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Review

# Future protein supply

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The food system appropriates over 30% of all ice-free land, 70% of available freshwater and 20% of energy. Sustainable food production for 2.3 billion more people in the next four decades requires societal transition and industrial transformation. Protein supply is crucial, nutritionally and environmentally. Livestock products have disproportionate impacts on biodiversity loss, freshwater depletion, climate change and other issues. Use of natural resources must be reduced by applying the biorefinery principle and closing cycles. The food industry can contribute to a sustainable future by development of novel plant protein products (NPFs) and continual innovations in food preservation and waste reduction.

## Introduction

Sustainability has many facets and food production is an important constituent. Definitions of sustainable food production generally address aspects from ecology, economy and society in various blends (Aiking & De Boer, 2004). In a recent paper Rockström *et al.* (2009) warn that certain biophysical thresholds should not be transgressed without disastrous consequences for humanity. From this perspective, we should focus primarily on rates of change and how to decelerate runaway impacts on ecology. If one can't do the math, then one may be removed from the equation. As a result of rapidly increasing world population and affluence, food security and sustainability are on a collision course by mid-century. So far, yield per hectare kept pace largely by increasing irrigation and fertiliser application, but these have upper bounds and environmental drawbacks. In fact, the food system (Tansey & Worsley, 1995) is a complex network of interlinked processes that are tightly coupled to many other issues. Interference in one area is bound to produce effects elsewhere. For example, improving food security – itself a constituent of sustainability – is likely to have social, economic and ecological repercussions (Fig. 1). Food, feed and fuel, production and consumption, nutrition, health, poverty, biodiversity, pollution and resource depletion are thoroughly intertwined and can no longer be addressed in isolation in a world speeding towards 9 billion inhabitants. Sustainability is a moving target.

We are living in a fascinating, yet extremely challenging era, during which we may have to redesign our lifestyles entirely. Everybody without exception needs water, food, shelter, and energy. By 2050, a world with 2.3 billion more people will need 70% more food (Bruinsma, 2009). In order to attain sustainability, the *grand total* of environmental impacts of all human activities should be reduced significantly, *in spite of* a growing world population and standard of living. Therefore, a stepwise change will be required, a societal *transition*. Food, water and energy were identified as targets for stepwise transition, rather than gradual improvement, by the International Human Dimensions Programme (Vellinga & Herb, 1999). Moreover, these main activities are not independent of one another, since food production (Green, Vieira, & Aiking, 1999) appropriates major shares of freshwater (70%) and energy (20%) production (Aiking, De Boer, & Vereijken, 2006). As an added complexity, biofuels (Wiebe *et al.*, 2008) may compete with food for the same scarce land and freshwater resources (Fischer, 2009).

It is evident that food demand is a function of world population, but it is equally obvious it is not the only determinant. For example, national diets and their environmental impacts are hugely different (De Boer, Helms, & Aiking, 2006). In addition, nutritionally optimal diets strongly depend on individual requirements (due to the huge genetic variation between individuals) and individual taste is strongly modified by cultural preferences, availability and economic potential. Thus, over 800 million people are currently malnourished (Alexandratos, 2009), and 1.6 billion people are overweight (WHO, 2006).

This paper is sketching the overall playing field of interlinked sustainability issues, the temporal aspects (Aiking & De Boer, 2004), and the pivotal role of nitrogen and protein. It is argued that a transition towards more plant protein based diets would simultaneously benefit the conservation of biodiversity, land, water, energy, climate, human health and animal welfare. Industrial challenges are addressed.

## Sustainability, cycles and population: increasing rates of change

Food is important to individuals as well as to society, both providing nutrients and generating income (Tansey

