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Sustainable food production: constraints, challenges and choices by 2050

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Abstract The way we grow and consume food is changing both landscapes and societies globally. The constraints and challenges we face in meeting the anticipated large increase in global food demand out to 2050 are examined to show that while they present significant difficulties on many fronts, we have a large range of choices in the way this food demand might be met. Meeting this future food demand has frequently been articulated as a crisis of supply alone by some dominant institutions and individuals with prior ideological commitments to a particular framing of the food security issue. Our analysis indicates that the crisis can be avoided by the choices we make. The food security debate will be enriched by a rigorous evaluation of all these choices and recognition that the eventual solution will reside in a mixture of these choices. We could shift from our current paradigm of productivity enhancement while reducing environmental impacts, to a paradigm where ecological sustainability constitutes the entry point for all agricultural development. If we embraced this new paradigm, sustainable governance and management of ecosystems, natural resources and earth system processes at large, could provide the framework for practical solutions towards an intensification of agriculture. Such a paradigm shift could reposition world food production from its current role as the world's single largest driver of global environmental change, to becoming a critical part of a world transition to work within the boundaries of the safe operating space for humanity with respect to the planet's biophysical processes and functions.

Keywords Agricultural intensification · Sustainability · Paradigm shift · Choices · 2050 · Food security

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Introduction

The way we grow and consume food is changing both landscapes and societies globally. Agricultural intensification has dramatically increased in recent decades and it has outstripped rates of agricultural expansion (Foley et al. 2011). The intensification of agriculture has the potential to be both a blessing and a curse, depending on how it is done and whom you ask. This paper focuses on food production in the context of better understanding what food security means in terms of the challenges faced in agricultural landscapes. We acknowledge that food production is only one component of the food security challenge. In recent years, the focus of many researchers, commentators and policy makers has been on the physical availability of food, facilitated by sufficient agricultural production. This has partly been fuelled by the widespread repetition of the claim that we need to increase global food production by 70–100 % in order to feed the world in 2050. These figures, and the framing of food security as an agricultural productivity challenge, have been widely critiqued – not least by the authors of the original source of the statistics (see Alexandratos and Bruinsma 2012). They go so far as to say that food security is only weakly linked to the capacity of the world as a whole to produce food, "to the point of becoming nearly irrelevant" (Alexandratos and Bruinsma 2012).

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Godfray and Garnett (2014) observe that the goal of producing more food is “unthinkingly accepted by some and vigorously contested by others”. Meanwhile Tomlinson (2014) concludes “these statistics are a key discursive device used by dominant institutions and individuals with prior ideological commitments to a particular framing of the food security issue.” However, as Tomlinson acknowledges, there have been social, institutional, scientific, and political challenges to this framing and the articulation of an alternative set of discourses around concepts of ecological food provision, food sovereignty, and agro-ecology. We accept the FAO definition that “food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”. That is, both availability and access (physical and economic) are important. Here, we focus on availability, whilst retaining consideration of access and consumption where possible.

How much food do we need to produce?

In terms of food availability The world average per capita availability of food for direct human consumption improved to 2770 kcal/person/day in 2005/2007. However, approximately 870 million people were still estimated to have been undernourished (in terms of dietary energy supply) in the period 2010–12. This figure represents 12.5 % of the global population, or one in eight people. The vast majority of these, 870 million, live in developing countries, where the prevalence of undernourishment is now estimated at 14.9 % of the population (FAO et al. 2012). Micronutrient deficiencies continue to affect around 2 billion people (FAO et al. 2012). More than 100 million children under the age of five are underweight, and therefore unable to realize their full socio-economic and human potential. Childhood malnutrition is a cause of death for more than 2.5 million children every year (FAO et al. 2012).

While food availability (i.e. crop production) is necessary for access to healthy, safe, and nutritious food, it is not sufficient to ensure food security. Food access is also required. The caloric content of the food produced worldwide would be sufficient to feed the whole global population - yet there are still countries in conditions of chronic food scarcity. South Asia has the largest number of food insecure people, while Sub-Saharan Africa has the highest proportion, as well as the highest rates of child underweight and infant and child mortality (FAO et al. 2012). About 33 % of people in Sub-Saharan Africa are undernourished, with more than 60 % of the undernourished being in eastern Africa (Z. R. Khan et al. 2014). The majority of countries whose population growth is expected to be fast in the future are precisely those showing inadequate food consumption and high levels of undernourishment. Most of them are in sub-Saharan Africa (Alexandratos and Bruinsma 2012).

In terms of food demand the projected global growth rate in consumption is 1.1 % per year from 2005/07-2050 (Alexandratos and Bruinsma 2012) which implies a 56 % increase over the period. Others such as Tilman et al. (2011) however forecast a 100–110 % (requiring a 1.4 to 1.5 % per year growth rate) increase in global crop production using a global relationship between per capita GDP and per capita demand for crop calories or protein. The magnitude of this dependence is surprisingly large in that per capita use of calories and protein by the richest nations (GDP~US$20,000) were 256 and 430 % greater, respectively, than use by the poorest nations (GDP~US$2,000). These large differences in crop demand partially result from greater meat consumption at higher income and the low efficiency with which some types of livestock convert crop calories and protein into edible foods. Therefore per capita food consumption can be expected to expand most rapidly in Eastern Europe, Asia and Latin America where incomes are rising and population growth is slowing. Vegetable oils, sugar, meat and dairy products should experience the highest increases in demand (OECD-FAO 2011). More recent very detailed work by Valin et al. (2014) examines the nature of food demand under the influences of population growth, economic wealth distribution and dietary change. For a world population of more than 9 billion by 2050 and more than a doubling in average income per capita globally, from 6700 USD in 2005 to 16,000 USD in 2050, generates a food demand increase of 59–98 % between 2005 and 2050. This is slightly higher than the most recent FAO projection of 56 % from 2005/2007. The range of results is large, in particular for animal calories (between 61 and 144 %), caused by differences in demand systems specifications, and in income and price elasticities. Their results show importantly that demand is more sensitive to socioeconomic assumptions than to climate change or bioenergy scenarios.

