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NITROGEN WORKSHOP SPECIAL ISSUE PAPER

The challenge of feeding 9–10 billion people equitably and sustainably

H. C. J. Godfray

Oxford Martin Programme on the Future of Food, University of Oxford, Department of Zoology, South Parks Road, Oxford OX1 3PS, UK

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SUMMARY

The present paper reviews some of the high-level challenges facing the global food system over the next 40 years, drawing in particular on the UK Government's Foresight Report on the 'Future of Food and Farming', to set the scene for discussions about the sustainable use of nitrogen in agriculture. It reviews the likely demand and supply pressures on the food system, and the pressing requirements to improve sustainability and address the needs of the world's poorest. It argues that the food system is entering a period of radical change, led particularly by growth in demand, which requires action on food production, diet, waste and efficiency, and governance. A key challenge on the supply side is sustainable intensification – producing more from the same amount of land with fewer and less profound negative effects on the environment. Increasing the efficiency of nitrogen fertilizer application will be critical for increasing yields while reducing the many major environmental consequences of leaching and run-off.

INTRODUCTION

Over the last 40 years the price of food, at least as experienced by people living in high-income countries, has been in real terms at historically low levels (Dorward 2011). The major policy issue concerning food supply in developed countries has been how to support farmers who, in a high-wage economy, could not survive if exposed to the price of food on world markets. Investment in agricultural research has declined in the face of over-production, and the rate of increase in yields has slowed (Piesse & Thirtle 2010). The widespread mid-20th century pessimism about the world's ability to feed itself was allayed by the great advances in productivity of the Green Revolution (Evenson & Gollin 2003). Although large numbers of people still suffer from hunger, progress in reducing this number has, until recently, been good and it looked as if the Millennium Development Goals on hunger were going to be met by 2015 (United Nations 2009). Although many voices had raised concerns about the long-term viability of current modes of food production (IAASTD 2008), sustainability has not been a central concern of food producers. Issues of balancing the demand and supply of food, and of keeping food prices within boundaries accepted by society, have not been the dominant political issues that they have been for most of human history.

The last 5 years have seen a sea-change in the attention paid to the security of food supply. The proximate reason for this was the sudden jump in food prices in 2007/08 and their persistence and high volatility since then (Fig. 1).

The origins of the food price spikes are still strongly debated and are likely to be a mixture of long-term trends interacting with more short-term factors (Piesse & Thirtle 2009; HM Government 2010; Swinnen & Squicciarini 2012). Of the former, the secular increase in food demand from a growing, richer population, especially in Southeast Asia, is particularly important. There has also been a long-term trend to reduce food stocks (in both the private and public sectors) so that stock-to-use ratios were at historically low levels. By the end of the first decade of the 21st century the growth in land area that had switched from food

Email: charles.godfray@zoo.ox.ac.uk

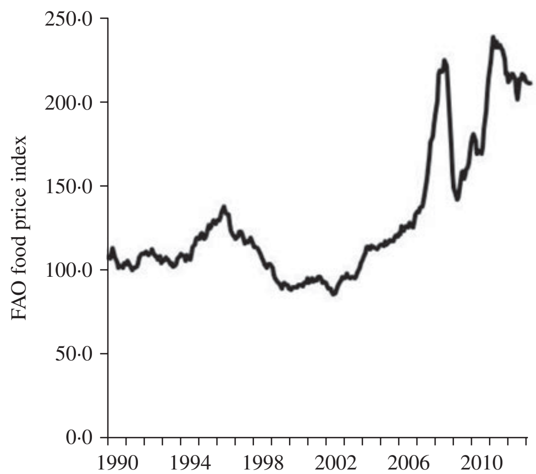

Fig. 1. FAO food price index January 1990 to February 2013.

to biofuel production grew large enough to begin to impact on supply. Of the more short-term factors the flight of investment capital into commodities during the financial crisis, as well as poor harvests in Australia and elsewhere, were also likely to have had some effect.

WHAT MIGHT HAPPEN TO THE FOOD SYSTEM IN THE NEXT 40 YEARS

Further analysis is required to understand the factors influencing current supply but the major food price spikes led to the commissioning of a series of reports that explored what might happen to food supplies over a longer period of time, typically to the mid-21st century (World Bank 2008; Paillard *et al.* 2009; Foresight 2011). Although their conclusions differ in detail, there is general agreement that the global food system is entering a new phase where excess demand will replace excess supply as the dominant policy issue in the rich world, with great risks that recent progress in reducing hunger in the poor world will stall or reverse. Unless action is taken throughout the food system, there is a real likelihood of food price rises that will give rise to political and economic dislocation. The reports also look at food production within an environmental context: not only the challenges of climate change but more generally the negative effects that current food production has on many aspects of the environment. Again there is general agreement that the way food is produced currently undermines the ability to produce food in the future: the natural capital upon which future food production will need to rely is being eaten into. For example, intensive agriculture that negatively affects soil structure reduces the capability of the land to produce food in the future.

