Crop production and resource use to meet the growing demand for food, feed and fuel: opportunities and constraints

J.H.J. Spiertz[1,*] **and F. Ewert**[2]

[1] Centre for Crop Systems Analysis, Wageningen University, P.O. Box 430, NL-6700 AK Wageningen, The Netherlands

[2] Institute of Crop Science and Resource Conservation, University of Bonn, Bonn, Germany

* Corresponding author (tel.: +31-317-485315; e-mail: huub.spiertz@wur.nl)

Received 23 September 2008; accepted 23 March 2009

Abstract

Global food and feed demands have been projected to double in the 21st century, which will further increase the pressure on the use of land, water and nutrients. At the same time, the political decisions to support renewable energy sources are accelerating the use of biomass, including grain, sugar, oilseed, and lignocellulosic crops for biofuel and power generation. Government directives – incited by climate change, high oil prices and geo-political tensions – promote partial replacement of fossil fuel by biofuels. Prices and availability of commodities used as staple food and feed are becoming already affected by the growing demand for bioenergy. Many implications of this demand for biofuel on the resource base (land, water, biodiversity), environment, rural economy, food prices and social impacts are unknown. The present study reviews and discusses the opportunities and limits of crops and resources for food, feed and biofuel production. There are gaps in our knowledge regarding the global capacity for sustainable plant-based bioenergy production, while maintaining food security; commercial biomass production will compete with food crops for arable land and scarce fresh water resources. The rapidly growing demand for food, feed and fuel will require a combination of further increases in crop yields (ca. 2% per annum) and a doubling or tripling of resource-use efficiencies, especially of nitrogen-use efficiency and water productivity in production systems with high external inputs, over the next 20 to 30 years. Adaptation of cropping systems to climate change and a better tolerance to biotic and abiotic stresses by genetic improvement and by managing diverse cropping systems in a sustainable way will be of key importance. An integrated assessment of resource-use efficiencies, ecological services and economic profitability may guide the choice of crop species and cultivars to be grown in a target environment and region, depending on the added value for specific purposes: food, feed or fuel. To avoid negative impacts on food security, governments should give high priority to 2nd, 3rd and 4th generation technologies for bioenergy.

Additional keywords: biodiversity, bioenergy, biofuel crops, crop productivity, energy security, food security, land use

Introduction

The general trend in global food security was characterized by a change from shortages to surpluses in the second half of the last century, resulting in food affluence and lower prices in the developed world (Anon., 2007a). However, the trend in food availability dramatically reversed during the last 5 years because of:
- a rising demand due to a growing global population and a change in diet;
- a steep increase in the conversion of food crops into biofuel;
- a decline of cereal stocks due to climate-induced crop failures (e.g., drought).

In the OECD–FAO Agricultural Outlook 2008–2017 (Anon., 2008a) it is estimated that global food demand will increase by 50% and the area of cultivated land by 10% (excluding land needed for the production of biofuel) by 2030, assuming yield increases of 40% for major commodity crops. Crop failure due to adverse weather conditions combined with low global stocks triggered immediate price reactions (Von Braun *et al.*, 2008). The policies on boosting biofuel production aggravated the instability of world markets, because of spill-over effects. However, the price spike ('bubble') of the main food crops (maize, rice and wheat) in 2008 was strongly affected by speculation. Also, in the long term, food prices for poor people are at risk; in many low-income countries, food expenditures average over 50% of the household income and higher prices will push more people into undernourishment and poverty. Runge & Senauer (2007a) estimated that the number of hungry people will increase by about 16 million for each percentage increase in food prices. Food scarcity mainly exists for poor people (> 800 million) in regions with severe drought, diseases and political instability. In the Millennium Development Goals (Anon., 2007b) the target is set to halve the number of hungry people by 2015. The Johannesburg Summit on Sustainable Development in 2002 defined both energy and water as vital elements for sustainable development (Anon., 2007b; Varis, 2007). It is still not clear to what extent the growing global food, feed and fuel demand can be met by taking more land into production or by a further increase in crop productivity.

In the present study the following topics:
- trends in global food demand and supply;
- trends in diet change and feed demand;
- bioenergy demand and supply;
- biofuel production: what, how and where;
- resource use of land, water and biodiversity;
- regional diversity in resources for food and fuel production.

were reviewed to better understand the opportunities and constraints of utilizing crops and resources for food and biofuel production. Emphasis is put on a global perspective of opportunities and constraints to meet the growing demand for food, feed and bioenergy. Some future actions to improve crop productivity and resource use are identified.

Trends in global food demand and supply

Since the famous essay of Robert Malthus on the principle of population growth and diminishing returns on a limited supply of arable land more than 200 years ago, recent studies express concerns about whether a growing and wealthier world population can be fed in a sustainable manner (e.g., Chen, 2007). Crop yields stagnated from 1800 to 1950s, showing an annual increase of only 0.5–1.0% (Evans & Fischer, 1999). Since the mid-1960s, when dwarfism was introduced in wheat and rice and new genotypes became more responsive to external inputs (nitrogen, water, pesticides) yields were raised by 2–3% per year during two to three decades (Tilman *et al.*, 2002; Borlaug, 2007). The Malthusian prognosis has been undermined by an exponential increase in world food supply since 1960, mainly due to genetic improvement and agronomic intensification (nitrogen fertilizer, irrigation and weed control) in growing the major staple crops: maize, rice and wheat (Evans, 1997). This green revolution took place in irrigated wheat and rice cropping systems, especially in India and south-eastern Asia, but also for winter wheat grown in the temperate regions of Europe (Spiertz *et al.*, 1992). The development of innovative technologies resulted in both improved genetic traits and advanced crop management (e.g., *dosing* and *timing* of inputs). So agronomic development in Asia and north-western Europe over the past decades has shown remarkable successes in raising yields per unit of land.

Despite these trends in the first two decades of the Green Revolution, stagnation in wheat yield increase and even a decline of rice yields from 1985 onwards has been reported for the Indo-Gangetic Plains in India (Pathak *et al.*, 2003). Climatic factors, such as a decrease in radiation and an increase of night temperatures were identified as the reasons of the yield decline. However, Kalra *et al.* (2007) found that the levelling off of the yield increase of wheat in the productive Punjab and Haryana regions was associated with a weaker response of the crops to external inputs (e.g., water, nitrogen). They concluded that there is little scope for yield improvement with the present genotypes by agronomic measures and therefore, breaking the genetic yield barrier is needed. Tilman *et al.* (2002) stated that raising yields is essential for saving land for nature, but that the prospects for yield increases comparable with those over the past 40 years are unclear.

The gap between actual and potential yield declined considerably, which applies to crops such as rice (Cassman, 1999), winter wheat (Spiertz, 2004) and potato (Haverkort & Kooman, 1997), but not for sugar beet (Jaggard & Semenov, 2007). Thus, for some crops genetic yield improvement should get priority whereas for other crops yields can be raised by further improving crop management practices. Also, the yield gap differs considerably among world regions (Oerke & Dehne, 1997). The yield gap is relatively small (about 20%) for wheat grown in temperate regions in Europe (Oerke & Dehne, 1997). Accordingly, Ewert *et al.* (2005) projected that yield increases in the future have to be realized mainly through genetic yield improvement for these regions. In hot and dry environments, like the Mediterranean climate, crops suffer from multiple stresses. For such environments improvement of yield capacity and stability can be more effectively achieved by taking into account genotype–environment–management (G×E×M) interactions (Reynolds & Trethowan, 2007). Cassman *et al.* (2003) argue that a quantum leap in crop productivity and resource-use efficiency is still needed to meet the demands of a global population of about 8 billion in 2020.

