currently take up 0.2 Gha of potential arable land in developing countries (Young, 1999).

Like the livestock revolution, claims to 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 concerned is little suited 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 8 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 50 USD per barrel (see also Campbell, 1997; Anon., 2001; 2006c; Hallock *et al.*, 2004).[9] 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 USA one-fourth of its maize for fuel ethanol (Anon., 2007c; Buntrock, 2007; Cassman & Liska, 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 biodiesel. 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 USA and the EU-15 could only do so at oil prices above 45 USD (Anon., 2006d), and the recent increase in cereal prices has pushed this threshold upwards. 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 phytomass 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 (Smil, 2003; Odell, 2004). New techniques including nanotechnology might even allow a further substitution of synthetic products for farm-produced materials like cotton and natural rubber (Anon., 2004c).

Nevertheless, in the longer term, the substitution of phytomass 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 (Demirbas, 2005; Anon., 2006e) will allow using whole plants rather than seeds or tubers, thereby making fuel ethanol competitive at lower oil prices (Anon., 2006d).[10] Moreover, there are more promising non-food applications of phytomass than fuel, heat or electricity. Especially functionalized chemicals – which contain elements like nitrogen or oxygen – can be made with less energy from phytomass 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 biochemicals and bioenergy on food markets should not be underestimated (see also Cassman & Liska, 2007). It has been suggested that phytomass for non-foods will price itself out of the market before having large effects on food markets (Schmidhuber, 2007), but by reducing conversion costs new techniques will push the price at which this occurs upwards. Bioenergy requires large inputs of land and water. With current conversion techniques, the USA would need 30 percent and the EU-15 72 percent of their cropland to replace a mere 10 percent of their fossil fuel consumption (Anon., 2006d). New techniques will improve these ratios but also raise the demand. An assessment of the claim 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 Anon., 2006d; Meeusen & Van Tongeren, 2006).

Some authors have suggested that bioenergy could be produced from residues, dung and waste only (e.g., Fischer & Schrattenholzer, 2001), or from feedstock that is grown without irrigation on land that is not very suitable for food crops (e.g., Woods, 2006). Several studies have explored the global room for bioenergy, assuming crop yields up to some agronomic potential and some socially desirable allocation of natural resources over food and energy crops (e.g., Wolf *et al.*, 2003; Hoogwijk *et al.*, 2005; Smeets *et al.*, 2006).[11] On this basis, optimistic assessments are given that range from 162 to 1440 EJ, i.e., 0.2 to 1.75 times the global energy consumption expected in 2050.[12] 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,[13] as cotton 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 (Smil, 2003; Pandit *et al.*, 2006), which is not expected before mid-21st century, the claim to farm production capacity for new non-foods may grow considerably (see also McCarl *et al.*, 2001; Berndes, 2002; De Wit, 2004). For a rough guesstimate one could use the middle-of-the road scenario of the World Energy Council (Anon., 2005c) in which bioenergy would provide around

84 EJ by 2050. With 15 GJ per ton, 5600 Mt of phytomass 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 to 1000 Mt by 2050. Some 1000 Mt of phytomass would be needed for this, which would bring the phytomass demand for energy and chemicals to 6600 Mt. This would require 0.66 Gha, assuming that 10 tons of dry matter per hectare would be an attainable global average.[14] Adding 0.04 Gha for other non-food crops would bring the total claim for non-foods to 0.7 Gha, or 9 percent of the global potential agricultural land. Together with the assumptions on the claims to human settlement (3 percent) and biodiversity conservation (at least 8 percent) that we have made in the foregoing, this would bring the total claim to 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 livestock-based 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. In the next chapter we shall discuss the technical options that are available for this.

Technical possibilities for raising food production

At present, the global output of agricultural phytomass amounts to 7 MT of grain equivalents (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 agro-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 grassland) were to be optimally fertilized and total losses in the agro-food production chain would be limited to 10 percent. It was concluded that world agriculture could produce 72 MT grain equivalents of food. This would suffice to provide an affluent diet of 4.2 kg grain equivalents per person per day to 47 billion people – or 5.2 times the medium UN population estimate for 2050 (scenario 2 in Table 4). (Without biocides and inorganic N-fertilizer, this ratio would fall to 2.2 times this expected population size.)

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

- As was indicated before, affluent consumers have a habit of wasting food, which is hard to eliminate because it is inherent in affluent lifestyles. We therefore assume 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.
- The production potential of 72 GT of grain equivalents presupposes that all suitable

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

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

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

[2] n.a. = not available.

Source: Luyten (1995) plus own calculations based on data in this paper.

land (including forests on land that is suitable for agriculture) is used for food production. Here two qualifications are needed. As we already stated in the previous chapter, we assume that the global area of suitable land is slightly smaller than the one indicated in the Limits-of-Food-Production study – 7.6 Gha rather than 7.9 Gha. More importantly, one has to reckon with claims for non-food purposes. Based on the considerations in the previous chapter, we assume that by mid-century, human settlements, biodiversity conservation and non-food crops will claim at least 20 percent of the potential agricultural land. We take 43 percent as a maximum 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 above, 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 reduce crop yields in large areas. Additionally, environmental considerations set limits to farm production growth, because this entails nitrate and phosphate emissions that may degrade aquatic ecosystems, thereby impairing the use of water for drinking and other purposes (e.g., Carpenter *et al.*, 1998). Even though increased nutrient applications do not necessarily involve higher nutrient loss rates (De Wit, 1992),[15] emissions cannot be avoided (Nijland & Schouls, 1997).[16] For these reasons, we consider a 20 percent yield gap as unavoidable.

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.) The upshot of the above 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 32–47 GT of grain equivalents. This would suffice to provide 16–24 billion people with an affluent diet, or 1.8–2.7 times the medium UN population estimate for 2050. The technical implications of realizing this potential are discussed below.

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 and 16 GT of grain enquivalents, depending on the claims to natural resources for non-food purposes. This would only allow an affluent diet for a population of 0.4–0.9 times the one 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 underutilized. 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 conversion ratios in developing and developed countries (Wirsenius, 2003).[17] 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 generalization of the yield gap of 40 percent that now prevails in the developed world. Global production could then attain 20–28 GT of grain equivalents. This would allow an affluent diet for a population of 1.2–1.6 times the medium UN estimate for 2050 (scenario 5 in Table 4).

A further rise to a range of 27–37 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 towards an output of 32–47 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 (see also Figures 4 and 5). This can only be achieved through massive agro-industrial R&D, skills improvement and co-operation, not just in less-favoured areas but also 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 local and 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 by growing legumes in association with techniques like inoculation with nitrogen-fixing growth-promoting rhizobacteria (Dobbelaere *et al.*, 2003; Giller & Merckx, 2003; Bashan *et al.*, 2004).

However, for the plants this is an energy demanding process, resulting in lower potential yields than can be achieved with fertilizer N.[18]

Despite options to increase resource use efficiencies, raising global production to 47 GT of grain equivalents would involve a large increase in energy inputs. Much of this would be needed for N-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, assuming that crops contain 2 percent of N and that 0.15 GT of N comes from other sources than inorganic fertilizers. 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 (see also 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 (Anon., 2005c), 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, land that is more humid, 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. Seckler *et al.*, 1999; Rosegrant *et al.*, 2002). 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 of 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 soils.[19] This would virtually deplete the world's potential phosphate reserves (see also Penning De Vries *et al.*, 1995; Steen, 1998). Subsequently, 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 and that cereal grains contain 0.5 percent P, around 0.23 GT of P – about 13 times the current global consumption – would be needed for this. 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 retrieve phosphorus from seawater. This would involve huge energy costs, but we are not aware of any attempt at a quantitative assessment.

Can the potential be stretched?

The potential of 32–47 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 (e.g., Jordan, 2002), it does not mean that they could not be stretched.

Land availability has been discussed in the previous chapter 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 deionization or nanotechnology (Anon., 2004e; Bouter, 2005; Savage & Diallo, 2005). 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. Although the actual yield increases of major crops show no tendency to diminish (Haffner, 2003), the yield potential of maize has barely increased during the past few decades (Duvick & Cassman, 1999; Tilman *et al.*, 2002; Peng & Khush, 2003). The same can be argued for rice (Tilman *et al.*, 2002; Peng & Kush, 2003), even though recent results with hybrid rice in China in particular seem promising.

From a genetic point of view, improving harvest indices no longer seems the only and most 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, although there may be interactions between the two (Reynolds *et al.*, 2005). In others words, yields cannot be further increased by changing plant architecture to reallocate phytomass 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 (e.g., 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, reducing the time during which sunlight remains unused could increase light-use efficiency. 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). It remains to be assessed whether these approaches would entail significant effects on yield potentials.

Boosting the yield potential of the major cereals requires enhanced photosynthesis to increase light-use efficiencies. For example, the most prominent route proposed for rice would be to change it from a C3 into a C4 plant.[20] Comparing the productivities of maize and rice crops with similar growing periods and grown under similar conditions led Sheehy *et al.* (2007) to the conclusion that C4 rice might result in yield increases of up to 50 percent (see also Long *et al.*, 2006). Additionally, C4 rice would enable strong improvements in water- and nitrogen-use efficiencies. However, whether it will be possible to breed C4 rice and whether this will result in such high yield increases at crop level is highly uncertain and no time horizon for such a hypothetical breakthrough can be given. Moreover, changing C3 plants into C4 plants will be effective only when they are grown in relatively warm climates. So for temperate regions, breeding for C4 is not a viable route.

Yin & Struik (2007) assessed 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 livestock-based products, the global room for food production is sensitive to changes in feed conversion ratios. There is still room for improving feed conversion ratios in developed countries (e.g., 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 (a notable exception is marbled beef in the USA).

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

Beyond the farm paradigm

Although one can anticipate some possibilities for expanding our map of the agro-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 has taken rather than by the physical complexity involved by these options themselves. Our map of the agro-production landscape can change, slowly and sometimes suddenly, as a consequence of new breakthroughs in human knowledge. In this sense, every notion of a production potential or carrying capacity has a historical–social dimension (Benton, 1992; Anon., 1995; Van Den Belt, 1995). This even holds for our concept of the physical agro-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, for instance by learning from converging developments in agricultural and industrial processes. Again, it would be highly speculative to attach any time horizon to the realization of the hypothetical options described hereafter.

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,[21] but one could argue that this is comparable to the over-exploitation that threatened Mesolithic foragers 10,000 years ago. Wild capture is mere fish hunting. Likewise, current seaweed harvesting is predominantly plant gathering. A marine variety of the Neolithic Revolution (not to be confused with aquaculture based on farm-produced 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 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 be profitably 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 from 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 phytomass production that is set by photoreception efficiency. Agricultural crops are restricted to photosynthesis, which is only triggered by the red spectrum of solar light. Seaweeds and marine microalgae, however, also have 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 significantly increase the potential for phytomass production.

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 phytomass 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 grown 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 production systems where phytomass 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; they rather 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 into 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 inorganic inputs (Moraru *et al.*, 2003 and other references in Anon., 2004c). 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 chemoautotrophs. Nevertheless, others think that synthetic techniques for food production will remain science fiction for a long time to come (Anon., 2004e).