In terms of the growth in agricultural production To match the 1.1 % growth in consumption, global production in 2050 would need to be approximately 60 % higher than that of 2005/2007 (Alexandratos and Bruinsma 2012). Fischer et al. (2014) provides a comprehensive analysis of improvements in crop yield and suggests that it would be prudent to have crop yield increases per annum of around 1.2–1.3 % which delivers around a 45 % increase in staples over 2010 yields with a 10 % increase in area cropped. As Alexandratos and Bruinsma (2012) note, this is not a reflection of what is required to feed the world population but a projection of the aggregate volume of world agricultural production. This means that productivity would need to increase at rates much *lower* than in the past.

This is because total agricultural output in the preceding equal period was 2.2 % p.a. (and 2.6 % in the previous decade OCED-FAO 2011), much more than the required 1.1 % p.a. from 2005/2007 to 2050. Currently, for 2010–2020, global agricultural production is projected to grow at 1.7 % annually, on average (OECD-FAO 2011). This is greater than the margin needed. While the need for lower growth rates is reassuring, the challenge is still significant, not least because of the projected reduction in annual growth rates of yields. There are fears that the trend in declining yields may not reverse and that the productivity of many intensive systems cannot be maintained with current management (Alexandratos and Bruinsma 2012; World Bank 2008; S. Khan and Hanjra 2009). In addition, it is predicted that up to 25 % of world food production may be lost during the 21st century due to climate change, water scarcity, invasive pests and land degradation (UNEP 2009). Even at a lower growth rate, the volumes are not trivial. Cereals production would need to increase by 940 million tonnes to reach 3 billion tonnes projected for 2050; meat by 196 million tonnes to reach 455 million tonnes by 2050; and oil crops by 133 million tonnes to reach 282 million tonnes (oil equivalent) by 2050 (Alexandratos and Bruinsma 2012).

At a global level, while there are risks associated with falling growth rates of global average yields, this is not necessarily indicative of an impending crisis. However, as with many things on this earth, productivity is not distributed evenly. At a local level, falling growth rates can lead to tragedy (Alexandratos and Bruinsma 2012). In this case, concern is greatest for sub-Saharan Africa where per capita food production has seen an annual decline of at least 3 % since 1990.

Are there limits to food production?

Given lower productivity growth rates, ongoing soil and water degradation and the loss of biodiversity and ecosystem services in agricultural landscapes, the big challenge is to maintain current levels of productivity growth, let alone seek increases. The question is, will this be possible? Based on the information reviewed below, we can say that, in theory, there are enough natural resources and yield growth potential to meet requirements. Although this is no guarantee of the long-term sustainability of food production in practice.

We have enough nitrogen, potassium and phosphorus From the 1960s and 70s, as is widely document, the green revolution turned developments in crop genetics, inexpensive pesticides and fertilizers, and mechanization into greater yields (Tilman 1998). From the 1950s, global fertilizer use rapidly expanded, increasing by 500 % in the past 50 years. At the same time, the production of pesticides increased by more than 850 % (Balmford et al. 2005; Foley et al. 2011). Industrial agriculture is increasingly reliant on external inputs. It now takes 2–3 times more fertilizers and 1.5 time mores pesticides to produce 1 kg of food than it did 40 years ago (UNCTAD 2010). Key biophysical drivers of crop yield include nitrogen (N), phosphate (P_2O_5) and potash (K_2O) fertilizers (Mueller et al. 2012). The world has enough potassium to last several centuries (Vaccari 2009). And with the Haber-Bosch process, N fertilizer can be produced without limits from atmospheric N_2 – although at a serious fossil fuel and climate change cost. However Rockström et al. (2009), point out that at the "planetary scale, the additional amounts of nitrogen and phosphorus activated by humans are now so large that they significantly perturb the global cycles of these two important elements". The manufacture of fertilizer for food production and the cultivation of leguminous crops convert around 120 million tonnes of N_2 from the atmosphere per year into reactive forms, which is more than the combined effects from all Earth's terrestrial processes (Sayer and Cassman 2013). Much of this new reactive nitrogen ends up in the environment, polluting waterways and the coastal zone, accumulating in land systems and adding a number of gases to the atmosphere. It slowly erodes the resilience of important Earth subsystems. Nitrous oxide, for example, is one of the most important non-CO_2 greenhouse gases and thus directly increases radiative forcing.

In contrast to the N cycle, the phosphorus (P) cycle has no gaseous atmospheric component. A key component of DNA, cell membranes and cellular energy transport, phosphorus is essential to every form of life. Yet most soils contain only low concentrations of this nutrient (Obersteiner et al. 2013). As is well known, the growing consumption of inorganic phosphorus (P) fertilizers has contributed to major increases in crop yields since the 1950s (MacDonald et al. 2011). For example, Ringeval et al. (2014) found that the contribution of anthropogenic P to food production in France was as high as 84 %. In the United States, crop production would decline at least around 50 % over time without N, P, and K commercial fertilizer (Ringeval et al. 2014). P mined from phosphate rock is a finite fossil resource with highly concentrated deposits - more so than that for oil reserves (Vaccari 2009). Morocco is estimated to hold 85 % of the global share, followed by China with 6 % and the US with 3 % (MacDonald et al. 2011; Obersteiner et al. 2013). Twenty three megatons of P (equivalent to 178.5 Mt of phosphate rock) are currently mined every year, mainly from these three countries (Ringeval et al. 2014; MacDonald et al. 2011).

