Journal of Agricultural Science, Page 1 of 11.
doi:10.1017/S0021859613000853

NITROGEN WORKSHOP SPECIAL ISSUE PAPER

Nitrogen use and food production in European regions from a global perspective

H. J. M. VAN GRINSVEN[1]*, J. H. J. SPIERTZ[2], H. J. WESTHOEK[1], A. F. BOUWMAN[1] AND J. W. ERISMAN[3,4]

[1] *PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands*
[2] *Center for Crop System Analysis, Plant Sciences Group, Wageningen University, Wageningen, The Netherlands*
[3] *Louis Bolk Institute for International Advice and Research on Sustainable Agriculture, Nutrition and Health Care, Driebergen, The Netherlands*
[4] *Free University Amsterdam, The Netherlands*

(*Received 13 March 2013; revised 2 October 2013; accepted 17 October 2013*)

SUMMARY

Current production systems for crops, meat, dairy and bioenergy in the European Union (EU) rely strongly on the external input of nitrogen (N). These systems show a high productivity per unit of land. However, the drawback is a complex web of N pollution problems contributing in a major way to degradation of ecosystems. European Union Directives and national policies have improved nutrient management and reduced fertilizer N use in most European countries, which has curbed the N pollution trends particularly in regions with high stocking rates of animals. However, improvement is slowing down and environmental targets for N are not within reach. Building on the 2011 European Nitrogen Assessment, the current paper reviews key features of the complex relationships between N use and food production in Europe in order to develop novel options for a more N-efficient, less N-polluting and secure European food system. One option is to relocate feed and livestock production from Northwestern to Central and Eastern Europe. This would allow a reduction of N rates and N pollution in cereal production in Northwest Europe by 30% (50 kg N/ha), while increasing total cereal production in Europe. Another option is a change towards legume-based cropping systems to produce animal feed, in order to decrease dependence on N fertilizer and feed imports. The greatest challenge for Europe is to decrease the demand for feed commodities, and thus for land and N, by a shift to more balanced (and healthier) diets with less animal protein. These drastic changes can be stimulated by targeted public–private research funding, while the actual implementation can be enhanced by smart payment schemes using, for example money from the Common Agricultural Policy, certification and agreements between stakeholders and players in the food and energy chain. Involving networks of consumers, producers and non-governmental organizations is critical. An effective strategy starts with convincing consumers with a Western diet to eat less meat and dairy by communicating the associated health benefits and smaller ecological footprints. Internalizing the cost of N pollution leading to increased prices for N-intensive food products may also enhance involvement of consumers and provide financial resources to compensate farmers for loss of income and extra costs for stricter N measures.

INTRODUCTION

Future global food availability is determined by the ability of agricultural production to accommodate climate change, growth of world population, socio-economic development and changes in diets (Godfray *et al.* 2010). On the global level, opportunities to increase the area of agricultural land are limited because of concerns about biodiversity loss, carbon emissions related to land conversion, climate change, soil erosion and competing claims such as bioenergy production and urbanization. The availability of relatively cheap nitrogen (N) fertilizer and the introduction of high-yielding semi-dwarf cultivars of wheat

* To whom all correspondence should be addressed. Email: hans.vangrinsven@pbl.nl

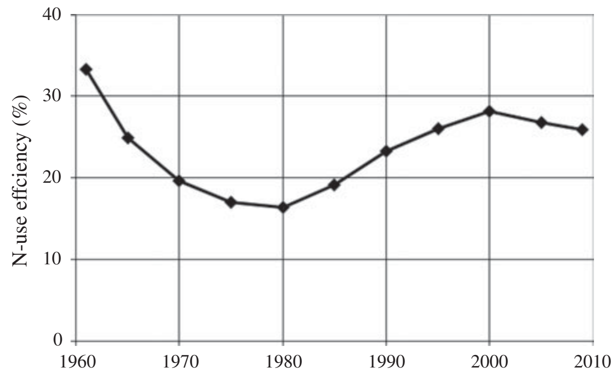

Fig. 1. Average nitrogen use efficiency (NUE) of the agricultural sector of the EU27. NUE values are derived from national N budgets, based on FAOSTAT data (http://faostat.fao.org/) on land use and fertilizer use, crop and livestock production, and trade of food and feed, by multiplying product volumes and their respective N contents.

and rice have been major factors in raising crop production per hectare over the past 5 decades and hence curb land requirements for food production (Erisman *et al.* 2008; Spiertz 2010). Since the mid-1960s, production of the major food commodities such as rice, maize and wheat increased by 50%, associated with only a 10% increase of area globally. In the European Union, the increase in scale and intensity of animal production, which is partly based on imported feed, has a major impact on N use and losses both from feed cultivation and the feeding operations (Westhoek *et al.* 2011). As a consequence of agricultural intensification, N emissions from agriculture have become a major cause of environmental problems at the local, regional and global scale (Sutton *et al.* 2011*a*). Major hot spots of N emissions by agriculture in Europe are associated with high stocking rates and the production of manure (Lesschen *et al.* 2011). This development underlines the importance of an increase in N use efficiency of animal-based production systems and a lower meat and dairy consumption by a shift towards less protein-rich diets.