Economic forces

The foregoing can be summarized 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 that 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.

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 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, whereas in Sub-Saharan Africa they have stagnated (Figure 9).

What explains this divergence? Above we have highlighted the population–price nexus as a mechanism in pre-industrial agricultural revolutions. Population growth raised agricultural prices, which acted as a catalyst for innovation and investment in larger farms. However, the global regime change in agricultural markets has broken this traditional relation. Population in the developing world soared 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 (Francks *et al.*, 1999; Dawe, 2001; Dorward *et al.*, 2004; Timmer, 2004; Kajisa & Akiyama, 2005). Such policies were introduced by 'developmental states' (see also Önis, 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

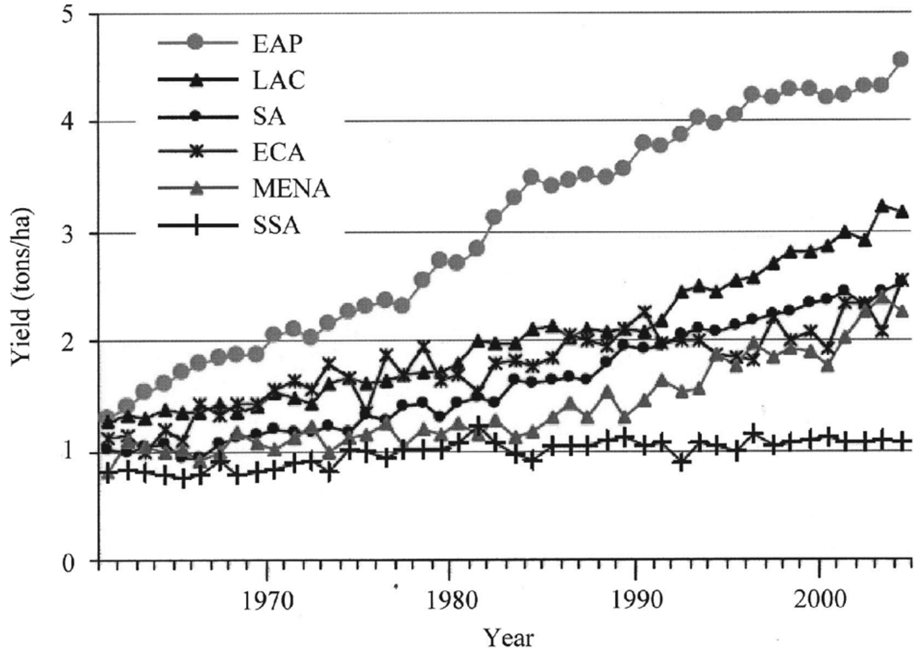


Figure 9. Cereal yields in various regions, 1961–2004. SSA – Sub-Saharan Africa; SA – South Asia; EAP – East Asia and Pacific; MENA – Middle East and North Africa; ECA – Eastern Europe and Central Asia; LAC – Latin America and Caribbean. Source: Anon (2007c), based on FAOSTAT.

of Asia had such a history, but other regions had not. They responded differently to the drop in international prices.

In Latin America after 1492, 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 (see also Johnston & Kilby, 1975; Anon., 2005d).[22] 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. Besides, latifundio capitalism and the marginalization of rural workers are driving a scramble for fragile natural resources, causing large-scale deforestation and soil degradation.

In Sub-Saharan Africa, the colonial scramble in the late 19th century 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; Munro, 1976; Huijzendveld, 1997). 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 (Goody, 1976; Bayart, 1989). This was normal for undifferentiated peasant societies with a recent history of long-fallow systems (see also Table 2), but not conducive to Asian-type developmental states. Politicians were obliged to remunerate many clients with 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 (e.g., Scoones, 1998). As poverty continued, however, social capital eroded and social networks degenerated into rent-seeking cliques (for examples see André & Platteau, 1998, Patterson, 1998 or Ikelegbe, 2001).

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 (e.g., 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 (Anon., 2004a). 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 (e.g., Bates, 1981; Djurfeldt *et al.*, 2005), but do not explain why badly governed countries in Europe in the 18th century still saw farm progress whereas African countries do not. For instance, it is well known that in France, rather than being halted by the bad governance under Louis XVI, agricultural growth helped paving the way for the changes of the French Revolution (Wertheim, 1974).

The deeper cause of agricultural stagnation in Africa is the way in which effectively post-Iron Age societies were plunged into global markets marked by chronic oversupply. Figure 10 illustrates the effects of this conjunction. As in pre-industrial situations (see 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 crisis similar to the one that 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 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-co-operative strategies that gave a high immediate

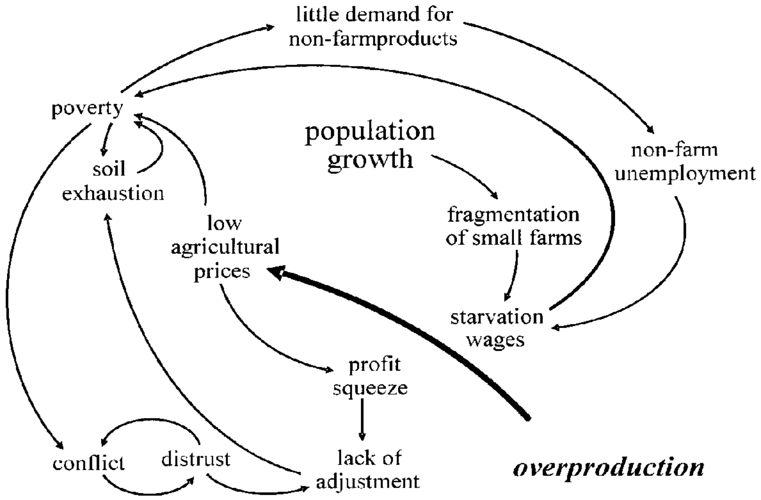


Figure 10. Unsustainability spiral in poor areas.

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. Whereas the former is undermined because the technical potential for food is underutilized, the latter is affected by a vicious cycle of poverty and high population growth (see also 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 1 US$ 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.[23] These countries are increasingly dependent on food imports and can hardly defend their poor if future import prices of food were to increase strongly.

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, as we have indicated above, the global food economy might approach a new relative ceiling before the technical room for expanding production is exhausted. 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. In the preceding chapter 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 the yield gap were to be reduced to 25 percent in those regions where the agricultural frontier areas are concentrated (North America, West and Central Europe, Oceania, and East, South-East and South Asia), but that in the former USSR, Latin America, and Africa it could only be reduced to 40, 60, 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 would 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 production 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.

Apart from the question as to 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, in agriculture it has continued expanding (Smil, 2003). In the USA, energy costs are now 25 percent of crop production costs. In a country like Argentina, they are as much as 43 percent (Anon., 2006d). 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 11, 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 that 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 curve *B* in Figure 8, which would mean 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 offset 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 N-fertilizer in the production costs of phytomass for food.

The fertilizer-output ratio would further increase if diminishing returns would set in earlier or the claim to phytomass for non-foods would be larger. Suppose that the fertilizer response were to follow curve *C*, and that the amount of phytomass for new non-foods would 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

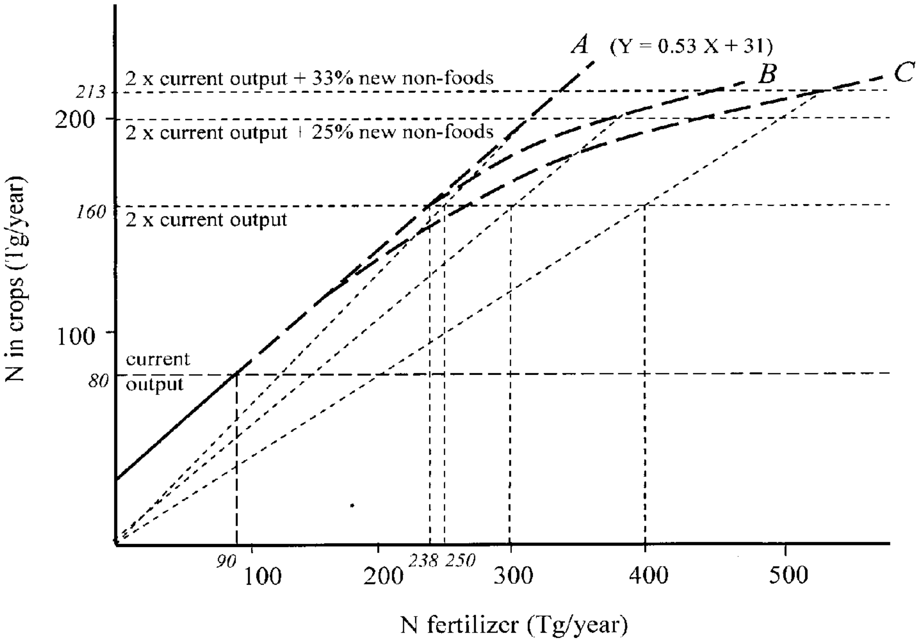


Figure 11. Hypothetical representation of the amount of N fertilizer required for a doubling of phytomass output (measured as N in crops) for food, assuming constant returns (*A*) or diminishing returns (*B* and *C*) to N input.

share of N-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 (Anon., 2006d). 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 systems 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 (e.g., Serageldin, 2001; Rosegrant *et al.*, 2002). 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). These authors believe that this will contribute to a halting of the long-term decline of cereal prices and possibly pressure food prices upwards.

A third factor that could influence the evolution of food prices would be 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. In the previous chapter 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. 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 these 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 (see also Anon., 2007c). 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.

Disturbances of international food markets

If the world food economy were to undergo a new trend change or approach a new ceiling, it could become more vulnerable to influences that might then disturb food markets. In the following we shall 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. 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 paddy rice production systems 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). (This could be reduced by rearing livestock in (sub)arctic areas or hermetically closed systems, but this will not readily occur.) More generally, increased transport and geographic concentration of production may facilitate the spread of pests and diseases (Anderson *et al.*, 2004).

Reduced genetic diversity and increased monocropping make crops more vulnerable (Edwards, 1996; Thrupp, 2000; Anderson *et al.*, 2004). 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 rice crop in 1976. New varieties put an end to the disaster, but not to the narrowing of the genetic base. In the 1990s, 95 percent of Philippine rice consisted of two varieties only (Anon., 1998b; Anderson *et al.*, 2004). Rice is a poor man's crop, where research is left to public institutions (Singh, 1999).[24] In maize, wheat and soya bean, 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 USA maize crop (Anderson *et al.*, 2004). Eighty-five percent of the crop was of one variety that was susceptible to these diseases (Anon., 1998b). 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 & Dehne, 2004). In the longer term, the rat race between agricultural research and pest adaptation might prove unsustainable (Tilman, 1998; Palumbi, 2001). Expectations that the gene revolution would provide an escape route (e.g., 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).