Fertiliser use varies greatly between different parts of the world. Total fertilizer nutrient consumption in Asia is 58.7 % of the world total, the bulk of which is in East Asia and South Asia. The total for America is 23.7 %, of which North America constitutes 13.2 % and Latin America & Caribbean 10.5 %. Europe's share in global consumption of total fertilizer nutrients is about 13 %. The share of Oceania in world consumption of total fertilizer nutrients is only 1.7 % (including Australia and New Zealand) – the same as for North Africa (FAO 2012). This unequal distribution means that only 10 % of cropland area contributes 45 % of the cumulative global P surplus. These large surpluses cover most of East Asia, as well as sizeable tracts of Western and Southern Europe, the coastal United States, and southern Brazil, but <2 % of the cropland in Africa (MacDonald et al. 2011). These soils are saturated with P because of historically high applications (Cordell and White 2011). Meanwhile, P deficits occur across 30 % of the world's cropland area. Prolonged P deficits can deplete soil P and limit crop yields (MacDonald et al. 2011). In general, the low-income and food-deficient countries in sub-Saharan Africa, central Asia and Latin America suffer from low P inputs (0–5 kg ha^{-1}) to their agricultural production systems. Perversely, Africa is a major exporter of phosphate and nitrogen but only accounts for about 2.9 % of world fertilizer consumption (FAO 2012).

Estimates of when existing P reserves could be exhausted range from the next 40 to 400 years (Cordell and White 2011; Obersteiner et al. 2013; Elser and Bennett 2011). P scarcity would seriously threaten soil fertility, agricultural production, and global food security (Ringeval et al. 2014; Cordell and White 2011). However, there is potential to manage this scarcity. Up to 80 % of the phosphorus supplied to crops is estimated to be lost before consumption, largely due to the erosion of agricultural soils (Obersteiner et al. 2013; Cordell and White 2011). Reductions in wastage could free up this resource for low-income, food-deficient countries (Obersteiner et al. 2013). At a global scale, if current volumes of P-fertilizer were used more efficiently and redistributed, there would be no P deficit cropland. If a 21 % reduction in P fertilizer use in all locations with high surpluses was redistributed across all P-deficit cropland, it would effectively meet the total crop P requirements in these locations, eliminating all P deficits globally (MacDonald et al. 2011). Mueller et al. (2012) also suggest it would be possible to close global yield gaps on major cereals to within 75 % of attainable yields with fairly minimal changes to total worldwide nitrogen and phosphate use by coupling targeted intensification with efforts to reduce nutrient imbalances and inefficiencies. It is also worth remembering that total N and P in animal manure generated by livestock production exceeds the global N and P fertilizer use in global crop production (Bouwman et al. 2013). Achieving more effective manure P recycling at the global scale would promote tighter P cycling in agricultural landscapes (MacDonald et al. 2011).

The bigger challenge is nutrient imbalance Global food security must address the dual challenges of closing yield gaps between actual and potential yield (which is largely about management of soil nutrient balance) while improving environmental sustainability. Nutrient balance is essential for achieving global food security (Ciampitti and Vyn 2014). The global spatial imbalance of fertilizer consumption in large parts of the developing world, particularly Africa, is compounded by an increasingly unsustainable regional nutrient consumption ratio (van der Velde et al. 2014). The availability of carbon from rising atmospheric carbon dioxide levels and of nitrogen from various human-induced inputs to ecosystems is continuously increasing. However, this is not being matched by similar increases in P inputs (Peñuelas et al. 2013). Unbalanced application of N versus P applications cause yield deficits by affecting the stoichiometric relationship between N and P in plant leaves (van der Velde et al. 2014). The change in the stoichiometry of carbon and nitrogen relative to phosphorus has no equivalent in Earth's history (Peñuelas et al. 2013).

In Africa, total N consumption increased by 120 % between 1975 and 2005 while total phosphate consumption only increased by 16 % in 2005 (van der Velde et al. 2014). If this increasing imbalance is not reversed, then significant reductions in future crop yields (>40 %) could also occur (van der Velde et al. 2014). Based on simulated maize yields, van der Velde et al. (2014) estimated N inputs would need to increase 5-fold to allow Africa to close yield gaps (ca. 70 %). This would require an associated 11.7-fold increase in P (van der Velde et al. 2014). The P demand to overcome these yield deficits would provide a significant additional pressure on current global extraction of P resources (van der Velde et al. 2014). As described above, this demand could be managed, if P was distributed more evenly and new reserves became economically viable.

The area of irrigated agriculture will continue to grow Food production requires more water than any other human activity – even more so for irrigated than rainfed lands (D'Odorico et al. 2014). In the past 50 years, the world's irrigated cropland area roughly doubled, with 70 % of global freshwater withdrawals now devoted to irrigation (Foley et al. 2011). This is driven by the fact that yields on irrigated croplands are, on average, 2–3 times higher than for dryland agriculture (UNEP 2009). Irrigated areas are heavily concentrated in South Asia, East Asia and parts of the United States (Mueller et al. 2012). In Africa, while there has been limited irrigation to date, there is the potential for much greater expansion. However, recent work by Sullivan and Pittock (2014) suggests that the next generation of irrigation development in Africa must focus on achieving clear socioeconomic benefits sustainably through increased emphasis on greater water productivity, poverty reduction and institutional arrangements and incentives that drive implementation at the local scale. This would address a big challenge for many African regions, where the problem is not lack of water (particularly for Central Africa), but unpredictable and highly variable rainfall patterns with occurrences of dry spells every 2 years causing crop failure (UNEP 2009). Demand for irrigated land is projected to increase by 56 % in Sub-Saharan Africa (from 4.5 to 7 million ha), and rainfed land by 40 % (from 150 to 210 million ha) (UNEP 2009; Tweeten and Thompson 2008). For this demand to be met, much greater human, institutional and financial capital would be needed to gain water access (Perrone and Hornberger 2014).