System approaches are used increasingly in research on food production studies, natural resource management, land use options and rural development (Van Keulen, 2007). An assessment of the earth's biophysical potential for biomass production by

Koning *et al.* (2008), taking into account social-economic constraints and competing claims on natural resources for biobased non-foods, estimated potential global food production at 32–47 Gt of grain equivalents, which would provide an adequate supply for 16–24 billion people with an affluent diet. However, this estimate may be far too optimistic, because impacts of climate change on crop yields and environmental consequences (e.g., water use, N losses) associated with increasing food production at a global scale are not addressed properly. Eickhout *et al.* (2006) concluded that despite improvements in overall system-N recovery in developed countries, total global reactive losses will grow in the period explored until 2030, because of an increase in fertilizer consumption in developing countries to feed the growing population and concurrently a steep rise in dairy and meat consumption in emerging industrialized countries (e.g., China, India). Spiertz (2009) summarized the productivity levels of different rice ecosystems and evaluated sustainability parameters for contrasting food production systems. It was shown that yields varied from 2 to 12 t ha^{-1} with a N-fertilizer input ranging from 50 to 260 kg ha^{-1}. The variation in N-use efficiencies was large. Thus, estimates of potential global food production should be based not only on the yield potential and availability of resources but also on the potential to maximize resource-use efficiencies and to minimize associated losses.

Trends in diet change and feed demand

The transition from conventional livestock husbandry to livestock industrialization during the last 50 years was the consequence of a steep increase in meat consumption associated with rising incomes in most developed countries. At the beginning of the 19th century, annual global meat consumption amounted to about 10 kg per capita and most of the meat came from animals raised primarily in small-holder operations using local resources of land, water and nutrients (Steinfeld *et al.*, 2006). Globally, the big change in meat consumption took place during the last 25 years, resulting in per capita meat supplies of ca. 40 kg per year on average and to ca. 80 kg per year in developed countries. The current trend is likely to result in a doubling of meat demand in developing countries over the next three decades. The growth of the livestock sector is worrisome because of the burden it places on natural resources globally and on nitrogen emissions regionally, as has been shown clearly for Asia (Shindo *et al.*, 2006). Globally, N fertilizers applied to feed crops represent roughly 40% of the total amount of applied N. Most of the N in imported feed fed to cows, pigs and poultry will be excreted in the faeces and urine, and the N accumulated in manure is prone to losses when this manure is stored or applied to the field (Galloway *et al.*, 2003).

The growing production of non-ruminants (pigs and chicken) relative to ruminants (e.g., cattle, sheep) is shifting the demand for feed from grass- or rangeland to arable produce (e.g., cereals, soya beans, pulses). It increases the pressure on the use of arable land, water and nutrients. In 2002, the feed use by ruminants was estimated at about 200 Mt of human-edible produce and about 800 Mt of forage, crop residues and by-products (Galloway *et al.*, 2007). For non-ruminants, feed use amounted to about 600 Mt of arable produce and only about 75 Mt of by-products. Because of the higher energy conversion rates from feed to meat of non-ruminants (0.26–0.29) compared with ruminants (0.05–0.33), more cereal- and oilseed-based concentrates are used to produce pork and poultry. In Brazil, the rapid expansion in growing soya beans, currently more than 10 million ha, is due to the growing demand for feed to raise pigs and chicken. In the past, most of this feed was used to grow pigs and chicken in Europe; however, recently China emerged as a big importer. This increasing demand for livestock feed leads to expansion of the acreage to grow feed at the expense of savannah and even rainforest ecosystems (Fearnside, 2001; 2005). Currently, non-ruminants consume over 70% of all feed grown globally on arable land. Thus, if non-ruminant production continues to increase, competition for scarce land and associated resources between food and feed production will further intensify.

The environmental consequences of intensification of animal production through the use of more external inputs (feed and fertilizers) are well-documented for the Netherlands (Schröder *et al.*, 2003; Langeveld *et al.*, 2007) and Denmark (Kyllingsbaek & Hansen, 2007). Nitrogen and phosphorus surpluses from these systems are the main cause of environmental pollution. N losses have a major impact on the functioning of ecosystems and human well-being. Prototyping and modelling have been applied mainly at the farm level to quantify alternative farming systems that meet multiple goals: profitability, food safety, and environmental impact (Ten Berge *et al.*, 2000). However, the mitigation of the environmental impact of industrialized animal production should be based on quantitative studies at various scales: field, farm, regionally and globally (Galloway *et al.*, 2003; 2007). Wirsenius (2003) examined the current efficiencies of food and feed commodities. Estimated overall efficiencies of biomass use varied from 0.35% for beef cattle to 31% for starch tubers. He concluded that there is a considerable potential for efficiency improvements.

The transition from locally to globally based systems has resulted in highly profitable, industrialized food chains for dairy, eggs and meat production, characterized by the import of feed to produce concentrates and the export of dairy products and meat. Generally, the growing trade liberalization and improved transportation infrastructure and technology have resulted in an increasing trade of feed and meat on international markets. Galloway *et al.* (2007) calculated the *virtual* and *embedded* resources, such as nitrogen, water and land, associated with trade and production. *Virtual* resources are involved in the primary production, whereas the *embedded* resources are contained in the traded product. Countries that import large amounts of meat and dairy products, like Japan, enjoy eating high-protein food without the burden of N-emissions to soil, water and atmosphere associated with the animal production. For Japan, the N embedded in the imported product is less (about 30%) than the total virtual N left in the exporting countries (USA, Denmark, the Netherlands). By linking production and consumption at a global scale, the effects of trade on N pools and associated N losses can be assessed spatially and quantitatively more accurately.

Bioenergy: demand and supply

In 2001 the global use of energy amounted to 10.2 Gt oil-equivalents and an average use per capita of 1.67 t per year. The division of energy sources over oil, coal, gas, traditional biomass (e.g., wood), nuclear power, hydroelectric power, modern biomass (energy crops) and other renewable sources (e.g., wind, solar) amounted to: 35, 23, 22, 9, 7, > 2, > 1 and < 1%, respectively (Wilkinson *et al.*, 2007). Bioenergy has two general categories: conventional–rural (traditional) and commercial–industrial (modern) energy services. Conventional–rural bioenergy is still the most important source for household (e.g., cooking, heating) energy supply for the 2.5 billion people, mainly in Asia and Africa, living in rural (83%) or peri-urban (23%) environments (Sagar & Kartha, 2007). For decades bioenergy has contributed a more or less stable fraction (about 12%) of total primary energy consumption. Bioenergy consumption has been important in many countries, e.g., Brazil, China and Scandinavian countries, for a long time. Wright (2006) reviewed the energy consumption in 2002 for some large countries and regions. The contribution of biomass to the total energy consumption in large countries ranged from 2.8 (USA) to 27.2% (Brazil), and in Europe from 1.3 (the Netherlands) to 20.0% (Finland). So for centuries, bioenergy has been playing a vital role in the provision of energy services at the household level. However, at the beginning of the 21st century large scale commercial use of biofuel is the most rapidly growing renewable energy source in the developed countries, despite huge investments during the last decades in solar and wind energy.