The challenges to the food system are both on the demand and supply sides (Godfray *et al.* 2010). As mentioned above, demand will increase because there will be more mouths to feed as populations grow. Current estimates suggest that global populations will plateau somewhere between 9 and 10 billion in the second half of the 21st century, but there is considerable uncertainty and recent estimates have tended to be revised upwards (Lutz & Samir 2010). Average wealth will increase, which in many ways is a good thing (especially as richer societies tend to have lower fertility), but wealthier people demand a more varied diet and typically consume food types that require more resources to produce, for example many types of meat. The dramatic increase in meat consumption in China over the last few decades is already reshaping trade in agricultural commodities (Anderson 2010). This rising demand will need to be met at the same time as a nexus of different factors threaten supply. Perhaps the most critical in the short term is water. Competition for freshwater will become ever fiercer from a growing population, while more will need to be retained to allow the environmental flows that are now understood to be essential to keep ecosystems functioning (Strzepek & Boehlert 2010). Many highly productive irrigated areas currently rely on water pumped from underground aquifers that are being exploited at rates far in excess of the rates at which they are replenished. Currently fertile areas of irrigated agriculture are likely to be abandoned in the next few decades. To produce food most types of agriculture require energy, both directly to power machinery, refrigeration etc., but indirectly in manufacturing agricultural inputs, in particular nitrogen fertilizer. No one can confidently predict energy prices into the future, but energy costs are likely to increase and volatility will probably be much greater (International Energy Agency 2012). Overarching these supply-side issues is the existential challenge of climate change (IPCC 2007). It is currently very hard to predict exactly how climate change will impact future food production. Some regions will actually benefit from climate change and it is likely that the northern boundary of many crops will advance towards the pole. However, it is almost certain that the negative consequences will outweigh (probably strongly outweigh), the positive. Temperature and rainfall patterns will change and adapting to these conditions will be a major challenge for farmers. The frequency of extreme events will increase, with more storms, floods and droughts, and these are likely to affect larger spatial areas. In some places, most likely the arid tropics, agriculture or pastoralism may no longer be possible (Gornall *et al.* 2010).

What might these supply and demand pressures mean to prices? Given that food is at the present time relatively cheap and people in the future will be wealthier, a modest increase in prices that consumers can afford might actually stimulate more investment and innovation in food production. Predicting future food prices is hugely difficult and a craft rather than a science. It is largely done using economic models that assume equilibrium conditions – that prices adjust quickly to supply and demand in a world where all actors act rationally. They are essentially the only tools available, although their projections must be treated with great caution. One of the best models available is called 'IMPACT' and is operated by the International Food Policy Research Institute in Washington (Rosegrant *et al.* 2008). Not only does it have a core economic module, but it has further components that integrate expected climate change scenarios as well as competition for water in the world's river basins. IMPACT can try to predict what happens to food prices in a world where current trends in the global food system continue and it is pretty much business as usual, or the same world but with climate change. The results are disturbing (Nelson *et al.* 2009, 2010). In the absence of climate change, the prices of most commodities rise by *c.* 30–70% between 2000 and 2050. However, in the presence of climate change the price rises are much higher. For example, price rises of well over 100% are projected for staple grains.

It is important to reiterate that these projections should be treated with great caution, and that the precise numbers should not be given undue weight. But at the very least, this and other studies that have come to similar conclusions show that more attention must be paid to food security. Food price rises of the magnitude described in Fig. 2 would result in major political and economic disturbances. Even the relatively modest price increases of the last 5 years resulted in food riots in several African and south Asian states and in the fall of at least one government (Madagascar) (Abbott & Borot de Battisti 2011). The ramifications of a doubling in food prices would be enormous.

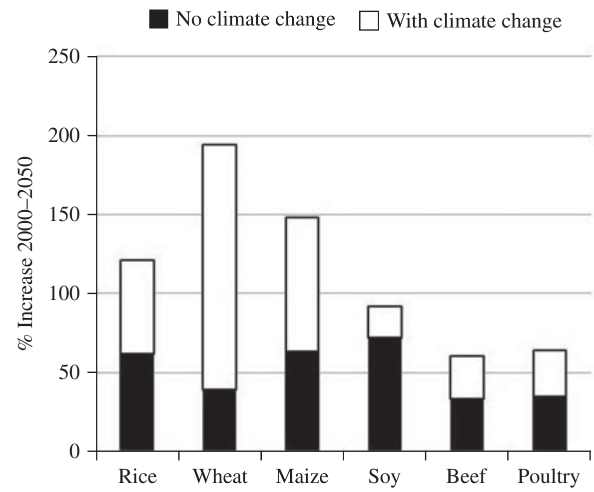

Fig. 2. Projected increases in the price of selected food categories between 2000 and 2050 with and without climate change. Source: Nelson *et al.* (2009).

