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Chapter 3

Nitrogen, planetary boundaries, and the metabolic rift: Using metaphor for dietary transitions toward a safe operating space

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"The using up of fertility is a transfer of past capital and of future possibilities to enrich a dishonest present: it is banditry pure and simple. Moreover, it is a particularly mean form of banditry because it involves the robbing of future generations which are not here to defend themselves".
Sir Albert Howard (1947) The Soil and Health, p.63

"Human modification of the N cycle is profound"
Rockström et al (2009a) p.13 of 33

Introduction

This chapter deploys two key metaphors as part of a critical examination of the global agri-food system, in particular, as a way of drawing attention to the wider environmental consequences arising from the deployment of technologies preoccupied with increasing productivity. As chapter one outlined, metaphors are a device, often used unconsciously, where we apply words or phrasing from quite different contexts in order to make sense of a situation. In relation to the food system many of the prevailing metaphors used by business focus upon 'growth', producing more in order to 'feed the world' safely and cheaply. However, for those of us concerned with sustainability the aspiration is to achieve a food 'system' that produces nourishment for all, of course, but also one that operates within the parameters of the biosphere's capabilities. Paying attention to metaphors, then, reminds us to be alert to the different views of the world and the values that are implicit in the framing of problems and their proposed solutions. This chapter makes use of two metaphors that help us to do this, by critically evaluating a technology which has become an apparently indispensable element of the food system: synthetic nitrogen fertiliser.

The first metaphor is to propose that the global agri-food system be regarded as constituting a 'planetary scale metabolic process'. Metabolism is most commonly applied to the human body and refers to the process of converting food intake into energy. Developing this a little further metabolism encompasses the chemical and physical processes by which an organism – or a system - utilises materials to produce energy and other substances necessary for its maintenance and reproduction. Applying metabolism to agriculture allows us to consider the way in which a variety of chemical and biological resources – including soil nutrients and their supplements – are utilised (metabolised) in order to produce the primary foods (and fuels and fibres) on which the human population depends. As agriculture has developed, becoming ever more reliant on energy and mineral resources from the lithosphere and biosphere to sustain and expand production, the metabolic process has grown in complexity and spatial extent such that flows of materials (inputs) and foodstuffs (outputs) cross all kinds of boundaries: ecological, national and planetary.

Consequently, the second metaphor I wish to draw upon here is that of 'planetary boundaries'. The framework of planetary boundaries (PB), as set out by Rockström et al (2009a, 2009b) and by Steffen et al (2015a), draws our attention to nine key Earth system processes. The framework attempts to establish critical thresholds that represent limits to a 'safe operating space' (another metaphor) for human societies. While we examine the scientific aspect of the PB model below, here we should note the metaphorical significance of the term. Clearly the notion of a boundary speaks to an outer limit or ceiling on what is permissible; transgressing this boundary then implies danger, or at least uncertainty about a possible outcome. There has been an important current of work within environmental science around the notion of boundaries and thresholds of which the Club of Rome report, 'Limits to Growth' (Meadows et al., 1972), was the most prominent. Calculating precise boundaries on levels of resource extraction and 'reserves' (consider 'Peak Oil') or on volumes of waste streams entering the environment (e.g. greenhouse gas emissions) has been an increasingly important but scientifically vexed endeavour since that time (and as we will see in relation to PB). However, it should be acknowledged that in contrast to a scientific view of 'limits' stands the 'cornucopian' metaphor (the horn of plenty) representing a belief in human ingenuity and our innate capacity to develop new technologies that will overcome foreseeable constraints. This approach is especially prevalent amongst proponents of the existing agri-food system who point out that it has delivered more calories for a lower proportion of consumer spending than at any time in human history. Moreover, times of rising food prices (as during the financial crisis of 2008-12) present justification for new technologies – plant and animal genetic engineering, precision farming – in order to ensure food security. Here, the pursuit of productivity overshadows concerns for the environment as the problem is framed as a supply shortage rather than failings of the market (incapacity of the poor to register a demand for food). Each side, then, deploys their metaphors accordingly in order to gain ascendancy in the battle of ideas and moral suasion.

Today, the technological, economic and political capabilities of the modern food system have enabled world population to grow to around 7.6 billion people, though at least two-fifths do not eat or absorb sufficient nutrients for a healthy life (IFPRI, 2016). Yet while more cultivated food is produced today than at any time hitherto, the global ecological costs of doing so are mounting quickly and these can be identified across a range of key biophysical processes.

For example, there are rising environmental concerns at the contribution of industrialised food production systems to land use change, habitat destruction and loss of biodiversity (Campbell et al., 2017; Foley et al., 2011); as well as to climate change through emissions of greenhouse gases (Vermeulen et al., 2012; Tilman and Clark, 2014; Niles et al., 2018). A quite different anxiety is emerging from analysis that has followed the development of the notion of 'virtual water' – i.e. the amount of water required to produce a certain volume of food and which might therefore be regarded as virtually embedded in it (Chapagain and Hoekstra, 2008; Allan, 2011). Here, the mapping of international flows has revealed the considerable risk posed by local water scarcity to downstream economies through globalised supply chains (Qu et al., 2018). Yet another, and less well-known, process has been the disruption to the global biogeochemical cycles of nitrogen and potassium, and it is this agri-food driven development that forms the primary focus of this chapter.