Shifting society's dependence away from fossil energy to renewable biomass resources is generally viewed as an important contributor to providing sustainable energy supply for developing and developed countries and effective management of greenhouse gas (GHG) emissions (Ragauskas *et al.*, 2006). As a renewable energy source, biofuels are a potential low-carbon energy source. To what extent low-carbon biofuels can meet future demands depends also on the trade-offs with food production, GHG emissions and native habitat conversion. Sims *et al.* (2006) calculated that the contribution of energy crops in 2025 will range from 2 to 22 EJ per year. This estimate is much lower and probably more realistic than the 200–400 EJ per year by 2050 in previous IPCC studies (Anon., 2000). The GHG-advantages of crop-based biofuels are challenged by Fargione *et al.* (2008) and Searchinger *et al.* (2008); they conclude that these biofuels will create a 'biofuel carbon debt' instead of a net profit. However, carbon savings depend strongly on the type of feedstock, production process, yield levels, changes in land use, and conversion into a usable biofuel (Sims *et al.*, 2006).

A fuel is considered a biofuel if it is derived from recently produced biomass, such as wood, agricultural products or residues (Granda *et al.*, 2007). Ideally, a biofuel should be carbon neutral, and should therefore not contribute to the overall accumulation of carbon in the atmosphere. Carbon in crops is the result of the photosynthetic conversion of carbon dioxide in the atmosphere (capturing CO_2) into dry matter determined by solar radiation during the growing season and by natural resources (e.g., climate, water) and external inputs (e.g., fertilizers, pesticides). Bioenergy and food production are both strongly linked with water use. Thus, under water-limited conditions food as well as bioenergy production will be restricted. The external inputs are mostly manufactured by using fossil fuels as is also the case for transporting and processing the biofuels. The 'greenness' of a bioenergy crop is therefore highly dependent upon the resource-use efficiency of external inputs (Hill, 2007). So the trade-off's between the use of land and water resources for food as well as for bioenergy should be taken into account (Müller *et al.*, 2008).

Presently, bioenergy production is expanding, especially in Brazil, the USA and South-East Asia, where sugar cane, maize and palm oil are converted into ethanol or biodiesel (Anon., 2008b). Also the European Union (Anon., 2003) set directives to increase the use of biofuels (Kondili & Kaldelis, 2007). There are three key arguments for the commercial use of bioenergy:

- economic-driven rise in consumption, resulting in higher prices for fossil fuels;
- energy security and geo-political dependence of regions with a high volatility;
- anthropogenic-based CO_2 emissions and climate change.

The rapid expansion of growing biofuel crops will have a big impact on land use and therefore also on food and feed production.

Biofuel production: what, how and where?

Since the mid-1970s many research initiatives have focused on increasing the biomass resource base for production of bioenergy. Perennials, including short rotation woody crops (e.g., oil palm, sugar cane, *Miscanthus*, willow, switch grass) as well as annual crops (maize, sugar beet, rapeseed) were considered (Table 1). Energy crops have been most successful in penetrating the energy market where governments have applied subsidies or tax incentives. With the high rate of economic development of China and India the demand for fossil energy will continue to increase, while at the same time the exploration of new oil and coal fields will face more constraints (costs, geo-political tensions, environmental regulation). As a result, the demand for biofuels will grow in correspondence with the costs of fossil energy supply and policies to reduce CO_2 emissions.

Several technologies used for the conversion of plant material into biofuel are available and depend on the type of feedstock. The conventional and new technologies can be classified into the following four groups:

1. *First generation technology*, based on the conversion of sugars (sugar cane) and starch (potato, cassava, maize) or oil (oil palm, rapeseed) accumulated in food crops into ethanol and biodiesel, respectively (Cassman & Liska, 2007). Generally, the corresponding cropping systems have been developed to produce high crop yields to deliver specific commodities (sucrose, starch, oil, protein). Seeds of oil crops do have higher energy contents than those of sugar crops (Penning De Vries *et al.*, 1974). Crops with a high oil yield per unit area are oil palm and coconut, whereas the yields of rapeseed and sunflower are much lower (Table 2). Yield potential of food crops has been genetically improved mainly by raising the harvest index, whereas yield stability gained from a better tolerance to abiotic and biotic stresses (Bänziger *et al.*, 2006; Witcombe *et al.*, 2008). Some have called for an integrated systems biology approach to define ideotypes that meet the requirements of feedstocks for biofuel (Gressel, 2008). However, the scientific evidence that crop traits can be genetically modified to meet the requirements for fuel without any trade-off on the value as a food crop is absent. Alternatively, different varieties may be developed for food and fuel production.
2. *Second generation technology*, based on the use of dedicated energy crops, like

Table 1. Average aboveground / root dry mass and energy yields for different groups of potential biofuel crops

Crop	Scientific name	Biomass [1] (Mg ha^{-1})	Energy [2] (GJ ha^{-1})	References for further reading
Carbohydrate crops				
Sugar cane	*Saccharum* spp. L.	30–35	120	Inman-Bamber (2004)
Sugar beet (roots)	*Beta vulgaris* L.	20–25	110	Jaggard & Semenov (2007)
Cassava (roots)	*Manihot ecsulenta* L.	10–15	80	El-Sharkawy (2006)
Cereals				
Maize	*Zea mays* L.	15–25	70	Duvick & Cassman (1999)
Sorghum	*Sorghum bicolor* L.	12–16	–	Young *et al.* (2008)
Wheat	*Triticum aestivum* L.	10–15	50	Jorgensen *et al.* (2007)
Oil and protein crops				
Oil palm (fruits)	*Elaeis guineensis* L.	ca. 20	190	Gerritsma & Wessel (1997) and Kelly-Yong *et al.* (2007)
Jatropha (seed)	*Jatropha curcas* L.	1–5	–	Achten *et al.* (2008) and Kumar & Sharma (2008)
Grain crops				
Rapeseed (seed)	*Brassica oleracea* L.	ca. 3	30	Habekotté (1997)
Soya bean (seed)	*Glycine max* L.	ca. 2.5	25	Salvagiotti (2008)
Lignocellulosic crops				
Miscanthus	*Miscanthus* sp. L.	15–20	200	Lewandowski *et al.* (2007)
Switchgrass	*Panicum virgatum* L.	5–11	60	Schmer *et al.* (2008)
Poplar	*Populus* sp. L.	10–15	125	Karp & Shield (2008)
Willow	*Salix* sp. L.	10–15	125	Karp & Shield (2008)

[1] Sources for biomass yield: estimates derived from various sources.

[2] Sources for energy yield: Sims *et al.* (2006) and Müller *et al.* (2008).

Table 2. Estimated bioethanol / biodiesel and energy yield of crop-based 1st generation biofuel crops grown under optimal conditions.

Commodity / crop		Feasible yield (litres ha^{-1})	Energy content (GJ ha^{-1})	Commodity / crop	Feasible yield (litres ha^{-1})	Energy content (GJ ha^{-1})
Bioethanol [1]				*Biodiesel* [2]		
Sugar cane	(Brazil)	6000	120	Oil palm	7100	250
Cassava	(Nigeria)	4000	80	Coconut	3200	105
Switchgrass	(USA)	3500	75	Jatropha	2300	80
Maize	(USA)	3500	70	Rapeseed	1400	50
Wheat	(France)	3000	60	Sunflower	1100	40

[1] Source: Anon. (2006).