The Common Agricultural Policy (CAP) of the European Union (EU) was initially aimed at food security and self-sufficiency for major commodities (e.g. dairy, meat and cereals). As a result, the production of major commodities received a boost and resulted in surpluses in the 1980s, but also the intensive use of fertilizers and manure led to environmental problems (air quality, eutrophication and contamination) and a decrease in nitrogen use efficiency (NUE) between 1960 and 1980 (Fig. 1). From the early 1990s onwards, the CAP and Environmental Directives encouraged member states to take environmental measures (legislation, monitoring, etc.). As a consequence, manure was more effectively utilized on grassland and arable crops, with fewer losses to the environment (van Grinsven *et al.* 2012). Therefore the use of fertilizer N and phosphorus in agriculture was lowered, while yields per hectare continued to increase. This improved use of nutrients has led to an overall increase of NUE in European agriculture since 1980 (Fig. 1). An additional factor for Central and Eastern European countries was the political transition in 1989, causing a collapse in fertilizer use. Currently, however, environmental improvements are stagnating and policy targets, especially those related to water quality, are not within reach (van Grinsven *et al.* 2012).

The present paper assesses the role of N in food production and associated environmental impacts, focusing on Europe. It builds on the European Nitrogen Assessment (ENA; Sutton *et al.* 2011*b*) and the European protein puzzle (Lesschen *et al.* 2011; Westhoek *et al.* 2011; Stehfest *et al.* 2013). For various aspects, the findings reported in ENA are updated and put into a global context using recent assessments by the United Nations Environment Programme, the Inter-Governmental Panel on Climate Change, the Organisation for Economic Co-operation and Development and the International Assessment of Agricultural Science and Technology for Development, as summarized in Kok *et al.* (2008), and using scenario analyses by Bouwman *et al.* (2011). The present paper further explores some options in addition to ENA for maintaining European and global food security while minimizing N losses to the environment. Details on data, calculation schemes and scenarios in the current review paper can be found in the abovementioned assessments.

ASSESSMENT

Global and regional outlook

In the United Nations (UN) reference scenario, the world population will increase to 9 billion in 2050. Between 2000 and 2050, the total global caloric intake is expected to increase by 65% and the average global consumption of animal products is expected to double (Stehfest *et al.* 2009). This compelling demand on the global food system will require an increase in the production of cereals in 2050 by about 60–70%

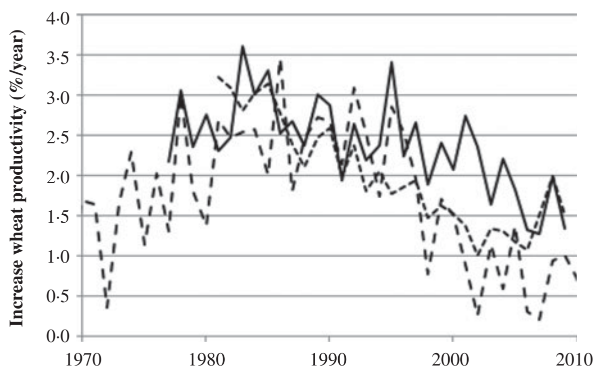

Fig. 2. Trends of the increase in wheat grain productivity since 1970 in Europe (—), The Netherlands (---) and globally (▪▪▪▪). NB: Trends are 20 years moving averages of annual data from FAOSTAT (http://faostat.fao.org/), for The Netherlands from CBS StatLine (http://statline.cbs.nl/statweb/).

(Bruinsma 2009; Godfray *et al.* 2010). The share of cereals needed for livestock production will remain at about one-third. The total area of agricultural land of 47 million km^2 in 2000 (with 31 million km^2 in use for grassland and 5 million km^2 for feed crops) is projected to increase to an area between 50 and 61 million km^2 in 2050 (Van Vuuren & Faber 2009). The projected increase for cropland is 2 million km^2 (Bruinsma 2009). Taking into account *c.* 3 million km^2 of land use in 2050 for bioenergy production (Bouwman *et al.* 2010), the 60% increase in cereal production to meet the increased food demand in 2050 has to be delivered by an increase of productivity per hectare. Between 1970 and 2010, the annual wheat productivity initially increased to a mean value of 2·5% between 1980 and 1990, but from the end of the 1980s decreased to just above 1% globally and less than 1% in Europe (Fig. 2) and the USA (Dixon *et al.* 2009). An average annual increase by 0·8% would suffice but achievement of this level is uncertain, because of land degradation and climate change (Bruinsma 2009), among other reasons. While crop area in Europe is not expected to increase in the future, Olesen & Bindi (2002) concluded that warming is expected to lead to a northward expansion of suitable cropping areas.

The trends in these average wheat productivities mask the underlying causes of the levelling off in crop productivity. Agronomic management, genetic effects and climate change (mainly extreme weather events) may play a role. In Western Europe, environmental policies and increased prices of fertilizer and relatively low commodity prices of cereals in the 1990s reduced fertilizer N use. Furthermore, the political transitions in Central and Eastern Europe caused a collapse in fertilizer use (Grzebisz *et al.* 2012). Genetic gain in yield potential of bread wheat in France has increased linearly from the 1970s up to the present time (Oury *et al.* 2012). However, since the end of the 1980s genetic progress has been partly or totally counter-balanced by the adverse effects of climate change on yields (Brisson *et al.* 2010). Wheat yields showed the highest sensitivity to warming during the grain-filling stage (Spiertz *et al.* 2006; Gourdji *et al.* 2013). In the last decade, short heat waves during grain filling occurred more frequently in Central and Northwest Europe. Thus, the response of crop yields to N will usually be affected by agroclimatic conditions as well as crop management (Spiertz 2010).