We have enough 'spare' agricultural land The average amount of arable land per person fell from 0.39 ha in 1960 to 0.23 ha in 2000 and 0.21 ha in 2007 (Evans 2010; FAO 2009). However, at a global scale, there is sufficient land that could be recruited in to agriculture - if and when economic, policy and institutional settings created the conditions to do so (Alexandratos and Bruinsma 2012). There are 7.2 billion hectares (ha) of land with rainfed production potential of various degrees of suitability. Of this, 1.4 billion ha is currently in use for crop production. 2.8 billion ha is under forest, in protected areas, or already occupied by non-agricultural uses. 1.5 billion ha is of poor quality for rainfed crops, leaving 1.4 billion ha of prime land and good land that could be brought into cultivation, in theory (Alexandratos and Bruinsma 2012). Clearly if this were done there would be a huge loss of biodiversity and significant consequences for the mitigation of climate change. Schmitz, et al. (2014) provide analysis of two different socio-economic scenarios and three climate scenarios for possible expansion of agricultural land. Across all models most of the cropland expansion takes place in South America and sub-Saharan Africa. As constraints in available land area arise, agricultural production will continue to expand into less developed areas and into marginal lands with lower fertility and higher risk of adverse weather events (OECD-FAO 2011). In a recent study, UNEP (2014) suggests that 1640 Mha is safe operating space as a preliminary and indicative value based on a cautious global target to halt the expansion of global cropland into grasslands, savannahs and forests by 2020. They show that under business-as-usual conditions the net expansion of cropland will range from around 123 to 496 Mha between 2005 and 2050. Shifts to more protein-rich diets in developing countries and a growing demand for biofuels and biomaterials, in particular in developed countries, are especially increasing the demand for land. In addition, cropland will be shifted to compensate for the expansion of built-up land and land degradation, leading all in all to a gross expansion of cropland in the range of 320 to 849 Mha. UNEP (2014) propose that with major actions to reduce cropland requirements and to relieve the social and environmental pressures associated with land-use change, the expansion of global cropland could be limited to an additional 8–37 % until 2050. Then, in the best case, the remaining net expansion of cropland by 2050 would be within the 'safe operating space'.

As with most other resources, this 'spare' land is not evenly distributed. Many regions of the world face a shortage of arable land for additional cropland expansion (Morton et al. 2006). Only 13 countries account for 60 % of this 1.4 million ha. of potential agricultural land: Brazil; United States of America; Russian Federation; Argentina; Australia; Sudan; China; Democratic Republic of the Congo; Kazakhstan; Angola; Canada; Mozambique; and Madagascar (Alexandratos and Bruinsma 2012). There is a reason this land hasn't been used in the past, including constraints such as lack of accessibility, lack of infrastructure, distance from markets and from other constraints such as the incidence of pests and disease (Alexandratos and Bruinsma 2012). As food demand increases, some of these constraints will be overcome. Further expansion of agricultural land is projected to 2050, particularly across central and southern Africa (UNEP 2009). Several developing countries are expected to experience area increases of more than one million hectares, including Nigeria, Brazil, Niger, Sudan, Ethiopia and the DRC (Foresight 2011). According to the World Bank (2013), Africa is a continent that "holds more than half of the world's unused fertile farm land, and impressive but untapped water resources". They predict that agriculture and agribusiness will expand to become a $1 trillion industry in Sub-Saharan Africa by 2030 (compared to $313 billion in 2010). However, the findings of Sullivan and Pittock (2014) are much more sanguine on the matter.

We don't use all the available agricultural land that we have Of the current global crop production area, not all is allocated to growing human food. A significant proportion goes to animal feed, bioenergy, seed and other industrial products (Foley et al. 2011). By 2020, an estimated 13 % of global coarse grain production, 15 % of vegetable oil production and 30 % of sugar cane production will be used for biofuel production (OECD-FAO 2011). North America and Europe devote only about 40 % of their croplands to direct food production, whereas Africa and Asia allocate typically over 80 % of their cropland to food crops (Foley et al. 2011). In addition to putting cropland to non-food related agricultural uses, we are also seeing existing cropland converted to other non-agricultural uses due to increasing urbanization, industrialization, energy demand and population growth (UNEP 2009).

We don't use all the available food that we have Developing countries lose more than 40 % of food post-harvest or during processing, not least due to storage and transport conditions (Lipinski et al. 2013). Industrialized countries have lower producer losses, but at the retail and consumer level more than 40 % of food may be wasted (PBL 2009; Foley et al. 2011). As a global average, 24 % of food loss and waste occurs at production, another 24 % during handling and storage, and 35 % at consumption. The amount of cropland used to grow this 'lost food' is approximately 198 million hectares per year, equivalent to an area the size of Mexico (Lipinski et al. 2013). In addition to food lost after harvest, significant potential food is lost during production due to pests and diseases. While pesticides have made a significant contribution to growth in productivity since the 1950s, losses globally are still high. Oerke (2006) suggests losses of 26–29 % for soyabean and wheat, and 30–40 % for maize, rice and potatoes (Beddington 2010). This isn't a matter of using more pesticides but in improving application. Only 50 % of the impact of crop protection products is accounted for by the effectiveness of the product itself; the rest is dependent on factors such as the timing of the application and the precision of delivery (Beddington 2010).