[2] Source: Bayer Crop Science AG (<www.bayercropscience.com>).

switchgrass (*Panicum virgatum*), grown with low external inputs and using conversion methods that result in a high net energy efficiency (output/input). Special emphasis is given to lignocellulosic material as a substrate for producing biofuels (Somerville, 2006). Conversion of cellulosic biomass, which is both abundant and renewable, is considered a promising alternative for ethanol produced from starch or sugar. The ideal characteristics ('ideotype') of non-food cellulosic crops are: a C_4 photosynthetic pathway resulting in a high photosynthetic efficiency, long canopy duration with a high interception efficiency of photosynthetically active radiation, perennial growth, strong vigour to out-compete weeds, a high water productivity and relocation of nutrients to non-harvestable plant parts (roots and storage organs) at the end of the growing season. It was found that *Miscanthus × giganteus* shows most of these characteristics (Beale & Long, 1995; Heaton *et al.*, 2004; Christian *et al.*, 2008). Annual biomass yields of *Miscanthus* grown in the Netherlands were associated with cumulative light interception (up to 1000 MJ m^{-2}) higher than those for maize (Van Der Werf *et al.*, 1993); however, light-use efficiencies were similar and amounted to 2.6 g dry weight per MJ (PAR). Besides improving the agronomy, plant traits that hamper the conversion efficiency of cellulosic biomass should be modified. Plant genetic engineering may be able to modify the lignin composition, which may facilitate the production of cellulosic ethanol production without costly pre-treatment processes (Sticklen, 2008).

Plant triacylglycerols are another potential feedstock to produce biofuels, especially biodiesel. Most vegetable oils are derived from triacylglycerols stored in seeds. *Jatropha curcas* is a drought resistant, toxic, perennial oil plant (ca. 40% oil content) with favourable traits for multipurpose uses (medicinal, pesticide), but especially as an energy source to produce biodiesel in unfavourable regions of India, Sub-Sahelian Africa and Latin America (Kumar & Sharma, 2008). Novel energy crops may be developed that produce triacylglycerols in non-seed tissues (Durrett *et al.*, 2008). To avoid competition with food crops there is a growing interest in woody oil plants. Native energy oil plants are more frequently present in tropical and subtropical regions (Shao & Chu, 2008).

3. *Third generation technology*, based on algae or cyanobacteria that contain a high oil mass fraction (up to 70%) and are grown in ponds. Micro-organisms can convert almost all of the energy in biomass residuals and wastes to methane and hydrogen. Certain algae and cyanobacteria have high lipid contents. Under proper conditions, these micro-organisms can produce lipids for biodiesel with yields per unit area that are 50–100% higher than those with any plant system (Chisti, 2008; Rittmann, 2008). However, it is still not proven that this high efficiency can be maintained after scaling-up the technology to a large production plant. Furthermore, the feedstock is waste derived from plant material used for food and feed. Yet, we do not know what the trade-off is between maximizing the utilization of primary production for food and feed and the use of residues and waste to produce methane or hydrogen. Chemical composition of the residues and waste will matter.

4. *Fourth generation technology*, based on biohydrogen production by embedding parts of the photosynthesis apparatus in artificial membranes (Kruse *et al.*, 2005). The mean conversion efficiency for the total solar spectrum amounts to ca. 20%, which is on average about 10 times higher than for annual crops. This high efficiency should be considered a potential level. The gap between the potential level and actual efficiency is

still not known. Currently, this technology is still expensive and not yet ready for commercial exploitation.

Biofuel feedstocks are still among the most productive crops grown for food and feed. However, competition for cultivated arable land and the risks of threatening food security argue for development of alternatives that use less fertile land and are more efficient in capturing solar energy and in energy conversion. The speed of the transition from first generation technology to second, third and fourth generation technologies will depend on market opportunities on the one hand and on public and private spending in advanced research and emerging technologies on the other.

New bioenergy crops are needed that fit into cropping systems on farmers' fields and minimize the use of external inputs (water and nutrients). Porter *et al.* (2007) concluded that the ideotype of a bioenergy crop will be quite different from that of food crops: a phenology that permits a long growing season (annual or perennial), a low partitioning to reproductive organs, a high level of low-molecular weight unpolymerized carbohydrates and a high water and nutrient efficiency. Generally, perennial C_4-plants (e.g., sugar cane) grown under tropical conditions will meet these standards; however, on-going research shows promise to develop new *ideotypes* for temperate conditions. It has been claimed that transgenics are imperative for biofuel crops (Gressel, 2008; Sticklen, 2008); however, a multi-faceted approach at different scales (gene, cell, plant, crop, ecosystem) should provide the knowledge to develop dedicated cropping systems for biofuels that meet economic as well as ecological sustainability objectives. Next to genetic traits also management becomes important to combine high biomass yields with sustainability goals (Miguez *et al.*, 2008).

Resource use of land, water and biodiversity

The main resources for plant and crop growth are fertile land, fresh water (rainfall and/or irrigation), solar radiation and a favourable climate (temperature range: 5–35 °C) during the growing season. Globally, annual net primary productivity (NPP) on land amounts to about 57 Gt of carbon (Field *et al.*, 2008); the annual fossil fuel use amounts to about 7 Gt of carbon. Only a fraction (ca. 25 %) of the global NPP on land can be harvested from cropland or pasture. Increased production of biomass for energy has the potential to slow down the use of fossil fuels, but it may also threaten food security, water resources and biodiversity. Field *et al.* (2008) concluded that the area with the greatest potential for producing bioenergy crops is abandoned agriculture land. Based on conventional data for crop productivity they estimated that these abandoned lands represent a potential for biomass production equal to 5% of the global primary energy consumption (483 EJ) in 2050. This is a conservative estimate, because net primary productivity is based on global NPP of 3.2 t C ha^{-1} per year. It was shown earlier that crops like *Miscanthus* can yield considerably more. Based on calculations with the Quickscan model, Smeets *et al.* (2007) estimated that the bioenergy potential on surplus agricultural land may equal 215 to 1272 EJ per year. In this analysis it is assumed that the advancement of agricultural technology will reduce the area needed for food and feed production by almost 30% on average. It can be questioned if this assumption will be realized with increasing scarcity of water in the major growing regions (Bouman *et al.*, 2007).

The acreage of land needed for producing sufficient food and feed and feedstocks for industrial use (e.g., cotton) and biofuel depends on the productivity per unit of resource (Monteith, 1977; Passioura, 1977; Hunt *et al.*, 1990). The incoming solar radiation depends on latitude and daylength (Monteith, 1972), whereas the cumulative light capture is determined by temperature-dependent canopy development under non-water and non-nitrogen limiting conditions. The ecoregional conditions (e.g., daylength, temperature) for capturing incoming solar radiation differ considerably around the globe. Perennial, double or triple cropping systems under (sub-)tropical conditions have the potential to capture more light than crops grown in a short season due to cold (northern and southern hemisphere) or water shortage (e.g., Mediterranean climate). Caviglia *et al.* (2004) reported higher water productivity (g mm^{-1}) on an annual basis for biomass yield of an intercropping system (1.85–2.20) compared with sole crops of wheat (1.15–1.57) or soya bean (0.83–1.16). The radiation-use efficiency (g MJ^{-1}) showed similar responses: higher for intercropping (0.79–1.04) and lower for wheat (0.57–0.65) and soya bean (0.30–0.65). The values for the sole crops are higher if the productivities are calculated on a seasonal instead of an annual basis.

Plant traits important for yield and quality improvement in bioenergy crops are (Karp & Shield, 2008):

1. Traits for yield improvement:
   - maximizing radiation interception (e.g., early vigour, frost resistance, canopy closure, leaf traits for efficient light capture);
   - maximizing radiation-use efficiency (e.g., low-temperature tolerant C_4 metabolism, high nutrient-use efficiency, disease and pest resistance);
   - maximizing water-use efficiency (e.g., drought avoidance, drought tolerance, rooting depth);
   - optimizing environmental sustainability (e.g., efficient nutrient recycling, root/shoot partitioning).
2. Traits for quality improvement:
   - ease of harvesting and storage (e.g., resistance to lodging, low moisture content);
   - suitability for thermal conversion technologies (e.g., energy density, optimal flowering and senescence);
   - suitability for biological conversion technologies (e.g., accessibility of carbon in the cell wall, high fraction of energy substrates);
   - health and safety (low dust, postharvest disease resistance).