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 at the same time the food economy were 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. 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.[25] In fact, the following scenarios are conceivable:

1. 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 production possibility 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.
2. 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, when 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.
3. 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 scenario 3 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 in general. 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 USA exhibits fluctuations of a length comparable with those in Gérard *et al.* (Díaz Jerónimo, 2006). Comparison with key events (Figure 12) suggests that some initial price rises 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,

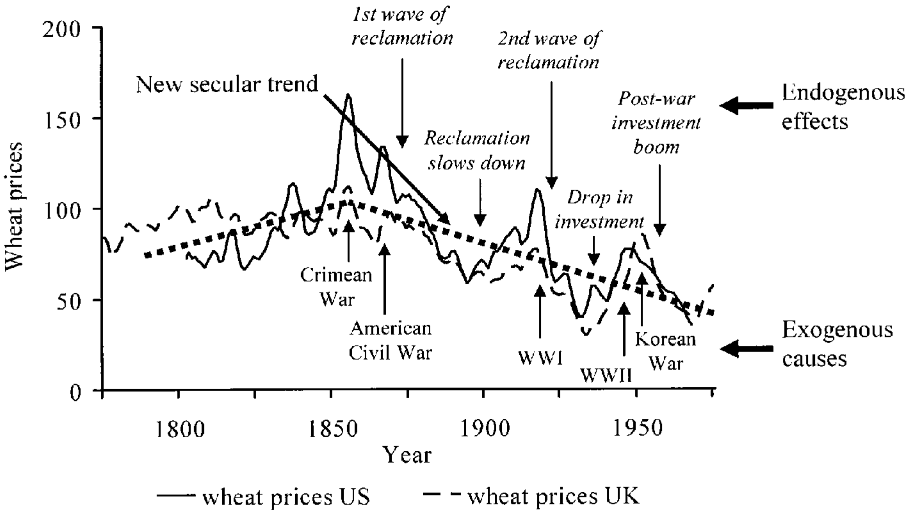


Figure 12. Fluctuations in real wheat prices in the USA and England & Wales, 1775–1970. Prices are 5-year moving averages. 1901–1905 = 100. Sources: Mitchell (1975; 1990; 1993), Anon. (1976).

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.

In the 1950s, an investment boom caused by high prices during WWII and the Korean War led to a new fall in international prices. This time, protective policies prevented a drop in investment in developed countries, while the effect of developed countries' dumping on investment in developing countries was partly redressed by donor support to the Green Revolution. Nevertheless, 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'. (Actually pseudo-liberalization: the USA and the EU still support their farmers through direct payments.) 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 1976–1981 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 (Anon., 2004f). Reinforcement of intellectual property rights complicated

Table 5. Annual growth rates (%) of investment in agricultural research, 1976–2000.

	1976–1981	1981–1986	1986–1991	1991–2000
Public research				
World total	4.5	2.9	3.0	1.6
Developed countries	2.5	1.9	2.2	–0.4
Private research				
Developed countries	–	–	3.9[1]	2.2

[1] 1987–1991.

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

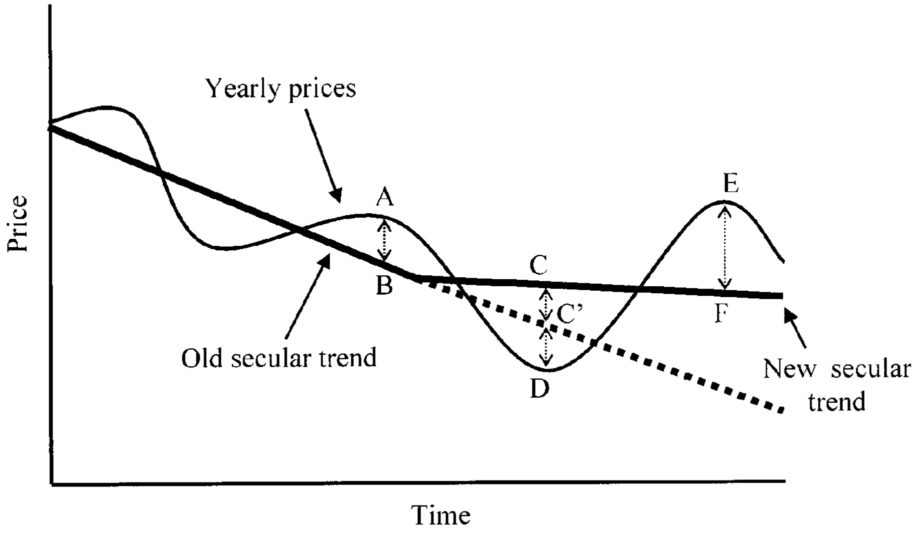


Figure 13. Schematic representation of the effect of trend change on cobweb fluctuation. If AB and C'D are the amplitude of the cobweb fluctuation under the old trend, the initial amplitude under the new trend is CD and EF.

the development of a public pool of germplasm, like the one that facilitated the Green Revolution in the 1960s–1970s (Falcon & Fowler, 2002; Safrin, 2004; Pingali, 2007). Private corporations prioritized things like herbicide resistance, which strengthened their position in farm inputs markets, rather than objectives like drought resistance that were vital for raising production in poor areas.

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 13. 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 above it (C'D = AB). However, in relation to the new trend, this is a larger price fall (CD > C'D), and the effect on investment causes a comparably large rise in prices above the trend in the subsequent phase (EF = CD). 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.

Policy implications

In the foregoing we have argued that the world's technical potential for food production is sufficient for feeding a significantly larger population than is expected by mid-century. Nevertheless, the low-hanging fruit is being depleted, so that decreasing returns, rising energy prices and the underutilization of potentials in some regions might cause a new change in the secular trend in food prices. This entails transition risks, not least by the interaction of a trend change with endogenous price fluctuations in world food markets.

Unnecessary scarcity is just one possible outcome to which this interaction may lead. If the trend change would coincide with a cyclic price rise rather than a cyclic decline, the effect could just as well be a smoothing of the transition. Unfortunately, the timing of a trend change is hard to predict. Today, many observers think that a trend change has already occurred because agricultural prices have increased since 2006. But it is equally possible that prices will decline again, and that a trend change will only follow later.

If we would live in a world of perfect information and with ample room for raising production under existing paradigms, spontaneous market forces could be relied upon to ensure a timely adjustment of the world food economy. Government action could be restricted to investment in infrastructure and human capital. Indeed, when assessed through equilibrium models that assume a linear behaviour of the economy, such an approach performs quite well (e.g., Ringler, 2006; Rosegrant, 2006). However, the real world is much more non-linear, and the risk that market forces would lead to unnecessary scarcity cannot be ruled out. Therefore, societal actors might be interested in policies that could mitigate this risk at low cost.

On the one hand, there are a number of options to mitigate any change in the secular trend in food prices. One is to stop subsidizing bioenergy, the environmental advantages of which are small anyhow. A second one is to moderate the consumption of feedlot beef, which couples health risks with especially unfavourable feed conversion ratios. A third one is to encourage smallholder-based agricultural growth in developing countries through public investment, public co-ordination in establishing agro-industrial chains, stabilization of agricultural prices, and measures to empower poor people. Such policies are vital for achieving Millennium Development Goals, and would also help to reduce the underutilization of potentials for food production in some regions.

On the other hand, there are options to limit the risk of cyclic underinvestment in global capacities for food production. Governments could strongly increase their investment in research for raising yields while reducing emissions to the environment. In addition, they could support research for biorefinery, effective meat substitutes, and new non-farm food production systems. Timely breakthroughs in these fields are vital for avoiding serious food shortages in the future. A more controversial option would be multilateral arrangements for stabilizing international food prices through supply management, including measures to limit the production of farm-based non-foods when food prices were to exceed a maximum. This goes against the current in economic thinking and trade policies, but it would still help to reduce the risk of unnecessary scarcity causing steep rises in food prices in the future.

Acknowledgements

We wish to thank Wiebe Aans, Henk Van Den Belt, Prem Bindraban, Erwin Bulte, Bert Janssen, Hans Lyklema, Rudy Rabbinge, Johan Sanders, Johan Vereijken, Johan Verreth, and the contributors and participants of workshops on the subject of this paper at Wageningen University on 26 January 2006 and on 10 March 2008 for their information, comments and suggestions. The responsibility for the content of this paper remains entirely that of the authors. Grateful acknowledgement is made to Wouter Gerritsma for carefully checking the list of references and helping to complete the bibliographic data.

References

Abel, W., 1978. Agrarkrisen und Agrarkonjunktur: eine Geschichte der Land- und Ernährungswirtschaft Mitteleuropas seit dem hohen Mittelalter. Paul Parey, Hamburg, 323 pp.

Adami, C., 2002. What is complexity? *BioEssays* 24: 1085–1094.

Aiello, L.C. & P. Wheeler, 1995. The expensive-tissue hypothesis: the brain and the digestive system in human and primate evolution. *Current Anthropology* 36: 199–221.

Aiking, H., J. De Boer & J. Vereijken (Eds), 2006. Sustainable Protein Production and Consumption: Pigs or Peas. Springer, Dordrecht, 226 pp.

Alston, J.M., C. Chan-Kang, M.C. Marra, P.G. Pardey & T.J. Wyatt, 2000. A Meta Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem? Research Report No 113. International Food Policy Research Institute (FPRI), Washington, D.C., 148 pp.

Anderson, P.K., A.A. Cunningham, N.G. Patel, F.G. Morales, P.R. Epstein & P. Daszak, 2004. Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers. *Trends in Ecology and Evolution* 19: 535–544.

André, C. & J.-P. Platteau, 1998. Land relations under unbearable stress: Rwanda caught in the Malthusian trap. *Journal of Economic Behavior & Organization* 34: 1–47.

Anonymous, 1976. The Statistical History of the United States from Colonial Times to the Present. US Bureau of the Census, New York, 1235 pp.

Anonymous, 1993. 1991 Census: Historical Tables. Her Majesty's Stationary Office, London, 22 pp.

Anonymous, 1995. Sustained Risks: a Lasting Phenomenon. Scientific Council for Government Policy (WRR), The Hague, 204 pp.

Anonymous, 1998a. The Fertilizer Industry, World Food Supplies and the Environment. International Fertilizer Industry Association (IFA), Paris & United Nations Environment Programme (UNEP), New York, 66 pp.

Anonymous, 1998b. The State of the World's Plant Genetic Resources for Food and Agriculture. Food and Agriculture Organization (FAO), Rome, 510 pp.

Anonymous, 2001. Energy Needs; Choices and Possibilities; Scenarios to 2025. Shell International, London, 60 pp.

Anonymous, 2003. Biofuels and the Environment. US Department of Energy. <http://permanent.access.gpo.gov/websites/www.ott.doe.gov/biofuels/environment.html>.

Anonymous, 2004a. Realizing the Promise and Potential of African Agriculture: Science and Technology Strategies for Improving Agricultural Productivity and Food Security in Africa. InterAcademy Council, Amsterdam, 266 pp.