Nitrogen, land use and crop production

Nitrogen fertilizer has been a key factor for increasing food production in developing countries in Asia (Green Revolution) as well as in many industrialized countries during the second half of the 20th century. Wheat yields in Western Europe increased from *c.* 4 tonnes (t)/ha in 1960 to 8 t/ha in the beginning of the 21st century. The magnitude of this yield response is in line with results for long-term continuous wheat trials at Rothamsted in the UK, where various nutrient management practices have been tested since 1843 (Goulding *et al.* 2008). A factor of four was reported for differences between the lowest and highest mean wheat yields in member states of the EU27 (Jensen *et al.* 2011). This variation in yields is only partly affected by N use (dose, placement and timing): local growing conditions, plant breeding (semi-dwarf cultivars), irrigation, pest control, availability of other nutrients and an overall improvement of farm management also play a role. Using various sources, Erisman *et al.* (2008) estimated that, globally, N fertilizer is responsible for *c.* 30–50% of the crop yield increase since 1960s. Such estimates should be viewed with some caution, because of the strong Genotype × Environment × Management interactions (Reynolds *et al.* 2002). Assessments of the contribution of genetic progress to raising yields show some variation.

Organic and low input *v.* intensive agriculture

It is difficult to single out the effect of synthetic N fertilizer on crop yields when comparing organic and conventional cropping systems (Erisman *et al.* 2008).

De Ponti *et al.* (2012) estimated that for food crops the average yield gap between organic and conventional arable agriculture is *c.* 20%. Some crops, such as potato, respond more strongly to the lower availability of N in organic systems than cereals. The yield gap increased to >30% for the most productive regions in Northwest Europe. Taking into account the differences in cropping sequence between the two systems, the yield gap is bigger (Seufert *et al.* 2012). Schröder & Sørensen (2011) also infer an average reduction of land productivity in cropping systems of *c.* 30% without synthetic fertilizer and more efficient recycling of organic N sources, in view of the need to grow and plough under N fixing crops every third year. However, even with an average yield gap of 30%, some individual organic farms performed much better than conventional farms and these outliers are interesting cases to explore further.

Fewer data are available on organic dairy farming, but reported milk production per unit of land lie in the range of 70–100% of conventional yields, mainly due to lower stocking rates (Offermann & Nieberg 2000). An important aspect of the profitability of organic farms in Europe, besides saving on inputs, is receiving higher prices for organically produced goods than for those produced conventionally. The other aspect of organic farming is the more sustainable attitude of consumers of organic products, who tend to consume less meat products and fossil energy.

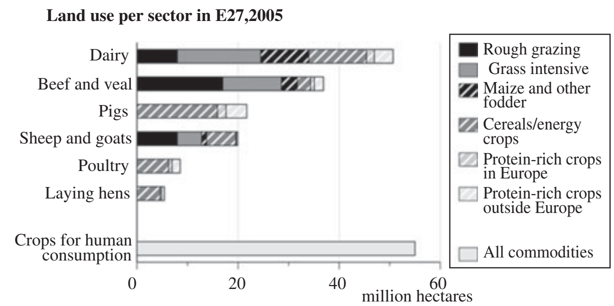

Fig. 3. Land use per agricultural sector in EU27 in 2005 to feed livestock (Westhoek *et al.* 2011).

Nitrogen, land use and animal production

Meat and dairy consumption in the EU has increased steadily over the past 50 years from 25 kg of protein per capita in 1960 to over 30 kg in 2007. The EU average per capita consumption of meat is twice the world average and consumption of dairy products exceeds the world average by a factor of three (Westhoek *et al.* 2011). Total protein consumption per capita in Europe is 1·7 times the intake recommended by the World Health Organization. Overconsumption of (red) meat increases the risk of intestinal cancers (González *et al.* 2006) and overconsumption of saturated trans fatty acids from animal products increases risks for cardiovascular health (Nishida *et al.* 2004).

Modern industrial livestock farming has increased the efficiency of conversion of feed to food to 2–3 kg feed/kg of eggs or poultry meat and to 3–4 kg feed/kg pork (Lesschen *et al.* 2011). As a result the increase in land demand for feed has slowed down. Nonetheless, feeding European livestock presently requires two-thirds (125–140 million ha) of the total agricultural land (Fig. 3). An additional 10–14 million ha is needed outside Europe for production of protein and oil-rich feedstuffs (Westhoek *et al.* 2011). Of the EU area allocated to animal production, about half (65–70 million ha) is grassland and half (60–70 million ha) is cropland used for growing cereals and silage maize. Consequently, less than half (50–60 million ha) of current arable land is used directly to produce food for human consumption. The average EU diet requires 0·4 ha per capita; 0·3 ha of this is for animal products and 0·02 ha lies outside the EU (inferred from Westhoek *et al.* 2011). As a comparison, this figure is much higher than the value of 0·12 ha per capita for the China plains (inferred from Liu *et al.* 2011).

Nitrogen and the environment

Current high N losses to the environment are a partly inevitable consequence of current levels of production and consumption of food. Typically, NUE for cereal grain production on research plots (N recovery of fertilizer N in grain) in Europe is *c.* 40% and 60% when including straw (Ladha *et al.* 2005; based on data for 107 research plots before 2004). Nitrogen use efficiency values derived from experiments under optimal conditions tend to overestimate farm values due to unfavourable soil and weather conditions and/or suboptimal management (Cassman *et al.* 2002; Spiertz 2010). Aggregated NUE values for European N budgets for agricultural land for the year 2000 range from 49 to 63% (de Vries *et al.* 2011*a*). Protein (or N) conversion efficiencies in livestock production range from 20 to 50% for poultry products, 15 to 30% in pork and dairy, and 5 to 13% in beef (Sutton *et al.* 2011*b*). This implies that consumption of animal proteins involves a large indirect consumption

Table 1. *Inputs and emissions of reactive nitrogen in EU27 (Bouwman* et al. *2011)*

	1900	1950	1970	1980	1990	2000	2005
Nitrogen inputs from all sources				Mt/year			
Energy & transport	0·63	1·71	6·82	6·96	5·89	4·49	3·88
Feed & food import	0·00	1·00	2·67	3·50	3·50	3·50	3·50
Fertilizer & Biological Fixation	4·24	4·37	11·06	16·10	15·89	13·44	12·74
Nitrogen emissions from agricultural sources							
NO_x	0·15	0·17	0·24	0·30	0·31	0·26	0·24
NH_3	1·32	1·76	3·23	4·02	3·70	3·16	3·04
N_2O	0·32	0·38	0·47	0·55	0·54	0·47	0·45
Nitrogen runoff	1·71	2·89	8·62	11·33	9·63	7·13	6·64

of proteins supplied by feed, and thus of N inputs to produce the feed crops and of the associated N pollution.