Different agroecological conditions require case-specific assessments of traits that determine the end-user value and meet sustainability goals. Life-cycle analysis (LCA) has shown to be promising in this respect (Schmidt, 2008; Smaling *et al.*, 2008).

Resource capture and resource-use efficiency determine the potential biomass production per unit of land area (Table 1). However, the actual yield refers to the plant part that can be used for food, feed or biofuel. In food crops this fraction is usually expressed as harvest index (HI) and for cereals calculated as: dry weight grain / dry weight aboveground biomass. Depending on growing conditions the HI of cereals will range from 0.35 to 0.55. In feed production systems like silage maize, part (corn/cob) or the bulk of the aboveground biomass will be harvested. In this case the HI will range from 0.70 to 0.90. In biofuel cropping systems the whole above-ground biomass is used or only crop residues, like stover and straw; consequently the HI will vary between 0.90 and 0.35. To prevent adverse affects on soil fertility the soil organic carbon (SOC) content should be maintained. The required amount of organic material that stays behind (roots and stubble) depends on the soil mineralization rates, which usually are higher in light sandy soils than in heavy clay soils. Blanco-Canqui & Lal (2007) found that only a small fraction (< 25%) of the total maize stover can be removed from sloping and erosion-prone soils. Lal (2008) concluded that increasing the SOC pool by 1 Mg ha^{-1} per year through residue retention can increase the annual world food grain production by 24 to 40 Mt and root and tuber production by 6 to 11 Mt.

The intensification of cropping systems during the last 50 years in response to new technologies (mechanization), the need to increase labour productivity, the introduction of high-yielding cultivars, the supply of fertilizer-N at low cost, the introduction of chemical crop protection, scarcity of land, and market pressure led to an unexpected increase in crop productivity per unit of land (Swaminathan, 2007). Currently, the most common strategy for food, feed and biofuel production is based on high-input low-diversity agricultural systems. Ecologists tend to characterize such systems by large-scale monocultures subject to large inputs of fertilizer, irrigation water, and pesticides (Wallace & Palmer, 2007), causing a loss of global biodiversity (Firbank *et al.*, 2008). However, in reality there is huge variation in cropping systems, determined by agro-ecological growing conditions (e.g., rainfed or irrigated, temperate or tropical, lowland or highland), soil traits (biological, chemical and physical), cropping systems (monoculture, intercropping, plant–animal systems). Groom *et al.* (2008) stress the importance of developing general principles, like 'best farming practices', saving land and a zero carbon balance, in developing guidelines for certifying biodiversity-friendly agricultural practices.

Regional diversity in resources for food and fuel production

What are the needs and demands of societies at a global scale? To analyse demands and resources we should differentiate between continents and regions. It is also important to take the convergence of the fuel, food and fibre markets into account (Roberts, 2008). It is predicted that tropical countries will be the 'winners' in the growing demand for bioenergy feed stocks, because of higher crop yields and lower land and labour costs. Some examples:

1. *Latin America* still has vast land resources. However, the inequity in land rights and weak governance cause exploitation of fragile land. With adequate knowledge and new technology a large potential exists for food and feed production as well as for sugar cane-based ethanol production. Brazil is the world leader in producing bioethanol (18 billion litres in 2006) based on sugar cane (7 million ha; about 2% of Brazil's arable land). It is a renewable resource that increasingly replaces fossil fuels (Nass *et al.*, 2007).
2. *The United States of America* is a technology and profit driven society, where multinationals and retailers play a dominant role in the food chain and trading of agricultural

commodities (e.g., Cargill). It is still the major exporting country of crop commodities, such as maize, wheat and soya bean. However, during the last 5 years the booming ethanol production from maize (7.6 to 22.7 billion litres) caused an imbalance between demand and supply of maize. As a consequence, maize prices rose abruptly (Cassman & Liska, 2007). The target is to increase biofuel production to > 75.7 billion litres in 2020. To meet the growing demand for maize the current trend in yield increase of about 110 kg ha^{-1} per year must be doubled if the present area for agricultural land use remains. Large seed companies (Monsanto) are optimistic that they can develop drought-tolerant maize cultivars that will accelerate the current rate of yield improvement. However, the requirement for non-food crops to replace maize as a feedstock for biofuel is growing. Most promising are lignocellulosic crops, such as switchgrass and *Miscanthus* (Christian *et al.*, 2008).

3. *Europe* is a continent with large resources of fertile land (Ewert *et al.*, 2005), but with declining population growth and therefore a stagnating demand for food. Europe does have ample resources (land, climate, infrastructure, processing industry) and a vast knowledge base to continue to play an important role in supporting a growing world population with food, feed and biofuel (Rounsevell *et al.*, 2005). The question is to what degree the policy shift from agricultural production to ecological and human services will affect the European role on the world food and bioenergy market. Recent assessments for the 15 original EU member states (EU15) have shown that with a further increase in productivity due to technology development (Ewert *et al.*, 2005) large areas of agricultural land can become available for biofuel production (Rounsevell *et al.*, 2005). The long-term (2080) land use change potential for biofuels was estimated at 3 to 8% of the total land area, depending on the set of scenario assumptions about climate change and socio-economic development (Rounsevell *et al.*, 2006). Van Dam *et al.* (2007) calculated that in Central and Eastern Europe 44 million ha of agricultural land can become available for the production of biofuel if high-technology cropping systems securing high crop productivity would be introduced. In Russia and the former Soviet states land resources are vast. Furthermore, labour and energy costs are low. This region can become very competitive in producing commodities like maize and other cereals, if crop management practices are improved and transportation of grain is facilitated by a better infrastructure. It is expected that the growth in commercial biomass production in the former USSR states will be higher than in Western Europe (Varis, 2007).

4. In *China*, sustained economic growth for the past 20 years increased prosperity. This economic boom has already changed the demand for food towards protein-rich diets (Chen, 2007). The consumption of rice decreased, while that of dairy, fish and (white meat) products increased. As a consequence, less of the crop produce is directly used for human consumption and more cereal-based products are needed for feeding the growing animal industry (Tong *et al.*, 2003). This change in diet will require more land to feed the population, because productivity per unit land area is already quite high. In China, 20% of the world population is fed from only 7% of the global agricultural land and 30% of the arable land is used for double or triple cropping. The limits of sustainable crop production are almost reached; in regions with intensive cropping systems there is already an overuse of fertilizers and in some regions a fast depletion of the fresh water in aquifers and rivers. However, this intensively cultivated land is only 13% of the

total land area (960 million ha); about 25% is used as forest and 27% as pasture. More of the so-called 'unused land' in China will be brought into cultivation for the production of food, feed as well as biofuel (Shao & Chu, 2008). The target for renewable energy sources is set to account for 10% by 2010 and 16% by 2020. Cellulosic-ethanol production is being encouraged. The impact of this policy on the biodiversity in semi-natural ecosystems and on water quality is still uncertain and needs to be closely monitored.

5. *South-East Asia* produces almost 90% of the world's palm oil, accounting for 12% of world's production of biological oils and fats. In South-East Asia, especially Malaysia and Indonesia (6.5 million ha in Sumatra and Kalimantan), the palm oil – biodiesel industry is becoming an important sector, creating employment opportunities and economic benefits. However, the transition of native forest into palm oil plantations creates major side-effects on the environment; especially oxidation of drained peat land (in Indonesia 25% of the oil palm plantations) has been adding to GHG emissions. Improved management to close the yield gap in palm oil production would save precious land. Murphy (2007) reported annual yields of 3.7 t ha^{-1} useful oil from plantations in Malaysia. This yield can almost be doubled by improving crop management and harvest practices. Oil yields could be increased even further, to as much as 8–10 t ha^{-1} per year by using high-yielding germplasm.