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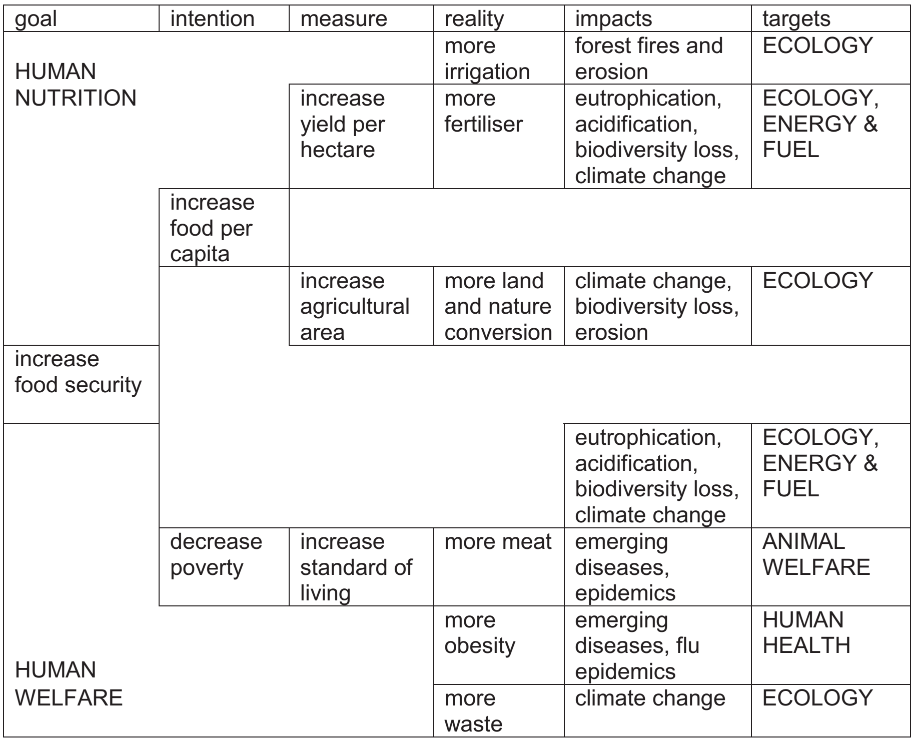


**Fig. 1**. Food sustainability: Network of interlinked social, economic and ecological issues.

& Worsley, 1995). The evolution of agriculture, industry and technology have both shaped and been shaped by world population growth (Evans, 1998). Fig. 2 illustrates the unprecedented world population and rate of increase during the last two centuries, in particular.

Evidently, food production and consumption, technology and society cannot be considered to be independent of one another. Due to continued growth of both world population and per capita income a major proportion of global environmental pressure is generated by food-related activities (Bruinsma, 2002; Evans, 1998). Crops are produced, processed and turned into food products in ever larger

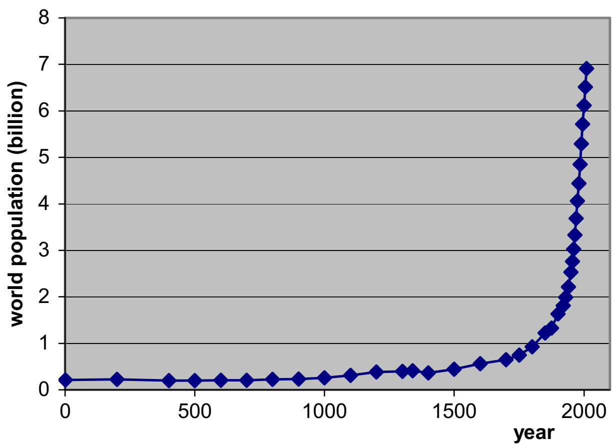


**Fig. 2**. World population 0–2010AD.

volumes, with ever-increasing impacts on the environment (Hoffmann, 2001; Tilman, Cassman, Matson, Naylor, & Polasky, 2002). Currently, about one third of all transport is food-related and, moreover, one third of the ice-free land area is used for food production, plus about three quarters of the available freshwater (Smil, 2002b). The environmental impacts of food production include resource depletion and pollution on all scale levels from local to global. Prominent examples include impacts on biodiversity (Nierenberg, 2006) and climate change (Stehfest *et al*., 2009; Van Beukering, Van der Leeuw, Immerzeel, & Aiking, 2008), as well as pollution by pesticides, targeting sustainability as well as human health (McMichael, Powles, Butler, & Uauy, 2007). This clearly shows that *via* food production the rate of population increase has brought numerous cycles way out of balance.