We already produce more than enough food While undernutrition is clearly an urgent food security challenge, especially for the 870 million people who suffer from it, obesity is also a serious problem. It affects more than 1 billion people (MODI 2013; Kjaergard et al. 2013; Lang 2006; UNEP 2009). This is especially true for developed countries, such as the United States, where obesity-related medical expenses are expected to top $344 billion per year by 2018 and in Australia, where obesity already costs an estimated $56 billion per year (MODI 2013). It is also true for developing countries. In fact, 80 % of the deaths caused by obesity and non-communicable diseases (NCDs) such as diabetes and cancer are now occurring in low- and middle- income countries (Dube et al. 2013). We live in a world where the majority of the population (65 %) lives in countries where overweight and obesity kills more people than under-nutrition (WHO 2013). That is, obesity, undernutrition and food insecurity co-exist in the same societies. The problem is likely to grow rapidly in coming years, even while problems of hunger and malnutrition persist (Godfray and Garnett 2014).

Not all food is created equal In developed and developing countries alike, societies are awash with cheap, highly processed, and nutritiously lacking "empty" calories (Carolan 2013). For example, in many small island states in the Pacific Ocean, nutrition security is being threatened by changing tastes, a growing dependence on store foods, and the poor quality of cheap imported processed food and drinks – the control of which is complicated by trade agreements. In a great irony, even tinned fish is becoming a common import, despite such states being surrounded by ocean (Connell 2013). This transition from subsistence agriculture to a Western-type diet is occurring in countries around the world (Dube et al. 2013). It is happening in the space of a few decades with little time for health systems to shift gears from infectious diseases to non-communicable diseases as a key cause of death. It is another challenge for societies that can least afford it – and while health systems bear the cost, the levers of change for nutrition security lie largely outside the health sector's reach (Dube et al. 2013). It is a challenge that doesn't fit neatly into the worldview or mandate of the agriculture and food sector (Benson 2012).

Can agriculture be sustainable?

So, we have enough resources and the potential to produce all the food needed for the population of the future. Despite the long-term threats to the sustainability of agricultural landscapes, it would appear that there are no hard biophysical limits to producing more food – nothing to stop humans from using more resources, more chemicals, more land and more energy. While many of us would hope to see the world produce more food with limited land and water, using less energy, fertilizer and pesticides and with less environmental impacts (Beddington 2010), that is not the trajectory we are on. If we want to take a different path, we will have to make the choice to do so. And we need to be clear that we do have choices – options that need to be debated rather than subsumed in a dialogue of crisis and food shortages. The following outlines some of the choices we could make, recognising that implementation of any of these choices has to be done at the national and local levels. This would require significant capacity building and policy development. But we have to start somewhere.

We could choose to limit agricultural expansion Agriculture requires more land (40 % of the world's terrestrial surface), water and human labour than any other industry (Kiers et al. 2008; PBL 2009). In the last two centuries, humans have cleared or converted 70 % of the grassland, 50 % of the savannah, 45 % of the temperate deciduous forest, and 27 % of the tropical forest biome for agriculture (Foley et al. 2011). Between 1985 and 2005 the world's croplands and pastures expanded by 154 million hectares (Foley et al. 2011). Across the tropics, between 1980 and 2000 more than 55 % of new agricultural land came at the expense of intact forests, and another 28 % came from disturbed forests (Gibbs et al. 2010). Up to 40 % of this global crop area may be experiencing some degree of soil erosion or reduced fertility (Foley et al. 2005) while more than 20 % of total global land area is thought to be degraded (Bai et al. 2008). Much of this area is concentrated in Africa south of the equator, South-East Asia and south China. As a whole, it is estimate that over 75 % of arable land in Africa is being degraded as a result of continuous cropping with minimal or no investment in soil improvement or even maintenance (Z. R. Khan et al. 2014). As constraints in available land area arise, agricultural production will continue to expand into less developed areas and into marginal lands with lower fertility and higher risk of adverse weather events (OECD-FAO 2011).

It has been suggested that the best way to minimise the expansion of new cropland is by increasing the productivity of existing cropland. This concept is referred to as the Borlaug (land sparing due to agricultural innovation) hypothesis. While some land sparing has occurred due to the Green Revolution in Asia, Latin America, and the Middle East, it is less clear that this would be the case of a prospective African Green Revolution (Hertel et al. 2014). This is not to imply that there shouldn't be a Green Revolution in Africa, but that the context is different and the likely trajectory will not be a repeat of the past. There are also new drivers for agricultural expansion beyond national borders. The purchase of quality agricultural land by foreign actors is increasing, particularly in Africa and Asia. In 2009, approximately 56 million hectares worth of large-scale farmland deals were announced (although not all announced deals proceeded) (Deininger and Byerlee 2012). Hertel et al. (2014) suggest that measures to discourage conversion of carbon-rich ecosystems to low-yielding crop production will help to boost environmental efficiencies in the region and limit the environmental and climate change impacts of expansion.

We could encourage new crops and greater genetic diversity Greater specialisation and homogenisation of agricultural systems is contributing to the loss of diversity at a local level. About 75 % of the genetic diversity of agricultural crops has been lost since 1900 while 32 % of livestock breeds are under threat of extinction within the next 20 years (FAO 2009). This is to say nothing of the more than 4000 plant and animal species threatened with extinction by agricultural intensification (UNEP 2009). We need to breed for a 2030 world (GSCSA 2011). This requires increasing crop and livestock genetic diversity to improve resilience, yield and pest management. There also needs to be a valuing of informal seed systems to facilitate the exchange of plant genetic resources at local scales (FAO 2014). Africa has a huge diversity of cropping systems, and many orphan crops there are central to food security. These crops should not be overlooked in the mad rush to grow more hectares of maize. Interventions focussing on strengthening the formal agricultural systems (such as maize) at the expense of local informal systems threaten to undermine the sources of diversity from which people in different localities need to draw if they are to build livelihoods that are resilient to shocks and long-term stresses (Westley et al. 2011). This is because policies that promoted staple crop production, such as fertilizer and credit subsidies, price supports, and irrigation infrastructure can crowd out the production of traditional non-staple crops (Pingali 2012).

