Science Progress (2015), 98(4), 379–390
Paper 1500147 doi:10.3184/003685015X14437845647018

Nitrogen, phosphorus, carbon and population

BERNARD GILLAND

Bernard Gilland is a British retired civil engineer. He graduated from University College London in 1957. From 1968 until 1986 he was a civil engineer with the Danish State Railway, Copenhagen, and then worked for the Danish Highways Authority until 1993. He is the author of a book entitled *The next seventy years*, and has also contributed to many professional journals. He lives in Copenhagen, Denmark and may be contacted by E-mail at bernardgilland1@gmail.com

ABSTRACT

Population growth makes food production increase necessary; economic growth increases demand for animal products and livestock feed. As further increase of the cropland area is ecologically undesirable, it is necessary to increase crop yields; this requires, inter alia, more nitrogen and phosphorus fertiliser, despite the environmental problems which this will exacerbate. It is probable that a satisfactory food supply and an environmentally benign agriculture worldwide cannot be achieved without reducing population to approximately three billion. The reduction could be achieved by 2200 if the total fertility rate – currently 2.5 – declined to 1.5 as a world average by 2050, and remained at that level until 2200, but the probability of such a global fertility trajectory is close to zero. It will also be necessary to replace fossil energy by nuclear and renewable energy in order to stabilise atmospheric carbon dioxide concentration, but the phase-out cannot be completed until the 22nd century, when the atmospheric concentration will be approximately 50% above the 2015 level of 400 ppm.

Keywords: *population, nitrogen fertiliser, phosphorus fertiliser, nonfossil energy, climate change*

Nitrogen fertiliser

Nitrogen constitutes 16% of protein; the protein content of cereal grain averages 10%; the average nitrogen content of cereal grain is thus 1.6%. The total amount of nitrogen in the grain, stalk and leaves corresponds to slightly more than 2% of the grain weight. Nitrogen in a form utilisable by crop plants is fixed by soil micro-organisms, released by crop residues, deposited by rainfall (from lightning and fossil fuel emission) and supplied by farmyard manure. The use of chemical fertilisers enables much higher yields to be obtained, although the efficiency of nitrogen fertiliser uptake by cereal crops is roughly 50% as a global average. As shown in Box 1, the global incremental yield-nitrogen ratio for cereals is approx. 25; the average ratio with 100% nitrogen uptake efficiency is almost 50. The ratio for rice is 62, maize 56, sorghum 45, barley 38, oats 33, rye 32, winter wheat 31, millet 28, spring wheat 27 [1].

At the International Center for Maize and Wheat Improvement, agronomist Norman Borlaug bred wheat varieties (dwarf wheat) that respond to heavy applications of chemical fertilisers; the resulting yield increases are known as the Green Revolution. Borlaug was awarded the Nobel Peace Prize in 1970. In his acceptance speech he said: "The Green Revolution has won a temporary success in man's war against hunger and deprivation; it has given man a breathing space. If fully implemented, the Revolution can provide sufficient food for sustenance during the next three decades. But the frightening power of human reproduction must also be curbed; otherwise the success of the Green Revolution will be ephemeral only" [3]. A few years later, he stated that " no one is more concerned about the disastrous consequences of rampant population growth than I am" (personal communication, 14 January 1976). In 2000, Borlaug extended the "breathing space" to 2025; he was confident that a world population of 8 billion could be adequately fed[4].

The Green Revolution has succeeded beyond all expectation. The world average wheat yield has increased from 1160 kg ha^{-1} in 1956[5] to 3,260 kg ha^{-1} in 2013 [6]. Varieties of rice bred at the International Rice Research Institute have raised the world average paddy yield from 1,860 kg ha^{-1} in 1956 to 4,530 kg ha^{-1} in 2013. Hybrid maize, first bred by Illinois farmer Lester Pfister, has raised the average maize yield from 1,720 kg ha^{-1} in 1956 to 5,520 kg ha^{-1} in 2013.

These yield increases are not only the result of plant breeding, but also of increasing applications of fertilisers and pesticides, expansion of the irrigated area and the rising atmospheric carbon dioxide concentration.