## Nitrogen and protein are pivotal

Technologically speaking, producing enough food for 10 billion people seems feasible (Evans, 1998). However, doing so without compromising sustainability — both by pollution and by resource depletion — will be a formidable challenge (Tilman *et al*., 2002). Dietary protein is nutritionally crucial (Smil, 2002a), since nitrogen is an indispensable constituent of DNA, RNA and protein. Smil (2001) calculated that before large-scale application of fertilisers, the global population was capped at ca. 3 billion people by nitrogen limitation, less than half the present number (Fig. 3). The tremendous energy input involved in nitrogen

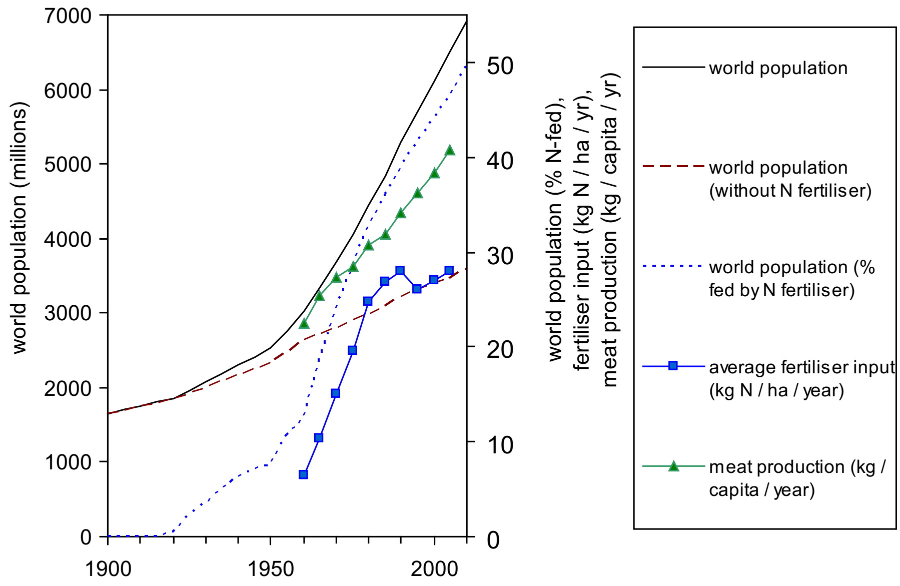


**Fig. 3**. World population, meat production and fertilisers. Source: Erisman *et al.* (2008).

fertiliser production causes significant climate change (Smil, 2001; Erisman, Sutton, Galloway, Klimont, & Winiwarter, 2008), and fertilisers leach more easily from the soil than natural nitrogen sources (Crews & Peoples, 2004). Thus, nitrogen is crucial to aquatic and terrestrial biodiversity loss, climate change, human health and many other issues (Erisman *et al.*, 2008; McMichael *et al.*, 2007; Townsend & Howarth, 2010). Anthropogenic contributions to the carbon cycle are 1–2%, but to the nitrogen cycle 100–200%. Consequently, Rockström *et al.* (2009) rank the impacts of disrupting the nitrogen cycle in between those of biodiversity loss and carbon cycle disruption, because the current status of biodiversity loss exceeds their proposed boundary by a factor of more than 10, that of nitrogen cycle disruption by a factor of 3.45, and that of carbon cycle disruption by a factor of 1.1–1.5 (Rockström *et al.*, 2009). In addition, nitrogen cycle disruption has strong impacts on both biodiversity and the carbon cycle. In fact, nitrogen pollution is considered to be among the top three threats to global biodiversity (Townsend & Howarth, 2010). More details can be found in the section on biodiversity loss below.

For 1–2 billion people fish supply 20–30% of the protein in their diets, versus 6% worldwide (Halweil & Nierenberg, 2008; Lang, Barling, & Caraher, 2009). However, it has to be realised that during the last few decades we have been seriously depleting fish stocks (Pauly *et al.*, 2002). Aquaculture is unlikely to fill that gap, since a) carnivorous fish are net fish consumers and b) herbivorous fish require a primary protein source from terrestrial agriculture and substantial energy input.

So far, food production has been able to keep up with population growth by increasing the yield per hectare (mainly by increasing irrigation and fertiliser application), and protein production by intensifying animal production. The latter has resulted in problems with human and animal health, as well as a decrease in animal welfare, as is evident from a string of food scares (BSE, foot-and-mouth disease, swine fever, avian influenza, dioxins, hormones, etc.) and an obesity epidemic. Resistant bacteria (e.g. MRSA) may result from antibiotics routinely added to livestock feed. Emerging diseases such as avian influenza are strongly coupled to intensive livestock production (Pilcher, 2004).