Anonymous, 2004b. World Population Program: 2001 Probabilistic Projections. International Institute for Applied Systems Analysis. <www.iiasa.ac.at/Research/POP/proj01/results.html#download>.

Anonymous, 2004c. Down on the Farm: the Impact of Nano-scale Technologies on Food and Agriculture. ETC Group, Ottawa. <http://www.etcgroup.org/en/materials/publications.html?pub_id=80>.

Anonymous, 2004d. Evaluation of the Dutch Manure Policy (1998–2003). Report No 500031001. National Institute for Public Health and the Environment (RIVM), Bilthoven, 170 pp. (in Dutch)

Anonymous, 2004e. Nanoscience and Nanotechnologies: Opportunities and Uncertainties. Royal Society & Royal Academy of Engineering, London, 116 pp.

Anonymous, 2004f. Official Development Assistance to Agriculture. Working paper Agriculture and Natural Resources Team. Department for International Development (DFID), London, 27 pp.

Anonymous, 2005a. A Paleo Perspective on Abrupt Climate Change. National Climate Data Center (NCDC). <www.ncdc.noaa.gov/paleo/abrupt/index.html>.

Anonymous, 2005b. World Economic Outlook: Globalization and External Imbalances. International Monetary Fund (IMF), Washington, D.C., 289 pp.

Anonymous, 2005c. Global Energy Scenarios to 2050 and Beyond. World Energy Council. <http://www.worldenergy.org/wec-geis/edc/scenario.asp>. Accessed 1 January 2006.

Anonymous, 2005d. Equity and Development, World Development Report 2006. World Bank, Washington, D.C., 340 pp.

Anonymous, 2005e. Ecosystems and Human Well-Being, Vol. 2. Scenarios: Findings of the Scenarios Working Group. Millenium Ecosystem Assessment. Island Press, Washington, D.C., 560 pp.

Anonymous, 2006a. Food Losses: Lost Effort. Consumentenplatform. Ministry of Agriculture, Nature Conversation and Food Quality, The Hague, 21 pp. (in Dutch)

Anonymous, 2006b. Global Forest Resources Assessment 2005: Progress towards Sustainable Forest Management. Food and Agriculture Organization (FAO), Rome, 320 pp.

Anonymous, 2006c. Annual Outlook 2006, with Projections to 2030. US Department of Energy, Washington, D.C., 221 pp.

Anonymous, 2006d. Agricultural Market Impacts of Future Growth in the Production of Biofuels. Working Party on Agricultural Policies and Markets, Directorate for Food, Agriculture and Fisheries. Organisation for Economic Co-operation and Development (OECD), Paris, 55 pp.

Anonymous, 2006e. Files biofuels and sustainable energy. AgriHolland. <www.agriholland.nl/dossiers/biobrandstoffen/home.html>. (in Dutch)

Anonymous, 2006f. How Much Bioenergy can Europe Produce Without Harming the Environment? Report No 7/2006. European Environment Agency (EEA), Copenhagen, 72 pp.

Anonymous, 2007a. World Population Prospects: the 2006 Revision. United Nations. < http://esa.un.org/unpp/ >. Accessed 11 January 2008.

Anonymous, 2007b. Climate Change 2007: the Physical Science Base. Summary for Policymakers. Intergovernmental Panel on Climate Change (IPCC), Geneva, 21 pp.

Anonymous, 2007c. Agriculture for Development. World Development Report 2008. World Bank, Washington, D.C., 365 pp.

Anonymous, 2007d. UNSD Millennium Indicator Database. United Nations. <http://mdgs.un.org/unsd/mdg/Data.aspx >. Accessed 11 January 2008.

Anonymous, 2007e. Environment for Development; Global Environmental Outlook 4. United Nations Environment Programme (UNEP). Progress Press, Valletta, 540 pp.

Anríquez, G. & R. López, 2007. Agricultural growth and poverty in an archetypical middle income country: Chile 1987–2003. *Agricultural Economics* 36: 191–202.

Antle, J.M., J.J. Stoorvogel & R.O. Valdivia, 2006. Multiple equilibria, soil conservation investments, and the resilience of agricultural systems. *Environment and Development Economics* 11: 477–492.

Azar C. & E. Larson, 2000. Bioenergy and land-use competition in Northeast Brazil. *Energy for Sustainable Development* 4: 51–58.

Azariadis, C. & A. Drazen, 1990. Thresholds externalities in economic development. *Quarterly Journal of Economics* 105: 501–526.

Bairoch, P., 1976. Commerce Extérieur et Developpement Economique de l'Europe au XIXe Siècle. Mouton, Paris, 355 pp.

Bairoch, P., 1999. L'Agriculture des Pays Développés, 1800 à Nos Jours: Production – Productivité – Rendements. Economica, Paris, 202 pp.

Bashan, Y., G. Holguin & L.E. De Bashan, 2004. *Azospirillum*-plant relationships: physiological, molecular, agricultural, and environmental advances (1997–2003). *Canadian Journal of Microbiology* 50: 521–577.

Bates, R.H., 1981. Markets and States in Tropical Africa: the Political Basis of Agricultural Policies. University of California Press, Berkeley, California, 178 pp.

Bauernfeind, W. & U. Woitek, 1996. Agrarian Cycles in Germany 1339–1670: Spectral Analysis of Grain Prices and Output in Nuremberg. *Explorations in Economic History* 33: 459–478.

Bayart, J.-F., 1989. L'Etat en Afrique: la Politique du Ventre. Fayard, Paris, 439 pp.

Beardsworth, A. & A. Bryman, 1999. Meat consumption and vegetarianism among young adults in the UK: an empirical study. *British Food Journal* 101: 289–300.

Benton, T., 1992. Ecology, socialism and the mastery of nature: a reply to Reiner Grundmann. *New Left Review* 194: 55–74.

Berndes, G., 2002. Bioenergy and water: the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change* 12: 253–271.

Berndes, G., C. Azar, T. Kåberger & D. Abrahamson, 2001. The feasibility of large-scale lignocellulose-based bioenergy production. *Biomass & Bioenergy* 20: 371–383.

Berry, P.M. & J.H. Spink, 2006. A physiological analysis of oilseed rape yields: past and future. *Journal of Agricultural Science* 144: 381–392.

Beveridge, W., 1929. A statistical crime of the seventeenth century. *Journal of Economic and Business History.* (referred to in Mitchell, 1990, pp. 752–755.)

Bialek, W., I. Nemenman & N. Tishby, 2001. Predictability, complexity, and learning. *Neural Computation* 13: 2409–2463.

Bindraban, P.S., 1997. Bridging the gap between plant physiology and breeding: identifying traits to increase wheat yield potential using systems approaches. PhD thesis Wageningen Agricultural University, Wageningen, 135 pp.

Boserup, E., 1965. The Conditions of Agricultural Growth: the Economics of Agrarian Change under Population Pressure. Allen & Unwin, London, 124 pp.

Boserup, E., 1981. Population and Technical Change: a Study of Long-term Trends. Basil Blackwell, Chicago, 255 pp.

Boserup, E., 1987. Agricultural development and demographic growth: a conclusion. In: A. Fauve-Chamoux (Ed.), Évolution Agraire and Croissance Démographique. Ordina, Liège, pp. 385–389.

Bouter, H., 2005. Cheap drinking water from salt water. *Resource* 3 November 2005. <http://www.wb-online.nl/krant/artikel.php?id=2239>.

Bouwman, A.F., K.W. Van Der Hoek, B. Eickhout & I. Soenario, 2005. Exploring changes in world ruminant production systems. *Agricultural Systems* 84: 121–153.

Breman, H., 1997. Building soil fertility in Africa: constraints and perspectives. Paper presented at the 'International workshop on Development of National Strategies for Soil Fertility Recapitalization in Sub-Saharan Africa (Including the Use of Phosphate Rock and Other Amendments), 22–25 April 1997, Lomé.

Britto, D.V. & H.J. Kronzucker, 2004. Bioengineering nitrogen acquisition in rice: can novel initiatives in rice genomics and physiology contribute to global food security? *Bio Essays* 26: 683–692.

Brown, L.R., 1995. Who Will Feed China? A Wake-up Call for a Small Planet. Norton, New York, 163 pp.

Bruinsma, J. 2003. World Agriculture: towards 2015/2030: an FAO Perspective. Earthscan, London, 432 pp.

Bundy, C., 1972. The emergence and decline of a South African peasantry. *African Affairs* 71: 369–388.

Buntrock, G., 2007. Cheap no more: rising incomes in Asia and ethanol subsidies in America have put an end to a long era of falling food prices. *The Economist* 6 December 2007.

Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Science of the United States of America* 96: 5952–5959.

Cassman, K.G. & A.J. Liska, 2007. Food and fuel for all: realistic or foolish? *Biofuels, Bioproducts & Biorefining.* (in press)

Cassman, K.G., A. Dobermann, D.T. Walters & H. Yang, 2003. Meeting cereal demand while protecting natural resources ad improving environmental quality. *Annual Review of Environmental Resources* 28: 315–358.

Campbell, C.J., 1997. The Coming Oil Crisis. Petroconsultants, Brentwood, 210 pp.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley & V.H. Smith, 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8: 559–568.

Chilcutt, C.F. & B.E. Tabashnik, 2004. Contamination of refuges by *Bacillus thuringiensis* toxin genes from transgenic maize. *Proceedings of the National Academy of Sciences of the United States of America* 101: 7526–7529.

Clark, G., 1991. Yields per acre in English agriculture, 1250–1860: evidence from labour inputs. *Economic History Review* 44: 445–460.

Cleaver, K.M. & G.A. Schreiber, 1994. Reversing the Spiral: the Population, Agriculture and Environment Nexus in Sub-Saharan Africa. World Bank, Washington, D.C., 293 pp.

Cleveland, C.J., 1995. The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910–1990. *Agriculture, Ecosystems and Environment* 55: 111–121.

Cochrane, W.W., 1959. Farm Prices – Myth and Reality. University of Minnesota Press, Minneapolis, Minnesota, 189 pp.

Cohen, J. & I. Stewart, 1994. The Collapse of Chaos: Discovering Simplicity in a Complex World. Penguin Books, New York, 495 pp.

Coleman, D. & J. Salt, 1992. The British Population: Patterns, Trends and Processes. Oxford University Press, Oxford, 680 pp.

Cowan, R.P. & P. Gunby, 1996. Sprayed to death: path dependence, lock-in and pest control strategies. *Economic Journal* 106: 521–542.

Cox, T.S., J.D. Glover, D.L. Van Tassel, C.M. Cox & L.R. DeHaan, 2006. Prospects for developing perennial grain crops. *BioScience* 56: 649–659.

Crok, M. & T. Jaarsma, 2007. Fog in the crystal ball. *Natuurwetenschap & Techniek* 75: 22–31. (in Dutch)

Crosson, P., 1994. Degradation of resources as a threat to sustainable agriculture. Paper presented at the first World Congress of Professionals in Agronomy, 5–8 September 1994, Santiago de Chile, 36 pp.

Dasgupta, P., 1995. The population problem. *Journal of Economic Literature* 33: 1879–1902.