The regional diversity in resource use for food and fuel production should always be evaluated in a global perspective. Further development of biofuels will take place in global integrated networks that require certification and labelling systems to guarantee quality and sustainability standards (Mol, 2007). The balance between food and energy security will differ between developed and developing countries. In his global biofuel projections Demirbas (2008) estimated that by 2050 one half of the total energy demand in developing countries will be based on modernized biomass energy. However, a comprehensive assessment of competing claims for food and fuel and the environmental impacts (Koh & Ghazoul, 2008) should guide the further development of potential sources of biomass-based alternative energy. More generally, loss of biodiversity is a major concern (Foley *et al.*, 2005).

Conclusions

Food and water are fundamental to life. The planet's ecological infrastructure experiences increasing pressure, because of the consumption patterns of a growing affluent society, the depletion of natural resources and the projected climate change. A new mindset is needed on how to integrate the different functions of production with other ecosystem services. The rapidly growing demand for food, feed and fuel will require a combination of further improvements of crop yields (> 2% per annum) and a doubling or tripling of resource-use efficiencies (e.g., nitrogen-use efficiency and water productivity) over the next 20 to 30 years. Policies that impose considerable savings on fossil energy use at large, may also contribute to reduce excess external inputs in cropping systems.

Taking into account that oil prices will stay at a higher level than in the past, ethanol and biodiesel production from various plant-based feedstocks will be profitable. To avoid negative impacts on food security, governments should give high priority to 2nd, 3rd and 4th generation technologies. Cellulosic feedstocks are much more abundant than food crops, but the processing costs are still much higher. Research on enzymatic digestion and converting cellulose into gas indicates that the costs of processing can decline considerably, especially if economies of scale can be improved.

Adaptation to climate change and a better tolerance to biotic and abiotic stresses by genetic improvement will be of key importance. Furthermore, knowledge-based tools should be developed to manage diverse cropping systems in a sustainable way and to exploit the genetic potential of crop species and cultivars, depending on eco-regional conditions. A comprehensive assessment of productivity, resource-use efficiencies and economic profitability may guide the choice of crop species and cultivars to be grown in a target environment and region, depending on the added value for specific purposes: food, feed or fuel.

References

Achten, W.M.J., L. Verchot, Y.J. Franken, E. Mathijs, V.P. Singh, R. Aerts & B. Muys, 2008. *Jatropha* bio-diesel production and use. *Biomass & Bioenergy* 12: 1063–1084.

Anonymous, 2000. Special Report on Emission Scenarios. Intergovernmental Panel on Climate Change (IPCC). <www.ipcc.ch/pdf/special-reports.spm/sres-en.pdf>.

Anonymous, 2003. CAP reform – a Long-term Perspective for Sustainable Agriculture. European Union. Impact Analysis, 27 pp. <http://ec.europa.eu/agriculture/capreform/index_en.htm>.

Anonymous, 2006. The Economic Feasibility of Ethanol Production from Sugar in the United States. <www.usda.gov.oce/reports/energy/EthanolSugarFeasibilityReport3.pdf>

Anonymous, 2007a. Crop Prospects and Food Situation: Global Cereal Supply and Demand. Report No 5. Food and Agriculture Organization of the United Nations (FAO), Rome. <www.fao.org/docrep/010/j9940e/>.

Anonymous, 2007b. Millennium Development Goals Report 2007. <www.un.org/millenniumgoals/pdf/mdg2007>.

Anonymous, 2008a. OECD–FAO Agricultural Outlook 2008–2017. ISBN 978-92-64-045910. <www.oecd.org>.

Anonymous, 2008b. Bio-fuels Research in the CGIAR: A Perspective from the Science Council. Position paper. Food and Agriculture Organization of the United Nations (FAO), Rome, 27 pp.

Banziger, M., P.S. Setimela, D. Hodson & B. Vivek, 2006. Breeding for improved abiotic stress tolerance in maize adapted to southern Africa. *Agricultural Water Management* 80: 212–224.

Beale, C.V. & S.P. Long, 1995. Can perennial C_4 grasses attain high efficiencies in radiant energy conversion in cool climates? *Plant, Cell and Environment* 18: 641–650.

Blanco-Canqui H. & R. Lal, 2007. Soil and crop response to harvesting crop residues for biofuel production. *Geoderma* 141: 355–362.

Bouman, B.A.M., E. Humphries, T.P. Tuong & R. Barker, 2007. Rice and water. *Advances in Agronomy* 92: 187–237.

Borlaug, N.E., 2007. Sixty-two years of fighting hunger: personal recollections. *Euphytica* 157: 287–297.

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

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

Biorefining 1: 18–23.

Cassman, K.G., A. Dobermann, D.T. Walters & Haishun Yang, 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environmental Resources* 28: 10.1–10.44.

Caviglia, O.P., V.O. Sadras & F.H. Andrade, 2004. Intensification of agriculture in the southeastern Pampas. I. Capture and efficiency in the use of water and radiation in double-cropped wheat–soybean. *Field Crops Research* 87: 117–129.

Chen, J., 2007. Rapid urbanization in China: a real challenge to soil protection and food security. *Catena* 69: 1–15.

Chisti, Y., 2008. Biodiesel from microalgae beats bioethanol. *Trends in Biotechnology* 26: 126–131.

Christian, D.G., A.B. Riche & N.E. Yates, 2008. Growth, yield and mineral content of *Miscanthus × giganteus* grown as a biofuel for 14 successive harvests. *Industrial Crops and Products* 28: 320–327.

Demirbas, A., 2008. Biofuel sources, biofuel policy, biofuel economy and global biofuel projections. *Energy Conversion and Management* 49: 2106–2116.

Durrett, T.P., C. Benning & J. Ohlrogge, 2008. Plant triaglycerols as feedstocks for the production of biofuels. *The Plant Journal* 54: 593–607.

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.

Eickhout, B., A.F. Bouwman & H. Van Zeijts, 2006. The role of nitrogen in world food production and environmental sustainability. *Agriculture, Ecosystems and Environment* 116: 4–14.

El-Sharkawy, M.A., 2006. International research on cassava photosynthesis, productivity, eco-physiology, and response to environmental stresses in the tropics. *Photosynthetica* 44: 481–512.

Evans, L.T., 1997. Adapting and improving crops: the endless task. *Philosophical Transactions of the Royal Society, London* B 352: 901–906.

Evans, L.T. & R.A. Fischer, 1999. Yield potential: its definition, measurement and significance. *Crop Science* 39: 1544–1551.

Ewert, F., M.D.A. Rounsevell, I. Reginster, M.J. Metzger & R. Leemans, 2005. Future scenarios of European agricultural land use. I. Estimating changes in crop productivity. *Agriculture, Ecosystems and Environment* 107: 101–116.

Fargione, J., J. Hill, D. Tilman, S. Polasky & P. Hawthorne, 2008. Land clearing and the biofuel carbon debt. *Sciencexpress* 7 Febr. 2008, 10.1126/science.1152747.

Fearnside, P M., 2001. Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation* 28: 23–38.

Fearnside, P.M., 2005. Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology* 19: 680–688.

Field, C.B., J.E. Cambell & D.B. Lobell, 2008. Biomass energy: the scale of the potential resource. *Trends in Ecology and Evolution* 23: 65–72.

Firbank, L.G., S. Petit, S. Smart, A. Blain & R.J. Fuller, 2008. Assessing the impacts of agricultural intensification on biodiversity: a British perspective. *Philosophical Transactions of the Royal Society, London* B 363(1492): 777–787.