Box 1 The incremental yield–nitrogen ratio in 2014 is calculated as follows:

- Global cereal yield 3,800 kg ha^{-1}
- Basal cereal yield (1961 – 1965 average + 10%) 1,600 kg ha^{-1}
- Yield from N fertiliser = 3800 – 1600 = 2,200 kg ha^{-1}
- Global nitrogen application on cereals = 114 × 0.55 = 63 Mt
- Cereal area 720 Mha
- Average nitrogen application on cereals 87 kg ha^{-1}
- Incremental yield–nitrogen ratio = 2,200 / 87 = 25
- Cereal yields of up to 2,500 kg ha^{-1} were obtained in the Netherlands as far back as 1850, but the world average yield without inorganic fertiliser would be much lower, chiefly due to variation in soil quality and moisture availability[44].

The world average supply of food energy in 2011 was 2,868 kcal per capita per day, and the supply of protein from meat, dairy products, eggs and marine products has risen to 32 g per capita per day (507 kcal food of animal origin per day), or 40% of the total protein supply[6]; both calories and animal protein are at record highs. Inequalities between countries and income classes have resulted in the numbers of the overweight exceeding those of the underfed.

The global nitrogen demand for agriculture in 2050 can be estimated at 150 – 166 Mton [Box 2]. Galloway *et al.* [7] estimate it at 135 Mton. Sutton *et al.*[8] estimate it at 80 – 190 Mton, with a "mid" value of 140 Mton. Winiwarter *et al.*[9] conclude: "Expectations regarding the future of the nitrogen cycle in the 21st century therefore range from a slight overall decrease in the anthropogenic impact to a strong increase. Despite the nitrogen-related problems already experienced, we need to expect the situation to deteriorate rather than to improve".

Increasing nitrogen fertiliser application will increase nitrogen runoff to rivers, thereby increasing eutrophication of lakes, estuaries and coastal waters and creating hypoxic ("dead") zones that cannot support marine life. These zones now number over 400, with a total area of 250,000 km^2 [13]. Part of the fertiliser volatilises as ammonia and nitrous oxide, the latter a greenhouse gas. Cassman *et al.*[14] conclude that "the dual goals of meeting food demand while protecting the environment from excess reactive nitrogen is one of the greatest challenges facing humankind".

Globally, nitrogen fertiliser applied in 2014 had a nitrogen content of 114 Mton [15]. It is produced as ammonia, using Haber–Bosch synthesis; the feedstock is natural gas, except in China, where coal is used. The most efficient ammonia plants consume 33 MJ per kg N; the theoretical minimum energy requirement is 23 MJ per kg N. Conversion of ammonia to urea, which is more

Box 2 The global nitrogen demand for agriculture in 2050 can be estimated as follows:

- Basal global cereal yield 1,600 kg ha^{-1} [Box 1]
- Global incremental yield/nitrogen ratio 2014 25 [Box 1]
- Cereal area 2050 [10] 763 Mha
- Total nitrogen consumption = 1.82 times the amount applied to cereals[11]
- Global cereal yield 2050 = 4,300 kg ha^{-1} [10]
- Cereal nitrogen application 2050 = (4,300 – 16,00) / 25 = 108 kg ha^{-1}
- Total nitrogen application on cereals 2050 = 0.108 × 763 = 82 Mton
- Total nitrogen consumption 2050 = 82 × 1.82 = 150 Mton
- A global cereal production in 2050 of 3500 Mton [12], 220 Mton higher than the Alexandratos–Bruinsma projection[10], would probably require a total nitrogen consumption of 150 + 1.82(220 / 25) = 166 Mton.

convenient to use than ammonia, adds 10 MJ per kg N [2]. Nitrogen fertiliser production currently consumes the equivalent of 4% of the world's natural gas, and its application accounts for more than half of world cereal production. Production of Haber–Bosch ammonia began in 1913 at Oppau, Germany; for some years thereafter, the ammonia was mainly used in the manufacture of explosives. The Nobel Prize was awarded to Fritz Haber in 1918 and to Carl Bosch in 1931.