Dawe, D., 2001. How far down the path to free trade? The importance of rice price stabilization in developing Asia. *Food Policy* 26: 163–175.

De Boer, J., A. Hoek & H. Elzerman, 2006. Social desirability: consumer aspects. In: H. Aiking, J. De Boer & J. Vereijken (Eds), Sustainable Protein Production and Consumption: Pigs or Peas. Springer, Dordrecht, pp. 99–127.

De Jager, C., 2005. Solar forcing of climate. 1. Solar variability. *Space Science Review* 120: 197–241.

De Jager, A., D. Onduru, M.S. Van Wijk, J. Vlaming & G.N. Gachini, 2001. Accessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. *Agricultural Systems* 69: 99–118.

De Janvry, A., 1981. The Agrarian Question and Reformism in Latin America. John Hopkins University Press, Baltimore, 311 pp.

Delgado, C.L., 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. *Journal of Nutrition* 133: 3907S–3910S.

Delgado, C.L., M. Rosegrant, H. Steinfeld, S. Ehui & C. Courbois, 1999. Livestock to 2020: the Next Food Revolution. International Food Policy Research Institute (IFPRI), Washington, D.C, 72 pp.

Demirbas, A., 2005. Bioethanol from cellulosic materials: a renewable motor fuel from biomass. *Energy Sources* 27: 327–337.

Den Hartog, A.P., 2003. Taboos. Encyclopedia of Food and Culture, Vol. 3. Charles Scribner's Sons, New York, pp. 384–386.

De Steenhuijsen Piters, 1995. Diversity of fields and farmers: explaining yield variations in northern Cameroon. PhD thesis Wageningen University, Wageningen, 227 pp.

De Vries, B., M. Thompson & K. Wirtz, 2002. Understanding: fragments of a unifying perspective. In: B. De Vries & J. Goudsblom (Eds), Mappae Mundi: Humans and their Habitats in a Long-term Socio-ecological Perspectives (Myths, Maps and Models). Amsterdam University Press, Amsterdam, pp. 257–299.

De Wit, C.T., 1965. Photosynthesis of Leaf Canopies. Agricultural Research Report No 663. Pudoc, Wageningen, 57 pp.

De Wit, C.T., 1979. The efficient use of labour, land and energy in agriculture. *Agricultural Systems* 4: 279–287.

De Wit, C.T., 1992. Resource use efficiency in agriculture. *Agricultural Systems* 40: 125–151.

De Wit, P., 2004. Dreaming with Realism; Professor Wim Van Swaaij Wins Royal Shell Prize for Biofuel Research. Shell Venster, November/December, pp. 8–11. (in Dutch)

Díaz Jéronimo, P., 2006. Global food projections: a price dependent investment in agricultural research scenario. MSc thesis Wageningen University (Agricultural Economics and Rural Policy Group & Development Economics Group), Wageningen, 116 pp.

Djurfeldt, G., H. Holmen, M. Jirstroml & R. Larsson (Eds), 2005. The African Food Crisis: Lessons from the Asian Green Revolution. CABI Publishing, Wallingford, 266 pp.

Dobbelaere, S., J. Vanderleyden & J. Okon, 2003. Plant growth-promoting effects of diazotrophs in the rhizosphere. *Critical Reviews in Plant Sciences* 22: 107–149.

Döös, B.R., 1994. Environmental degradation, global food production, and risk for larger-scale migrations. *Ambio* 23: 124–130.

Dorosh, P., 2001. Trade liberalization and national food security: rice trade between Bangladesh and India. *World Development* 29: 673–689.

Dorward, A., J. Kydd, J. Morrison & I. Urey, 2004. A policy agenda for pro-poor agricultural growth. *World Development* 32: 73–89.

Dorward, A., J. Kydd & C. Poulton, 2007. Price intervention in Sub-Saharan African agriculture: can an institutionalist view alter our conception of the costs and benefits. In: N. Koning & P. Pinstrup-Andersen (Eds), Agricultural Trade Liberalization and the Least Developed Countries. Springer, Dordrecht, pp. 61–66.

Dosi, G., 1982. Technological paradigm and technological trajectories: a suggested interpretation of the determinants and directions of technical change. *Research Policy* 11: 147–162.

Duvick, D.N. & K.G. Cassman, 1999. Post-Green Revolution trends in yield potential of temperate maize in the North-Central United States. *Crop Science* 39: 1622–1630.

Eastwood, P., 1993. Variations in food choices: commentary from the 1st Food Choice Conference. *Appetite* 21: 287–290.

Edwards, R., 1996. Tomorrow's bitter harvest – the genetic diversity of our agriculture is rapidly vanishing; leaving our crops prone to pest and plague. *New Scientist* 17: 14–15.

Ehrlich, P.R., 1968. The Population Bomb. Ballantine Books, New York, 223 pp.

Ezekiel, M., 1938. The cobweb theorem. *Quarterly Journal of Economics* 53: 225–280.

Fairhead, J. & M. Leach, 1996. Misreading the African Landscape: Society and Ecology in a Forest-Savanna Mosaic. Cambridge University Press, Cambridge, 354 pp.

Falcon, W. & C. Fowler, 2002. Carving up the commons – emergence of a new international regime for germplasm development and transfer. *Food Policy* 27: 197–222.

Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare & D.M. Kammen, 2006. Ethanol can contribute to energy and environmental goals. *Science* 311: 506–508.

Fiddes, N., 1991. Meat: a Natural Symbol. Routledge, London, 261 pp.

Fischer, G. & L. Schrattenholzer, 2001. Global bioenergy potentials through 2050. *Biomass & Bioenergy* 20: 151–159.

Fischer, G., M. Shah, H. Van Velthuizen & F.O. Nachtergaele, 2001. Global agro-ecological assessment for agriculture in the 21st century. International Institute for Applied Systems (IIASA) Laxenburg & Food and Agriculture Organization (FAO), Vienna, 33 pp.

Foley, R.A., 2001. The evolutionary consequences of increased carnivory in hominids. In: C.B. Stanford & H.T. Bunn (Eds), Meat-eating and Human Evolution. Oxford University Press, Oxford, pp. 305–331.

Francks, P., J. Boestel & C.H. Kim, 1999. Agriculture and Economic Development in East Asia: from Growth to Protectionism in Japan, Korea and Taiwan. Routledge, London, 255 pp.

Fraser, E.D.G, W. Mabee & F. Figge, 2005. A framework for assessing the vulnerability of food systems to future shocks. *Futures* 37: 465–479.

Freeman, C., 1991. Innovations, changes of techno-economic paradigm and biological analogies in economics. *Revue Economique* 42: 211–232.

Freeman, C. & C. Perez, 1988. Structural crises of adjustment: business cycles and investment behaviour. In: G. Dosi, C. Freeman, R.R. Nelson, G. Silverberg & L. Soete (Eds), Technical Change and Economic Theory. Pinter Publishers, London, pp. 38–66.

Fuller, F., D. Hayes & D. Smith, 2000. Reconciling Chinese meat production and consumption data. *Economic Development and Cultural Change* 49: 23–43.

Gandah, M., A. Stein, J. Brouwer & J. Bouma, 2000. Dynamics of spatial variability of millet growth and yields at three sites in Niger, West Africa, and implications for precision agriculture research. *Agricultural Systems* 63: 123–140.

Geertz, C., 1963. Agricultural Involution: the Processes of Ecological Change in Indonesia. University of California, Berkeley, California, 176 pp.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Cambridge University Press, Cambridge, 457 pp.

Gérard, F., M.-G. Piketty & J.M. Boussard, 2003. Libéralisation des échanges et bien-être des populations pauvres: illustration à partir du modèle ID3 de la faiblesse des impacts et de la sensibilité des resultants aux hypotheses de fonctionnement des marchés. *Notes et Études Économiques* 19: 111–134.

Geschiere, P., 1995. Sorcellerie et Politique en Afrique: la Viande des Autres. Karthala, Paris, 311 pp.

Giles, J., 2005. Hikes in surface ozone could suffocate crops. *Nature* 435: 7.

Giller, K.E. & R. Merckx, 2003. Exploring the boundaries of N_2-fixation in cereals and grasses: a hypothetical and experimental framework. *Symbiosis* 35: 3–17.

Goody, J., 1976. Production and Reproduction: a Comparative Study of the Domestic Domain. Cambridge University Press, Cambridge, 157 pp.

Greene, N., 2004. Growing Energy: how Biofuels can Help End America's Oil Dependence. National Research and Development Centre (NRDC), New York, 86 pp.

Grigg, D.B., 1980. Population Growth and Agrarian Change: an Historical Perspective. Cambridge University Press, Cambridge, 340 pp.

Haffner, S., 2003. Trends in maize, rice and wheat yields for 188 nations over the past 40 years: a prevalence of linear growth. *Agriculture, Ecosystems and Environment* 97: 275–283.

Hallock, J.L., P.J. Tharakan, C.A.S. Hall, M. Jefferson & W. Wu, 2004. Forecasting the limits to the availability and diversity of global conventional oil supply. *Energy* 29: 1673–1696.

Hardin, G., 1968. The tragedy of the commons. *Science* 162: 1243–1248.

Harris, M., 1985. Good to Eat: Riddles of Food and Culture. Simon and Schuster, New York, 289 pp.

Hatcher, J., 1996. Plague, population and the English economy, 1348–1530. Economic History Society 1977. (Reprinted in M. Anderson (Ed.), British Population History: from the Black Death to the Present Day. Cambridge University Press, Cambridge, pp. 9–93.)

Hayami, Y. & V.W. Ruttan, 1985. Induced Innovation: an International Perspective. John Hopkins University Press, Baltimore, 367 pp.

Hejazi, M.A. & R.H. Wijffels, 2004. Milking of microalgae. *Trends in Biotechnology* 24: 189–194.

Hentzepeter, V.J.H., 2005. Fishing to size. *Voedingsmiddelentechnologie* 2005-6: 10–13. (in Dutch)

Holling, C.S. & L.H. Gunderson (Eds), 2002. Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, D.C., 507 pp.

Holm, L. & M. Møhl, 2000. The role of meat in everyday food culture: an analysis of an interview study in Copenhagen. *Appetite* 34: 277–283.

Hoogwijk M., A. Faaij, B. Eickhout, B. De Vries & W. Turkenburg, 2005. Potential of biomass energy out to 2100, for four IPCCSRES land-use scenarios. *Biomass & Bioenergy* 29: 225–257.

Horwith B., 1985. A role for intercropping in modern agriculture. *Bioscience* 35: 286–291.

Huijzendveld, F.D., 1997. Die ostafrikanische Schweiz: Plantations, Planters and Rural Development in West-Usambara, East-Africa, ca. 1870–1930. N.W. Posthumus Series No 7. N.W. Posthumus Instituut, Amsterdam, 523 pp. (in Dutch)

Ikelegbe, A., 2001. The perverse manifestation of civil society: evidence from Nigeria. *Journal of Modern African Studies* 39: 1–24.