The framework of planetary boundaries draws our attention to nine key Earth system processes each of which are being affected by human activity[i]; PB therefore make evident the ways in which anthropogenic activity is pressing against biospheric limits. Of the nine processes, for three – climate change, biodiversity loss, and nitrogen and phosphorous flows – there is evidence of a clear breaching of their respective boundaries. However, there is reluctance on the part of the proponents of PBs to suggest that we have passed a critical 'tipping point' and, subsequently, there has been an effort to reframe the notion of 'planetary limits' in relation to a 'safe operating space' for humankind while recognising that these 'planetary' processes have rather different regional characteristics. However, the metaphor of PBs clearly serves to convey a sense that human activity is disrupting planetary scale processes.

While climate change has arguably become the single most important issue of our time and around which there is considerable scientific consensus about the process, this cannot be said to extend to the notion of a safe boundary limit. For while a 2 °C warming target may be perceived by the public as a universally accepted goal, no scientific assessment has clearly justified or defended this target as a safe level of warming (Knutti et al., 2016). This consequently raises profound questions regarding the atmospheric concentration of CO_2 and whether its planetary boundary should be set at 350 or 450 parts per million by volume (Steffen et al., 2015a). Other planetary scale processes are even less easily quantified, may be less directly connected to specific drivers, or their boundaries similarly under dispute (Jaramillo and Destouni, 2015). One process that <u>can</u> be attributed to anthropogenic activity, not least because it has come to underpin the survival of the species through food production, is that of the biogeochemical flow of nitrogen (N).

The development of the Haber-Bosch process early in the 20th century to synthesise atmospheric nitrogen (N_2) into the form of fertiliser and thereby provide a source of reactive nitrogen (N_r) that could be taken up by crops has had a transformative effect on the global nitrogen cycle (Galloway et al., 2002). Together with the subsequent development of fertiliser-responsive high yielding seeds, it has been argued that without the Haber-Bosch synthesis about 40 percent of the world's current population could not be fed (Smil, 2002). Yet it has also been estimated that only 43 percent of the reactive nitrogen applied to cropland worldwide is converted into harvested products and that more than half is lost to the environment (Billen et al., 2014). The global alteration of the N cycle leads to many different, cascading effects on human and ecosystem health (Galloway and Cowling, 2002). These include nitrate leaching into groundwater which is harmful for populations drawing domestic water supplies from such resources; eutrophication of aquatic ecosystems resulting in fish kills and the creation of coastal 'dead zones' (Van Meter et al., 2018); loss of terrestrial and marine biodiversity; agricultural emissions of ammonia that combine with small particulate matter to create toxic air quality (Lelieveld et al., 2015); and contributions to climate change through N_2O, a potent greenhouse gas. Yet despite representing a large-scale biogeochemical experiment on planetary health it is arguably one of the least recognised environmental issues amongst the general public.

These planetary scale processes, especially those that are approaching – or even transgressing – limits, bring us back to the metaphor of metabolism and a particular application that can be traced back to the Nineteenth century: the notion of 'metabolic rift'. The term has its origins in the work of Karl Marx who used it to highlight the disturbed metabolic interaction between human society and the environment under capitalist production. Given Marx's original concern for the robbing of soil fertility by capitalist agriculture – discussed in more detail below - it seems appropriate to consider the way in which an apparently highly successful solution – the application of large volumes of nitrogen fertiliser capable of restoring levels of this key nutrient - has served to so dramatically disrupt a key global nutrient cycle. Thus, I seek to develop and extend the metaphor of metabolic rift by focussing upon the nitrogen cycle and the ways in which its global disequilibrium has been caused by an agri-inputs industry that has reshaped agriculture around the world. If we are to recover and restore planetary balance in this particular area, then it becomes clear that we must examine the potential for transition not only towards a different model of food production but also examine those dietary patterns that feature foods that are implicated in a high nitrogen loading.

Consequently, following a brief explanation of the notion of metabolic rift, the chapter proceeds to discuss the planetary boundaries framework, in particular examining the changing status of nitrogen within global biogeochemical cycles. This takes us, inevitably, into a discussion of the global food system and its embedded flows of nitrogen. Thus, this chapter is largely concerned with highlighting the fate of nitrogen by exploring the scientific basis of the PB and metabolic models and from here pays rather less attention to the metaphorical implications until we arrive at the conclusion.

The Metabolic Rift: Forms of ecological rupture

Influenced by the scientific writings of Justus von Liebig, regarded as the father of agricultural chemistry, Marx considered how the intensification of agriculture results in the depletion of nutrients from soils, where this failure to replenish nutrient loss - the 'robbing of fertility' - was analogous to the exploitation of the worker (Foster & Magdoff, 2000). Von Liebig's analysis highlighted how nutrients drawn from the soil were carried away by harvested foods to be consumed far away from sites of production with those nutrients not directly utilised by the body then lost in waste streams and urban sewers. This view would suggest that human excrement, humanure, had provided an important - even primary - source of added fertility prior to the nineteenth century, a view challenged by McMichael and Schneider (2010) who highlight the role played by crop and field rotations in restoring nutrient balance. Whether the recovery and return to the land of 'night-soil' would ever have kept pace with nineteenth century urbanisation is not a matter of concern here. But, in its absence, a rising demand for replacement nutrients led to the utilisation of Napoleonic battlefield bones, then to the lucrative trans-Atlantic trade in Peruvian guano – accumulated deposits of seabird droppings on islands off the Peruvian coast - and Chilean nitrates (Foster, 2013).