GENERAL POLICY RESPONSES

What should be the policy response to these challenges? The next two paragraphs describe the recommendations in the UK Government's Foresight study *The Future of Food and Farming* (Foresight 2011), which are in line with most recent analyses. First, the likelihood of there being major problems ahead is sufficiently high that action is needed throughout the food system. Certainly more food will need to be produced, but in addition diets will need to change, especially in the rich world. Second, the food system will need to be made more efficient, its governance improved and the amount of food waste reduced – perhaps 0·30 of all food produced is, for different reasons, never used. Third, sustainability must move centre stage in food policy. The use of inputs needs to be much more efficient to reduce the negative environmental externalities of excessive water consumption and over-use of nitrogen. Food production will need to adapt to climate change and play its part in mitigation – by greater efficiency and by using agricultural land to lock up carbon. Finally, in an ever more globalized world the moral imperative to reduce hunger and poverty is increasingly aligned with the self-interests of the rich world, who will not be able to escape the consequences of famine and food scarcity in least-developed countries.

In the past one of the main options for increasing food supply was to increase the area under cultivation and even today there are considerable tracts of land that might be brought into agriculture. But this land is often forested, wetlands, or ancient grassland.

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Conversion to agriculture would liberate large quantities of greenhouse gases and would risk major exacerbation of climate change. Indeed, food security is intimately linked to climate change because if the former is not achieved it will be much harder to address the latter. The world must thus operate on the assumption that to a good approximation there is no new land for agriculture (although restoration of degraded farmland will often be a priority). Therefore, more must be produced from the same area of land, and this must be done with less effect on the environment. This has been called sustainable intensification (Royal Society 2009) and working out how it may be achieved is the greatest supply-side challenge in the coming decades. Much can be done using existing knowledge, especially if a pluralistic approach is taken, picking the best of all types of agricultural practice, from advanced conventional, through organic and agroecological approaches to learning from the experience and knowledge of indigenous peoples. But new research is also needed, not only to increase yield and productivity but also to maintain current yields in the face of new challenges from global change, from biological challenges such as weeds, pests and diseases that are continually evolving to exploit crops and livestock. It will also be important to address the particular needs of the world's poorest, who have not benefitted from the scientific advances enjoyed by more wealthy food producers.

NITROGEN AND FOOD SECURITY

Nitrogen is one of the most important requirements for plant growth and the invention of the Haber–Bosch process in the early 20th century that allowed for the relatively cheap manufacture of artificial fertilizers must rank as one of the most important scientific breakthroughs of all time (Smil 2001). Cheap artificial fertilizers enabled the Green Revolution to occur and for hunger to be ended in many parts of the world (Evenson & Gollin 2003). Nitrogen (N) is also the single most important environmental pollutant produced by agriculture: nitrates entering the hydrological cycle contaminate human drinking water and pollute rivers, lakes and the ocean, often leading to drastic reductions in biodiversity through eutrophication. Ammonia and other nitrogen compounds enter the atmosphere from farmland and are deposited on natural habitats, altering the ecological balance and in some areas rendering impossible the persistence of the highly diverse plant communities often associated with low nutrient soils (Vitousek *et al.* 1997). Agriculturally derived nitrous oxide (N_2O) is directly emitted from N fertilizer application, N deposited by domesticated animals, nitrogen fixation and mineralization of N residues in soils. In addition, agriculture contributes significantly to the emission of carbon dioxide and methane (Stern 2007). Nitrogen is both bane and boon to mankind (Sutton *et al.* 2013) (and see also studies carried out under the aegises of the European Nitrogen Assessment, http://www.nine-esf.org/node/342, and the International Nitrogen Initiative http://www.initrogen.org).

What are the challenges to the research community involved in nitrogen as the world grapples with food security and the need for sustainable intensification? The first is straightforward and obvious – nitrogen needs to be used more efficiently. There are at least four different strands to increasing efficiency.

There is much that can be done with existing knowledge, especially if techniques from all types of agriculture are considered (Dawson & Hilton 2011). Many agronomic techniques for different crops and cropping systems have been developed that get the fertilizer to the places where it is needed by the crop and at the right times, as well as retaining nitrogen in the field and reducing losses (Day 2011). These methods involve reduced application of artificial fertilizer and the more efficient use of manures and nitrogen-fixing plants (including grass–clover leys and legume rotations). The barriers to the wider uptake of these methods are often insufficient skills and human capital, particularly acute in areas where extension services are poorly developed (Foresight 2011).