Many solutions to the crops for food have been proffered, but most are from limited perspectives and often represent vested interests of some sort - economic, political, or academic (Gready 2014). Gready (2014) argues that new ideas and disruptive ways of thinking are necessary to conceive adequate solutions to these challenges, and that disruptive 'technologies' will be necessary for their effective implementation. She suggests we need to reconceptualise the requirements for global food systems for the future, with a view to identifying best-fit options, especially for crop staples such as grains and legumes. Her focus is not merely to address the commonly perceived issue of 'food security', which represents public concerns and responsibilities of governments for food provision, but 'food insecurity' and its crippling impacts on people most at risk of being unable to obtain sufficient, affordable, safe and nutritious food reliably (Gready 2014).

We could choose to protect the ecological foundation of food security Agricultural ecosystems are managed by humans largely to optimize 'provisioning ecosystem services', such as food, fibre and fuel. However, these outputs depend upon 'regulating ecosystem services', for example pollination and pest regulation, from the wider landscape and environment for their long-term provision and sustainability (Poppy et al. 2014). This is the ecological foundation of food security (McKenzie and Ashton 2012). At a local level, ecosystem services are crucial to the food security of many poor households. Every year, even in good years, households can still have days when they have no access to food. Food availability for many of the world's rural poor is particularly dependent on their being able to benefit from the flow of ecosystem services from non-agricultural ecosystems, for example wild foods (Poppy et al. 2014). Such food stuffs do not appear in agricultural statistics as they are not traded commercially (Poppy et al. 2014).

Despite being dependent on ecosystem services (or perhaps because of) agricultural landscapes continue to face major challenges (Mueller et al. 2012). For decades now, we have watched as landscapes around the world have experienced declines in regulating (eg. climate regulation, pollination, water purification) and supporting (eg. soil formation, nutrient cycling, primary production) ecosystem services (IAASTD 2008; Trumper et al. 2009). The increased use of nitrogen (N) and phosphorus (P) fertilizers has had unintended consequences in water use, soil degradation, and chemical runoff, increased energy use and widespread pollution (Bouwman et al. 2013). Nearly 25 years ago, Chen (1990) and then Tilman (1998) described the intensification of agriculture as having broken what was once the tight, local recycling of nutrients on individual farms. These consequences are having impacts beyond the areas farmed and are widely recognized as potential threats to the long-term sustainability and replication of the green revolutions' success (Pingali 2012).

To protect the ecological foundation of agriculture, we could choose to act in the way that the world agreed in the Convention on Biological Diversity in 2000 (CBD 2000) to:

- Align incentives to promote biodiversity conservation and sustainable use
- Manage ecosystems within the limits of their functioning
- Adopt an integrated landscape approach to produce ecosystem services as well as agricultural products
- Value ecosystem services by ensuring that well-functioning markets provide the right signals to reflect the scarcity value of natural resources

Protecting the ecological foundation of agriculture requires protecting the land on which agriculture is already based. This would mean protecting existing agricultural land through land use planning that zones agro-ecological areas, protecting productive agricultural land from being concreted over for car parks, buildings or other non-agricultural uses. It would also mean reversing soil and water degradation. One of the biggest opportunities to sustainably produce more food is to restore the millions of hectares of degraded soils in existing agricultural areas (UNCCD 2012). Another essential action is to better manage sources of rainwater and runoff for multifunctional agroecosystems at the catchment scale. There is also an urgent need for the regulation of groundwater aquifers to reduce unsustainable water withdrawals. Two-thirds of global water supplies for irrigation are drawn from underground aquifers at unsustainable rates (FAO 2011). Any country using more than 20 % of its renewable resources for irrigation is considered as crossing the threshold of impending water scarcity. There are already 22 countries (developing but including some in the Central Asia region) that have crossed this threshold. Large agricultural regions with unsustainable water withdrawal rates include eastern Australia, southern Spain, north Africa, the Great Plains of North America, northwestern India and northern China (Godfray and Garnett 2014; Tweeten and Thompson 2008).

We could choose to focus on integrated farming systems The way land is being used is changing, particularly in developed countries with a longer history of industrial agriculture. What had been mixed cropping and livestock systems in Western Europe and North America since the middle of the twentieth century have increasingly become separate specialised enterprises (Brown and Schulte 2011; Kirkegaard et al. 2011). More recently in Australia, in the higher rainfall areas of the eastern and western wheat/sheep belts, there has already been a swing away from traditional mixed crop-livestock systems towards either crop or livestock systems (McKenzie 2014). These trends towards land use specialisation can confound alternative visions for sustainable agriculture. Rather than moving into a more multifunctional or post-productivist modes of agriculture, production in many dryland agriculture areas is in fact becoming more intensified with fewer, not more, land uses (McKenzie 2014). As developing country agriculture moves towards more intensive agricultural systems, greater homogenisation and the spread of monocultures is likely. Agricultural research and development has largely focused on single system component or single enterprises - neglecting the interaction between crops and livestock. What has resulted is a poor understanding of the complexities of inter-relationships between enterprises on mixed farms. Gaining a renewed appreciation of the benefits of multiple land uses for productivity will be an important means of not only moving towards a more sustainable agricultural sector, but ensuring that mixed farming systems survive (McKenzie 2014).