Von Liebig's experimental work resulted in his identification of nitrogen, potassium and phosphorous as being essential plant nutrients and while his Law of the Minimum noted that yield was constrained by the scarcest mineral, he nonetheless highlighted the critical role performed by nitrogen. This element, N_2, is the most abundant of the gases in our atmosphere, yet in this form it remains chemically and biologically unusable. To create a reactive form of nitrogen, N_r, took the work of later German chemists, principally Fritz Haber and Carl Bosch. The development of the Haber-Bosch process of synthesizing atmospheric nitrogen into ammonia and scaling this into a continuous industrial process has since provided for almost all of the inorganic nitrogen requirements of world agriculture, at around 100 Tg N per year (or 100 M tonnes)[ii].

However, while the metaphor of a metabolic rift - as representing the theft of nutrients from the soil – may appear to be solved by the addition of chemical fertiliser, it is important to recognise that Marx considered the rift to extend beyond resource extraction and to serve as metaphor for a more profound alienation of society from nature under capitalism. For Marx, capitalist production concentrates the historical motive force of society while disturbing the metabolic interaction of humans and the earth (Foster, 2013). In Clark and York's (2005) interpretation of Marx's analysis, they argue that capitalism created a rupture in the metabolic interaction between humans and the Earth, one that was only intensified by large-scale agriculture, long-distance trade, and urban growth. They continue,

"Capitalism is unable to maintain the conditions necessary for the recycling of nutrients. In this capitalism creates a rift in our social metabolism with nature. In fact, the development of capitalism continues to intensify the rift in agriculture and creates rifts in other realms of the society-nature relationship, such as the introduction of artificial fertilizers" (Clark and York, 2005: 399)[iii].

The broadening and deepening of global food production and supply under capitalism and the intensification of multiple rifts with nature extends beyond environmental disruptions. Indeed, particularly during the last half century, profound changes extend beyond the realm of agriculture into the very heart of consumption practices. In this respect, it is possible to develop and apply the metaphor of metabolic rift to represent a more thorough ecological, social and cultural rupture around food systems. For example, Dixon et al (2014) argue that the contemporary metabolic rift extends beyond the disrupted exchange between social and natural systems, and is being propelled by four major ecological ruptures:

1. Depleted agro-ecologies - the environmental support systems to sustain food production - due to bio-physical system degradation including waste generation.

2. An erosion of food sovereignty at the nation state level, due to a reconfiguration of food system governance arrangements and foreign direct investments in food retailing systems.
3. The erosion of cuisines – consisting of knowledge, rules, cooking skills and food provisioning strategies - due to the penetration of corporate interests.
4. Stressed human metabolic states, as a result of easy access to dietary energy together with a lack of physical activity, and the corporate restructuring of local food environments which, in turn, reduces options for obtaining 'good nutritional' diversity. (Dixon et al., 2014: 135)

Although these wider interpretations of metabolic rift are not explored here[iv], Dixon et al's typology serves to highlight the multiple disruptions generated by the industrial agri-food system and how these can serve as the basis for new metaphors. Point four, for example, speaks to the disruption of human metabolism, most visibly manifest in rising levels of body mass and obesity with direct consequences for well-being, arising from multiple changes in the global agri-food system. These stretch from huge increases in agricultural productivity through the development of cheap, processed foodstuffs to changes in retailing which makes energy-rich, nutrient-poor products so ubiquitous. Ultimately, these developments have been underpinned by changes in the realm of agricultural production and we explore these through the lens of planetary boundaries.

Planetary Boundaries

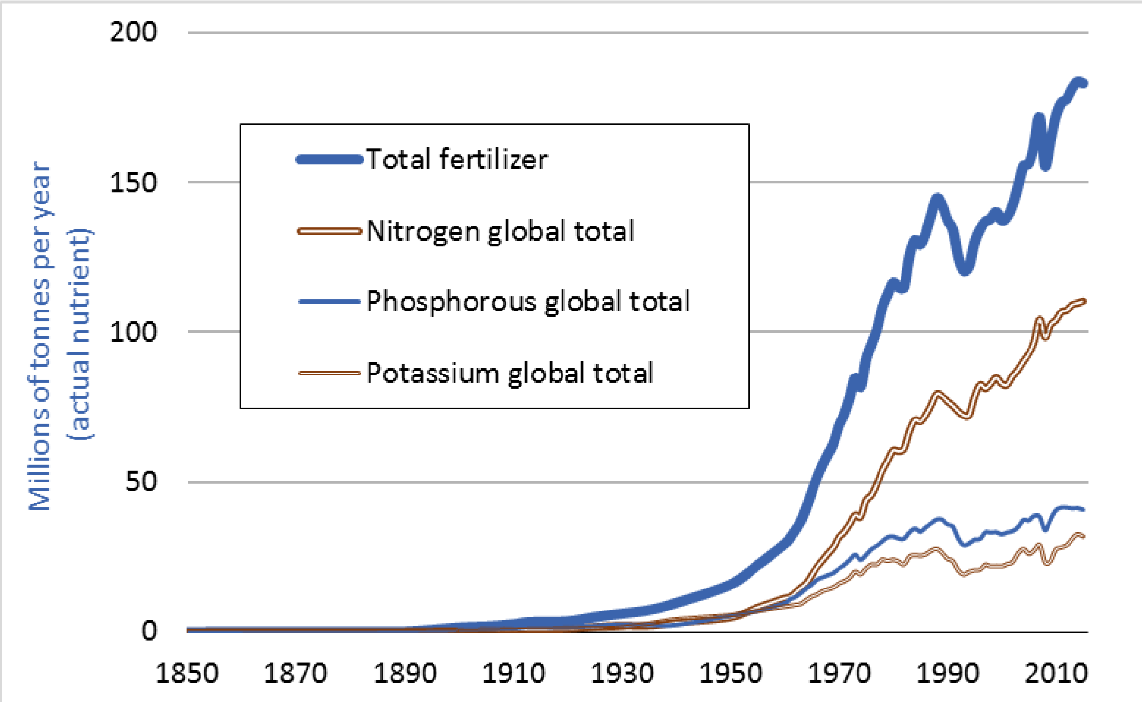
As noted at the start of this chapter, the planetary boundaries model set out by Rockström et al (2009a, 2009b) and further developed by Steffen et al (2015a) highlighted nine key Earth system processes (listed in Endnote 1). Each of these processes are directly affected by human activity and for each the authors attempted to establish critical thresholds that represent limits to a safe operating space for human societies. The framework has emerged as a way of monitoring trends in Earth system processes with particular concern for deviation from the conditions that marked the past 12,000 year Holocene era which, Steffen et al. suggest, is the only state of the planet that has appeared capable of supporting contemporary human societies. It presents a precautionary, systems integrity approach in establishing boundary limits at a distance from possible tipping points, thus establishing parameters for stable and resilient global ecosystems to support human wellbeing (Häyhä et al., 2016). However, while planetary boundaries emphasize the urgency of global environmental problems – with three of the nine boundaries breached – the model has been subject to critique for using a language of universals that fail to speak to the differentiated interests, concerns and capabilities of people (Hajer et al., 2015). Moreover, it deploys a narrow conception of planetary thresholds (Cornell, 2012) while different behaviours and practices can give rise to breaching some regional boundaries, which may not affect other regions (de Vries et al., 2013). Consequently, there is a need to translate global boundaries into specific national and regional contexts for effective policy making while the work of further defining boundary limits continues.