Ammonia can also be produced electrically by combining atmospheric nitrogen with electrolytic hydrogen; the electricity consumption at the Glomfjord plant in Norway around 1980 was 13 kWh (47 MJ) per kg N. Production of 114 Mtons of nitrogen fertiliser electrically would therefore require 1500 TWh, or 6.5% of world electricity generation in 2013 (23,000 TWh). The price of nitrogen produced by this method would be in the same ballpark as the U.S. price in June 2015, $640 per metric ton N as urea. Ammonia was produced electrically in Norway from 1929 to the 1980s, using extremely cheap hydroelectricity, but natural gas has replaced it.

The total on-farm energy consumed per hectare per growing season in intensive cereal cultivation is roughly three times the energy consumed in the production of the applied nitrogen fertiliser, and the off-farm energy consumed in processing, packaging, storage, transportation and cooking is larger than the on-farm energy.

Non-fossil energy

It is virtually certain that global electricity generation will increase more rapidly than primary energy consumption in the next few decades. It is also virtually certain that non-fossil electricity will account for an increasing fraction of electricity generation. World electricity generation in 2040 is projected by the International Energy Agency at 40,000 TWh (billion kWh), of which fossil fuels account for 56%, nuclear 12%, and renewables 32% [16]. Although the fossil fraction is projected to decline from the current 67%, the absolute amount will rise from 15,000 TWh today to 22,000 TWh.

Nuclear power is the only readily available large-scale alternative to fossil fuels for generation of base-load electricity (the fraction of total generation that is needed 24 hours per day all year round, approx. 60%). Theoretically, nuclear fission could meet global electricity demand for several thousand years, but this would involve the conversion of uranium-238 and thorium-232 to the fissile isotopes plutonium-239 and uranium-233 respectively by means of breeder reactors. The development of uranium-238 breeders has stalled for political reasons, but development of thorium-232 breeders continues. Nuclear fission is currently based on uranium-235, the only natural fissile isotope, present in natural uranium at a concentration of 0.7%.

A major problem with nuclear is finding acceptable locations for the permanent sequestration of radioactive fission products and transuranic elements; the problem is not technical, but psychological – the NIMBY (not in my back yard) syndrome. Nuclear scientist James Conca[17] has pointed out that "most people cannot distinguish between nuclear energy and nuclear weapons and that is the root of the misconceptions of nuclear energy and nuclear waste".

The nuclear generation of 2,570 TWh in 2013 is projected to rise to 4,800 TWh in 2040; this projection is optimistic, as all reactors commissioned earlier than 1980, as well as some commissioned in the 1980s, will have been retired by 2040. The construction cost of a nuclear power plant in 2013 was approx. $5,500 per kWe generating capacity, corresponding to a capital investment-annual output ratio (CIAOR) of $700 million per TWh per year. The largest reactors (1,500 MWe generating capacity) can produce up to 12 TWh per year.

If fusion reactors (based on the fusion of deuterium and lithium-6 to form helium) ever become practical, they would produce energy in discontinuous bursts, and therefore be unsuited for continuous electricity generation; however, they could be used as breeders for producing fissile isotopes (the fusion-fission hybrid). The complete replacement of nuclear fission by nuclear fusion is a remote possibility. The only fusion energy source likely to contribute to global energy supply is the Sun, which converts mass to energy at a rate of 4 million tons per second, and will continue to do so for several billion years.

Theoretically, solar energy could meet global electricity demand indefinitely (provided that a satisfactory method of electricity storage is found), but solar power plants, both thermal and photovoltaic, have a high CIAOR. The 392 MWe Ivanpah CSP (concentrated solar power) plant in California, commissioned in January 2014, cost $2.2 billion and the expected generation is 1.06 TWh per year. (Mainly as a result of cloudy weather, production in May – August 2014 was only 0.19 TWh, less than half the expected production in that period). The plant is permitted to use 10,600 metric tons of natural gas per year for the daily start-up. The 280 MW Solana parabolic trough CSP plant in Arizona, commissioned in 2013, cost $2 billion; the planned annual output is 0.944 TWh; generation in 2014 was 0.604 TWh.