Increasing nitrogen efficiency should be a major goal of agronomic research. At the more high-technology end of the research spectrum different forms of precision agriculture can greatly reduce the amount of fertilizer that needs to be applied, while plants can be bred (using conventional and GM techniques) to take up and utilize nitrogen more efficiently (Dunwell 2011). Looking further into the future it may be possible to engineer nitrogen fixation into grains and other crops. High-technology research is attractive to the private sector as it generates intellectual property (IP) but the importance of low-technology research to improve efficiency through better farming practices and soil management is equally important and will probably require public funding (IAASTD 2008).

The behavioural economics of fertilizer application are complex and often not properly appreciated. Incorrect incentives can be set, such as in China where in some places extension workers were paid by kilogram of fertilizer offloaded on farmers, leading to dire pollution and in some cases crop stunting by nitrogen toxicity (Conway 2012). Individual farmers will sometimes apply more fertilizer than economically rational because they are risk averse, or just because it is perceived as the right thing to do. Fertilizer manufacturers clearly have no interest in lessening this behaviour.

Nitrogen application is a classic example of an action whose benefits are reaped by the farmer but whose harm is experienced by other people, for example people drinking water from the same catchment, or the global population in the case of greenhouse gas emissions. These are negative externalities whose costs do not influence farmer behaviour. There are different ways that these negative externalities can be reduced. The major one in most developed countries is through regulation (for example the EU Nitrates Directive and Water Framework Directive). An alternative would be to 'internalize the externalities' by for example a nitrogen tax, although the effect this would have on food prices would need careful attention (Bateman *et al*. 2011).

Increasing efficiency without decreasing yields is an uncontroversial example of a 'win–win' situation, but by how much should yields be sacrificed to reduce negative externalities (typically in high-income countries) or increased pollution accepted as a price for increased yield (for example in low-income countries)? There is no simple answer to this as the amount of food the world will need to produce in the coming decades depends on progress made on the demand side (restraining population growth, changing diets), and on efficiency (such as reducing waste) and better governance. But in thinking about these issues it is important to take several things into account.

First, the critical issue in comparing farming systems is not kg N fertilizer/ha or pollutant loading/ha but kg N fertilizer/kg food produced. There are indirect consequences of reducing yields that must be considered in assessing alternatives. The consequences for global greenhouse gas emissions of the Green Revolution and in particular the direct and indirect effects of increased nitrogen use (the latter including, for example, the energy used in fertilizer application and the Haber–Bosch process) are rightly highlighted as an issue demanding greater efficiency. Yet if the same amount of food was produced through extensification, and in particular through land conversion, the greenhouse gas emissions would have been much worse (Burney *et al*. 2010). A study comparing land conversion and increased nitrogen application as alternative means of increasing substantially food supply by mid-century again came down firmly in favour of fertilizers (Tilman *et al*. 2011). Conversion of land can also have drastic effects on biodiversity and for some habitat types, tropical rainforests in particular, there is a growing evidence base that land 'sparing' is a better strategy to conserve biodiversity than land 'sharing' (Phalan *et al*. 2011). Such strategies will require both elevated yields on existing farmland, and a land use governance system that delivers 'spared land' in the face of strong and conflicting contrary interests. Second, there is evidence that subsidising fertilizers in least developed countries may stimulate agriculture to move from subsistence to small business scales (Dorward & Chirwa 2011). It may increase local food production, increase local incomes, and perhaps put money into sections of society that are hard to reach through other routes. But there are potential negative consequences that it will be important to try to minimize. Increased nitrogen application may lead to pollution, especially if subsidies are such that there are few incentives to be efficient. Input subsidies clearly distort markets and world trade negotiations are aimed at reducing them, although transitory special arrangements are allowed for poor nations. Nevertheless, as some countries are finding, removing subsidies can be politically very difficult, even when they are becoming a drain on national finances (Wiggins & Brooks 2010). More economic and political science research on fertilizer subsidies would be helpful.

CONCLUSIONS

The last 50 years have been unusual in human history, in that for large parts of the world food has been plentiful and cheap and a low priority for governments and policy makers. The next 50 years will be unusual for other reasons: it is highly likely (but not certain) that human populations will peak while mankind will come to dominate virtually all the biogeochemical cycles, including the nitrogen cycle. But though population growth will decelerate there will still be many more (and more wealthy) mouths to feed, at a time when competition for water and land will be intensive and the effects of climate change becoming stronger. Demand will need to be moderated, waste reduced, and the governance of the food system will need to be improved, but in addition more will need to be grown with less effect on the environment. A greater understanding of how nitrogen, in its many forms, can be used to increase yields in ways that do not damage the environment and compromise future food production (and other ecosystem services) will be critical to achieve sustainable food security.

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