In the updated treatment of the model Steffen et al (2015a) further develop the planetary boundaries framework, especially by introducing a two-tier approach for several of the Earth system processes to account for regional heterogeneity; and by updating boundary limits in light of new findings. Their paper also makes clear that the segmented architecture of the framework should not disguise the complex interactions between processes. They argue that two of the boundaries—climate change and biosphere integrity—are highly integrated, emergent system level phenomena that are connected to all of the other planetary processes that operate at the level of the whole Earth system and provide the planetary-level overarching systems within which the other boundary processes operate. Furthermore, large changes in the climate or in biosphere integrity would likely, on their own, push the Earth system out of the Holocene state and into a new era widely recognised as the Anthropocene (Steffen et al., 2011; Steffen et al., 2015b; Castree, 2017). A further refinement of the original framework is also made in relation to nitrogen and phosphorous where the paper proposes a more generic planetary boundary to encompass human influence on biogeochemical flows in general. Yet a lack of data and clarity regarding other elements and their respective independent and combined influence means that their focus remains on N and P. While, for the purpose of this chapter, our attention is focussed on the biogeochemical flows of nitrogen, it is recognised that phosphorous, too, is essential for life, is largely secured by mining of phosphate rock – which is finite – and represents a hazard as it accumulates in the aquatic environment (Wironen et al., 2018; Mew, 2018; Smil, 2000).

It is important to be clear, however, that for both N and P the role of the agri-food system is central with the contribution from synthetic fertilisers responsible for the overwhelming anthropogenic perturbation of both cycles and which is most visible in the eutrophication of aquatic ecosystems. Yet the particular demand for nitrogen as the element required in the largest quantity for crop growth was responsible for driving an incessant search by nineteenth and early-twentieth century scientists for a way of creating a reactive form of N that would overcome the rift of nutrient extraction. Prior to the 1840s and the trans-Atlantic trade in Peruvian guano and then Chilean nitrates, soil nitrogen enhancement was only possible by planting leguminous cover crops that support symbiotic rhizobium bacteria that fix N in the soil but which reduce the area for staple food crops. With deposits of guano exhausted by the 1870s, the search for a chemically reactive form of nitrogen was a scientific priority.

In the most authoritative text on the topic, Vaclav Smil (2001) carefully traces the history of Fritz Haber's eventual success in synthesising atmospheric nitrogen at high pressure and temperature into the useable form of ammonia (NH_3). Unfortunately, Haber's misplaced patriotism drove the production of ammonia for the manufacture of explosives such that he had a significant influence on both World Wars and subsequent conflicts and perhaps can be held responsible for the deaths of up to 150 million people during the twentieth century (Erisman et al., 2008). However, the post Great War intervention of Carl Bosch brought further developments in high-pressure chemical engineering and enabled the large-scale continuous production of ammonia – the Haber-Bosch process – to be used for industrial fertiliser manufacturing. By 1930, according to Smil, worldwide ammonia synthesis amounted to around 1 million tonnes nitrogen (1mt N), which accounted for around half of the world's inorganic nitrogen and volumes and proportions rose sharply, especially after 1945. In 1950 fertiliser applications amounted to 3.6mt N; by 1960 to 9.2mt N; in 1970 to 32mt; doubling to 61mt by 1980 then 100mt by 2000. Critically, the greater part of this is used in low and middle-income countries and for this we have to understand the role of the Green Revolution in driving chemical fertilizer use.