## Affluent diet

Within the realm of food, meat takes a unique place for its high social status (Beardsworth & Keil, 1997). While the world population doubled during the second half of the 20th century, its appetite for meat increased fivefold, resulting in 40% of the world grain harvest to be fed to livestock (Evans, 1998). Table 1 illustrates this effect of increasing average income. While another 50% will be added to the world population during the period 2000-2050, it is estimated that another 100% will be added to meat production (Steinfeld *et al.*, 2006: p. 275). This projected doubling holds for animal food products in general, since dairy production is projected to increase from 580 to 1043 million tonnes (Steinfeld *et al.*, 2006: p. 275). Both projections

**Table 1. World population and meat production 1950–2050.**

| Year | World population (billion) | Meat production (billion kg) |
|---|---|---|
| 1950 | 2.7 | 45 |
| 2000 | 6.0 | 229 |
| 2050 | 9.1 | 465 |

Source: Steinfeld *et al.* (2006).

for 2050 were confirmed in later work (Alexandratos, 2009; Bruinsma, 2009).

Primarily due to rising incomes, between 1970 and 1996 the relative proportion of people suffering from malnutrition and hunger has halved (from 37% to 18% of the world population), however, the absolute number of people afflicted has just decreased from 960 to 790 million (Bruinsma, 2002). Subsequently, the number went up again (Alexandratos, 2009). Another result of this increasing welfare is that the number of obese people (Body Mass Index $\geq$ 30) has shown a tremendous increase to at least 400 million people at present and 700 million projected by 2015 (WHO, 2006).

## Environmental impacts of animal protein

The inherently inefficient conversion of plant protein into animal protein makes meat responsible for a disproportionate share of environmental pressure (Brown, 1996; Gilland, 2002; Raney *et al.*, 2009; Steinfeld *et al.*, 2006). As a result of animal metabolism, 6 kg of plant protein is required to yield 1 kg of meat protein, on average (Pimentel & Pimentel, 2003; Smil, 2000). Consequently, a mere 15% of protein and energy in these crops will ever reach human mouths (indirectly), and 85% are wasted. In 2000, for example, 942 and 617 million tonnes of grains were required for food and feed, respectively (Msangi & Rosegrant, 2009: p. 27). Of the latter, therefore, over 500 million tonnes are essentially wasted for human consumption and, moreover, turned into polluting emissions by animal metabolism. In addition to 40% of the grain harvest, some 75% of soy is fed to livestock, with similar resource losses of some 85%. Evidently, the actual protein conversion efficiency depends on the type of animal under consideration, as well as on the conditions (such as the prevailing diet and climate). Poultry and pigs are more efficient protein converters than beef cattle, but when grass-fed, the latter do not appropriate feed crops. In addition, their multiple stomachs are unsuited to digest maize, which turns them ill. In a watershed report on the environmental impacts of livestock production, the FAO are explicitly addressing both resource depletion and pollution (Steinfeld *et al.*, 2006). Overall, meat and dairy production are playing a crucial role in *all three* of the "planetary boundaries" that have already been overstepped by humanity (i.e. biodiversity loss, nitrogen cycle disruption and carbon cycle disruption), and livestock production is deeply involved in *at least three more* (i.e. land-use change, freshwater use and the phosphorus cycle) "planetary boundaries" under threat of transgression (Rockström *et al.*, 2009). Most issues are addressed in this paper, but for peak phosphorus see Cordell, Drangert, and White (2009).

## Land use and land-use change

With respect to land use the FAO report (Steinfeld *et al.*, 2006) summarizes:

"The livestock sector is by far the single largest anthropogenic user of land. The total area occupied by grazing is equivalent to 26 percent of the ice-free terrestrial surface of the planet. In addition, the total area dedicated to feedcrop production amounts to 33 percent of total arable land. In all, livestock production accounts for 70 percent of all agricultural land and 30 percent of the land surface of the planet. Expansion of livestock production is a key factor in deforestation, especially in Latin America where the greatest amount of deforestation is occurring – 70 percent of previous forested land in the Amazon is occupied by pastures, and feedcrops cover a large part of the remainder."

The permanent pasture area will sustain livestock, but most of it is unsuitable for crops. However, feed and food crops are in direct competition. Table 2 provides an overview.