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F. Stuart Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I. Colin Prentice, N. Ramankutty & P. K. Snyder, 2005. Global consequences of land use. *Science* 309: 570–574.

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling & B.J. Cosby,

2003. The nitrogen cascade. *Bioscience* 53: 341–356.

Galloway, J.N., M. Burke, M. Bradford, R. Naylor, W. Falcon, A.K. Chapagain, J.C. Gaskell, E. McCullough, H.A. Mooney, K.L.L. Oleson, H. Steinfeld, T. Wassenaar & V. Smil, 2007. International trade in meat: the tip of the pork chop. *AMBIO* 36: 622–629.

Gerritsma, W. & M. Wessel, 1997. Oil palm: domestication achieved? *Netherlands Journal of Agricultural Science* 45: 463–475.

Granda C.B., Li Zhu & M.T. Holtzapple, 2007. Sustainable liquid biofuels and their environmental impact. *Environmental Progress* 26: 233–250.

Gressel, J., 2008. Transgenics are imperative for biofuel crops. *Plant Science* 174: 246–263.

Groom, M.J., E.M. Gray & P.A. Townsend, 2008. Biofuels and biodiversity: principles for creating better policies for biofuel production. *Conservation Biology* 22: 602–609.

Habekotté, B., 1997. Options for increasing seed yield of winter oil seed rape (*Brassica napus* L.): a simulation study. *Field Crops Research* 54: 109–126.

Haverkort, A.J. & P.L. Kooman, 1997. The use of systems analysis and modeling of growth and development in potato ideotyping under conditions affecting yields. *Euphytica* 94: 191–200.

Heaton, E., T. Voigt & S.P. Long, 2004. A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water. *Biomass & Bioenergy* 27: 21–30.

Hill, J., 2007. Environmental costs and benefits of transportation biofuel production from food- and lignocellulose-based energy crops: a review. *Agronomy and Sustainable Development* 27: 1–12.

Hunt, R., J. Warren Wilson & W. Hand, 1990. Integrated analysis of resource capture and utilization. *Annals of Botany* 65: 643–648.

Inman-Barber, N.G., 2004. Sugarcane water stress criteria for irrigation and drying off. *Field Crops Research* 89: 107–122.

Jaggard, K.W. & M.A. Semenov, 2007. The impact of climate change on sugar beet yield in the UK: 1976–2004. *Journal of Agricultural Science* 145: 367–375.

Jorgensen, J.R., L.C. Deleuran & B. Wollenweber, 2007. Prospects of whole grain crops of wheat, rye and triticale under different fertilizer regimes for energy production. *Biomass & Bioenergy* 31: 308–317.

Kalra, N., D. Chakraborty, P.R. Kumar, M. Jolly & P.K. Sharma, 2007. An approach to bridging yield gaps, combining response to water and other resource inputs for wheat in northern India using research trials and farmers' fields data. *Agricultural Water Management* 93: 54–64.

Karp, A. & I. Shield, 2008. Bioenergy from plants and the sustainable yield challenge. *New Phytologist* 179: 15–32.

Kelly-Yong, T.L., K.T. Lee, A.R. Mohamed & S. Bhatia, 2007. Potential of hydrogen from oil palm biomass as a source of renewable energy worldwide. *Energy Policy* 35: 5692–5701.

Koh, L.P. & J. Ghazoul, 2008. Biofuels, biodiversity, and people: understanding the conflicts and finding the opportunities. *Biological Conservation* 141: 2450–2460.

Kondili, E.M. & J.K. Kaldelis, 2007. Biofuel implementation in East Europe: current status and future prospects. *Renewable and Sustainable Energy Review* 11: 2137–2151.

Koning, N.B.J., M.K. Van Ittersum, G.A. Becx, M.A.J.S. Van Boekel, W.A. Brandenburg, J.A. Van Den Broek, J. Goudriaan, G. Van Hofwegen, R.A. Jongeneel, J.B. Schiere & M. Smies, 2008. Long-term global availability of food: continued abundance or new scarcity? *NJAS – Wageningen Journal of Life Sciences* 55: 229–292.

Kruse, O., J. Rupprecht, J.H. Mussgnug, G.C. Dismukes & B. Hankamer, 2005. Photosynthesis: a blueprint for solar energy capture and biohydrogen production technologies. *Photochemical and Photobiological Science* 4: 957–969.

Kumar, A. & S. Sharma, 2008. An evaluation of multipurpose oil seed crop for industrial uses (*Jatropha curcas* L.): a review. *Industrial Crops & Products* 28: 1–10.

Kyllingsbaek, A. & J.F. Hansen, 2007. Development in nutrient balances in Danish agriculture 1980–2004. *Nutrient Cycling in Agroecosystems* 79: 267–280.

Lal, R., 2008. Crop residues as soil amendments and feedstock for bioethanol production. *Waste Management* 28: 747–758.

Langeveld, J.W.A., A. Verhagen, J.J. Neeteson, H. Van Keulen, J.G. Conijn, R.L.M. Schils & J. Oenema, 2007. Evaluating farm performance using agri-environmental indicators: recent experiences for nitrogen management in The Netherlands. *Journal of Environmental Management* 82: 363–376.

Lewandowski, I. & U. Schmidt, 2006. Nitrogen, energy and land use efficiencies of miscanthus reed, canary grass and triticale as determined by the boundary line approach. *Agriculture, Ecosystems and Environment* 112: 335–346.

Miguez, F.E., M.B. Villamil, S.P. Long & G.A. Bollero, 2008. Meta-analysis of the effects of management factors on *Miscanthus* × *giganteus* growth and biomass production. *Agricultural and Forestry Meteorology* 148: 1280–1292.

Mol, A.P.J., 2007. Boundless biofuels? Between environmental sustainability and vulnerability. *Sociologia Ruralis* 47: 297–315.

Monteith, J.L., 1972. Radiation and productivity in tropical systems. *Journal of Applied Ecology* 9: 747–766.

Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society, London* B 281: 271–294.

Müller, A., J. Schmidhuber, J. Hoogeveen & P. Steduto, 2008. Some insights in the effects of growing bio-energy demand on global food security and natural resources. *Water Policy* 10 (Suppl. 1): 83–94.

Murphy, D.J., 2007. Future prospects for oil palm in the 21st century: biological and related challenges. *European Journal of Lipid Science and Technology* 109: 296–306.

Nass, L.L., P.A. Pereira & D. Ellis, 2007. Biofuels in Brazil: an overview. *Crop Science* 47: 2228–2237.

Oerke, E.C. & H.W. Dehne, 1997. Global crop production and the efficacy of crop protection – current situation and future trends. *European Journal of Plant Pathology* 103: 203–215.

Passioura, J.B., 1977. Grain yield, harvest index, and water use of wheat. *Journal of the Australian Institute of Agricultural Sciences* 43: 117–120.

Pathak, H., J.K. Ladha, P.K. Aggarwal, S. Peng, S. Das, Yadvinder Singh, Bijay Singh, S.K Kamra., B. Mishra, A.S.R.A.S. Sastri, H.P. Aggarwal, D.K. Das & R.K. Gupta, 2003. Trends in climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Research* 80: 223–234.

Penning De Vries, F.W.T., A.H.M. Brunsting & H.H. Van Laar, 1974. Products, requirements and efficiency of biosynthesis: a quantitative approach. *Journal of Theoretical Biology* 45: 339–377.

Porter, J.R., M.M. Norddahl-Kirsch, J. Streibig & C. Felby, 2007. Choosing crops as energy feedstocks. *Nature Biotechnology* 25: 716–717.