The total use of reactive N by agriculture in the EU27 increased by a factor of three in the 20th century and was *c.* 14 Mt in 2005, mainly in the form of chemical N fertilizer (Table 1; Bouwman *et al.* 2011). This amount constitutes 75% of the total input of reactive N. Approximately 60% of the total emission to air and water is related to agricultural sources. Nitrogen pollution from agricultural sources has become the main cause of coastal eutrophication and depletion of stratospheric ozone, and contributes significantly to air pollution, contamination of drinking water, freshwater eutrophication, biodiversity loss and disruption of the greenhouse balance (Sutton *et al.* 2011*b*).

Nitrogen and society

It is difficult to convey the N issue to a wider audience (Sutton *et al.* 2011*b*). Possible explanations are the complexity of causes and effects of N pollution, the dominant perception of people that N is good for food production and food security and the competition in the media with other compelling global environmental issues such as climate change and the looming water crisis. With regards to the climate and biodiversity issues, the communication of N footprinting and costs of N pollution for society should become more effective (Ingram 2008; Sonneveld & Bouma 2003; Leach *et al.* 2012). Scientists should interact with stakeholders to develop innovative concepts based on sound production-ecological, environmental and socio-economic research to facilitate the transition to food systems that optimize N use from the farm level to the end-users.

The N footprint of individual consumption patterns provides insight into the consequences of diets and underlying agricultural production processes (Leach *et al.* 2012). As for the economy of N it is important to acknowledge both the benefits and costs (Brink *et al.* 2011). Nitrogen contributes to the farm income and gross national product by increasing agricultural output and for some regions by a positive export balance of agricultural products. The total value of agricultural production in the EU27 (including industrial processing) in 2008 amounted to >350 billion €/year, of which a large share (*c.* 40%) depended on the response of primary productivity to N. However, environmental pollution causes a loss of common goods and services. The total damage (or external cost) for the EU related to agricultural emissions of N has been estimated at 35–230 billion €/year (van Grinsven *et al.* 2013) and appears to be in the same order as the (direct) economic benefits of N (Table 2). The largest cost for society from agricultural sources of N is due to ecosystem damage, of which two-thirds are related to N runoff and one-third to N deposition. The N cost due to impacts on human health appears to be considerable but is dominated by uncertain and debated effects of air-borne ammonium- and nitrate-containing salt particles. Currently, N appears to have no net climate-warming effect because the warming effects of agricultural emissions of nitrous oxide (N_2O) are cancelled out by the current cooling effect of particles containing ammonia (NH_3) (Butterbach-Bahl *et al.* 2011; de Vries *et al.* 2011*b*).

Damage costs are based on surveys of willingness-to-pay to prevent environmental impacts of N and need further debate in view of large uncertainties and of conceptual issues (van Grinsven *et al.* 2013). In spite of these issues, the comparable values of costs and benefits of N fertilization for the European food system suggest that lower fertilization levels, even when

Table 2. *Estimated economic losses due to environmental damage in the EU27 in 2008 caused by nitrogen emission from agricultural production and energy generation*

	All sources	Agricultural sources			
	Total	Human health	Ecosystems	Climate	Total for agricultural sources
		billion €/year			
Nitrogen runoff	40–155	0–1	25–95	0	25–95
NH_3-N	15–145	5–65	15–60	– 8 to 0*	10–120
NO_x-N	20–170	1–4	1–3	– 1 to 0	1–7
N_2O-N	5–15	0–1	0	1–5	2–6
Total	75–485	10–70	35–155	– 8 to 6	35–230

* Negative values denote climate benefits (cooling).
NB: values exceeding 10 rounded to the nearest 5 to avoid over accuracy.

accompanied by a modest loss of crop production, could increase overall welfare. However, there is also large scope for progress by fine-tuning fertilizer management in agriculture (Powell *et al.* 2010; Oenema *et al.* 2012) and recycling waste materials in the food system at large (Nakakubo *et al.* 2012).

Future nitrogen use

Global use of N fertilizer projected for 2050 (Erisman *et al.* 2008; Bouwman *et al.* 2009, 2011) is very uncertain, because of the many drivers and options to increase N use efficiencies. Relative to 2000, projections of global use in 2050 range from double to a small decrease. In contrast, these scenarios show a consolidation for Europe in the use of N fertilizer and a small increase in manure production; however, only with a modest increase in nutrient use efficiency. A worst case scenario for global food security and N pollution would be a further shift to global animal protein-rich diets combined with an expansion of land allocated to bioenergy crops. The combined effect could result in escalating food and fertilizer prices, as was observed in 2008 (Fig. 4). The 2008 peak of fertilizer prices was attributed to a variety of reasons (Roberts 2009*a*), the major one being a temporary shortage of supply due to a rising global demand by farmers and their intermediaries, which in part was an overreaction to increasing food commodity prices. Economic feedback should be able to counteract these trends, but current prices of fertilizer, food and fuel in developing countries are highly volatile.