Johnson, A.W. & T. Earle, 2000. The Evolution of Human Societies: from Foraging Group to Agrarian State. Stanford University Press, Stanford, 374 pp.

Johnston, B.F. & P. Kilby, 1975. Agriculture and Structural Transformation: Economic Strategies in Late-developing Countries. Oxford University Press, New York, 444 pp.

Jeggo, M.H. & B.T. Eaton, 2003. Emerging diseases: causes, conditions and controls. In: A.G. Brown (Ed.), The Livestock Revolution: a Pathway from Poverty? ATSE Crawford Fund, Canberra, pp. 65–73.

Jenssen, T.K. & G. Kongshaug, 2005. Energy consumption and greenhouse gas emissions in fertiliser production. The International Fertiliser Society Proceedings No 509 (2003). (Quoted in T. Tzilivakis, D.J. Warner, M. May, K.A. Lewis & K. Jaggard, 2005. An assessment of the energy inputs and greenhouse emissions in sugar beet (*Beta vulgaris*) production in the UK. *Agricultural Systems* 85 : 101–119).

Jordan, C.F., 2002. Genetic engineering, the farm crisis, and world hunger. *BioScience* 52: 523–529.

Kajisa, K. & T. Akiyama, 2005. The evolution of rice price policies over four decades: Thailand, Indonesia and the Philippines. *Oxford Development Studies* 33: 305–329.

Kauffman, S., K. Dijkshoorn, J. Huting & S. Mantel, 2005. Farmers and Soils Determine Green and Blue Water Resources; a Pilot Study of the Save Basin, Zimbabwe. Poster World Soil Information (ISRIC), Wageningen.

Kempenaar, C., L.J.M. Van Der Eerden & A.E.G. Tonneijck, 1999. Air pollution and crop production in the developing world. In: P.S. Bindraban, H. Van Keulen, A. Kuijvenhoven, R. Rabbinge & P.W.J. Uithol (Eds), Food Security at Different Scales: Demographic, Biophysical and Socio-economic Dimensions. Wageningen University and Research Centre, Wageningen, pp. 79–93.

Keyzer, M.A., M.D. Merbis, I.F.P.W. Pavel & C.F.A. Van Wesenbeeck, 2005. Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? *Ecological Economics* 55: 187–202.

Koning, N., 1994. The Failure of Agrarian Capitalism: Agrarian Politics in the UK, Germany, The Netherlands and the USA, 1846–1919. Routledge, London, 292 pp.

Koning, N. & E. Smaling, 2005. Environmental crisis or 'lie of the land'? The debate on soil degradation in Africa. *Land Use Policy* 22: 3–11.

Koning, N., P.S. Bindraban & A.J.A. Essers (Eds), 2002. Wageningen Views on Food Security. Plant Research International, Wageningen University and Research Centre, Wageningen. <http://library.wur.nl/way/catalogue/documents/Wageningen_UR_visions.pdf>.

Laxminarayan, R. & R.D. Simpson, 1976. Refuge strategies for managing pest resistance in transgenic agriculture. *Environment and Resource Economics* 22: 521–536.

Leach, G., 1976. Energy and Food Production. IPC Science and Technology Press, Guildford, 151 pp.

Lems, S., H.J. Van Der Kooi & J. De Swaan Arons, 2003. Thermodynamic optimization of energy transfer in (bio)chemical reaction systems. *Chemical Engineering Sciences* 58: 2001–2009.

Long, S.P., X.G. Zhu, S.L. Naidu & D.R. Ort, 2006. Can improvement in photosynthesis increase crop yields? *Plant, Cell and Environment* 29: 315–330.

Loomis, R.S. & J.S. Amthor, 1999. Yield potential, plant assimilatory capacity, and metabolic efficiencies.

Crop Science 39: 1584–1596.

Lucas, R.E., 1988. On the mechanics of economic development. *Journal of Monetary Economics* 22: 3–42.

Lundin, M., M. Olofsson, G.J. Petterson & H. Zetterlund, 2004. Environmental and economic assessment of sewage sludge handling options. *Resources, Conservation and Recycling* 41: 255–278.

Luyten, J.C., 1995. Sustainable world food production and environment. Report No 37, Institute for Agrobiology and Soil Fertility (AB-DLO), Wageningen, 159 pp.

Ma, H., J. Huang & S. Rozelle, 2004. Reassessing China's livestock statistics: an analysis of discrepancies and the creation of new data series. *Economic Development and Cultural Change* 53: 445–473.

Malthus, T.R., 1798. An Essay on the Principle of Population. Johnson, London, 500 pp.

Mann, C.C., 2005. 1491: New Revelations of the Americas before Columbus. Vintage, New York, 465 pp.

Martinez-Alier, J., 1987. Ecological Economics: Energy, Environment and Society. Blackwell, Oxford, 287 pp.

Mazoyer, M. & L. Roudart, 2006. A History of World Agriculture: from the Neolithic Age to the Current Crisis. Earthscan, New York, 528 pp.

McCarl, R.M., R.M. Adams & B. Hurd, 2001. Global climate change and its impact on agriculture. <http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/879.pdf>.

McEvedy, C. & R. Jones, 1978. Atlas of World Population History. Penguin Books, Harmondsworth, 368 pp.

McKitrick, R. (Ed.), 2007. Independent Summary for Policymakers of the IPCC 4th Assessment Report. The Fraser Institute, Vancouver, 64 pp.

McLaughlin, S.B., D.G. De La Torre Ugarte, C.T. Garten, L.R. Lynd, M.A. Sanderson, V.R. Tolbert & D.D. Wolf, 2002. High-value renewable energy from prairie grasses. *Environmental Science Technology* 36: 2122–2129.

Meadows, D.H., D.L. Meadows, J. Randers & W.W. Behrens, 1972. The Limits to Growth: a Report for the Club of Rome's Project on the Predicament of Mankind. Universe Books, New York, 207 pp.

Meeusen, M. & F. Van Tongeren, 2006. Understanding the factors which determine biomass availability. In: L. Kuiper (Ed.), Quick-scans on Upstream Biomass; Yearbook 2004 and 2005. Biomass Upstream Consortium, Wageningen, pp. 219–237.

Meul, M., F. Nevens, D. Reheul & G. Hofman, 2007. Energy use efficiency of specialised dairy, arable and pig farms in Flanders. *Agriculture, Ecosystems* & *Environment* 119: 135–144.

Meuvret, J.-M, 1946. Les crises de subsistances et démographie de la France d'Ancien Régime. *Population* 2: 643–650.

Mew, T.W., D.S. Brar, S. Peng, D. Dawe & B. Hardy (Eds), 2004. Rice Science: Innovations and Impact for Livelihood. Proceedings of the International Rice Research Conference, 16–19 September 2002, Beijing. International Rice Research Institute (IRRI), Manila, 1022 pp.

Mitchell, B.R., 1975. European Historical Statistics. Cambridge University Press, Cambridge, 827 pp.

Mitchell, B.R., 1990. British Historical Statistics. Cambridge University Press, Cambridge, 886 pp.

Mitchell, B.R., 1993. International Historical Statistics: the Americas, 1750–1988. Macmillan, New York, 817 pp.

Mitchell, D.O., M.D. Ingco & R.C. Duncan, 1997. The World Food Outlook. Cambridge University Press Cambridge, 216 pp.

Molden, D. (Ed.), 2007. Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture. Earthscan, London, 645 pp.

Moore, D.C., 1965. The corn laws and high farming. *Economic History Review* 18: 544–561.

Moraru, C.I., C.P. Panchapakesan, Q. Huang, P. Takhistov, S. Liu & J.L. Kokini, 2003. Nanotechnology: a new frontier in food science; understanding the special properties of materials of nanometer size will allow food scientists to design new, healthier, tastier, and safer foods. *Food Technology* 57: 24–29.

Munro, J.F., 1976. Africa and the International Economy 1800–1960: an Introduction to the Modern Economic History of Africa south of the Sahara. Dent, London, 230 pp.

Myrdal, G., 1968. Asian Drama: an Inquiry into the Poverty of Nations. Penguin Books, New York, 2284 pp.

Nakagaki, B.J. & G.R. DeFoliart, 1991. Comparison of diets for mass rearing *Acheta domesticus* (Orthoptera: Gryllidae) as a novelty food, and comparison of food conversion efficiency with values reported for livestock. *Journal of Economic Entomology* 84: 891–896.

Nerlove, M., 1958. Adaptive expectations and cobweb phenomena. *Quarterly Journal of Economics* 72: 227–240.

Nevens, F., I. Verbruggen, D. Reheul & G. Hofman, 2006. Farm gate nitrogen surpluses and nitrogen use efficiency of specialized dairy farms in Flanders: evolution and future goals. *Agricultural Systems* 88: 142–155.

Nijland, G.O. & J. Schouls, 1997. The relation between crop yield, nutrient uptake, nutrient surplus and nutrient application. Wageningen Agricultural University Papers No 97-3. Backhuys, Leiden, 151 pp.

Odell, P.R., 2004. Why carbon Fuel will Dominate the 21st Century's Global Energy Economy. Multi-Science Publishing, Brentwood, 192 pp.

Oerke, E.C. & H.W. Dehne, 2004. Safeguarding production – losses in major crops and the role of crop protection. *Crop Protection* 23: 275–285.

Oerke, E.C., H.W. Dehne, F. Schohnbeck & A. Weber, 1995. Crop Production and Crop Protection: Estimated Losses in Major Food and Cash Crops. Elsevier, Amsterdam, 808 pp.

Oldeman, L.R., R.T.A. Hakkeling & W.G. Sombroek, 1990. World Map of the Status of Human-induced Soil Degradation. World Soil Information (ISRIC), Wageningen & United Nations Environment Programme (UNEP), Nairobi, 30 pp.

Olson, M., 1965. The Logic of Collective Action: Public Goods and the Theory of Groups. Uitgever, Cambridge, Massachusetts, 176 pp.

Öni , Z., 1991. The logic of the developmental state. *Comparative Politics* 24: 109–126.

Ostrom, E., 1990. Governing the Commons: the Evolution of Institutions for Collective Action. Cambridge University Press, New York, 280 pp.

Palumbi, S.R., 2001. Humans as the World's Greatest Evolutionary Force. *Science* 293: 1786–1790.

Pandit, A., H. De Groot & A. Holzwarth (Eds), 2006. Harnessing Solar Energy for the Production of Clean Fuels. <www.ssnmr.leidenuniv.nl/content_docs/cleansolarfuels.pdf>.

Pardey, P.G. & N.M. Beintema, 2001. Slow Magic: Agricultural R&D a Century after Mendel. International Food Policy Research Institute (IFPRI), Washington, D.C., 30 pp.

Pardey, P.G., N. Beintema, S. Dehmer & S. Wood, 2006. Agricultural Research: a Growing Global Divide? International Food Policy Research Institute IFPRI, Washington, D.C., 30 pp.

Patterson, A.S., 1998. A reappraisal of democracy in civil society: evidence from rural Senegal. *Journal of Modern African Studies* 36: 423–441.