The rival type of solar power plant is based on photovoltaic (PV) cells. The 550 MWe Topaz PV plant in San Luis Obispo County, California was commissioned in 2014; the construction cost was $2.5 billion and the expected generation is 1.10 TWh per year. The CIAOR for solar power plants is thus more than $2 billion per TWh per year. Photovoltaic cells do not last as long as nuclear reactors and also give reduced output as they age[18].

The 12,600 MWe Itaipu hydropower plant (Brazil–Paraguay), completed in 1991, generated an average of 92 TWh per year in 2005 – 2014 (approximately equal to the annual generation of China's Three Gorges plant). The construction cost was $20 billion, which corresponds to approx. $30 billion today. The average CIAOR for large hydropower plants in OECD countries is roughly

$500 million per TWh per year. The global hydroelectric potential is approx. 9000 TWh per year, over 10% of the energy dissipated annually by the world's rivers. Global hydroelectric generation in 2014 was 3900 TWh [19]; it is projected at 6400 TWh in 2040.

Electricity generated by wind turbines fluctuates rapidly between zero and maximum, and cannot exceed about 20% of the total annual generation for a national grid. Wind power in 2040 could reach 10% of the annual global demand. Other renewables – geothermal, biomass, tidal and wave energy – will remain minor sources of electricity.

With an interest rate of 5% and an amortisation period of 25 years, the annual debt service would amount to 7% of the construction cost. The cost of solar PV electricity (based on the design output and excluding operation and maintenance) would then be 14 US cents per kWh), of nuclear electricity 5 cents (8 cents including operation, maintenance and fuel), and of hydroelectricity 4 cents (excluding operation and maintenance).

Carbon dioxide and climate change

Of the global carbon dioxide emission from fossil fuel combustion, cement production and land use change, about 46% remains airborne; the balance is taken up by vegetation and the oceans[20]. Atmospheric carbon dioxide concentration (400 ppmv in 2015, increasing at an average 2.1 ppmv per year) cannot be stabilised at a level lower than double the concentration of 280 ppmv in 1800, be the consequences what they may. In 1906, the Swedish scientist S.A. Arrhenius calculated that a doubling of the atmospheric carbon dioxide concentration (then ~300 ppmv) would result in a global temperature rise of 2.1 K. According to the Intergovernmental Panel on Climate Change[21], the transient climate response, defined as the change in global mean surface temperature at the time when atmospheric carbon dioxide concentration has doubled after increasing at 1% annually, is likely to be in the range 1.5–3.0 K. Another recent estimate is 1.05–1.80 K, with a median value of 1.33 K [22].

Since 1993, the rise in mean sea level has been determined by satellite altimetry; the rise in 1993–2014 was linear at 3.3 ± 0.4 mm per year [23] despite rising atmospheric carbon dioxide concentration throughout the period and rising global surface temperature during the first half of the period [24]. Part of the sea level rise is undoubtedly caused by human activity, but this activity is not confined to fossil fuel combustion; it is estimated that depletion of aquifers and lowering of groundwater levels account for a significant fraction of the 1,200 km^3 annual increase in the volume of the oceans. The net melting rate of the Greenland and Antarctic glaciers and ice sheets has been estimated at 503 km^3 per year [25], thereby adding 460 km^3 to the volume of the oceans, corresponding to 40% of the total sea level rise. Direct measurements of ocean warming above 2,000 m depth account for about 32% of the observed annual rate of global mean sea level rise [26].

Sea level rise resulting from temperature rise has occurred many times in interglacials; two rises, each of several metres, took place towards the end of the Eem interglacial, over 115,000 years ago. The Eem interglacial was followed by an ice age that lasted 100,000 years; from 30,000 to 19,000 years ago sea level was 120 – 135 m lower than it is now. Sea level then rose by about 120 m over a period of about 6,000 years. The rate of rise slowed down, but did not fall to zero, about 9,000 years ago. The average natural rise in mean sea level from glacier melting in 1851 – 2010 is estimated at 0.6 mm per year[27]. Anthropogenic global warming probably accounts for more than half the current sea level rise.