Figure 3.1: Global consumption of nitrogen - and other - fertilizers, 1850 to 2015



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While the post-1945 period saw the rapid recovery from conflict and development of the metropolitan industrialised countries, food insecurity continued to blight large parts of the emerging post-colonial world. Here, plant-breeding efforts – principally in rice, maize and wheat – got underway within a modernizing paradigm that placed considerable emphasis upon technological progress and efficiencies. As raising food output was the primary goal, then new methods were introduced and the development of high yielding crop varieties (often labelled 'miracle seeds') were at the centre of this 'revolution'. Designed to be fertiliser-responsive, these plants demanded optimal conditions for successful performance including adequate moisture (requiring irrigation), weed and pest suppression (requiring often-frequent applications of pesticide) as well as abundant macro-nutrients (N, P, and potassium, K). The Green Revolution is most usually represented as a hugely significant breakthrough with one of its leading scientists, Norman Borlaug, awarded the Nobel Peace Prize in 1970. In his acceptance speech, Borlaug noted:

"If the high-yielding dwarf wheat and rice varieties are the catalysts that have ignited the green revolution, then chemical fertilizer is the fuel that has powered its forward thrust. The responsiveness of the high-yielding varieties has greatly increased fertilizer consumption". (Borlaug, 1970).

There is little doubt that the combination of high-yielding crop varieties together with high levels of fertiliser application produced by the Haber-Bosch process have been critical to enabling population growth. Erisman et al (2008) estimate that the number of humans supported per hectare of arable land increased from 1.9 to 4.3 persons between 1908 and 2008 and that between 30 to 50 percent of crop yield increase has been due to nitrogen fertiliser application. Indeed, their calculations are consistent with Smil estimating,

"that by 2000, nitrogen fertilisers were responsible for feeding 44 percent of the world's population. Our updated estimate for 2008 is 48 percent – so the lives of around half of humanity are made possible by Haber-Bosch nitrogen." (Erisman et al., 2008: 837).

It is important to recall that nitrogen is essential for plants to synthesise amino acids, which are the building blocks for protein, a vital component of our diets. Cropping systems consequently convert nitrogen inputs to the soil into plant matter that is harvested and utilised for human consumption. Note that nitrogen can be supplied as chemical fertilisers, but also as manure or fixed through biological symbiosis using legumes. A lesser amount is deposited through other environmental pathways arising from fossil fuel burning or other industrial processes[v]. The ratio of this total supply of nitrogen to the amount contained in the harvested plant matter is known as nitrogen-use efficiency (NUE). This varies enormously across cropping systems, between regions but above all reflects fertilisation practices. Billen et al. (2014) report an overall global NUE of 43 percent for cropping systems, which implies that 57 percent of all supplied nitrogen is lost to the environment. They suggest this amounts to 95Tg N year^{-1}, three-quarters of which is emitted in China, India, Europe and North America. We look briefly at these regional patterns in the next section but to close this discussion we need to consider this total load of nitrogen emissions in relation to planetary boundaries.

In the original formulation of the PB framework, Rockström et al (2009) suggest that the nitrogen boundary initially be set at approximately 25% of the estimated value for anthropogenic fixation at about 35 Mt N yr^{-1}, which they themselves refer to as "a first guess". Subsequently, de Vries et al (2013) dismiss this estimate as unnecessarily low and develop a more sophisticated analysis to derive a planetary boundary for nitrogen. They discount the contribution of nitrogen oxides (NOx) derived from industrial emissions and focus upon: atmospheric releases of NH_3 and N_2O; groundwater concentrations of NO_3; and surface water concentrations of dissolved inorganic N. Given the different levels of sensitivity across ecosystems to nitrogen contamination, as well as its different pathways through the environment, they emphasise the difficulty of deriving a singular planetary boundary for N. Moreover, regional variations that arise from the presence of intensive agriculture as well as the food security needs of the current global population – thereby establishing a 'social floor' alongside an 'environmental ceiling' – further complicate the derivation of singular measures. However, using the most stringent criteria – which Steffen et al (2015a) do - their planetary boundary at which the eutrophication of aquatic ecosystems would be risked falls at 62 Tg N year^{-1} while for atmospheric ammonia the boundary would be at 89 Tg N year^{-1}. Zhang et al (2015) conclude that the maximum allowable amount of anthropogenic newly fixed N in agriculture that can be introduced into the earth system is consequently in the order of 62–82 Tg N yr^{-1} while surplus to the environment is currently in the order of 100 Tg N yr^{-1}. For them, the critical challenge is to find ways to achieve ambitious rates of NUE such that better technologies and farm management practices will convert greater proportions of applied N to plant matter leaving less for dispersion into the environment. The question we now have to examine is whether the application of more science and technology to the current food system will deliver sustainable food security for all in the decades ahead.

Nitrogen and the Global Food System

The development of the global food system has utterly transformed the volume and variety of foodstuffs made available for purchase to consumers in many regions of the world. As we have seen, this has been underpinned by the application of science and technology to seeds, other agricultural inputs and to farming practices that has resulted in extraordinary productivity in primary production. Yet the supply of cheap primary food commodities, their processing, manufacturing into final foods and distribution has resulted in significant environmental burdens (Sage 2012). Agriculture and food production together account for around 30 percent of greenhouse gas emissions, cause pollution of freshwater and marine aquatic ecosystems and have been most responsible for land use change and biodiversity loss (Campbell et al., 2017). But alongside this biophysical degradation, one that we might regard as a broader environmental rupture, the global food system has also been responsible for leading a dietary transition resulting in stressed human metabolic states. Exploring the implications of changes in dietary practices is becoming increasingly necessary if we are to recover a safe operating space for humankind. Doing so makes clear that it is no longer sufficient simply to focus upon improving levels of technical efficiency such as NUE in order to achieve the illusion of 'sustainable intensification'. Rather, a focus on diets establishes the critical link between environmental and human health (Tilman and Clark, 2014).