Peng, S. & G.S. Khush, 2003. Four decades of breeding for varietal improvement of irrigated lowland rice in the International Rice Research Institute. *Plant Production Science* 6: 157–164.

Penning De Vries, F., H. Van Keulen & R. Rabbinge, 1995. Natural resources and limits of food production in 2040. In: J. Bouma, A. Kuyvenhoven, J.C. Luyten & H.G. Zandstra (Eds), Eco-regional Approaches for Sustainable Land Use and Food Production. Kluwer Academic Publishers, Dordrecht, pp. 65–87.

Phelps Brown, E.H. & S.V. Hopkins, 1956. Seven centuries of the prices of consumables, compared with builders' wage-rates. *Economica, New series* 23: 296–314.

Pingali, P.L., 2007. Will the Gene Revolution Reach the Poor? Lessons from the Green Revolution. Mansholt Lecture, 26 January 2007. Wageningen University, Wageningen. (in press)

Pingali, P.L. & G. Traxler, 2002. Changing locus of agricultural research: will the poor benefit from biotechnology and privatization trends? *Food Policy* 27: 223–238.

Pingali, P.L., Y. Bigot & H.P. Binswanger, 1987. Agricultural Mechanization and the Evolution of Farming Systems in Sub-Saharan Africa. John Hopkins University Press, Baltimore, 216 pp.

Pomeranz, K., 2000. The Great Divergence: Europe, China and the Making of the Modern World Economy. Princeton University Press, Princeton, New Jersey, 382 pp.

Popkin, B., S. Horton & S. Kim, 2001. The nutrition transition and prevention of diet-related chronic diseases in Asia and the Pacific. *Food and Nutrition Bulletin* 22: 3–58.

Postel, 1999. Pillar of sand. Can the irrigation miracle last? Norton, New York, 313 pp.

Rabbinge, R., 2005. Possibilities and impossibilities of bio-energy production. *Spil* 5: 25–28. (in Dutch)

Ragauskas, A.J., C.K. Williams, B.H. Davison, G. Britovsek, J. Cairney, C.A. Eckert, W.J. Frederick, J.P. Hallett, D.J. Leak, C.L. Liotta, J.R. Mielenz, R. Murphy, R. Templer & T. Tschaplinski, 2006. The path forward for biofuels and biomaterials. *Science* 311: 484–489.

Rathje, W.L. & C. Murphy, 1992. Rubbish! The Archaeology of Garbage. HarperCollins, New York, 263 pp.

Reith, J.H., E.P. Deurwaarder, K. Hemmes, A.P.W.M. Curvers, P. Kamermans, W. Brandenburg & G. Zeeman, 2005. Bio-offshore; Large-scale cultivation of sea weeds combined with offshore windmill parks in the North Sea. Energy Research in the Netherlands (ECN), Petten & Wageningen University and Research Centre, Wageningen, 137 pp. (in Dutch)

Reynolds, M.P., A. Pellegrineschi & B. Skovmand, 2005. Sink-limitation to yield and biomass: a summary of some investigations in spring wheat. *Annals of Applied Biology* 146: 39–49.

Richards, P., 1997. Towards an African Green Revolution? An anthropology of rice research in Sierra Leone. In: E. Nyerges (Ed.), The Ecology of Practice: Studies of Food Crop Production in Sub-Saharan West Africa. Gordon and Breach, Newark, New Jersey, pp. 201–252.

Richardson, N.J., R. Shephers & N.A. Elliman, 1993. Current attitudes and future influences on meat consumption in the U.K. *Appetite* 21: 41–51.

Ricardo, D., 1817. Principles of Political Economy and Taxation. John Murray, London, 300 pp.

Rijsberman, F.R., 2006. Water scarcity: fact or fiction? *Agricultural Water Management* 80: 5–22.

Ringler, C., 2006. Global Food, Fiber and Bioenergy Demand Prospects: Implications for Natural Resources – drawing on the Millennium Ecosystem Assessment. International Food Policy Research Institute (IFPRI), Washington, D.C., 19 pp.

Robert, P.C., 2002. Precision agriculture: a challenge for crop nutrition management. *Plant and Soil* 247: 143–149.

Robinson, W. & W. Schutjer, 1984. Agricultural development and demographic change: a generalization of the Boserup model. *Economic Development and Cultural Change* 32: 355–366.

Rogers, J.E.T., 1866. A History of Agriculture and Prices in England, Vol. 1. Clarendon Press, London, 711 pp.

Romer, P.M., 1986. Increasing returns and long-run growth. *Journal of Political Economy* 94: 1002–1037.

Rosegrant, M.W., 2006. IMPACT-WATER and the Global Scenarios of the Millennium Ecosystem Assessment. Presentation at the Workshop Long-term Global Availability of Food: Continued Abundance or New Scarcity, 26 January 2006, Wageningen. Wageningen University, Wageningen.

Rosegrant, M.W. & P.L. Pingali, 1994. Policy and technology for rice productivity growth in Asia. *Journal of International Development* 6: 665–688.

Rosegrant, M.W., M.S. Paisner, S. Meijer & J. Witcover, 2001. Global Food Projections to 2020: Emerging Trends and Alternative Futures. International Food Policy Research Institute (IFPRI), Washington, D.C., 224 pp.

Rosegrant, M.W., X. Cai & S.A. Cline, 2002. World Water and Food to 2025: dealing with Scarcity. International Food Policy Research Institute (IFPRI), Washington, D.C., 322 pp.

Rosenzweig, C. & D. Hillel, 1998. Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture. Oxford University Press, New York, 324 pp.

Rozin, P., 2003. Meat. Encyclopedia of Food and Culture, Vol. 2. Charles Scribner's Sons, New York, pp. 466–471.

Ruthenberg, H., 1980. Farming Systems in the Tropics (3rd edition). Clarendon Press, Oxford, 424 pp.

Ruttan, V., 2001. Technology, Growth, and Development: an Induced Innovation Perspective. Oxford University Press, New York, 656 pp.

Safrin, S., 2004. Hyperownership in a time of biotechnological promise: the international conflict to control the building blocks of life. *American Journal of International Law* 98: 640–685.

Sanders, J.P.M., 2004. Green chemistry by farmers with power. Inaugural address Wageningen University, 20 June 2004, Wageningen, 38 pp. (in Dutch)

Sanders, J., E. Scott, R. Weasthuis & H. Mooibroek, 2007. Bio-refinery as the bio-inspired process to bulk chemicals. *Macromolecular Bioscience* 7: 105–117.

Savadogo, K., 2007. Poverty, land conservation and intergenerational equity: will the least developed countries benefit from agricultural trade liberalization? In: N.B. Koning & P. Pinstrup-Andersen (Eds), Agricultural Trade Liberalization and the Least Developed Countries. Springer, Dordrecht, pp. 67–81.

Savage N. & M.S. Diallo, 2005. Nanomaterials and water purification: opportunities and challenges. *Journal of Nanoparticle Research* 7: 331–342.

Savary, S., N.P. Castilla, F.A. Elazegui & P.S. Teng, 2005. Multiple effects of two drivers of agricultural change, labour shortage and water scarcity, on rice pest profiles in tropical Asia. *Field Crops Research* 91: 263–271.

Schultz, Th.W., 1945. Agriculture in an Unstable Society. McGraw-Hill, New York, 299 pp.

Scheffer, M. & S.R. Carpenter, 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology and Evolution* 18: 648–656.

Scherr, S.J. & S. Yadav, 2001. Land degradation in the developing world: issues and policy options for 2020. In: P. Pinstrup-Andersen & R. Pandya-Lorch, The Unfinished Agenda. International Food Policy Research Institute (IFPRI), Washington, D.C., pp. 133–138.

Schiere, J.B., 1995. Cattle, Straw and System Control: a Study of Straw Feeding systems. Royal Tropical Institute (KIT), Amsterdam, 216 pp.

Schmidhuber, J., 2007. Impact of an increased biomass use on agricultural prices, markets and food security. In A. Haverkort, P. Bindraban & H. Bos (Eds), Food, Fuel or Forest? Opportunities, Threats and Knowledge Gaps of Feedstock Production for Bio-Energy. Plant Research International, Wageningen, pp. 21–26.

Schutkowski, H., 2006. Human Ecology: Biocultural Adaptations in Human Communities. Springer, Berlin, 303 pp.

Scoones, I., 1998. Sustainable Rural Livelihoods: a Framework for Analysis. Working Paper No 72, Institute of Development Studies, University of Sussex, Brighton, 22 pp.

Seckler, D., R. Barker & U. Amarasinghe, 1999. Water scarcity in the twenty-first century. *International Journal of Water Resources Development* 15: 29–42.

Sen, A., 1981. Poverty and Famines: an essay on Entitlement and Deprivation. Oxford University Press, Oxford, 257 pp.

Serageldin, I., 2001. Assuring water for food: the challenge of the coming generation. *International Journal of Water Resources Development* 17: 521–525.

Seur, H., 1992. Sowing the good seed: the interweaving of agricultural change, gender relations and religion in Serenje District, Zambia. PhD thesis Wageningen Agricultural University, Wageningen, 474 pp.

Shapouri, J.A., J.A. Duffield & M. Wang, 2005. The Energy Balance of Corn Ethanol: an Update. Agricultural Economic Report No 813. United States Department of Agriculture (USDA), Washington, D.C., 16 pp.

Shearman, V.J., R. Sylvester-Bradley, R.K. Scott, & M.J. Foulkes, 2005. Physiological processes associated with wheat yield progress in the UK. *Crop Science* 45: 175–185.

Sheehy, J.E., A.B. Ferrer, P.L. Mitchell, A. Elmido-Mabilangan, P. Pablico & M.J.A. Dionora, 2007. How the rice crop works and why it needs a new engine. In: J.E. Sheehy, P.L. Mitchell & B Hardy (Eds), Charting New Pathways to C4 rice. International Rice Research Institute (IRRI), Los Baños, pp. 3–26.

Sherk, G.W., P. Wouters & S. Rochford, 2002. Water Wars in the Near Future? Reconciling Competing Claims for the World's Diminishing Freshwater Resources – The Challenge of the Next Millennium. <http://www.dundee.ac.uk/cepmlp/journal/html/vol3/article3-2.html>.

Shiel, R.S., 1991. Improving soil productivity in the pre-fertilizer era. In: B.M.S. Campbell & M. Overton (Eds), Land, Labour and Livestock: Historical Studies in European Agricultural Productivity. Manchester University Press, Manchester, pp. 51–77.

Singh, RK, 1999. Genetic resource and the role of international cooperation in rice breeding. *Genome* 42: 635–641.

Slicher Van Bath, B.H., 1963. The Agrarian History of Western Europe, A.D. 500–1800. Arnold, London, 364 pp.

Smeets, E.M.W., A.P.C. Faaij, I.M. Lewandowski & W.C. Turkenburg, 2006. A bottom up quickscan and review of global bio-energy potentials to 2050. *Progression in Energy and Combustion Science* 33: 56–106.