An important point illustrated by Table 2 is that 4 million square kilometres of land world wide (about the surface area of EU-27) is devoted to feed crops, primarily grains and oilseeds. A rough estimate (Aiking, De Boer, *et al.*, 2006: p. 172) indicates that these feed crops contain about 144 million tonnes of feed protein. Assuming a conversion efficiency of 20% (5 kg plant protein to 1 kg meat protein) – based on long-term USDA statistics for poultry (Smil, 2002c) – this may yield a maximum of 29 million tonnes of meat protein, but less in reality.

In contrast, 29 million tonnes of plant proteins for direct human consumption would require approximately 0.25 million sq. km (about the size of the UK) of soy, freeing 3.75 million sq. km of land world wide (Aiking, De Boer, *et al.*, 2006: p. 173). Thus – without interfering with grazing livestock – abolishing intensive livestock farming would result in a tremendous reduction of agricultural land demand (worldwide, an area slightly smaller than EU-27), and a concomitant reduction of its ever-increasing pressure on biodiversity. In this respect, Smil (2000: p. 158) estimates that "assuming that the area now devoted to feed crops were planted to a mixture of food crops, and only their milling residues were used for feeding" could easily feed 1 billion people.

## Freshwater depletion

So far, agriculture has been able to keep up with population growth largely by increasing irrigation and fertiliser inputs. The physical limits of freshwater availability are

**Table 2. World land use.**

| Land-use type | Area (million ha) |
|---|---|
| Arable & permanent cropland | 1500 |
| of which for feed crops | 400 |
| Permanent pastures | 3500 |
| Forest and woodlands | 4200 |
| All other land | 3900 |
| Total ice-free land area | 13,100 |

Source: Aiking *et al.* (2006: p. 171)

approaching rapidly, however. Smil (2002c: p. 309) summarizes:

> "Adequate water supply is emerging as one of the key concerns of the 21st century, and few economic endeavors are as water-intensive as meat production in general, and cattle feeding in particular. Most of these large requirements are due to low conversion efficiencies of feed. Assuming an average of 1000 kg of water to produce 1 kg of feed grain (an average of C3 and C4 demands) and about 20 kg of concentrated feed to produce 1 kg of edible beef results in an overall requirement of 20 t of water per kg of meat."

Using different assumptions, Millstone and Lang (2003) estimate water use of beef production at 250,000 L (250 tonnes) per kg, stating that 1 kg of beef requires 1000 times more water than 1 kg of cereal. In contrast, the Stockholm International Water Institute estimates that the production of 1 kg of grain-fed beef requires 5–40 times as much water as 1 kg of cereal (SIWI-IWMI, 2004). In the same publication they describe the current water use as "undermining its own resource base and threatening the resilience of ecosystems". In this respect, irrigation of agricultural land is one of the leading causes of water tables dropping world wide to the extent that water shortages seem inevitable (Brown, 2009; Ye & Van Ranst, 2009).

Pimentel and Pimentel (2003) state that the water required to produce various crops ranges from 500 to 2000 L/kg and, therefore, depending on the ratio between grain and forage, producing 1 kg of beef may require up to more than 200,000 L of water. The latter is close to the Millstone and Lang (2003) estimate, which is at the high end of the range. On average, it seems a fair conclusion by Pimentel and Pimentel (2003) that producing 1 kg of animal protein requires about 100 times more water than 1 kg of grain protein.

On the more aggregate level of diets, Smil (2000: p. 43) estimates that a vegetarian diet requires ca. 1 million litres of water per person per year and a meaty diet over 2 million. In that respect, an estimated 2 billion people live primarily on a meat-based diet, and an estimated 4 billion people live primarily on a plant-based diet. However, the former group is growing rapidly as a result of booming economies, such as those of China, India and Brazil, with obvious impacts on future freshwater availability worldwide (Croft, Hess, & Weatherhead, 2008; Liu, Yang, & Savenije, 2008; Liu & Savenije, 2008; Myers & Kent, 2003; Ye & Van Ranst, 2009).

## Biodiversity loss

Continued productivity of the land is a growing concern because of soil degradation. Livestock production contributes extensively to soil erosion and desertification, with 85 percent of topsoil loss in the USA directly attributable to livestock ranching (Millstone & Lang, 2003: p. 34). New land suitable for agriculture is scarce. Consequently, rainforests are cut down at an alarming rate with devastating impacts on biodiversity. These hotspots are cleared largely for soy and beef production (Verweij *et al.*, 2009). In addition, increased water use and pollution are not good news for either terrestrial or aquatic biodiversity, and the latter is already under pressure from fisheries (Pauly *et al.*, 2002).