The discovery of an exploitable oil or gas field always gives rise to jubilation; until it results in a decision to let the oil or gas remain underground, stabilisation of atmospheric carbon dioxide concentration will remain a distant prospect. The ultimately recoverable fossil fuel resources from the beginning to the end of the fossil fuel era have been estimated by Mohr *et al.*[28] at between 48.4 zettajoules (ZJ) and 121.5 ZJ, with a "best guess" of 75.7 ZJ. One ZJ corresponds to 23.9 billion metric tons oil equivalent; the carbon emission from burning fossil fuel depends on the proportions of coal, oil and natural gas; for the "low" estimate the carbon emission is 840 kg per 1,000 kg oil equivalent of fossil fuel, for the "best guess" it is 820 kg, for the "high" estimate it is 760 kg. It is assumed that 50% of the carbon released into the atmosphere remains airborne. One billion tons atmospheric carbon corresponds to 0.469 ppmv of carbon dioxide. The "best guess" for the peak atmospheric carbon dioxide concentration is then given by:

$$280 + (75.7 \times 23.9 \times 0.82 \times 0.50 \times 0.469) = 630 \text{ ppmv.}$$

The magnitude of the task of phasing out fossil fuel can be illustrated by the following calculation:

One hundred nuclear power plants, each of 1,000 MWe, operating at 90% load factor throughout a service life of 60 years, would produce a total of 47,000 TWh electricity. Production of this amount of electricity by coal-fired power plants would result in a carbon emission of 9 Gt. If 50% of this emission remained airborne, it would increase the atmospheric carbon dioxide concentration by 2 ppm. If the 100 nuclear plants replaced coal-fired plants, the ultimate carbon dioxide concentration would, for example, be 628 ppm instead of 630 ppm. If the cumulative consumption of fossil energy reaches 121 ZJ, the peak concentration would be approx. 800 ppmv.

Phosphorus fertiliser

Phosphorus is an essential plant nutrient and a non-renewable resource. When phosphorus production has passed its peak, there will be a massive die-off unless world population has been drastically reduced. Some analysts are optimistic: "IFDC estimates of world phosphate rock reserves and resources indicate that phosphate rock of suitable quality to produce phosphoric acid will be available far into the future. Based on the data reviewed, and assuming current rates of production, phosphate rock concentrate reserves to produce fertiliser will be available for the next 300–400 years" [29]. Others emphasise the great uncertainty in the size of utilisable phosphate resources. According to Mohr and Evans[30], the ultimately recoverable resources (from the beginning of the Industrial Revolution) are at least 2,000 Mton, probably over 4,000 Mton, and possibly over 9,000 Mton. The cumulative production to date is estimated at 950 Mton. Production could peak at 28 Mton in 2011, at 50 Mton in 2027, or at 55 Mton in 2118.

Physicist Charles Galton Darwin[31] was aware of the importance of phosphorus in the long term: "….the future numbers of humanity will depend on the abundance in the surface of the earth of the chemical elements which are necessary for life……Two only deserve comment, nitrogen and phosphorus…. The question of phosphorus is far more serious [than that of nitrogen], though less of it is needed. There are great tracts of land, in particular in Africa, which are permanently deficient in phosphorus, and these can never be raised to the fertility of the more favoured regions, unless large quantities of it can be supplied to them. So it may well be that the future numbers of the human race will depend on the abundance of phosphorus in the earth's surface".

Population

Writing in 1948, mathematician Michael Roberts[32] concluded:"Within a century or so, the world's population will almost certainly be stabilised at something like three thousand millions, which is the utmost that the earth is likely to be able to feed". He had no inkling of the coming Green Revolution, and did not believe that inorganic fertilisers could be more than a short-term palliative.