Smil, V., 1991. General Energetics: Energy in the Biosphere and Civilization. John Wiley & Sons, New York, 369 pp.

Smil, V., 1999. Long-range Perspectives on Inorganic Fertilizers in Global Agriculture. Travis P. Hignett Lecture. International Centre for Soil Fertility (IFDC), Florence, Alabama, 36 pp.

Smil, V., 2000. Feeding the World: a Challenge for the Twenty-first Century. MIT Press, Cambridge, Massachusetts, 360 pp.

Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. MIT Press, Cambridge, Massachusetts, 338 pp.

Smil, V., 2002. Eating meat: evolution, patterns, and consequences. *Population and Development Review* 28: 599–639.

Smil, V., 2003. Energy at the Crossroads: Global Perspectives and Uncertainties. MIT Press, Cambridge, Massachusetts, 443 pp.

Soon, W., 2007. Implications of the secondary role of carbon dioxide and methane forcing in climate change: past, present, and future. *Physical Geography* 28: 97–125.

Spolaore, P., C. Joannis-Cassan, E. Duran & A. Isambert, 2006. Commercial applications of microalgae. *Journal of Bioscience and Bioengineering* 101: 87–96.

Stanford, C.B., 1999. The Hunting Apes: Meat Eating and the Origins of Human Behavior. Princeton

University Press, Princeton, New Jersey, 253 pp.

Steen, I., 1998. Phosphorus availability in the 21st century: management of a non-renewable resource. *Phosphorus & Potassium* 217: 25–31

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales & C. De Haan, 2006. Livestock's Long Shadow: Environmental Issues and Options. Food and Agriculture Organization (FAO), Rome, 390 pp.

Stern, N., 2006. Stern Review on the Economics of Climate Change. <http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm>. Accessed 12 January 2008.

Stoop, N., R. Stoop & L. Bunimovich, 2004. Complexity of dynamics as variability of prediction. *Journal of Statistical Physics* 114: 1127–1137.

Svensmark, H., J.O.P. Pedersen, N.D. Marsh, M.B. Enghoff & U.I. Uggerhoj, 2007. Experimental evidence for the role of ions in particle nucleation under atmospheric conditions. *Proceedings of the Royal Society A: Mathematical, Physical & Engineering Sciences* 463: 385–396.

Tainter, J.A., 1990. The Collapse of Complex Societies. Cambridge University Press, Cambridge, 260 pp.

Tainter, J.A., T.F.H. Allen, A. Little & T.W. Hoekstra, 2003. Resource transitions and energy gains: contexts of organization. <http://www.consecol.org/vol7/iss3/art4/>.

Thrupp, L.A., 2000. Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture. *International Affairs* 76: 283–297.

Tilman, D., 1998. The greening of the green revolution. *Nature* 396: 211–212.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor & S. Polasky, 2002. Agricultural sustainability and intensive production practices. *Nature* 418: 617–677.

Timmer, C.P. 2004. Food security and rice price policy in Indonesia: the economics and politics of the food price dilemma. In: T.W. Mew, D.S. Brar, S. Peng, D. Dawe & B. Hardy (Eds), pp. 777–789.

Tuong, T.P., B.A.M. Bouman & M. Mortimer, 2005. More rice, less water – integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. *Plant Production Sciences* 8: 229–239.

Uhlin, H.-E., 1999. Energy productivity of technological agriculture: lessons from the transition of Swedish agriculture. *Agriculture, Ecoystems and Environment* 73: 63–81.

Ulijaszek, S.J., 2002. Human eating behaviour in an evolutionary ecological context. *Proceedings of the Nutrition Society* 61: 517–526.

Van De Koppel, J., M. Rietkerk & F.J. Weissing, 1997. Catastrophic vegetation shifts and soil degradation in terrestrial grazing systems. *Trends in Ecology and Evolution* 12: 352–356.

Van Den Belt, H., 1995. Measuring the environmental utilization space: natural or social limits? Paper presented at the meeting of the International Society for Hermeneutics and Science, 12–15 July 1995, Leusden.

Van Der Zijpp, A.J., 2001. Animal production systems: on integration and diversity, Inaugural address. Wageningen University, Wageningen, 66 pp.

Van Huis, A., 2003. Insects as food in Sub-Saharan Africa. *Insect Science and its Application* 23: 163–185.

Van Ittersum, M.K. & R. Rabbinge, 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research* 52: 197–208.

Vörösmarty, C.J., P. Green, J. Salisbury & R. Lammers, 2000. Global water resources: vulnerability from climate change and population growth. *Science* 289: 284–288.

Van Keulen, H., 1982. Graphical analysis of annual crop response to fertiliser application. *Agricultural Systems* 9: 113–126.

Vasey, N. & A. Walker, 2001. Neonate body size and hominid carnivory. In: C.B. Stanford & H.T. Bunn (Eds), Meat-eating and Human Evolution. Oxford University Press, Oxford, pp. 332–349.

Wade, R., 2003. What strategies are viable for developing countries today? The World Trade Organization and the shrinking of 'development space'. *Review of International Political Economy* 10: 621–644.

Watson, R., I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo & D.J. Dokken, (Eds), 2000. Land Use, Land-use Change, and Forestry: A Special Report of the IPCC. Cambridge University Press, Cambridge, 377 pp.

Wertheim, W.F., 1974. Evolution and Revolution; the Rising Waves of Emancipation. Penguin Books, Harmondsworth, 416 pp.

Willets, A., 1997. Bacon sandwiches got the better of me: meat-eating and vegetarianism in South-East London., In: P. Caplan (Ed.), Food, Health and Identity. Routledge, London, pp. 111–130.

Wirsenius, S., 2003.Efficiencies and biomass appropriation of food commodities on global and regional levels. *Agricultural Systems* 77: 219–255.

Wolf, J., P.S. Bindraban, J.C. Luijten & L.M. Vleeshouwers, 2002. Exploratory study on the land area required for global food supply and the potential global production of bioenergy. *Agricultural Systems* 76: 841–861

Wong, J., 2004. The adaptive developmental state in East Asia. *Journal of East Asian Studies* 4: 345–362.

Wood, J.W., 1998. A theory of preindustrial population dynamics. *Current Anthropology* 39: 99–135.

Woods, J., 2006. Science and technology options for harnessing bioenergy's potential. In: P. Hazell & R.K. Pachauri (Eds), Bioenergy and Agriculture: Promises and Challenges. International Food Policy Research Institute (IFPRI), Washington, D.C., 26 pp.

Wrigley, E.A., R.S. Davies, J.E. Oeppen & R.S. Schofield, 1997. English Population History from Family Reconstitution, 1580–1837. Cambridge University Press, Cambridge, 657 pp.

Yin, X. & P.C. Struik, 2007. Crop systems biology – an approach to connect functional genomics with crop modelling. In: J.H.J. Spiertz, P.C. Struik & H.H. Van Laar (Eds), Scale and Complexity in Plant Systems Research. Springer, Dordrecht, pp. 63–73.

Young, A., 1999. Is there really spare land? A critique of estimates of available cultivable land in developing countries. *Environment, Development and Sustainability* 1: 3–18.

Zimmermann, A., 1996. Zur Bevölkerungsdichte in der Urgeschichte Mitteleuropas. *Tübinger Monographien zur Urgeschichte* 1: 49–61.

Notes

[1] Strictly speaking, water-use efficiency is not seen as a determinant of potential yield because water supply is regarded 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.

[2] The unknown aspects of the biophysical landscape can be assumed to conform to basic thermodynamic laws (see also Georgescu-Roegen, 1971; Martinez-Alier, 1987).

[3] Malthusian crises could be aggravated by causes like hierarchical mentalities that were fostered by involution and hampered adjustment (De Vries *et al.*, 2002), or by the multi-equilibrium nature of agro-ecosystems. The latter can be caused by conservation investment (Antle *et al.*, 2006), but the effect may be strengthened when the ecosystem is characterized by a physical multi-equilibrium. Social disruption could occur because poverty affected the time preference of people, inducing them to select exhaustive farming techniques and non-co-operative (social-capital eroding) strategies that gave higher immediate returns but hurt them in the longer term.

[4] Projections of the increase in the global consumption of livestock-based foods are obscured by poor statistics on meat consumption and livestock in China (e.g., Fuller *et al.*, 2000; Ma *et al.*, 2004). This may affect projections of strongly decreasing growth of meat consumption in East Asia (e.g., Anon., 2007c). Nevertheless, most projections are in line with the general impression that the global consumption of animal products may double.

[5] Luyten (1995) and Penning De Vries *et al.* (1995) assume that 3.8 Gha is suitable for cropland and 4 Gha for grazing. Young (1999) thinks that the usable land in the developing world has been overestimated by 10 to 15 percent. We assume that 84 percent of all suitable land occurs in the developing world and that half of the land that should be deducted from the cultivatable area cannot be used for grazing either.

[6] 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.

[7] Part of this water is returned to the source and reused downstream so that the final water consumption for irrigation is about 1400 km^3.

[8] See also Svensmark *et al.* (2007) for evidence supporting the possibility that global warming is largely due to solar forcing.

[9] Lower expectations, like that of the International Monetary Fund (Anon., 2005b) that crude oil prices will stabilize around 34 USD per barrel after 2007, seem too optimistic.

[10] Moreover, feedstocks like wood and switchgrass (*Panicum virgatum*) are traditionally grown on marginal land and promote soil regeneration and fixing carbon in soils (Watson *et al.*, 2000; McLaughlin, 2002), and the net energy balance and CO_2 reduction effects of second generation biofuels will be better than those of existing biofuels, which are at most slightly positive (Berndes *et al.*, 2001; Shapouri *et al.*, 2002; Anon., 2003; Greene, 2004; Farrell *et al.*, 2006). These characteristics will encourage policy measures to stimulate the use of advanced biofuels if the greenhouse hypothesis holds.

[11] The assessment by the European Environment Agency (Anon., 2006f) 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.

[12] Bioenergy 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 bioenergy from residues and surplus forest growth).

The medium projection of global primary energy consumption in 2050 of the World Energy Council is 836 EJ (Anon., 2005c).

[13] 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).

[14] 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.

[15] 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.)

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

[17] 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.

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

[19] Penning De Vries *et al.* (1995) estimated 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.

[20] Other routes include e.g., the introduction of improved forms of Rubisco from algae into C3 plants (Long *et al.*, 2006).

[21] Over 90 million tons of fish are being captured annually, whereas the estimated quantities that are sustainably available for human consumption vary between 74 and 114 million tons.

[22] Similar conditions existed in South Africa, parts of South Asia, and for some time in the southern USA.

[23] Calculation based on United Nations poverty indicators (Anon., 2007d) and United Nations population projections (Anon., 2007a). The share of extreme poverty in all least developed countries is assumed to equal that in those (22 out of 49) for which poverty indicators for the years between 1990 and 2005 were available.

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

[25] The outcomes of these models 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 e.g., Gérard *et al.* (2003) for a global agricultural trade model where imperfect information leads to endogenous price fluctuations that influence investment decisions.