We could distribute phosphorus more equitably and efficiently Scarcities in phosphorus supplies and constraints in accessibility are likely to lead to marked rises in the cost of phosphorus (Obersteiner et al. 2013). On the one hand, it will become increasingly economical to mobilise previously unaccessed reserves, which are probably currently underestimated (Godfray and Garnett 2014). On the other hand, this would see phosphorus become economically inaccessible to low-income and food-deficient countries. Continuation of business as usual would favour the short-term interests of those able to pay for high-priced fertilizers, exacerbating food crises and agricultural expansion in the short-term (Obersteiner et al. 2013). Low-income food-deficient countries, many of which are now endowed with phosphorus-deficient soils, often as a result of unsustainable management practices, will want to see inequalities in access to phosphorus supplies addressed (Obersteiner et al. 2013). Obersteiner et al. (2013) are pessimistic about this likelihood. They contend that the interests of rich phosphorus consumers, poor and food-insecure phosphorus consumers, and phosphorus producers are, to a large degree, conflicting - with competing interests in the longevity, equitability and cost of phosphorus supplies (Obersteiner et al. 2013). They note that wealthy phosphorus consumers are already using their political and economic weight to secure future supplies from phosphorus producers. The divergent agendas of these three groups of nations render a sustainable management regime of finite phosphorus resources almost impossible (Obersteiner et al. 2013).

We could choose to avoid dangerous climate change In the next two decades, climate change is predicted to cause major crop losses in the world's poorest regions (Kiers et al. 2008). According to the IPCC's Fifth Assessment Report, all aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (Porter et al. 2014). Elevated CO_2 already has the potential to negatively affect the nutritional quality of food and fodder, including protein and micronutrients (Porter et al. 2014). While agriculture will be adversely impacted by climate change it is also well recognised that food production is also a major contributor to the emissions that drive climate change. Bajželj et al. (2014) draw attention to the imperative of finding ways to achieve global food security without expanding crop or pastureland and without increasing greenhouse gas emissions. Many authors have emphasized a role for sustainable intensification of Agriculture in closing global 'yield gaps' between the currently realized and potentially achievable yields. However, Bajželj et al. (2014) show in their analysis that even if yield gaps are closed, the projected demand will drive further agricultural expansion. They argue that there has to be a reduction in demand. Although it is theoretically possible to decarbonize energy supply, such complete reductions are unattainable in the livestock part of the agricultural sector. Their work indicates that a decrease in overall agriculture-related emissions can only be achieved by employing demand-side reductions. Reducing emissions from agriculture is essential to reduce the risks of dangerous climate change. Bajželj et al. (2014) conclude that while agricultural production must strive to improve yields and food distribution, improved diets and reductions in food waste are also essential to deliver emissions reductions, and to provide enough food for the global population of 2050.

We could choose how investment is directed From an economic point of view, it has been estimated that cumulative gross investment requirements for developing countries' agriculture is approximately US$9.2 trillion for the 44 years from 2006 to 2050 (Schmidhuber et al. 2009). Of this total, investments in primary agriculture would account for about US$5.2 trillion, while the remaining US$4.0 trillion would be absorbed by downstream needs (processing, transportation, storage, etc.). Within primary agriculture, mechanisation and improvements to irrigation would be the single biggest investment items. The average annual spend would be approximately US$210 billion gross and US$83 billion net. US$210 billion is the projected size of the agricultural products market in 2020 (TEEB 2010). As Schmidhuber et al. (2009) note, these estimates have nothing to do with achieving Millenium Development Goals or any sustainability agenda. They are simply cost estimates for achieving the levels of crop and livestock production that the FAO has forecast as baseline levels through to 2030 and 2050. Nor do such estimates take in to account the potential cost implications of reforms to trading rules and market access. Assuming US$210 billion was required each year, how much should come from the public and private sectors? In a World Bank report on land acquisitions, Deininger et al. (2011) suggested that the rediscovery of investment in the agricultural sector could be an opportunity for land abundant countries to gain better technology and create rural jobs. However, if managed improperly, it could result in "conflict, environmental damage, and a resource curse" (p. xvx). We could make strategic decision about how to manage the interlinkages and trade-offs between different investment decisions.

We could choose to limit consumption Decision makers are reluctant to wade in to question of limiting consumption or to tackle the global convergence to a western diet (Stokstad 2010). Yet, we live in a world where under and over-nutrition are impacting seriously on human health, side by side in the same countries. If diets were changed and if waste in the food system were reduced, then not only could we feed the world on existing agricultural land, but it might also be possible to reduce inputs and the environmental damage current food production causes. Radical choices would need to be made for this to happen (Godfray and Garnett 2014). Evidence indicates this now must receive attention and that improved diets and decreases in food waste are essential to deliver emissions reductions and to provide global food security in 2050 (Bajželj et al. 2014). This would not just mean improving storage for crops (via small metal silos, hermetically sealed plastic storage bags and plastic crates) but potentially also policies to change food date labels to reduce consumer confusion about when food is no longer safe to eat (Lipinski et al. 2013).

We could focus on alternative sources of energy for agricultural intensification It is well recognised that modern agriculture was built on cheap fossil fuels to power not only on-farm operations, transport to and from farm of supplies and products, but more importantly, the embodied energy in fertiliser and to less extent pesticides (Steinbuks and Hertel 2013). A bag of synthetic nitrogen is a bag of energy. We overlook this at our peril. Utz (2011) provides a useful examination of energy in modern agriculture operated by smallholder farmers in the developed world. There are two main energy requirements for greater agricultural productivity in a market-oriented agriculture, provided by either renewable or conventional energy sources or a combination of both: energy for transport (fossil fuels or biofuels) for many services within the supply chain; and energy for production and processing. We need to be creative in how this energy is produced.