Economist Nicholas Georgescu-Roegen[33] pointed out that industrial society is based on a "unique mineralogical bonanza", and concluded that "at all times population must remain near the level at which it can be maintained biologically by organic agriculture". The global population that can be maintained by organic agriculture is approximately three billion. This is based on an average grain yield of 1,600 kg ha^{-1} on a harvested area of 750 Mha, and a per capita grain consumption of 400 kg per year. The assumed grain consumption is composed of roughly 150 kg for humans, 150 kg for livestock feed and 100 kg for seed, ethanol, starch, beer, whisky, vodka, *etc*. Sverdrup *et al.*[34] arrive at a similar conclusion by another route: "The sustainable population from a perspective of energy and phosphorus is on the order of 1.5–2.5 billion people on Earth". Norman Borlaug estimated that organic agriculture could feed a population of four billion provided that all animal manure, human waste and crop residues were utilised[4]. Erisman *et al.*[35] estimate that without Haber–Bosch ammonia, world population would now be about 3.5 billion. Agronomists Keith Goulding and Kenneth Cassman agree with Borlaug's estimate (personal communications, September 2015).

The long-term sensitivity of population size to differences in fertility rate has been investigated by Basten, Lutz and Scherbov[36]. They have shown that if the global total fertility rate (TFR, currently 2.5) falls to 1.5 by 2050, and remains at that level, the world population in 2200 would be 2.3 – 2.9 billion, the precise number depending on the assumed life expectancy. A TFR of 1.75 would result in a 2200 population of 5.0 – 6.0 billion; a TFR of 2.00 would result in 9.9 – 11.5 billion. The TFR in 2010 – 2015 is 1.50 or lower in Japan, South Korea, Taiwan, Hong Kong, Singapore, Mauritius and many European countries, including Germany, Italy, Spain, Poland, Ukraine and Romania[37].

Extremely low fertility could result in an even more rapid population decline. South Korea is an example: The TFR declined from 6.0 in 1960 to 2.1 in 1983 and 1.19 in 2013. If fertility remains at this level, the population would decline from 50 million in 2013 to 22 million in 2100; the 65+ age group would then constitute 48% of the population[38]. Life expectancy in 2100 was assumed to be 89.3 years for males, 93.2 years for females (Lee, personal communication, 30 July 2014). With a TFR of ~1.4, the demographic outlook for Japan is similar to that for South Korea. The 2014 population of 127 million is projected to decline to 50 million in 2100, with 41% in the 65+ age group[39]; the UN "low" projection for Japan in 2100 is 53 million[37]. The changes in age distribution have advantages and drawbacks. "Elderly citizens provide a wealth of skills, knowledge, wisdom and mentorship, not fully utilised by governments, companies, communities and families" [40]. The drawbacks include the need to raise the retirement age. Economist Nathan Lewis[41] has pointed out that "a pattern of continuous government deficits and growing total debt can be sustained for some time if nominal GDP is also growing quickly. Alas, this continuous-growth Ponzi does not work well in an environment of population shrinkage".

Population declines in Japan, South Korea, Taiwan and Europe will be far more than counterbalanced by population increases elsewhere. The UN "medium" projection for 2050 is 9.72 billion, rising to 11.21 billion in 2100 [37]. The projection is based on the assumption that the global average TFR will decline to 2.0 in 2095 – 2100. By extrapolation, the peak population will be 11.4 billion around 2120. There is an 80% probability that the 2100 population will be in the range 10.04 – 12.50 billion[37].

China introduced the one-child policy in 1979; it applied only to the urban population. In rural areas, a second child was permitted if the first was a girl. China's population is projected to peak around 2030, and to decline thereafter. In January 2014, the one-child policy was relaxed to permit couples to have a second child if either parent is an only child. In October 2015, China scrapped its one-child policy, allowing all couples to have two children for the first time. The decision to allow families to have two children is designed "to improve the balanced development of population'' and to deal with an ageing population, according to the statement from the Community Party's Central Committee.

An editorial in the Hong Kong newspaper *South China Morning Post* (14 November 2013) comments: "The one-child policy may get some credit for China's economic miracle. But it remains divisive, with a painful legacy of sex determination and abortion, distortion of the birth ratio in favour of boys, an ageing society and the prospect of millions of men without partners". (The birth ratio is 115 males per 100 females, far above the normal 105. The abnormal ratio is only partially the result of the one-child policy, as India has a ratio of 111.) The TFR in China began a steep decline around 1970; it is possible that the decline would have continued even if the one-child policy had not been implemented, but this is a counterfactual that cannot be proved. To discuss whether the aim of China's demographic policy justifies the human costs of its implementation is outside the scope of this paper.