An alarming recent observation is that global N fertilizer use increased by >25% between 2000 and 2009, and already approaches the level that was projected by FAO for 2030 (Bruinsma 2003).

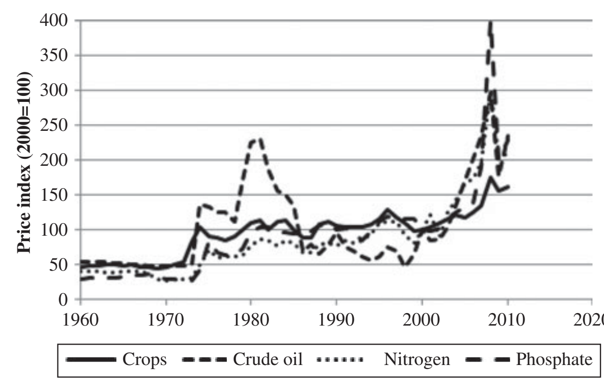

Fig. 4. Historic price trends in the USA of N and phosphate fertilizers and of crops (http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx) and crude oil (http://www.wtrg.com/prices.htm).

Challenges and options for Europe

The challenges to maintaining global food security while minimizing impacts due to N pollution are: increasing nutrient use efficiency, consolidating and preserving the quality of agricultural land and changing diets. Reducing food waste, amounting to 30% globally and in Europe, appears to be an easy and no-regret first priority. In Europe, consumers waste 20% of purchased food (Bellarby *et al.* 2013), but reduction of this waste is difficult as it is deeply embedded in the food chain and in consumer behaviour in industrialized countries (Roberts 2009*b*; Gustavsson *et al.* 2011). Complicating factors not yet included in most scenarios are the effects of climate change on agricultural production, and particularly for Europe,

Table 3. *Grain yields, nitrogen fertilizer rates and nitrogen productivities in six European regions (FAO stat; 2006–10) and the estimated long term sustainable potential cereal production (Fischer* et al. *2002; note for Western EU this yield is below current yield levels)*

	West	Central	East	South	North	Eastern non-EU
Grain yield (t/ha)	7·5	4·5	3·3	2·3	4·7	2·4
Fertilizer N rate (kg N/ha)	153	102	68	74	110	26
Nitrogen productivity (kg grain/kg N)	49	44	48	32	42	92
Cereal production (Mt) 2006–10	88·4	21·5	15·3	15·1	3·4	41·4
Sustainable potential grain production (Mt) (% change relative to 2006–2010)	78·0 (−12%)	29·5 (+37%)	28·9 (+89%)	26·4 (+75%)	–	62·3 (+50%)

stricter demands on animal welfare, and controlling human health risks and use of antibiotics in animal production, which will probably decrease feed conversion efficiencies (Stehfest *et al*. 2013). However, in the long run new food sources such as proteins from aquaculture or insects, with low land requirements and high conversion efficiencies, may replace some of the current protein sources (Verkerk *et al.* 2007; Oonincx & de Boer 2012).

Major improvements in N-use efficiency may be expected from adapting the cropping systems to change in agro-ecological conditions. The shift from wheat to maize in warmer and dryer climates is one option (Timsina *et al.* 2010) and the introduction of legumes in cropping systems that are deprived of fertilizer N is another (Giller *et al.* 2006). In a study by Parr *et al.* (2011), 16 winter annual cover crop cultivars were grown to assess total N accumulation, biological N fixation and organic-grown maize performance; their study showed that total N content of these cover crops ranged from 23 to 182 kg N/ha with most of it derived from biological N fixation. The recovery of this N source by the maize crop depended largely on crop management. A great opportunity for Europe is to substitute a large part of the imports of protein-rich feed by developing legume-based forage systems (Hirel *et al.* 2011; Peltonen-Sainio & Niemi 2012). Furthermore, the introduction of smart technologies to develop agricultural practices in the Central and Eastern EU-member states and in the western states of the Former Soviet Union (FSU) will contribute to enhance land productivity and as a consequence a higher agronomic N-use-efficiency (Jensen *et al.* 2011).

A well-integrated EU food and N policy would stimulate a transition from economically and agronomically optimal N fertilizer rates to environmentally optimal rates (Brink *et al.* 2011; Good & Beatty 2011). Using N damage costs from Brink *et al.* (2011), the optimal ecological and economical balanced N rates for winter wheat in Northwest Europe would be 30–90 kg/ha (median 55 kg/ha), 30% lower than current rates. The concurrent reduction in cereal yield according to conventional N response curves would be 1–2 t/ha (*c*. 15% lower for Northwest European yields) and could compromise food security. Yield loss from lower inputs of N fertilizer could be compensated for, to some extent, by adapting nutrient conservation and recycling practices of organic farming. Alternatively, this yield loss may be compensated by increased yields in the new member states of the EU27. For example Romania and Bulgaria hold 20% of the agricultural land in the EU27, while yields and N use are still low. Based on current yield gaps (Fischer *et al.* 2002), wheat production in Europe could be increased by 40 Mt (20%) relative to production in 2000–06 (Table 3) and the EU27 could thus become a net exporter of cereals. However, the EU decision to lift the milk quota system in 2015, for the very purpose of meeting the increasing demand for dairy in Asia, may absorb a large quantity of this potential yield increase. Decreasing food waste and meat and dairy consumption in Europe have a larger potential to lower feed demand and turn the EU into an exporter of cereals (Westhoek *et al*. 2011).