In short, biodiversity may bear the brunt of the impact by increased use of land and water. Unfortunately, there are not just **direct** impacts of food and livestock production on biodiversity *via* land use and water use. In addition, there are also **indirect** impacts – which are considered to be on *at least the same order of magnitude* as the direct impacts – *via* polluting emissions, primarily ammonia (see the review papers by Erisman *et al.*, 2008; Townsend & Howarth, 2010). Pesticides, antibiotics and biological agents have additional impacts on biodiversity.

The most important may be "reactive nitrogen" emissions, such as ammonia. Invariably, a large proportion of fertiliser nitrogen is lost to the environment. In 2005, just 17% was consumed by humans in crop, dairy and meat products and the global nitrogen use efficiency of crops is decreasing consistently. Much of the environmental emissions of this reactive nitrogen is transported by air to be deposited in nitrogen-limited ecosystems. There it leads to unintentional fertilisation and loss of terrestrial biodiversity (Erisman *et al.*, 2008; Townsend & Howarth, 2010). Fertiliser runoff in coastal ecosystems may lead to algal blooms and dead zones, with inevitable repercussions on aquatic biodiversity (Erisman *et al.*, 2008; Townsend & Howarth, 2010). The same holds for pollution from livestock enterprises (Raney *et al.*, 2009: p. 59). A notorious example is the Gulf of Mexico dead zone, a 22,000 square kilometre (8500 square mile) coastal shelf receiving high-nutrient runoff from the US Corn Belt *via* the Mississippi River.

## Countering rising impacts of food and protein production

To make food production more sustainable, a stepwise improvement is required – known as a societal transition or industrial transformation (Green *et al.*, 1999; Weaver *et al.*, 2000). A promising solution for the tremendous impacts may be offered by partial replacement of meat proteins with plant protein products (Novel Protein Foods, NPFs) in the human diet (Smil, 2002c), although some economists argue that actual practice may be less straightforward (Seidl, 2000; White, 2000). The multidisciplinary (technological, environmental, social, economic, political, ecological, and chemical) PROFETAS programme (Protein Foods, Environment, Technology And Society) showed unequivocally that partly replacing animal proteins with NPFs might result in a 3–4 fold lower requirement of agricultural land and freshwater and, moreover, world wide there is a clear potential for a 30–40 fold reduction in water use, and the same beneficial factor holds for acidification (Aiking, De Boer, *et al.*, 2006).

In PROFETAS (2010), at least four barriers to such a transition towards decoupling protein production from concomitant environmental impacts have been identified: 1) social forces opposing change are strong, because meat has a high status, 2) economic forces opposing change are strong, because established interests in the meat chain are powerful, 3) technological know-how on novel (plant) protein foods is lacking, and 4) for centuries the meat chain has been optimised for exhaustive use of all by-products, potentially offsetting a large part of the theoretical environmental gain (Aiking, De Boer, *et al*., 2006). Relevant actors include consumers, retailers, food processors, farmers, NGOs and policymakers from government and industry, both nationally and internationally, including WTO and OECD, but the real environmental benefits of NPFs depend on their acceptance by the consumers (Aiking, De Boer, *et al*., 2006). It is clear that the consumer will be crucial to set a sustainable course (Naylor *et al*., 2005).

To estimate the order of magnitude of a potential diet change we'll make a rough calculation. Adding a conservative 15% to the Dutch recommended daily intake (RDI = 50 g) adds up to 57.5 g of protein that is nutritionally required as a generous minimum. If only one third of this protein were supplied by meat this would boil down to circa 57.5 g of meat per person per day, since on average meat consists of protein for about one third. Adding 25% that is wasted (Quist, 2000), daily per capita meat *supply* would be ca. 72 g and annual per capita meat *supply* would be 26.2 kg. Therefore, the 6 billion people around in the year 2000 would have required 157.4 million tons, when – in spite of severe local undernourishment – the actual supply was 229 million tons (=145%). So we may conclude that, without putting a healthy nutrition in jeopardy, the year 2000 *global average meat consumption* could easily be cut by *one third* (Aiking, De Boer, *et al*., 2006). The real question is, however, would consumers in developed countries be prepared to do so? De Boer, Boersema, and Aiking (2009) showed that certain groups of consumers do, indeed, have that inclination.