Horton (2017) itemises a number of deep-seated flaws that characterise a deeply dysfunctional food system that fails to deliver global food security yet imposes a high level of impact on the environment. Amongst his 13 'root causes' of agri-food system failure lies a clear sense that the current growth-driven model is intrinsically unsustainable due to:

- Intensive fertilisation practices using fossil fuel produced chemicals that are heavily responsible for the transgression of biogeochemical planetary boundaries for N, P and carbon.
- The production of surpluses that leads, inevitably, to high volumes of food – and packaging - waste while reducing system resilience and leaving it vulnerable to shocks and disruption.
- The dominance of a "small number of large global businesses who relentlessly pursue growth and monopoly" that reinforce the industrial model. Their promotion of unhealthy, ultra-processed, high calorie foods leads to poor dietary health outcomes.
- Globalisation of food results in many perverse outcomes, including the diversion of land to export crops (over domestic staples); externalising (and thereby excluding) many of the hidden costs to environmental and human health; and compartmentalisation of research and policy.
- Aggressive marketing together with human omnivorousness has led to an expansion of meat production that is "resource inefficient, demands large lands areas and adds significantly to greenhouse gas emissions" while contributing to "global epidemics of non-communicable disease". (Horton, 2017: 1324).

It is this last point that will provide a final focus for this chapter. While the global expansion of the meat and livestock industry is often represented as a solution to improve dietary intake, particularly in low-income countries where significant numbers of people display nutrient deficiencies, the associated growth of the global feed industry has become a matter of concern. This has largely arisen over recent decades from a process that has seen livestock become progressively decoupled from land (Lassaletta et al., 2014a). The rise of intensive animal rearing – in units often known as confined animal feeding operations (CAFOs) or 'factory farms' - has become the dominant mode of production for pork, eggs and poultry and regionally important for dairy and beef. Such operations necessitate the supply of feeds often requiring long-distance trade. For example, the EU livestock sectors annually use around 500 million tonnes of animal feed, about 40 percent of which is grass – mostly from intensively fertilised pastures - and 30 percent cereals. Around 60 percent of EU cereal production is used for animal feed, while 75 percent of the protein rich feed – in excess of 35 million tonnes per year – is imported as soybean meal, mainly from Brazil and Argentina (Westhoek et al., 2011).

It is clear that the global ecological footprint for the livestock industry is both large and set to grow as projections of rising demand for meat require new areas to produce feeds. As Havlik et al (2014) observe, 30 percent of the global land area is used for livestock rearing; livestock contribute around 80 percent of all agricultural non-CO_2 emissions; and the sector has been a major driver of land use change, especially in the tropics. This has been especially evident in the expansion of the soybean frontier in South America. Moreover, as Billen et al (2014) report using 2009 data, at the global scale 74 percent of cropland protein production is devoted to livestock feeding and only 26 percent is directly consumed by humans.

In an effort to connect these developments back to the notion of metabolic rift it is useful to draw upon the distinction made by Billen et al (2014) between the main types of animal farming practices. The first, extensive pastoral systems, are not generally regarded as commercially significant – though vital to support livelihoods in marginal environments – and so are disregarded here. The second, mixed farming systems where there is a close connection between livestock and crops, including the use of crop residues and manure, were once dominant but have been increasingly displaced by market-driven forces encouraging intensification and specialisation. Finally, a third type are those livestock systems decoupled from land and local cropping systems, so that they become supported by trade in feedstuffs often from distant regions. It is this third and increasingly dominant form worldwide which exemplifies a contemporary metabolic rift which can be illustrated in the following ways:

1. Animal feeds comprise crops that can be used to feed humans directly and consequently places livestock in direct competition with human need.
2. Concentrated animal production units (CAFOs) prevent the efficient cycling of crop residues or manure, a feature of mixed farming systems.
3. With manure now less a resource for fertilising fields (accounting for less than one-fifth of cropland fertilisation compared to three-fifths for synthetic fertilisers) it has become a more problematic and concentrated waste stream often containing high levels of antibiotics and heavy metals (Heinrich Böll Foundation, 2014).
4. The scaling-up and intensification of animal rearing reduces the unit cost of meat enabling rising levels of consumption that contributes to increased incidence of cardio-vascular disease and other diet-related forms of ill-health.
5. Regional specialisation results in significant amounts of N embedded in agricultural products, including meat, being traded internationally. This can result, depending upon agricultural practices, diet and the composition of imports and exports, in high nitrogen retention that can cause significant environmental contamination.