Moving part of the cereal production, and the associated high N fertilization and pollution per hectare, from Northwestern to Central and Eastern Europe could improve the balance between profit and sustainability in both regions. Expressed per capita per year, current N benefits in food production in Northwestern and Eastern Europe are €290 and 250, while pollution costs are €200 and 165, respectively (Table 2; van Grinsven *et al.* 2013). A transition to simultaneously productive and more N efficient

European agriculture would involve long-term targets and short-term incentives, combined with a vision on the future optimal structure and spatial layout of agricultural production. Ewert *et al.* (2005) estimated future changes in crop productivity of wheat in Europe taking into account climate change and technology development.

IMPLICATIONS FOR POLICY AND RESEARCH

Theoretically, there are many technical possibilities for developing future food systems that are more N efficient, less polluting and yet productive. A strategy for implementing these possibilities requires not only technological and management innovations in the agri-food system, but also changes in governance and institutions. Global competition between land for food, feed, biodiversity or bioenergy, urbanization, recreation and nature is influenced strongly by policies for economy, trade, land use planning, agricultural and energy. Development of more efficient and less polluting production systems for food, feed and bioenergy can be stimulated by targeted public-private funding of innovations, while actual implementation can be enhanced by smart payment schemes, certification and agreements between large players in the food and energy chain. To find a better balance between increasing productivity and reducing pollution of agricultural production systems, both the internal and external costs of food production need to be quantified and discounted in food prices. The critical components of the food system need to be identified, where changes can make a difference for the performance of the system as a whole. In Europe, the best examples of N policies along these lines are those that have stimulated the reduction of fertilizer inputs and improved manure and ammonia management (housing, storage and application). These measures reduced losses of N considerably, but often with considerable costs for individual livestock farmers. From the perspective of the farmer, the recurring question is who will pay for a transition to more N efficient, less polluting farming systems that will probably be somewhat less productive per unit of land and labour, and less profitable when these additional costs are not covered by higher commodity prices. Stricter N policies for agriculture should go hand in hand with more targeted allocation of CAP payments and investments in research, technology and management tools enabling a more N efficient agriculture. Together with higher prices for N intensive and more polluting food products, this could provide part of the funds to compensate farmers for loss of production and costs of measures and transition. It could stimulate development of more resource-efficient farming systems that depend less on N fertilizer, and perhaps also a partial return to more N efficient spatially integrated feed and livestock production. A major challenge in the EU would be to decrease the individual land and N requirement for diets rich in meat and dairy by a change to more balanced (and healthier) diets that will not be more costly than current diets. Therefore, convincing or perhaps nudging consumers to eat less meat and dairy by communicating the associated health benefits and smaller ecological footprints could also be an effective strategy to decrease N pollution and increase food security. However, in spite of apparent benefits for public health and goods, governments are reluctant to interfere with what people eat, while the food industry and retail are very effective using marketing to influence food choices.

REFERENCES

Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J. P. & Smith, P. (2013). Livestock greenhouse gas emissions and mitigation potential in Europe. *Global Change Biology* **19**, 3–18.

Bouwman, A. F., Beusen, A. H. W. & Billen, G. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. *Global Biochemical Cycles* **23**, GB0A04. doi:10.1029/2009GB003576.

Bouwman, A. F., van Grinsven, J. J. M. & Eickhout, B. (2010). Consequences of the cultivation of energy crops for the global nitrogen cycle. *Ecological Applications* **20**, 101–109.

Bouwman, A. F., Klein Goldewijk, K., Van der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, W. J., Rufino, M. C. & Stehfest, E. (2011). Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *PNAS*, doi:10.1073/pnas.1012878108.

Brink, C., van Grinsven, J. J. M., Jacobsen, B. H., Rabl, A., Gren, I.-M., Holland, M., Klimont, Z., Hicks, K., Brouwer, R., Dickens, R., Willems, J., Termansen, M., Velthof, G., Alkemade, R., van Oorschot, M. & Webb, J. (2011). Costs and benefits of nitrogen in the environment. In *The European Nitrogen Assessment* (Eds M. A. Sutton, C. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven & B. Grizzetti), pp. 513–540. Cambridge, UK: Cambridge University Press.

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F-X. & Huard, F. (2010). Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research* **119**, 201–212.

Bruinsma, J. E. (2003). *World Agriculture towards 2015/2030: An FAO Perspective*. London: Earthscan Publications Ltd.

Bruinsma, J. E. (2009). The resource outlook to 2050: by how much do land, water and crops yields need to increase by 2050? In *Proceedings of the Expert Meeting on How to Feed the World in 2050, 24–26 June 2009, FAO Headquarters, Rome* (Ed. FAO), pp. 1–33. Available online from: http://www.fao.org/docrep/012/ak542e/ak542e00.htm (accessed 3 October 2013).

Butterbach-Bahl, K., Nemitz, E., Zaehle, S., Billen, G., Boeckx, P., Erisman, J. W., Garnier, J., Upstill-Goddard, R., Kreuzer, M., Oenema, O., Reis, S., Schaap, M., Simpson, D., De Vries, W., Winiwarter, W. & Sutton, M. A. (2011). Nitrogen as a threat to the European greenhouse balance. In *The European Nitrogen Assessment* (Eds M. A. Sutton, C. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven & B. Grizzetti), pp. 434–462. Cambridge, UK: Cambridge University Press.

Cassman, K. G., Dobermann, A. R. & Walters, D. T. (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO* **31**, 132–140.

Dixon J., Braun H. J., Kosina P. & Crouch J. (Eds.) (2009). *Wheat Facts and Futures 2009*. Mexico, DF: CIMMYT.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z. & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience* **1**, 636–639.

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

Fischer, G., van Velthuizen, H. T., Shah, M. M. & Nachtergaele, F. O. (2002). *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results*. IIASA Research Report RR-02-002. Laxenburg, Austria: IIASA.