In developed countries only a minority of the consumers is prepared to avoid meat and if they do, health issues provide much stronger incentives than environmental issues (Beardsworth & Bryman, 2004). In developing countries the proportion of meat in the diet is rising rapidly (Bruinsma, 2002). Consumer taste, cultural aspects, crop familiarity, and incentives vary strongly, so these differences have to be taken into account. Price is an important incentive (Keyzer, Merbis, Pavel, & Van Wesenbeeck, 2005), but until consumers see meat prices reflecting the full societal and environmental costs of declining land, water and biodiversity resources, these may continue to be stressed by the growing industrial livestock sector (Galloway *et al*., 2007; Raney *et al*., 2009).

## Agriculture and the biorefinery principle

Biofuels are controversial (Wiebe *et al*., 2008; Fischer, 2009), but they may be useful by-products of NPF production. In fact, the first generation (sugarcane, maize, palm oil) competes with food, and the second generation (Jatropha etc.) is likely to waste environmentally precious nitrogen. In order to prevent atmospheric, aquatic and terrestrial pollution with active nitrogen compounds, nitrogen should always be removed before combustion. Furthermore, the energy put into nitrogen fertiliser production should be recovered. So a sustainable generation of biofuels can be derived exclusively by fractionating a crop in a food – feed – fibre – feedstock – fuel cascade, retaining the nitrogen in the edible (front) part of the chain.

Crop growth modelling may reveal optimal geographic locations for sustainable protein production (Aiking, Zhu, *et al*., 2006). In Europe, potential crops may include lupin, pea, quinoa, triticale, lucerne, grasses, rapeseed/canola and potato, and elsewhere soy should be added. Since just 20–40% of the seeds is protein, useful application of the non-protein fraction is indispensable to sustainability – and so to a protein transition – and should influence crop selection. At present, therefore, oilseed crops (such as soy or rapeseed) seem preferable over starchy crops (such as pea) with regard to biofuel production. In this respect, it is evident that combining sustainable production of protein and energy in one crop will simultaneously mitigate resource depletion, pollution, as well as climate change: a clear case of win-win-win (Aiking, De Boer, *et al*., 2006). In contrast, dedicated energy crops (such as oil palm, maize and sugarcane) may be considered a waste of valuable protein and energy-intensive nitrogen fertiliser, as well as a waste of precious land and water resources (Tilman *et al*., 2009).

## Food industry and consumers

It should be noted that modern "meat replacers" generally contain 20–30% egg protein. This is added to keep the plant proteins – which are globular – together when fried by consumers. Resulting from the inherent conversion loss from plant protein to egg protein, their environmental performance can be improved substantially. Like in-vitro meat, they provide stepping stones on the road to fully plant-derived NPFs, with inherently lower environmental impacts. So with R&D directed towards developing NPFs devoid of animal proteins, the food industry can provide a concrete contribution towards a sustainable future (Aiking, De Boer, *et al*., 2006). In fact, World Bank researchers recently suggested opportunities for carbon reduction by industrial initiatives for development of meat and dairy analogs (Goodland & Anhang, 2009). The challenge, evidently, will be to make their taste appealing to the general public in Western society and their price competitive.

All natural resources will have to be used more efficiently, so a second important issue on the road to sustainability is waste reduction, anywhere along the chain from primary production to consumption (Smil, 2003), explicitly excluding harvest residues, which should be kept to maintain soil quality and soil carbon stocks (Blanco-Canqui & Lal, 2007). Whether by new preservation techniques, packaging, optimising logistics, container size, or otherwise, this is another field where the food industry can play an important part by developing more sustainable solutions. Innovative new ideas about waste reduction may also include the application of insects such as grasshoppers (Vogel, 2010) to upgrade agricultural and urban waste streams to high-quality protein. The challenge here will be to bring down the cultural barriers of − and to educate − Western consumers. So, with respect to both approaches to make future protein more sustainable − NPFs development and waste reduction − the food industry should be receptive to consumer demands, on the one hand, and they should take part in consumer education, on the other hand. Their position in the food supply chain is ideally suited for it.