That there is a significant difference in the nitrogen balance between major world regions is made clear by Billen et al (2014). In their analysis of the global agro-food system they identify 12 regions, seven of which are net protein (N) importing regions, three net exporting and two which are close to a trade balance. Again, it is important to emphasise that differences in N fluxes between regions reflects sharp differences in farming systems - including fertilisation methods – and dietary patterns. Thus, amongst the seven net nitrogen importing regions is Sub-Saharan Africa, with low per capita protein availability, low levels of fertilisation (both from synthetic fertilisers and manure) but with potential for increasing use of legumes (for biological fixation). In contrast to Africa's net imports of 340 GgN year^{-1} or less than 10 percent of total crop production as proteins, China imports 2900 GgN year^{-1} or 24 percent. Levels of synthetic fertiliser application in China are the highest in the world at 35 TgN year^{-1}, however it scores poorly in NUE (25.7) and together with high levels of soy imports for animal feed, China consequently records considerable environmental losses of N, around one-third for the global agro-food system. On the other side of the equation, Billen et al identify a regional grouping as the South American Soy Countries (comprising Brazil and Argentina, but also Bolivia, Uruguay and Paraguay). This group is responsible for the export of 5260 GgN year^{-1} or 58 percent of its total crop production. Given the importance of soy it achieves the highest level of symbiotic N fixation, but also exports large volumes of embedded N in soy products that are converted to animal protein in importing countries.

In highly simplified terms calculating the regional – or national – nitrogen balances involve accounting for anthropogenic N inputs to domestic agriculture (invariably dominated by synthetic fertilisers), estimating the volume of N embedded in imported agricultural products as well as those exported, and that metabolised via domestic consumption. This is an analysis conducted for Spain by Lassaletta et al (2014b) who note how scarce are such studies. Their longitudinal analysis over the period 1961 to 2009 is certainly highly revealing for during this time Spain underwent transformative change. Agricultural intensification witnessed huge increases in fertiliser application as well as mechanisation, irrigation and associated environmental consequences. Livestock numbers increased considerably, particularly pigs (+358%) and poultry (+256%), with a consequent jump in the importation of animal feeds, especially soy products (by almost 3000%) to over 6 Mt by 2009. Critically they note how total protein consumption has risen in Spain from 4.6 to 6.5 kg N cap^{-1} year^{-1} and where the share of animal protein in the diet has increased from 37 percent to 65 percent over this period. It is worth noting that Billen et al (2014) report that with WHO dietary recommendations of per capita protein intake of 2.8 and 3.5 kg N year^{-1} for women and men respectively, places Spain in the highest category of protein ingestion and where high consumption of meat and dairy products is associated with cardiovascular diseases and colorectal cancer risks.

As a consequence of agricultural intensification, anthropogenic nitrogen inputs in Spain have tripled over the period under study with imports of N growing at a faster rate than in Europe as a whole (1986-2009 by 109% as opposed to 8% in Europe). This is explained by the high import volumes of feed commodities (cereals and soy) accounting for 76 percent of imported N used to feed livestock, 80 percent of which is consumed domestically. On the other hand, the main Spanish export crops (citrus, wine, tomatoes, olive oil) have low protein (and hence low N) content[vi]. Given the huge net surplus of N within Spanish territory the question that arises is with respect to its fate. Oxidised compounds of N have increased substantially, and a greater part are atmospherically exported. However, the amount of N exported through river systems is very low (6.5%) meaning that the remainder is retained or eliminated inside the country. This is in sharp contrast to, say the Mississippi River which transports huge volumes of N (and P) into the Gulf of Mexico that is responsible for the anoxic conditions over a wide area around its mouth (van Meter et al., 2018). Given such retention, partly a consequence of traditional Mediterranean water management practices, while there is less leakage to the marine environment there is nevertheless high nitrate loading of important aquifers. Given these supply 80 percent of drinking water in Spain, this has huge implications for human consumption.

In concluding their study Lassaletta and colleagues highlight the systemic vulnerability of Spain to dependence upon fossil fuel-based inputs such as N fertilisers, and to a reliance on imported inputs such as feeds to maintain dietary consumption practices that present public health risks. Consequently, they argue that a change toward a more traditional Mediterranean diet with lower animal protein content would be a win-win and result in a reduction in N cycle perturbation within and outside Spain. Their work also demonstrates that it is only through auditing such fluxes of nitrogen at national level can measures then be taken to mitigate their consequences.

Finally, widening the lens further, we should note that the average per-capita EU consumption of animal proteins in the form of meat and dairy produce is about 52 kg year $^{-1}$ (corresponding to 85 kilograms in carcass weight), about twice the global average (Westhoek, et al., 2011). Maintaining European and other rich country dietary practices, while rising levels of meat consumption take off in middle- and low-income countries, can only be supported by the continuing expansion of animal feed cultivation. Unfortunately, the inefficient conversion of vegetal to animal protein means that animal food production contributes almost two-thirds of reactive N losses to the environment. With the amount of N traded between countries dramatically increasing (from 3 to 24 Tg N, 1961–2009) (Lassaletta et al., 2014b), the international trade of food and feed constitutes a significant component of the global N cycle. While mainstream approaches will emphasise innovative agricultural technologies in order to improve nitrogen use efficiency, a more holistic and convincing argument will embrace the need for dietary change in order to bring ourselves back within a safe – and just - operating space (Dearing et al., 2014).

Conclusions

As a scientific framework planetary boundaries draws our attention to the ways in which anthropogenic activity is pressing against biospheric limits. While quantitative measures of boundary thresholds for each of the environmental processes may remain contested and its failure to acknowledge different spatial scales leaves it subject to criticism, it nevertheless provides a framework through which to grasp the urgency of reducing human impacts. One area highlighted by this chapter is the significant environmental burden arising from rising global consumption of livestock products. Moreover, recent work has built upon and extended the PB model in order to draw a tighter relationship between human and planetary health (Raworth, 2017) and especially in rethinking diet through a 'Great Food Transformation' (Willett et al., 2019). Consequently, the question is whether the metaphor of PB can serve to chart a course of dietary transition, a transformative change, toward a 'safe operating space' characterised by lower levels of meat consumption worldwide.