Giller, K. E., Rowe, E. C., De Ridder, N. & Van Keulen, H. (2006). Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agricultural Systems* **88**, 8–27.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M. & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *Science* **327**, 812–818.

González, C. A., Jakszyn, P., Pera, G., Agudo, A., Bingham, S., Palli, D., Ferrari, P., Boeing, H., del Giudice, G., Plebani, M., Carneiro, F., Nesi, G., Berrino, F., Sacerdote, C., Tumino, R., Panico, S., Berglund, G., Simán, H., Nyrén, O., Hallmans, G., Martinez, C., Dorronsoro, M., Barricarte, A., Navarro, C., Quirós, J. R., Allen, N., Key, T. J., Day, N. E., Linseisen, J., Nagel, G., Bergmann, M. M., Overvad, K., Jensen, M. K., Tjonneland, A., Olsen, A., Bueno-de-Mesquita, H. B., Ocke, M., Peeters, P. H. M., Numans, M. E., Clavel-Chapelon, F., Boutron-Ruault, M.-C., Trichopoulou, A., Psaltopoulou, T., Roukos, D., Lund, E., Hemon, B., Kaaks, R., Norat, T. & Riboli, E. (2006). Meat intake and risk of stomach and esophageal adenocarcinoma within the European prospective investigation into cancer and nutrition (EPIC). *Journal of the National Cancer Institute* **98**, 345–354.

Good, A. G. & Beatty, P. H. (2011). Fertilizing nature: a tragedy of excess in the commons. *PLos Biology* **9**, e1001124. doi:10.1371/journal.pbio.1001124.

Goulding, K., Jarvis, S. & Whitmore, A. (2008). Optimizing nutrient management for farm systems. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 667–680.

Gourdji, S. M., Mathews, K. L., Reynolds, M., Crossa, J. & Lobell, D. B. (2013). An assessment of wheat yield sensitivity and breeding gains in hot environments. *Proceedings of the Royal Society B: Biological Sciences* **280**, 2012. doi:10.1098/rspb.2012.2190.

van Grinsven, H. J. M., ten Berge, H. F. M., Dalgaard, T., Fraters, B., Durand, P., Hart, A., Hofman, G., Jacobsen, B. H., Lalor, S. T. J., Lesschen, J. P., Osterburg, B., Richards, K. G., Techen, A.-K., Vertès, F., Webb, J. & Willems, W. J. (2012). Management, regulation and environmental impacts of nitrogen fertilization in Northwestern Europe under the Nitrates Directive; a benchmark study. *Biogeosciences* **9**, 5143–5160.

van Grinsven, H. J. M., Holland, M., Jacobsen, B. H., Klimont, Z., Sutton, M. A. & Willems, W. J. (2013). Costs and benefits of nitrogen for Europe and implications for mitigation. *Environmental Science & Technology* **47**, 3571–3579.

Grzebisz, W., Gaj, R., Sassenrath, G. F., & Halloran, J. M. (2012). Fertilizer use and wheat yield in Central and Eastern European countries from 1986 to 2005 and its implications for developing sustainable fertilizer management practices. *Communications in Soil Science & Plant Analysis* **43**, 2358–2375.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. & Meybeck, A. (2011). *Global Food Losses and Food Waste: Extent, Causes and Prevention*. Rome: FAO.

Hirel, B., Tétu, T., Lea, P. J. & Dubois, F. (2011). Improving nitrogen use efficiency in crops for sustainable agriculture. *Sustainability* **3**, 1452–1485.

Ingram, J. (2008). Agronomist-farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. *Agriculture and Human Values* **25**, 405–418.

Jensen, L. S., Schjoerring, J. K., Van Der Hoek, K. W., Poulsen, H. D., Zevenbergen, J. F., Palliere, C., Lammel, J., Brentrup, F., Jongbloed, A. W., Willems, W. J. & van Grinsven, J. J. M. (2011). Benefits of nitrogen for food, fibre and industrial production. In *The European Nitrogen Assessment* (Eds M. A. Sutton, C. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven & B. Grizzetti), pp. 32–61. Cambridge, UK: Cambridge University Press.

Kok, M. J. T., Bakkes, J. A., Eickhout, B., Manders, A. J. G., van Oorschot, M. M. P., van Vuuren, D. P., van Wees, M. & Westhoek, H. J. (2008). *Lessons from Global Environmental Assessments*. Bilthoven, The Netherlands: PBL-Netherlands Environmental Assessment Agency.

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J. & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy* **87**, 85–156.

Leach, A. M., Galloway, J. N., Bleeker, A., Erisman, J. W., Kohn, R. & Kitzes, J. (2012). A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. *Environmental Development* **1**, 40–66.

Lesschen, J. P., van den Berg, M., Westhoek, H. J., Witzke, H. P. & Oenema, O. (2011). Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science & Technology* **166**, 16–28.

Liu, X., He, P., Jin, J., Zhou, W., Sulewski, G. & Phillips, S. (2011). Yield gaps, indigenous nutrient supply, and nutrient use efficiency of wheat in China. *Agronomy Journal* **103**, 1452–1463.

Nakakubo, T., Tokai, A. & Ohno, K. (2012). Comparative assessment of technological systems for recycling sludge and food waste aimed at greenhouse gas emissions reduction and phosphorus recovery. *Journal of Cleaner Production* **32**, 157–172.

Nishida, C., Uauy, R., Kumanyika, S. & Shetty, P. (2004). The Joint WHO/FAO Expert Consultation on diet, nutrition and the prevention of chronic diseases: process, product and policy implications. *Public Health Nutrition* **7**, 245–250.