## Food prices, food security and food policy trends

Food has become more affordable, as it is now less than half as expensive in real terms as it was in 1960. To a large extent this is a result of increases in yield per hectare. Even per capita, the world now produces 40% more food than forty years ago. However, in the next forty years another 70% more is required. In addition, climate change and accompanying degradation of land and water resources are to intensify in future. In contrast to ever-optimistic projections of OECD-FAO (2009), world market price projections of the International Food Policy Research Institute (IFPRI) show that world grain prices will increase 30−50% before 2050, and that meat prices will increase an additional 20−30% beyond current high levels (Msangi & Rosegrant, 2009).

The UK government, for example, is acting on such global projections by implementing and evaluating a national food strategy (DEFRA, 2009a), assessing national food security (DEFRA, 2009b) and declaring a war on food waste. As it turns out, as much as a third of the food bought by UK consumers is discarded, some 6.7 million tonnes annually, over 60% of which could have been eaten if it had been managed better (Ventour, 2008). In The Netherlands, household losses used to be 25% (Quist, 2000) and may also be 30% by now. Sweden, the UK and the Netherlands are studying on policies to decrease meat and dairy consumption for health and environmental reasons (DEFRA, 2009b; LNV, 2009; LV, 2009). Options include promotion of NPFs development, consumer education, and taxation (Vinnari, 2008). Stakeholder dialogue is a must according to the Royal Society (Baulcombe *et al*., 2009), and a framework to help consumers, producers and policymakers out of deadlock and into negotiation is available (MacMillan & Durrant, 2009).

So we seem on the brink of a transition, but food habits change slowly (De Boer *et al*., 2006). Therefore, Western politicians should prod consumers a little harder, because if they don't, a transition towards less animal protein may be brought about by rising prices, which will hurt the poor and increase world hunger. Therefore, authors increasingly feel that the FAO projections are overly optimistic and that by 2050 the world population should be closer to 8 billion, rather than 9 billion (Brown, 2009; Sachs, 2009).

## Conclusions

Globally, demand of meat, dairy and fish products is still on the rise and so are the environmental impacts of their production. Inevitably, the prices of meat, fish, soy and cereals will rise also, primarily hurting the poor. Whether for environmental reasons, exploding prices, or − more likely − a combination, a trend reversal towards diets containing less animal protein and more plant protein in Western countries seems not just strongly recommendable, but inevitable. The positive impacts on sustainability will largely depend on the extent of a diet shift. In actual reality, a new equilibrium between plant products and animal products is likely to be critically dependent on economic variables such as income and relative and absolute prices of the commodities under scrutiny, i.e. meat, fish, milk, eggs, cereals and soy.

Since biofuel crops are unlikely to exceed 2.5% of the worldwide agricultural area by 2030 (Wiebe *et al*., 2008: p. 45), blaming biofuels for rising food prices is inappropriate yet, but it may change in the near future (Alexandratos, 2009) unless policies change (Tilman *et al*., 2009). Currently, food prices are primarily determined by food demand, which is determined in turn by world population, income and consumer preferences. With respect to the latter, it was shown earlier (Aiking, De Boer, *et al*., 2006) that if consumers in developed countries were to reduce their overall protein intake by about one third, and replace their intensively produced meat by either plant-derived protein products or extensively produced meat, the majority (87−94%) of prime agricultural land currently used for feed crops (400 million hectares world wide, approximately equal to the surface area of EU-27) might be set free, and become available for biodiversity and/or biomass, with additional benefits to animal welfare and human health, including reduced emerging diseases such as MRSA and avian influenza. Moreover, this diet transition would result in a tremendous reduction of the pressure on land and freshwater resources, as well as aquatic and terrestrial biodiversity.

Before 1950, animal protein was a luxury that globally few people could afford to eat on a daily basis. Large-scale nitrogen fertiliser application subsequently removed the nitrogen-limited capping of the world population at 3 billion people, which is projected to increase to 9 billion in less than one hundred years. The price we may have to pay is that animal protein will become a luxury once more. We must economize our use of natural resources, including land and biodiversity, and conserve water and energy in every possible way. Sustainability driven innovation should focus on protein, deriving and combining insights from the food, biodiversity, water, climate change, biofuels and health research communities. Replacing animal protein with novel plant protein products and reducing food waste will be crucial. Thus, food industry challenges include development of more sustainable novel plant protein products (NPFs) and continual innovations in food preservation and waste reduction. But speed is urged, in order to be able to feed 2.3 billion more mouths within just four decades.

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