Ragauskas, A.J., C.K. Williams, B.H. Davison, G. Britovsek, J. Cairney, C.A. Eckert, W.J. Frederick Jr., 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.

Reynolds, M.P. & R.M. Trethowan, 2007. Physiological interventions in breeding for adaptation to abiotic stress. In: J.H.J. Spiertz, P.C. Struik & H.H. Van Laar (Eds), Scale and Complexity in Plant Systems Research: Gene-Plant-Crop Relations, Springer, Dordrecht, pp. 129–146.

Rittmann, B.E., 2008. Opportunities for renewable bioenergy using microorganisms. *Biotechnology & Bioengineering* 100: 203–212.

Roberts, D.G., 2008. Convergence of the fuel, food and fibre markets: a forest sector perspective. *International*

Forestry Review 10: 81–94.

Rounsevell, M.D.A., F. Ewert, I. Reginster, R. Leemans & T. Carter, 2005. Future scenarios of European agricultural land use. II. Estimating land use changes and regional allocation. *Agriculture, Ecosystems and Environment* 107: 117–135.

Rounsevell, M.D.A., I. Reginster, M.B. Araujo, T.R. Carter, N. Dendoncker, F. Ewert, J.I. House, S. Kankaanpaá, R. Leemans, M.J. Metzger, C. Schmit, P. Smith & J. Tuck, 2006. A coherent set of future land use change scenarios for Europe. *Agriculture, Ecosystems and Environment* 114: 57–68.

Rowe, R.L., N.R. Street & G. Tailor, 2009. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. *Renewable and Sustainable Energy Reviews* 13: 217–290.

Runge, C.F. & B. Senauer, 2007. How biofuels could starve the poor. *Foreign Affairs* 3: 41–46.

Sagar, A.D. & S. Kartha, 2007. Bioenergy and sustainable development? *Annual Review of Environmental Resources* 32: 131–167.

Salvagiotti, F., K.G. Cassman, J.E. Specht, D.T. Walters, A. Weiss & A. Dobermann, 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: a review. *Field Crops Research* 108: 1–13.

Schmer, M.R., K.P. Vogel, R.B. Mitchell & R.K. Perrin, 2008. Net energy of cellulosic ethanol from switch grass. *Proceedings National Academy of Sciences* 105: 464–469.

Schmidt, J.H., 2008. System delimitation in agricultural consequential LCA. Outline of methodology and illustrative case study of wheat in Denmark. *International Journal of Life Cycle Assessment* 13: 350–364.

Schroder, J.J., H.F.M. Aarts, H.F.M. Ten Berge, H. Van Keulen & J.J. Neeteson, 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. *European Journal of Agronomy* 20: 33–44.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes & T.H. Yu, 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319: 1238–1240.

Shao, H. & L. Chu, 2008. Resource evaluation of typical energy plants and possible functional zone planning in China. *Biomass & Bioenergy* 32: 283–288.

Shindo, J., K. Okamoto & H. Kawashima, 2006. Prediction of the environmental effects of excess nitrogen caused by increasing food demand with rapid economic growth in eastern Asian countries, 1961–2020. *Ecological Modelling* 193: 703–720.

Sims, R.E., A. Hastings, B. Schlamadinger, G. Taylor & P. Smith, 2006. Energy crops: current status and future prospects. *Global Change Biology* 12: 2054–2076.

Smaling, E.M.A., R. Roscoe, J.P. Lesschen, A.F. Bouwman & E. Comunello, 2008. From forest to waste: assessment of the Brazilian soybean chain, using nitrogen as a marker. *Agriculture, Ecosystems and Environment* 128: 185–197.

Smeets, E.M.W., A.P.C. Faaij, I.M. Lewandowski & W.C. Turkenburg, 2007. A bottom-up approach and review of global bioenergy potentials to 2050. *Progress in Energy and Combustion Science* 33: 56–106.

Somerville, C., 2006. The billion-ton biofuels vision. *Science* 312 (5778): 1277.

Spiertz, J.H.J., 2004. Cropping systems: yield improvement of wheat in temperate Northwestern Europe. In: Encyclopedia of Plant and Crop Science, pp. 367–369.

Spiertz, J.H.J., 2009. Nitrogen, sustainable agriculture and food security. a review. *Agronomy and Sustainable Development* 29 (in press) [DOI: 10.1051/agro:2008064]

Spiertz, J.H.J., H.D.J. Van Heemst & H. Van Keulen, 1992. Field-crop systems in North-Western Europe. In: Field-crop Ecosystems of the World, Elsevier, Amsterdam, pp. 357–371.

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 of the United Nations (FAO), Rome, 390 pp.

Sticklen, M.B., 2008. Plant genetic engineering for biofuel production: towards affordable cellulosic ethanol. *Nature Review of Genetics* 9: 433–443.

Swaminathan, M.S., 2007. Can science and technology feed the world in 2025? *Field Crops Research* 104: 3–9.

Ten Berge, H.F.M., M.K. Van Ittersum, W.A.H. Rossing, G.W.J. Van De Ven, J. Schans & P.A.C.M. Van De Sanden, 2000. Farming options for The Netherlands explored by multi-objective modeling. *European Journal of Agronomy* 13: 263–277.

Tong, C., C.A.S. Hall & H. Wang, 2003. Land use changes in rice, wheat and maize production in China (1961–1998). *Agriculture, Ecosystems and Environment* 95: 523–536.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor & S. Polasky, 2002. Agricultural sustainability and intensive production practices. *Nature* 418: 671–677.

Van Dam, J., A.P.C. Faaij, I. Lewandowski & G. Fischer, 2007. Biomass production potentials in Central and Eastern Europe under different scenarios. *Biomass & Bioenergy* 31: 345–366.

Van Der Werf, H.M.G., W.J.M. Meijer, E.W.J.M. Mathijssen & A. Darwinkel, 1993. Potential dry matter production of *Miscanthus sinensis* in the Netherlands. *Industrial Crops and Products* 1: 203–210.

Van Keulen, H., 2007. Quantitative analyses of natural resource management options at different scales. *Agricultural Systems* 94: 768–783.

Varis, O., 2007. Water demands for bioenergy production. *Water Resource Development* 23: 519–535.

Von Braun, J., K. Asenso-Okyere, S. Fan, A. Gulati, J. Hoddinott, R. Pandya-Lorch, M.W. Rosegrant, M. Ruel, M.Torero, T. Van Rheenen & K. Von Grebmer, 2008. High Food Prices: the What, Who, and How of Proposed Policy Actions. Policy Brief 1A CH, International Food Policy Research Institute (IFPRI), Washington, D.C., 12 pp.

Wallace, L. & M.W. Palmer, 2007. LIHD biofuels: towards a sustainable future. *Frontiers in Ecology and the Environment* 5: 115.

Wilkinson, P., K.R. Smith, M. Joffe & A. Haines, 2007. Energy and health 1. A global perspective on energy: health effects and injustices. *The Lancet* 370: 965–978.

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

Witcombe, J.R., P.A. Hollington, C.J. Howarth, S. Reader & K.A. Steel, 2008. Breeding for abiotic stresses for sustainable agriculture. *Philosophical Transactions of the Royal Society, London* B 363: 703–716.

Wright, L., 2006. Worldwide commercial development of bioenergy with a focus on energy-based projects. *Biomass & Bioenergy* 30: 706–714.

Young, R.R., P.-J. Derham, F.X. Dunin, A.L. Bernhardi & S. Harden, 2008. High crop productivity with high water use in winter and summer on the Liverpool Plains, Eastern Australia. *Australian Journal of Agricultural Research* 59: 303–320.