Other developing countries are either unable or unwilling to follow in the wake of China (TFR 1.55), but countries such as Thailand (TFR 1.53) have been able to achieve a similar fertility decline without coercive measures. Many developing countries will pay a high price for their future population growth, especially those in Sub-Saharan Africa, where it is unlikely that the Green Revolution will increase crop yields as it has done in Asia[42]; the poorest countries will not have sufficient foreign exchange for a major increase in food imports, and will become increasingly dependent on foreign aid and emigrants' remittances[43].

Conclusion

It is virtually certain that world population in 2100 will be at least 9 billion. This means an increasing demand for food and energy. This in turn means using more nitrogen and phosphorus fertiliser and would mean a higher fossil fuel consumption unless nuclear and renewable energy production is increased at unprecedented rates. Both fertiliser and fossil fuel create ecological problems. These problems can be mitigated by increasing the efficiency of nitrogen use, the efficiency of conversion of fossil energy to electricity, and the ratio of GDP to energy consumption, but there are limits to these increases. Reducing world population to approx. 3 billion would make it possible to phase out both nitrogen fertiliser and fossil fuel by the end of the 22nd century. The price would be a long period in which the TFR would have to be 1.5 or lower, and about 40% of the population would be in the 65+ age group. If world population reduction to a sustainable level is not achieved by fertility decline, it is probable that sustainability will be attained by mortality rise. The risks involved in global population rising to 11 billion are greater than those involved in a doubling of the pre-industrial atmospheric carbon dioxide concentration. Striving to bring about a global population peak by 2070 (which implies a peak population of about 9.6 billion) is more urgent than attempting to bring about a reduction, regardless of cost, in the global carbon dioxide emission.

Acknowledgements

I thank Professor Ken Cassman (University of Nebraska at Lincoln), Dr Hans-Joachim Braun (International Center for Maize and Wheat Improvement) and Dr Jane O'Sullivan (University of Queensland) for comments that enabled me to improve the paper.

References

1. IPNI (2014) International Plant Nutrition Institute. www.ipni.net
2. Smil, V. (2008). *Energy in nature and society*. MIT Press, Boston.
3. Borlaug, N. (1972) *The green revolution, peace and humanity*. CIMMYT Reprint and Translation Series, No. 3.
4. Bailey, R. (2000) *Reason*, April 2000. http://reason.com
5. Stamp, L.D. (1968) *Our developing world.* Revised edn. Faber and Faber, London.
6. FAO (2015) Food and Agriculture Organization. www.fao.org
7. Galloway, J.N. *et al.* (2004) *Biogeochemistry,* **70**, 153–226.
8. Sutton, M.A. *et al.* (2013) *Our Nutrient World: The challenge to produce more food and energy with less pollution*. Centre for Ecology and Hydrology, Edinburgh, on behalf of the Global Partnership on Nutrient Management and International Nitrogen Initiative. http://initrogen.org
9. Winiwarter,W., Erisman, J.W., Galloway, J.N., Klimont, Z. and Sutton, M.A. (2013) *Climat. Change,* **120**, 889–901.
10. Alexandratos, N. and Bruinsma, J. (2012) *World agriculture towards 2030/2050*: The 2012 Revision. FAO, ESA Working Paper No. 12-03.
11. Heffer, P. (2013) Assessment of Fertilizer Use by Crop at the Global Level 2010–2010/11. International Fertilizer Industry Association, Paris. www.fertilizer.org
12. Fischer, R.A. (2012) Progress and prospects for crop yield across the globe: can yield increase continue to feed the world? CSIRO Plant Industry, Canberra, Australia. www.sap.uchile.cl
13. Diaz, B. (2008) Dead zones. Virginia Institute of Marine Science. www.vims.edu
14. Cassman, K.G., Dobermann, A.R. and Walters, D.T. (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio,* **31**, 132–140. http://digitalcommons.unl.edu/cgi/
15. Heffer, P. and Prud'homme, M. (2014*) Fertilizer Outlook 2014–2018*. International Fertilizer Industry Association, Paris. www.fertilizer.org
16. Patel, S. (2015) IEA: Renewables will overtake coal's share in world power mix by 2040. www.powermag.com
17. Conca, J. (2010) Nuclear waste disposal – not the problem it appears. Nuclear Energy Insider, October 2010. http://analysis.nuclearenergyinsider.com
18. Jordan, D.C. and Kurtz, S.R. (2012) Photovoltaic degradation rates – An analytical review. National Renewable Energy Laboratory. www.nrel.gov
19. BP. (2015). Statistical review of world energy 2015. British Petroleum.
20. Le Quéré, C. *et al.* (2014) *Earth Syst. Sci. Data*, **6**, 235–263. www.earth-syst-sci-data.net/6/235/2014
21. IPCC. 2013. Summary for Policymakers. In: *Climate change 2013: the physical science basis.* Contribution of Working Group 1 to the Fifth Assessment Report of the IPCC. Cambridge University Press, Cambridge and New York. 1 Nov. 2014. www.ipcc.ch
22. Lewis, N. and Curry, J.A. (2014) *Clim. Dyn.,* **45**, 1009–1023.
23. Colorado University (2015). Global mean sea level time series. http://sealevel.colorado.edu
24. Humlum, O. (2015) Climate4you update August 2015. www.climate4you.com
25. Helm, V., Humbert, A. and Miller, H. (2014) *The Cryosphere*, **8**, 1539–1559. www.the-cryosphere.net