Oenema, J., Van Ittersum, M. & Van Keulen, H. (2012). Improving nitrogen management on grassland on commercial pilot dairy farms in the Netherlands. *Agriculture, Ecosystems & Environment* **162**, 116–126.

Offermann, F. & Nieberg, H. (2000). *Economic Performance of Organic Farms in Europe. Organic Farming in Europe: Economics and Policy*, Vol. 5. Stuttgart, Germany: University of Hohenheim.

Olesen, J. E. & Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy* **16**, 239–262.

Oonincx, D. G. A. B. & de Boer, I. J. M. (2012). Environmental impact of the production of mealworms as a protein source for humans – a Life Cycle Assessment. *PLoS ONE* **7**, e51145. doi:10.1371/journal.pone.0051145

Oury, F-X., Godin, C., Malliard, A., Chassin, A., Gardet, O., Giraud, A., Heumez, E., Morlais, J-Y., Rolland, B., Rousset, M., Trottet, M., & Charmet, G. (2012). A study of genetic progress due to selection reveals a negative effect of climate change on bread wheat yield in France. *European Journal of Agronomy* **40**, 28–38.

Parr, M., Grossman, J. M., Reberg-Horton, S. C., Brinton, C. & Crozier, C. (2011). Nitrogen delivery from legume cover crops in no-till organic corn production. *Agronomy Journal* **103**, 1578–1590.

Peltonen-Sainio, P. & Niemi, J. K. (2012). Protein crop production at the northern margin of farming: to boost, or not to boost. *Agricultural & Food Science* **21**, 370–383.

de Ponti, T., Rijk, B. & van Ittersum, M. K. (2012). The crop yield gap between organic and conventional agriculture. *Agricultural Systems* **108**, 1–9.

Powell, J. M., Gourley, C. J. P., Rotz, C. A. & Weaver, D. M. (2010). Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environmental Science & Policy* **13**, 217–228.

Reynolds, M. P., Trethowan, R., Crossa, J., Vargas, M. & Sayre, K. D. (2002). Physiological factors associated with genotype by environment interaction in wheat. *Field Crops Research* **75**, 139–160.

Roberts, T. L. (2009*a*). The role of fertilizer in growing the world's food. *Better Crops* **93**, 12–15.

Roberts, P. (2009*b*). *The End of Food. The Coming Crisis in the World Food Industry. London Evening Standard, 19 June 2008*. London: Bloomsbury.

Schröder, J. J. & Sørensen, P. (2011). *The Role of Mineral Fertilisers in Optimising the Use Efficiency of Manure and Land*. Proceedings 701. Leek, UK: International Fertiliser Society.

Seufert, V., Ramankutty, N. & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature* **485**, 229–232.

Sonneveld, M. P. W. & Bouma, J. (2003). Methodological considerations for nitrogen policies in the Netherlands including a new role of research. *Environmental Science & Policy* **6**, 501–511.

Spiertz, J. H. J. (2010). Nitrogen, sustainable agriculture and food security. A review. *Agronomy and Sustainable Development* **30**, 43–55.

Spiertz, J. H. J., Hamer, R. J., Xu, H., Primo-Martin, C., Don, C. & Van der Putten, P. E. L. (2006). Heat stress in wheat (*Triticum aestivum* L.): Effects on grain growth and quality traits. *European Journal of Agronomy* **25**, 89–95.

Stehfest, E., Bouwman, A. F., van Vuuren, D. P., den Elzen, M. G J., Eickhout, B. & Kabat, P. (2009). Climate benefits of changing diet. *Climatic Change* **95**, 83–102.

Stehfest, E., van den Berg, M., Woltjer, G., Msangi, S. & Westhoek, H. (2013). Options to reduce the environmental effects of livestock production – comparison of two economic models. *Agricultural Systems* **114**, 38–53.

Sutton, M. A., Oenema, O., Erisman, J. W., Leip, A., van Grinsven, H. & Winiwarter, W. (2011*a*). Too much of a good thing. *Nature* **472**, 159–161.

Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, J. J. M. & Grizzetti, B. (2011*b*). *The European Nitrogen Assessment; Sources, Effects and Policy Perspectives*. Cambridge, UK: Cambridge University Press.

Timsina, J., Jat, M. L. & Majumdar, K. (2010). Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. *Plant & Soil* **335**, 65–82.

Verkerk, M. C., Tramper, J., van Trijp, J. C. M. & Martens, D. E. (2007). Insect cells for human food. *Biotechnology Advances* **25**, 198–202.

de Vries, W., Leip, A., Reinds, G. J., Kros, J., Lesschen, J. P. & Bouwman, A. F. (2011*a*). Comparison of land nitrogen budgets for European agriculture by various modeling approaches. *Environmental Pollution* **159**, 3254–3268.

de Vries, W., Kros, J., Reinds, G. J. & Butterbach-Bahl, K. (2011*b*). Quantifying impacts of nitrogen use in European agriculture on global warming potential. *Current Opinion in Environmental Sustainability* **3**, 291–302.

van Vuuren, D. P. & Faber, A. (2009). *Growing Within Limits. A Report to the Global Assembly 2009 of the Club of Rome*. Bilthoven, The Netherlands: PBL-Netherlands Environmental Assessment Agency.

Westhoek, H. J., Rood, G. A., van den Berg, M., Janse, J. H., Nijdam, D. S., Reudink, M. A. & Stehfest, E. E. (2011). *The Protein Puzzle: The Consumption and Production of Meat, Dairy and Fish in the European Union*. The Hague, The Netherlands: European PBL Netherlands Environmental Assessment Agency.