We could encourage more resilient and equitable trade regimes Trade plays a crucial role in allowing societies in conditions of food deficit to meet their demand through imports from other regions of the world. The amount of food calories traded in the international market more than doubled between 1986 and 2009, while the number of links in the trade network increased by more than 50 % (D'Odorico et al. 2014). This still only adds up to about 23 % of total food produced for human consumption being traded internationally (D'Odorico et al. 2014). Still, the fact that about one quarter of all food is traded suggest that global food security can be threatened not only by regional climate extremes (drought, flood, frost) but also by price volatility and changes in the food market (Headley 2010; D'Odorico et al. 2014). Almost 50 % of the net exports are contributed by only five countries: United States; Brazil; Argentina; Indonesia; and France (D'Odorico et al. 2014). Countries that strongly rely on trade are expected to be particularly vulnerable, especially if their economies are not strong enough to absorb the shocks of food price volatility in the global market (FAO-OECD 2011; D'Odorico et al. 2014). The urban poor in least developed countries are much more exposed to global food market prices than the rural poor. This is crucial given that many urban areas are now dependent on globalised food production and distribution networks, with a supply of food and water that would support their population for only a few days at most in an emergency (Pelletier et al. 2011). As urbanization increases, so does the likelihood that food price increases and fluctuations will lead to political and social instability (Godfray and Garnett 2014).

Many argue that the global trading system itself needs to be redesigned to maintain the economic viability of agriculture as well as environmental sustainability (Kissinger and Rees 2009). There have been calls for more diversified international supply chains with reduced reliance on a small number of agro-companies, for reformed international trade policies that are supportive of ecological agriculture, and for improved market access for developing country producers. Yet suggestions on exactly how to achieve this realistically are not easy to find nor are many decision makers willing to take on this particular political dynamite. In recent years, negotiations over market access and domestic support have not gone well and it is not likely that issues of free trade in relation to environmental and social sustainability will be addressed in the near future (Dibden et al. 2009).

We could choose to support smallholders and agriculture for development Agriculture at a global scale is an important source of food. At the local and national scales, particularly in developing and emerging countries, it is also an important source of income and economic growth (Pingali 2012). The choice to promote agriculture as a development pathway has been made by many nations, development agencies and organisations. However, agriculture for development does not necessarily have the same objectives as agriculture for food security. Indeed, food scarcity can be of greater economic benefit where producers can earn more from higher prices. If the choice is made to promote agriculture for development, this needs to be reconciled with alternative goals of food security and sustainability. Growing more food doesn't necessarily mean a better livelihood for farmers. Sustainable food production does not necessarily mean sustaining farmer's livelihoods or even farming communities.

Likewise, the industrialisation of agriculture doesn't necessarily mean a better life for smallholders either. As Holt-Gimenez and Altieri (2013) suggest, the expansion of industrial agriculture and the formalisation of associate markets for seed, land and other inputs has the potential to destroy the livelihoods of many smallholders. According to the FAO, agricultural growth involving smallholders, especially women, will be most effective in reducing extreme poverty and hunger when it increases returns to labour and generates employment for the poor (FAO et al. 2012). This may mean choosing a pathway that avoids greater mechanisation of agriculture. Or it could mean promoting diversified rural economies and markets and alternative opportunities for rural employment outside agriculture. Positive results can come from policies that support micro-enterprise development, which reduce reliance on land and provide alternative livelihoods that require less space (Muriuki et al. 2010).

Lastly, we need to pay attention to the marginal environments where many smallholders are located. Technologies in the Green Revolution period did not focus on the constraints to production in more marginal environments, especially tolerance to stresses such as drought or flooding. More often than not, marginal environments were left behind, because the climate and resource constraints were such that returns to investment in green revolution varieties were low (Pingali 2012). In Sub-Saharan Africa, high yielding varieties would often yield less than the traditional farmer varieties if grown under the conditions typical of smallholder cultivation (Sayer and Cassman 2013). Greater attention needs to be paid to the production challenges of agriculture in marginal and degraded areas.

We could choose a different paradigm We could shift from our current paradigm of productivity enhancement while reducing environmental impacts, to a paradigm where ecological sustainability constitutes the entry point for all agricultural development. If we embraced this new paradigm, sustainable governance and management of ecosystems, natural resources and earth system processes at large would provide the basis for practical solutions to intensification of agriculture and deliver the huge increase in food production required by a global population of nine billion. Such a paradigm could reposition world agriculture from its current role as the world's single largest driver of global environmental change, to becoming a critical part of a world transition to a safe operating space on our planet (Rockström et al. 2009; Rockström et al. 2010). This is our choice to make.

Conclusion

We have options in how we go about meeting the food security challenge. There are serious choices facing humanity that we haven't even begun to properly debate or address. We will need to make value judgements that cannot be avoided. The physical limits to intensification are not enough to constrain our behaviour and keep us in within the safe operating space of the planet. As is made clear by current and emerging trends, the visions of a sustainable or green agriculture are a long way from the trajectory that food and agricultural systems are on. Around the world, there is growing recognition of the importance of sustainability and the need to take immediate and sustained action to transform our agricultural and food systems is an imperative, particularly in the face of climate change. We have choices in how we go about producing food – choices that we need to face up to instead of waiting for limits to be imposed by nature, or hoping for crises to knock some sense in to us. Both will come too late. If the world decided it was ready to take serious action, what would be required? Social, environmental and economic considerations come in to play. Issues of livelihoods, rural development and health are central. There is no right answer. There are many choices, many possible scenarios and many system interlinkages to consider. We need to move forward.

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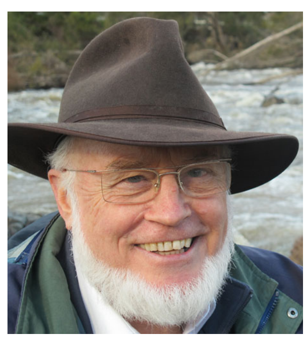

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