Larson (2018) alerts us to the ways metaphors may be value-laden and advocate for a particular view, and most generally serve to normalize the existing social order. Yet, if it were possible to 'populate' the world with environmental rather than productivist metaphors ('duty of care' over ‘business as usual’) would that have sufficient consequences for purchasing decisions that we might make as ‘consumers’ within the food system? We should note, however, that once we move from the simplest metaphor (eg ‘food as fuel’) towards embracing more complex relationships (‘eating for planetary health’) it becomes more difficult for a metaphor to find its place in the popular lexicon. Two comparative examples here might be ‘food miles’ and ‘ecological footprint’ for which we could ask: just how effectively have they worked to enrol individuals? Arguably, the first has had more success than the second as it presupposes ‘local food is good’ (though the evidence does not necessarily support this assertion). Even if it is scientifically apt, can a metaphor nurture a positive attitude amongst people toward the environment (Larson, 2018) and encourage change in behavioural practice? Rising numbers of people choosing plant-based diets (vegetarian and vegan) testify to the willingness of many to change in the interests of personal and/or planetary health although it is unclear to what degree – if any - a knowledge of PB has encouraged this.

Many see in the Sustainable Development Goals a way of translating aspirations for human wellbeing into a programme for living within planetary boundaries (O’Neill et al., 2018). There may well be a strong case as part of this process for calculating national fair shares for a more equitable redistribution of resources (Hayha et al., 2016). However, as this chapter has argued in relation to the N cycle, and following a broader argument made elsewhere, tackling dietary practices in the wealthiest countries has to be a priority for it would immediately ease environmental burdens while improving human health (Tilman and Clark, 2014). Healthier diets – comprising more vegetables, fruit, and plant-based oils rather than animal products - require less cropland, less pressure on freshwater resources, more opportunities for co-existence with nature and more potential for nutrient cycling without excessive disruption to the global N cycle. However, it is doubtful that the metaphor of metabolic rift would play a key role in encouraging many rich country meat eaters to better understand the global nitrogen cycle and the disruptive effects caused by diets with a high embedded N. In contrast, and rather idealistically, the notion of commensality, or sharing of food around a hearth or table, might serve to engender a sense of belonging to a common entity – a family or community – where we partake in the abundance of the Earth but within its clearly defined boundaries and on an equitable basis. Yet the prospect of achieving popular support for such an idea demonstrates that the work of formulating effective metaphors that will help us navigate dietary transitions and transformative change across the complex world of food remains a key challenge.

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NOTES

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i In the original formulation (Rockström et al., 2009a) the following planetary boundaries were identified: climate change, ocean acidification, stratospheric ozone depletion, interference with the global phosphorus and nitrogen cycles, rate of biodiversity loss, global freshwater use, land-system change, aerosol loading and chemical pollution. In Steffen et al (2015) paper these are largely reproduced but with novel entities replacing chemical pollution. Further discussion of the PBs follows in a subsequent section.

ii Following convention in the literature, I use teragrams (Tg) which is a unit of mass equal to 10^{12} (one trillion) grams with reference to geophysical flows of nitrogen, though use tonnes in relation to manufactured production.

iii In the interests of brevity, this chapter has avoided a detailed discussion of the metabolic rift as used by Marx and subsequently forensically interrogated by contemporary materialist theorists. Besides struggles over the 'correct' interpretation of Marx's meaning – which are at least partly rooted in dating the origins of capitalism – many social scientists have utilised metabolic rift in their analysis of agrarian change (Schneider, McMichael, 2010; Wittman, 2008) or with particular reference to food as an urban question (McClintock, 2010; Tornaghi et al., 2016; Dehaene et al., 2016).

iv Sage and Kenny (2017) provide a brief application of points 1, 3 and 4 in the context of recent developments in the Republic of Ireland.

v I have chosen to keep quantitative evidence to a minimum in the text in order to avoid unnecessary clutter and to focus upon the key concepts and relationships of interest. However, to underpin this paragraph it is worth citing Galloway et al (2002) who succinctly summarise the sources of nitrogen loading: "Globally, humans currently ingest c. 20 Tg N yr-' in their food. All of this Nr (reactive nitrogen) enters the environment. The resulting environmental consequences are magnified substantially, however, because an additional c.100 Tg N yr^{-1} that was involved in food production, but never entered human mouths, also was released to the environment. In addition to this total of 120 Tg N yr-1, another c.25 Tg N yr--' of Nr was created by fossil fuel combustion, and still another c.20 Tg N yr-l was created for other uses by the Haber-Bosch process, for a total of c.165 Tg N yr-'. This amount is about twice the amount of reactive N created by biological nitrogen fixation (BNF) in natural terrestrial ecosystems 90 Tg N yr-1" (Galloway et al., 2002: 60).

vi Table 2 in Lassaletta et al (2014b) provides clear evidence of the contrast in the nitrogen content of key import and export commodities. For example, the top four imports for the period 2005-09, their volume and their percentage N content was: wheat 5.5mt (1.95%); maize 5mt (1.52%); soybean cake 3.4mt (7.36%); soybeans 2.7mt (6.08%). In contrast, the top four exports for the same period were: tangerines 1.5mt (0.18%); wine 1.5mt (0%); oranges 1.3mt (0.18%); tomatoes 0.9mt (0.14%).