26. Llovel, W., Willis, J.K., Landerer, F.W. and Fukumori, I. (2014) *Nature Climate Change*. Doi:10.1038/nclimate2387.
27. Marzeion, B., Cogley, J.G., Richter, K. and Parkes, D. (2014) *Science*, **345**, H.919–921.
28. Mohr, S., Wang, J., Ellem, G., Ward, J. and Giurco, D. (2014) *Fuel,* **141**, 120–135.
29. Van Kauwenbergh, S.J. (2010) World phosphate rock reserves and resources. International Fertilizer Development Center, Muscle Shoals, Alabama. www.ifdc.org
30. Mohr, S. and Evans, G. (2013) Projections of future phosphorus production. Philica.com, Article No. 380. www.resilience.org
31. Darwin, C.G. (1952) *The next million years.* Hart-Davis, London.
32. Roberts, M. (1951) *The estate of man*. Faber & Faber, London.
33. Georgescu-Roegen, N. 1979. Comments on the papers by Daly and Stiglitz. In: Kerry Smith, V. (ed.), *Scarcity and growth reconsidered*, pp. 95–105. Johns Hopkins University Press, Baltimore.
34. Sverdrup, H.U., Koca, D. and Ragnarsdottir, K.V. (2013) *J. Environ. Sci. Eng.,* **B2**, 189–222. www.davidpublishing.com
35. Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. and Winiwarter, W. (2008) *Nature Geosci.,* **1**, 636–639.
36. Basten, S., Lutz, W. and Scherbov, S. (2013) *Demogr. Res.,* **28**, 1145–1166. www.demographic-research.org
37. UN (2015) World Population Prospects, the 2015 Revision. United Nations Population Division. www.un.org/esa/population
38. Lee, S.S. (2009) Low fertility and policy in Korea. Korea Institute for Health and Social Affairs, Seoul, Republic of Korea. www.neaef.org
39. NIPSSR (2012) *Population projection for Japan: 2011 to 2060*. National Institute of Population and Social Security Research. Tokyo. www.ipss.go.jp
40. Hajkowicz, S., Cook, H. and Littleboy, A. (2012) *Our future world: Global megatrends*. CSIRO, Brisbane, Australia. www.csiro.au
41. Lewis, N. (2014) Economic abundance with shrinking population: Why not? 28 August 2014. www.forbes.com
42. Frison, E. (2008) Indispensable Resources. D+C. www.dandc.eu/en/article/green-revolution-africa-will-depend-biodiversity
43. Alexandratos, N. (2005) *Populat. Devel. Rev.,* **31**, 237–258.
44. Smil, V. (1994) *Popul. Devel. Rev.,* **20**, 255–292.